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Introducing the Default Effect: Reducing the Gap Between Theoretical Prediction and Actual Energy Consumed by Dwellings Through Characterising Data More Representative of National Dwellings Stocks

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Introducing the default effect:

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Abstract

Dwelling stock models that include the renovation status of the dwelling stock enable energy analyses of the stock. Using Ireland's predominant single-family housing typology as a case study dwelling, the overarching objective of this research is to define a transparent generalisable methodology to create a stock model from a large empirical Energy Performance Certification (EPC) database, employing reference dwellings (RDs) defined using a 'bottom-up' approach. RDs are to be reported in compliance with Regulation No. (EU) 244/2012. The generalisable methodology defined allows for the development of stock models from EPC datasets.

Where obtaining the required data would be prohibitively costly, nationally applicable default-values are used in EPC assessments. To ensure that dwellings are not assigned wrongly-higher energy ratings, worst-case base-thermal-default U-values are used which, in the absence of empirical data, are determined by building type and prevailing building codes at time of construction date. A structural 'default effect' error in the EPC data was identified.

It was found that 58 % of walls and 67 % of roofs had significant retrofits of insulation, leading to; (i) less association between a dwelling's age and its energy efficiency, and (ii) currently used default U-values being outmoded.

Outmoded default U-values; (i) decrease the credibility of both the EPC and its associated advisory report so inhibiting investment in energy efficiency, and (ii) lead to overestimation of potential residential energy savings, estimated at 22 % in post-thermal regulation dwellings and 70 % in pre-thermal regulation dwellings. To address this, generalisable methodologies have been developed to derive from an EPC dataset;

- i) statistically relevant contemporaneous default U-values,
- ii) a dwelling stock model derived from largely-default-free synthetically averaged RDs,
- iii) the renovation status of a dwelling stock,
- iv) a stochastically based energy-improvement payback calculation methodology, to be used where pessimistic default U-values are necessarily employed.

Use of the statistically-derived empirical data created will increase the validity and hence credibility of residential stock energy consumption models, the EPC, and its associated advisory report; enabling more valid quantification of the;

- a) energy saving potential within Ireland's predominant housing typology,
- b) effect of default U-value use on the prebound effect, and
- c) overall national building energy consumption.

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Declaration

I certify that this thesis which I now submit for the award of PhD is entirely my own work and has not been taken from the work of others, save and to the extent that such work has been cited and acknowledged within the text of my work.

This document was prepared according to the regulations for graduate study by research of Technological University Dublin (TU Dublin) and has not been submitted in whole or in part for another award in any other third level institution.

The work reported on in this thesis conforms to the principles and requirements of the University's guidelines for ethics in research.

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Signature Candidate

C. Ahern

Date 27th April 2018

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List of abbreviations

1S	Single Storey
2S	Two Storey
ACH	Air exchange rate per hour (h^{-1}) induced by wind of a normally exposed site between the inside and outside of the building, including the effects of air inlets
BER	Building Energy Rating
BREDEM	Building Research Establishment Domestic Energy Model
DEAP	Dwelling Energy Assessment Procedure
DHW	Domestic Hot Water
EPBD	European Performance of Buildings Directive
ESRI	Economic and Social Research Institute
EPC	Energy Performance Certificate
EU-27/28	Total EU member countries as of time of publication of referenced work
GRG	Generalised Reduced Gradient
IEE	Intelligent Energy Europe
INSHQ	Irish National Survey of Housing Quality
IWEC	International Weather for Energy Calculations
Low E	Low Emissivity
NEEAP	National Energy Efficiency Action Plan
PVC	Polyvinyl Chloride
ReEx	Real Example Building
ReAv	Real Average Building
RB	Reference Building
RD	Reference Dwelling
RSD	Ratio of standard deviation over the mean or relative standard deviation
SAP	Standard Assessment Procedure (UK)
SEAI	Sustainable Energy Authority of Ireland (formerly Sustainable Energy Ireland - SEI)
SyAv	Synthetically Average Building
TABULA	Typology Approach for Building Stock Energy Assessment
WMO	World Meteorological Organisation

Nomenclature

ACH_{20}	Air exchange rate per hour (h^{-1}) resulting from a pressure difference of 20 Pa between the inside and outside of the building, including the effects of air inlets
ACH_{50}	Air exchange rate per hour (h^{-1}) resulting from a pressure difference of 50 Pa between the inside and outside of the building, including the effects of air inlets
A_{exp}	Total exposed building fabric area (m^2)
A_f	Floor area (m^2)
A_{fg}	Ground floor area (m^2)
A_mA_f	Ratio of 'thermally massive' elements to total floor area
α	Statistical confidence level (%) indicates the probability that the value of a parameter falls within a specified range of values or Shape parameter of a gamma distribution function (statistics)
β	Scale parameter of a gamma distribution function (statistics)
d_w	Depth of wall (m)
e	Statistical margin of error expresses the maximum expected difference between the true population parameter and a sample estimate of that parameter.
εn	Emissivity of low E glass (ratio 0 to 1)
g-value	Solar transmittance value associated with glazing (ratio 0 to 1)
H_0	Null Hypothesis (statistics)
H_1	Opposite of the null Hypothesis or alternative hypothesis (statistics)
H_{TB}	Heat loss due to thermal bridging (W/mK)
IH	Coefficient representing effect of thermal inertia on the thermal building loads in the case of intermittent heating
Mtoe	Million tonnes of oil equivalent
μ	Statistical mean
N_p	Population size
N_s	Sample size
P_f	Floor perimeter (m)

P_f/A_{fg}	Floor perimeter to ground floor area ratio
P-value	Probability in statistics of obtaining the measured values if the null hypothesis is true (%)
q_{50}	Air flow rate required to maintain an indoor dwelling pressure of 50 Pascal's (Pa) above outdoor air pressure ($m^3/(h/m^2)$
R-value	Thermal resistance of a building element (m^2K/W)
ΣR	Sum of the thermal resistances of composite building elements (m^2K/W)
R_a	Thermal surface resistance of any air gap within a composite building element (m^2K/W)
R_{si}	Internal thermal surface resistance of a building element (m^2K/W)
R_{se}	External thermal surface resistance of a building element (m^2K/W)
R_f	Thermal resistance of a solid-ground floor (m^2K/W)
σ	Standard deviation (statistics) - measure used to quantify the amount of variation or dispersion of a set of data values.
TWh	Terawatt hours
UH	Coefficient representing effect of thermal inertia on the utilisation of free heat gains
U_m	maximum average U-value (W/m^2K)
U-value	Thermal transmittance coefficient that describes the rate of heat transfer (in watts) through one square meter of the building element divided by the difference in temperature across the element structure expressed in W/m^2K
V	Volume (m^3)
Y-value	Thermal transmittance coefficient that describes the sum of all the non-repeating thermal bridges divided by the total exposed area of the building envelope (A_{exp}), expressed as W/m^2K
λ	Thermal conductivity is measure of the rate at which heat passes through a uniform slab of unit thickness of that material or substance, when unit temperature difference is maintained between its faces (W/mK)
λ_g	Thermal conductivity of the ground (W/mK)
Ψ	Linear thermal transmittance coefficient (W/K)
X	Random variable, in probability and statistics, whose possible value is an outcome of random phenomena
$\bar{X}$	Mean of sample (N_s)

z-score	Standardised dimensionless quantity, in probability and statistics, indicating how many standard deviations (σ) a random variable (x) is away from the mean (μ)

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Chapter 1 – Introduction

"If you cannot measure it, you cannot improve it"

Sir William Thomson, Lord Kelvin

1.1 Policy Context

Households consume 27 % of end-use energy in the EU 28, second to transport at 32 % and followed by industry at 26 % [1]. New energy-efficient dwellings are only a small fraction of the total EU stock, so the thermal characteristics of existing dwellings dominate overall stock characteristics [2]. The extent and duration of the dominance of pre-existing houses depends on the construction rate, floor areas and specifications of new dwellings.

The long lifespans of buildings and infrastructures mean there are significant risks of undesirable sub-optimal or partial refurbishments being 'locked-in', rendering future energy performance improvements more difficult or expensive [10]. Understanding existing dwellings stocks, before making energy efficiency interventions, is therefore vital.

Hindered by a lack of investment in empirically-driven large-scale building monitoring projects [11-13], relevant research in buildings and energy is usually carried out on relatively small samples of buildings [9, 11]. Studies of trends and patterns in energy demand in buildings, that include simple descriptions of population and stock segmentations have been limited [9, 11, 12, 14], with little common [9, 15], transparent or prescribed data reported [9, 11, 12]. This absence of a robust detailed mulitvariate evidence base inhibits the effectiveness of policy frameworks [11, 16].
"Effective policy making starts with an accurate picture of the challenge" [17], research has recommended there should thus be [12-14, 18-21]:

- A strong foundation of evidence-based policies leading to strategies to achieve targets for energy demand, climate change, and other socio-economic goals.

- Robust evidence – "made up of the latest best-practice information drawn from relevant research that is properly designed, conducted, interpreted and presented; and drawn from inter-disciplinary activities that address the complex, contextually distinct and politically diverse nature of energy demand" [11].

1.2 Energy analysis of a building stock

Energy analyses of dwelling stocks combine a stock model and an energy model [10]. The stock model describes the stock size, composition and renovation status, whereas the energy model describes the average energy intensities of the various segments of the stock, and assumed energy savings obtained when dwellings are renovated [10]. Historically, building stock energy consumption models were informed by poor or outdated information attributed to [11, 12, 14, 18];

i) paucity of observed data,
ii) a lack of documented transparency around energy performance model inputs,
iii) a lack of prioritisation of the topic for research investment, and
iv) low influence of research on policy leading to regulations.

In recent years there has been a surge in the development and use of energy consumption models to depicting dwelling stocks [12, 22], this has been driven by policy [23] that seeks to reduce domestic energy use to;

a) lower greenhouse gas emissions,
b) reduce dependence on imported fuels,
c) reduce the cost of energy, and
d) contribute to quality of life, in particular alleviating fuel poverty.

The EU's main legislative tools to reduce energy consumption of buildings are the;

(i) 2010 Energy Performance of Buildings Directive (EPBD recast, 2010/31/EU) [24] that requires EU Members States (MSs) to set minimum energy performance requirements [25] for; (a) new buildings, (b) for the major renovation of buildings and, (c) the replacement or retrofit of windows, roof, wall, heating and cooling systems, and

(ii) 2012 Energy Efficiency Directive (2012/27/EU) [26] that requires EU MSs to include long term national building renovation strategies in their National Energy Efficiency Action Plans (NEAPP).

Multi-collinearity between factors make it difficult to isolate the greatest influences on dwelling energy consumption [27, 28] with one study finding half of the variability in energy consumption to be unexplainable [27]. The thermophysical characteristics of the building, climate and the building occupants' consumption of energy underlie domestic heat energy consumption [27, 29]. Heat energy consumption of residential buildings, in some parts of Europe, is considered dominated by building fabric characteristics [30-32]. In Ireland and UK, some studies show heating system efficiencies, primary fuel types and heat source (system characteristics) to have the greatest influence on energy consumption [33, 34] and carbon emissions of a dwelling [35] while others [11, 36] consider the building fabric to have the greatest influence. In many instances, both assertions may be valid but at different times depending on the prevailing weather and density of occupancy. This emphasises the importance of disaggregating thermophysical characteristic data when seeking to understand the consequential residential energy consumption drivers at a stock level [27, 37].

The average change in energy intensity of a total dwelling stock is gradual [37], changing over time due to complex interaction between prevalent;

- construction techniques [38],
- construction materials [38],
- costs of materials [39],
- costs of labour [39],
- architectural forms [38],
- heating systems [40],
- occupant comfort expectations [38],
- patterns of use of space within dwellings [41],

- use of appliances [42],
- economic factors [39],
- applicable building regulations [38], and
- retrofit interventions [43].

Modelling residential energy consumption can be;

a) Top-down – Historic cumulative energy assessments are regressed to determine the energy consumption of the dwelling stock as a function of high-level variables such as national energy statistics, gross domestic product, population and general climate data. Causal relationships are derived between determinants and energy consumption values. This approach does not distinguish between energy consumption due to individual end-uses. It is therefore less than ideal for modelling technical measures applied to predict future scenarios. Consequently, bottom-up models are preferred [44-47].

b) Bottom-up – The estimated energy consumption of a representative set of individual houses are extrapolated to regional and national levels to determine relationships between dwelling characteristics and energy use [44, 48]. Bottom-up approaches are classified broadly as statistical, engineering or a hybrid of both [49]. Statistical approaches use historical data to correlate relationships between energy end-uses and total energy demand. Engineering approaches, determine the end-use energy demands based on building geometry and thermophysical relationships. Bottom-up engineering models that explicitly address the effect of occupant behaviour and passive solar gains are thus most suited to considering thermal retrofit measures on residential housing stocks [44, 46, 47, 49].

EPBD energy refurbishments are to be assessed against cost-optimal criterion to [2, 50];

(i) ensure coherent, well-planned and ambitious minimum refurbishment standards that avoid 'lock-in' of low-cost but sub-optimal improvements, and
(ii) avoid over-investment in interventions that will not recoup their life-cycle costs.

The all-encompassing disaggregated thermophysical input data required to effectively inform bottom-up cost-optimality models is computationally intensive [51]. Since it has been impractical to calculate the cost-optimal interventions for every single building, the EPBD guidelines [52] requires each EU MS to define a set of reference buildings (RBs) that are representative of typical national or regional building stocks [43, 53, 54]. RBs are used to produce overall energy saving extrapolations consistent with those produced if the detailed characteristics of the overall building stock were used [43, 53, 55].

Use of dynamic simulation programmes to model RBs facilitates [16];

i) the identification of sensitive parameters important to overall performance,
ii) through changing such parameters, forecasting the consequences of specific scenarios or policy-interventions,
iii) policy-makers in preparing substantive arguments for particular building designs and insight-driven policies,
iv) through first using the dynamic models created for use at RB or end-use level and then aggregating upwards, researchers and policymakers to observe, analyse and resolve energy use and environmental performance with greater ease.

Accordingly, appropriate RB characterisation is a prerequisite for an overall national building energy consumption model to produce valid outcomes [51]. The characterisation should ideally be;

a) based on high-quality empirical data [9, 11, 12, 42, 56, 57],
b) derived from statistically significant sample sizes [20],
c) as contemporaneous as possible [56],
d) a result of transparent and appropriate processes [11, 42, 58, 59].

The building stock will be reflected more validly when a higher number of RBs are used [52]. The effectiveness of use of RBs therefore depends on the;

(i) number of building subcategories employed [60],
(ii) level of detail in defining the RB [54],
(iii) validity of the information used to characterise the RB [54, 58, 61],
(iv) proper selection of default data and/or the terms of reference [43, 51, 61].

Directive 2002/91/EC of the EPBD mandates comparable energy performance classifications, in the form of Energy Performance Certificates (EPCs), be issued for buildings constructed, sold or leased across the European Union [62, 63]. The EPC energy performance assessment procedure quantifies the detailed empirical information regarding a national dwelling stock by presenting statistically significant thermophysical databases. These databases can be exploited to empirically inform the characterisation of contemporaneous RBs [43, 64], leading to national building stock energy consumption models across Europe.

RBs are required for new and existing buildings in the following building categories [24]; (i) single-family dwellings (including detached, semi-detached and terraced typologies), (ii) apartment blocks/multi-family buildings and (iii) office buildings. Single-family dwellings constitute nearly half (49.4 %) of the total building floor area in the EU [65] while households consume a little over a quarter (27 %) of end-use energy in the EU 28 [1].

Just over one third (34 %) of the EU 28 population lived in detached single-family houses in 2013 [43]. Detached dwellings, with relatively high surface area to volume ratios, generally exhibit larger heat losses than other dwelling types of the same construction period [51]. Detached dwellings tend to be heated for longer than other types [57] with higher cost of heating to a given comfort level [66]. Detached dwellings are therefore targeted in energy-efficiency retrofit programmes [57, 67, 68].

1.3 Case study dwelling typology

As shown in Figure 1, Ireland's predominant house typology, comprising 31 % of the pre-2006 stock, are rural detached, single-family dwellings. This dwelling typology was chosen as a representative case study reference dwelling as:

i) 67 % of European housing was built prior to 1980 [69], before the introduction of meaningful thermal building regulations for the housing sector. Mirroring this, 70 % of Irish detached dwellings were constructed before the mid 1970's when constructional changes caused primarily by amendments to draft or actual building thermal regulations led to increased levels of thermal insulation [39, 43, 70-72].

ii) As is shown in Figure 2, whilst Ireland has the highest proportion (circa 90 %) of single-family dwellings in Europe, UK, Greece, Norway and The Netherlands have similar profiles [43].

iii) The mean-weighted-average heated floor area[1] of an Irish detached dwelling is approximately twice the average European floor area at 149m^2 [69]. As roof and wall areas are a direct function of floor area, detached dwellings have relatively high surface area to volume ratios and generally exhibit larger heat losses than other house types of the same construction period [51].

i) Detached dwellings in Ireland have a stronger association with fuel poverty than other dwelling types due to;

a) a higher cost of heating them to a given comfort level [66],

b) being classified as 'hard to treat[2]' [73],

c) having a higher proportion (88 %) of middle-aged (50 -64 year olds) and older adults (aged 75 and over) compared to those living in and around the country's capital (16 %) or other towns or cities (38 %) [68]. Older adults [68];

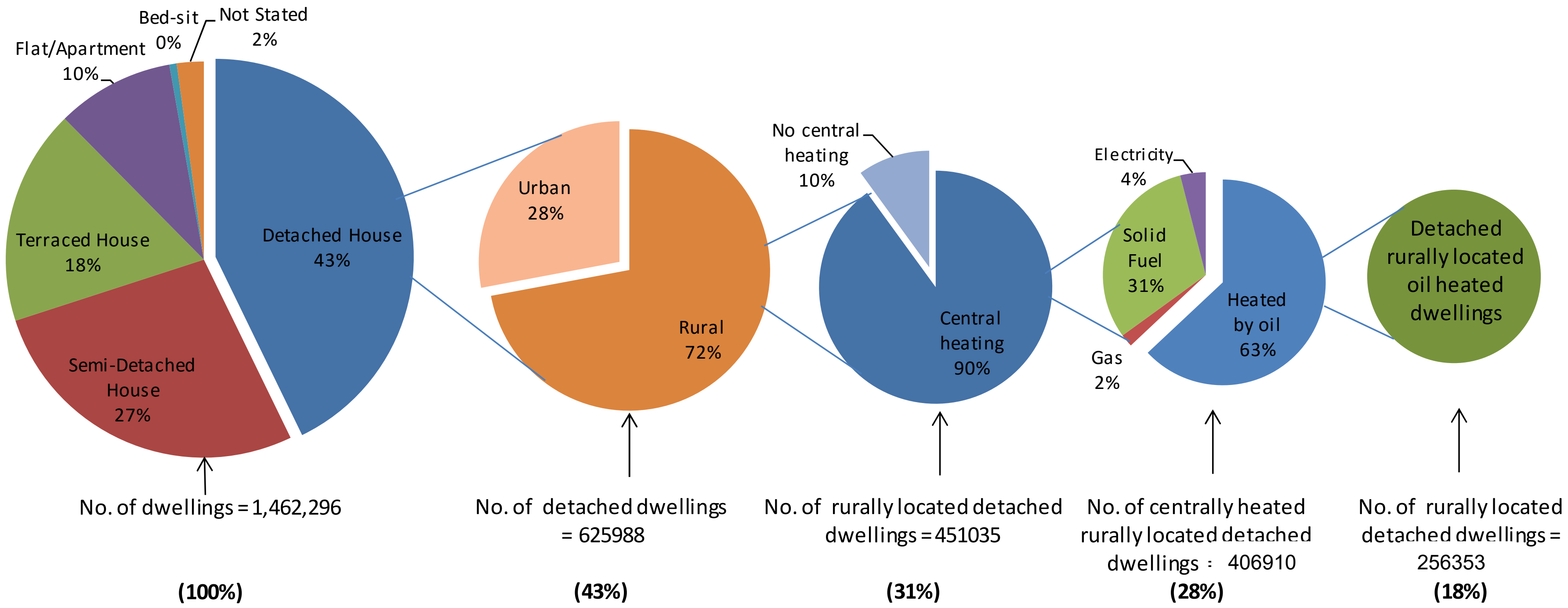
- spend more time at home than younger adults,
- are more likely to live in homes built before 1970 and so with lower thermal insulation standards than younger age groups[3],
- have a higher likelihood of living alone which puts them at risk of experiencing difficulty maintaining and heating their home, whilst
- sedentary older adults prefer a minimum of a 2-3 °C higher internal temperature over the 18 °C minimum temperature recommended by the World Health Organisation.

[1] Mean (μ) of the sum of the floor areas by period of construction (m^2) weighted by dwelling quantity per period of construction (N) given by the following equation; Mean weighted floor area = μ x ∑ [Floor area (m^2) x dwelling quantity by period of construction (N)]

[2] Dwellings with solid walls, off the gas network or with no loft

[3] 69 % of those aged 75 and over versus 53 % of 65-74 year olds and 36 % of 50-64 year olds

Figure 1 Number of Irish dwellings by type[4] [71]



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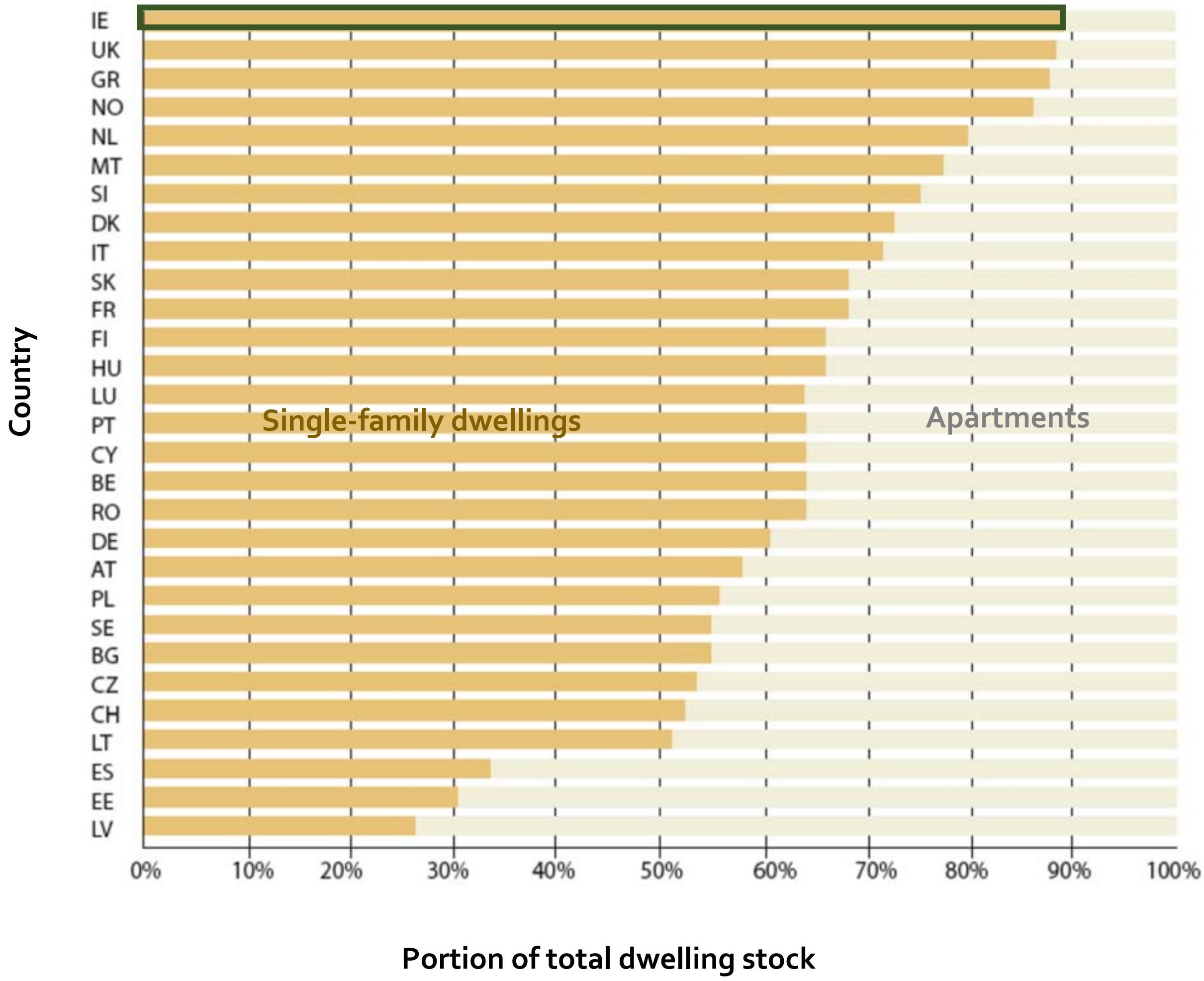
[4] To allow quantification of default effect by comparison to previous study detailed in Chapter 8 Future Work (Ref: Figure 48), 2006 census data was used. Figures for 2016 census [74] CSO, Profile 1: Housing in Ireland, in: C.S.O.o. Ireland (Ed.), Cork, Ireland, 2016. ; Total number of dwellings 511, 787 (+60,752), no central heating 1 %, Heated by oil 68 %, Gas 2 %, Electricity 2 %, Solid Fuel 24 % , other and not stated 2 % .

Figure 2 Distribution of single-family and apartment buildings in Europe [17]



The European Commission developed a common reporting methodology (Regulation No 244/2012) for RDs to address, (i) the lack of transparent reporting, (ii) to allow comparison of dwelling stocks across EU member states, and (ii) to allow cost-optimal refurbishment interventions for the housing stock to be developed.

EPCs in Ireland are generated through a methodology embodied in the national Dwelling Energy Assessment Procedure (DEAP) software programme administered by the Sustainable Energy Authority of Ireland (SEAI). SEAI made this detailed national empirical dataset publicly available in 2014 [75]. 463,582 dwellings representing 31.7 % of the total dwelling stock constructed up to 2006 received an EPC by August 2014 [76].

1.4 Methodology

Using Ireland's predominant single-family housing typology as a case study dwelling, the overarching objective of this research is to define a generalisable transparent methodology to create a stock model from a large empirical EPC database employing reference dwellings (RDs) defined using a 'bottom-up' approach. RDs created are to be reported in compliance with the EU common reporting methodology (Regulation No. (EU) 244/2012 [55]). The generalisable methodology defined allows for the development of stock models from EPC datasets.

Both the methodology developed and the stock model created enable building energy analysts, engineers, scientists, statisticians and personnel involved in planning, building development and national retrofit strategies, to;

- identify where potential exists for improvement in energy efficiency,
- perform quick "what-if?" analyses,
- optimise regulations and market incentives to achieve specific targets,
- analyse how energy retrofit intervention policies influence greenhouse gas emissions or energy demand, and
- develop research priorities for dwellings, particularly single-family dwellings.

The overarching methodology used to describe a building stock through RDs from an empirical database is adapted from [22, 77]. The methodology follows four distinct stages:

1. **Segmentation** by housing typology (by common characteristics such as heating type, period of construction etc.).
2. **Analysis** of single field (microscopic) empirical building data.
3. **Characterisation** of (macroscopic) RDs.
4. **Aggregation** of RDs to stock level.

To ensure that RDs created, represent correctly, the real world constructs to which they refer, at each methodological stage, the data and the information resulting from the data is assessed to verify an acceptable level of data consistency before proceeding to the next stage [78].

1.5 Organisation of thesis

Chapter 2 details the methodological stages 1 and 2 – segmentation, analysis and validation of microscopic data as well as methodological approaches to ensure a certain level of quality in the final microscopic data [79, 80] and hence in the validity of macroscopic information (in the form of reference dwellings) resulting from the data.

Chapter 3 explores a structural data error discovered in the EPC dataset during the data validation process identified as the 'default effect'. The implications of this default effect on the results of the EPC methodology and on the quality of data within the EPC dataset is discussed. The renovation status of the stock and the level of compliance with thermal building regulations is also assessed in Chapter 3.

Chapter 4 expresses the methodological stages 3 and 4 relating to the characterisation of reference dwellings described in terms of operation, form (geometry), thermal and system characteristics. Chapter 4 also outlines how the reference dwellings characterised were aggregated to stock level.

Chapters 2, 3 and 4 outline the methodologies particular to the specific objectives outlined within the chapters. Chapters 3 and 4 also contain the results, discussions and conclusions relating to the chapter objectives.

Chapter 5 outlines the limitations of this study. Chapter 6 draws together summary discussions and recommendations while overall conclusions are summarised in Chapter 7. Chapter 8 outlines possibilities for future study arising from this work.

Chapter 2 –Segmentation, analysis and validation of Dataset

2.1 Introduction

"If you are not thinking segments, you're not thinking"

Levitt, T. [81]

The overarching methodology used to describe a building stock through RDs from an empirical database is adapted from [22, 77]. As outlined in Chapter 1, the creation of a stock model through RDs follows four distinct methodological stages: 1) Segmentation, 2) Analysis 3), Characterisation and 4) Aggregation.

The effectiveness of use of RDs depends on the validity of the information used to characterise the RD [54, 58]. As stated in Chapter 1, at each of the stages, the data and the information resulting from the data must be validated. Data validation ensures final data quality [79, 80], that can be deemed high quality when correctly representing the real-world construct to which it refers [78]. Data validation is defined by Eurostat [79] as an "an activity verifying whether or not a combination of values is a member of a set of acceptable combinations".

This chapter describes the segmentation, analysis and validation of the microscopic single-field data within an EPC database before the data can be characterised into macroscopic reference dwellings. The chapter objectives are to:

1) Assess the quality of microscopic field data within the EPC Dataset.
2) Segment the dataset by dwelling typology or 'archetype'.
3) Validate the segmentation as being a statistically significant representation of the dwelling typology-at-large.
4) Remove any structural data errors identified (as opposed to one-off outliers).
5) Validate the dataset.

In order to validate the data, the research reported in this chapter:

a) Reviews the literature to discuss data validation and data validation techniques.
b) Reviews the quality assurance mechanisms for EPC data collection in Ireland.
c) Presents the frequency distributions of thermal transmittance coefficients or U-values (W/m^{2}K) by period of construction for dwellings walls, roofs and floors.
d) Discovers a data anomaly and investigates this anomaly to find it relates to thermal-default selection by the dwelling assessor.
e) Describes the method for, and comments on, default selection in the EPC methodology.
f) Reviews the literature to establish vernacular characteristics of Irish dwellings.
g) Comments on default use in EPC assessments and its relationship to the energy performance gap wherein the theoretical or rated prediction and actual measured energy consumption in homes can differ greatly.
h) Establishes a structural data error identified as the 'default effect'.
i) Through data quality checks and measures, verifies an acceptable level of data consistency, removing the structural data error relating to thermal-default use.
j) Summarises data quality checks and measures undertaken to ensure quality in the final data.
k) Accepts data suitable for the characterisation of the reference dwelling.

2.2 Validation of data and information

"If you torture the data long enough, it will confess"

Coase, R.H [82]

Data quality results from intrinsic characteristics of the data accuracy, coherence, compatibility, clarity and accessibility [80];

- Accuracy - defined terms of "accepted range of deviation" refers to the absence of substantial errors or, in other words, to the closeness of results to the 'truth' or to the 'real' value of the phenomenon measured. Consistency checks (see Table 1 and Figure 3) can identify values that do not comply with well-defined logical or other kinds of empirically defined conformity rules. The identified outliers (lying out of the expected or usual range of values) are potential errors.
- Coherence and comparability - statistics should be consistent internally, over time and comparable between regions and countries. Quality checks test the internal *coherence* of a single statistical output (for example arithmetic relations between variables) or the *comparability* of its results over time or over space. Consistency and comparability can also be tested between two or more different statistical outputs (domains): in this case, the possibility of developing quality checks depends on the degree to which the different statistical providers make use of the same harmonised concepts (definitions, classifications relating to period of construction, etc.).
- Clarity and accessibility – data should be comprehensible by infrequent users that typically make up the majority of dataset users [83].

Data validation;

- is the practice of ensuring that data has undergone data cleaning[5]. Data cleaning is a process of detecting, diagnosing, and removing errors and inconsistencies from data in order to improve the quality of the data [84, 85].

[5] also referred *data cleansing* or *scrubbing*

- "aims at verifying whether data have a certain level of quality", what it verifies is an acceptable level of data consistency (a positive outcome will not guarantee that the data is correct, but a negative outcome will guarantee that the data is incorrect) [79].
- is a decisional procedure ending with an acceptance or refusal of data as acceptable [79, 84, 85].

Acceptance of the data infers it is valid for the final use it is intended for. As stated previously, the overarching objective of this work is to define a generalisable methodology to create a stock model from a large empirical EPC database employing reference dwellings (RDs) defined using a 'bottom-up' approach. The stock model created will inform a national dwelling stock energy consumption model.

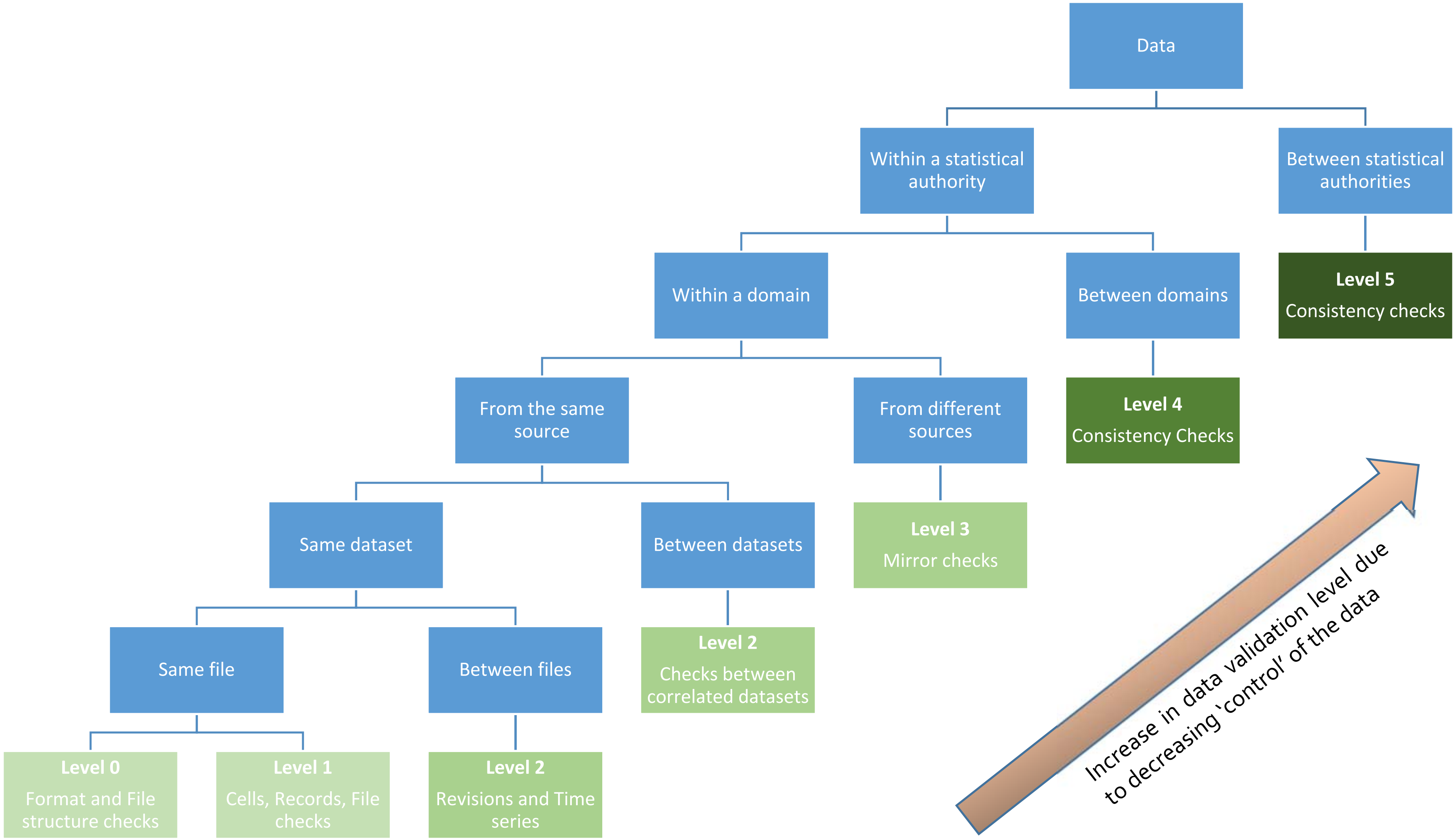
Eurostat [79, 80] outline 6 levels of validation, levels 0 to 5, described in terms of consistency (see Table 1), as shown in Figure 3. The classification of validation levels presented implies a growing degree of complexity and a lesser 'control' of the data from one level to another.

Table 1 Levels of data validation [79]

Level	Consistency of data:	Note:
0	With the expected information technology structural requirements	Data is accessible and can be easily and correctly interpreted.
1	Within the dataset	Data is checked for consistency within the elements of the dataset, for instance – check whether the number included in column four is not negative (as expected).
2	With other datasets within the same domain[6] and within the same data source	Includes time series checks, data is checked for consistency across periods of construction to identify structural errors (as opposed to one-off outliers).
3	Within the same domain between different data sources	Includes mirror checks to verify consistency between declarations from different sources referring to the same phenomenon.
4	Between separate domains collated by the same statistical authority	Availability of data implies a certain level of 'control' over the methodology and the data.
5	With data of other statistical authorities	Implies 'no control' over the methodology or the data.

[6] A domain is defined as a set of information and data covering a certain topic.

Figure 3 Quality checks for consistency of data with corresponding data validation levels [80].



2.2.1 Quality of the microscopic field data within the EPC dataset

EPCs in Ireland are generated through a methodology embodied in the national Dwelling Energy Assessment Procedure (DEAP) software programme administered by the Sustainable Energy Authority of Ireland (SEAI). SEAI made this detailed national empirical dataset publicly available in 2014 [75]. DEAP requires EPC assessors to gather the disaggregated thermophysical properties necessary to an energy performance calculation.

The quality of data delivered by assessors is central to the reputation and effectiveness of the EPC scheme, to fulfilling legal obligations to the building owner, and for stimulating action to improve the energy performance of buildings [86].

As the issuing authority responsible for the EPC scheme and as part of an overall suite of provisions governing the registration and performance of EPC assessors (EU EPBD Regulations 2012, S.I. No 243/2012 [87]), SEAI has put in place a quality assurance system for assessors and a related disciplinary procedure pursuant to its powers under EU regulations. Through system and procedures, SEAI seek to uphold the quality of the database through the technical competence and professional conduct of assessors [86].

The overall approach by SEAI to the quality assurance of assessments consists of a combination of [86]:

i) Entry (upstream) measures, for instance to register with SEAI, assessors must;
    - have a level 5 higher certification on the European Qualification Framework (EQF) in construction studies or similar,
    - have completed a training course and passed a state examination,
    - be insured, have a relevant tax clearance certificate and provide appropriate state issue identification,
    - agree to the SEAI Code of Practice [88].

ii) In-line delivery measures, for instance, validation rules on the EPC register and feedback (downstream) measures.

The objective of the code of practice [88] is to ensure that assessors have a clear understanding of their obligations to deliver a high quality service in the marketplace. An assessor is required to act with integrity and diligence to ensure that each assessment is executed competently, in an independent manner and in accordance with the Regulations [89], the Code of Practice [88] and any other directions issued by SEAI. An assessor is responsible for ensuring that, within reason, the data compiled and inputted to DEAP software, and all related and recorded calculations are an accurate representation of characteristics relevant to the energy performance of the dwelling, and are capable of being verified as such in any subsequent monitoring and compliance processes commenced by SEAI.

SEAI engage, as a matter of routine, in monitoring and auditing activities to verify compliance by registered assessors. These activities provide a basis upon which to monitor the effectiveness of the Scheme, to protect the integrity of the Scheme and to ensure continual improvement of the Scheme [88]. The overarching objective of the quality assurance system is to ensure widespread operation compliance with the code of practice prevailing. Other objectives include [86, 90]:

- Improving the knowledge base of assessors by providing feedback and direction on technical findings on an individual or collective basis, in respect of common clarification issues, sources or error or misunderstanding.
- Identifying potential priority areas for additional focus in the training provided to assessors.
- Identifying requirements for the creation of automated in-line validation boundary values when uploading files to the register.
- Informing the decision-making process on selection of assessors for more detailed or intensive auditing.
- Informing the decision-making process on corrective action required, including, where appropriate, disciplinary action.

Approximately 500 registered assessors published circa 98,000 residential EPCs in 2017 [90, 91]. All registered assessors and all published/currently valid EPC assessments are subject to audit. EU legislation [87] requires that 2 % (circa 1,960) of all dwelling assessments be audited, this requirement was met by SEAI in 2017 [90]. Selection of EPC assessments for audit is on both a targeted and random basis. In 2017 circa 80 % of assessment audits (circa 1574) were on a targeted basis and 20 % (circa 386) were on a random basis. As EPC assessment audits are carried out both on a targeted and random basis, assessors publishing regularly can expect to receive more audits. There are two types of audits as detailed below [86, 90-92]:

a) Desk review or documentation and practice audits. Such audits may require provision of evidence/substantiation by an assessor in support of data inputted. In 2017, circa 551 or 0.6 % assessments were audited in this manner.

b) Additional document requests and best-practice audits based on a frequency reflecting the number of EPCs published, length of time since last assessment published, complaints or other indicators. Such audits are intensive, entailing detailed inspection at the site of the dwelling subject to the assessment, in the presence of the assessor. These audits are aimed at reviewing an assessor's compliance, and the process audits comprehensively, all relevant aspects of assessor's activities. A number of the assessor's assessments can be audited to determine if any error patterns exist. In 2017, circa 1,409 or 1.4 % assessments were audited in this manner.

To ensure issues from previous audits have been adequately resolved, SEAI carry out routine follow-up audits. Findings on non-compliance lead to an accumulation of penalty points and/or revocation of the relevant EPC data files. Accumulation of penalty-points may lead to suspension and/or termination from the register. The objective basis for the disciplinary process is the classification of non-compliance relative to the transgression's impact on the integrity of the data and hence the accuracy of the rating and the database. In 2017, no assessors merited termination, however some were suspended for two months at a time with all returning to publishing on return [90].

SEAI also run a successful mentoring programme that endeavours to ensure that all EPC assessors participate, but particularly EPC assessors who (i) registered recently for the first time, (ii) have not carried out assessments for more than 12 months or (iii) have been subject to suspension [90]. As this audit is designed to educate and support, it carries no penalty, thus, even the busiest, most consistent assessors are reported to appreciate this type of audit [90]. Even in an advisory audit, the EPC will be revoked if errors are found [90].

Auditing is a key tool through which quality control of EPC assessors is implemented. The aim of the SEAI EPC audit programme is to identify technical, procedural or system issues and errors in a timely manner so that as appropriate [86]:

- Any issues or errors identified in published assessments can be corrected or other suitable action taken.
- Such issues or errors are avoided in future through;
  - feedback directly to the EPC assessors concerned and to other EPC assessors, and
  - disciplinary action.

Given this, the data within the EPC dataset is considered valid to Level 1, as shown in Figure 3 and described in Table 1. As referred to previously, data validation is a process and is necessary at all stages in the methodology outlined. Higher levels of validation are realised in the following chapters.

2.3 Segmentation of EPC Dataset

"To be useful, segments must be measureable, substantial, accessible, differentiable, and accountable"

Kotler, P. [93]

The definition of reference buildings belonging to a climatic area, construction age and building size is developed generally via three different methodological approaches [53]:

1. The "Real Example Building" (*ReEx*) approach identifies the building type by means of experience. The building type is selected by a panel of experts within an actual climatic context as the most representative of specific size by period of construction. This approach is applied when statistical data is unavailable.
2. The "Real Average Building" (*ReAv*) approach identifies the building type through the statistical analysis of a large building sample. Analysis is performed to find a real building mirroring the characteristics of mean geometrical and construction features of the statistical sample.
3. The "Synthetical Average Building" (*SyAv*) approach identifies the building type as an "archetype" based on the statistical analysis of a large building sample. The "archetype" is defined as "a statistical composite of the features found within a category of buildings in the stock" [94]. The archetype is not a particular building, it is a notional building characterised by a set of properties detected statistically in a category of buildings [22, 38, 95-97].

The approach adopted in this work is to employ a large, empirical and contemporaneous sample EPC dataset, where available appropriate, to create SyAv reference dwellings representative of this dwelling typology at stock level.

EPCs in Ireland are generated through a methodology embodied in the national Dwelling Energy Assessment Procedure (DEAP) software programme administered on behalf of the state by the Sustainable Energy Authority of Ireland (SEAI). SEAI made this detailed national empirical dataset publicly available in 2014 [75]. 463,582 dwellings representing 31.7 % of the total dwelling stock constructed up to 2006 which had received an EPC by August 2014 were downloaded from the SEAI website into Excel® [76].

A detailed analysis of the segmentation is detailed in Appendix A; in summary 25 % (N=116,354) of the dwellings within the database are detached dwellings, this figure mirrors the percentage of centrally heated detached dwellings nationally (28 % in 2006 census – see Figure 1). 60 % of detached dwellings within the database are rurally located while an average of 76 % (19 % nationally) of those are heated by fuel oil [76]; this distribution also mirrors the percentage of oil-heated detached dwellings nationally (18 % - see Figure 1). 97 % of detached dwelling are either single or two-storey while 98 % are naturally ventilated [76].

As shown in Figure 1, rural, single and two-storey, oil centrally-heated and naturally-ventilated dwellings, accounting for 18 % of the dwelling stock nationally and 63 % of detached dwellings are the predominant and hence the SyAv dwelling type in Ireland. Accordingly, dwellings consistent with these prevalent characteristics were isolated from the larger dataset as described in Appendix A. Dwellings carrying a 'provisional' certificate were also filtered. As shown in Table 2, this resulted in a sample of 50,236 dwellings representing 12.35 % of the detached dwelling typology nationally.

Table 2 Frequency of detached dwellings in representative empirical dataset compared with actual dwelling frequency by period of construction [71, 76]

			Actual number and percentage of detached dwellings nationally (CSO dataset)		Sample number and percentage of detached dwellings in empirical EPC dataset		Margin of error at confidence level of 99 %
			N (Population)	%	N (Sample)	%	
Period of Construction	Post-thermal regulation	2005-2006	21910	5%	3693	7%	2%
		2000-2004	52764	13%	8867	18%	1%
		1994-1999	45694	11%	7080	14%	1%
		1983-1993	60233	15%	8375	17%	1%
		1978-1982	29817	7%	5695	11%	2%
	Pre-thermal regulation	1967-1977	52457	13%	6559	13%	1%
		1950-1966	32245	8%	3662	7%	2%
		1930-1949	32453	8%	2110	4%	3%
		1900-1929	34552	8%	2901	6%	2%
		< 1900	44784	11%	1294	3%	4%
	Total/%		406910/100%		50236/100%		

2.3.1 Statistical significance of segmented EPC dataset

As described by Equation (1), margin of error (e), z-score (z) and standard deviation (σ) measure how well a sample (N_s) represents a population (N_p) [98];

$$Sample\ size\ (N_S) = \frac{\frac{z^2 \times \sigma(1-\sigma)}{e^2}}{1+\left(\frac{z^2 \times \sigma(1-\sigma)}{e^2 N_p}\right)} \qquad (1)$$

Where;

σ - Standard Deviation; is a measure used to quantify the amount of variation or dispersion of a set of data values [99]. A low standard deviation indicates that random variables (X) tend to be close to the mean (μ) within a statistical population, data set or probability distribution (N), while a high standard deviation indicates that random variables are spread out over a wider range of values. The standard deviation of a random variable (X) within a statistical population, data set or probability distribution (N), is the square root of its variance, given by Equation (2) [99];

$$\sigma = \sqrt{\frac{\sum(X-\mu)^2}{N}} \tag{2}$$

z-score – is a standardised dimensionless quantity indicating how many standard deviations (σ) a a random variable (X) is away from the mean (μ), obtained by subtracting the population mean (μ) from a random variable and then dividing the difference by the population standard deviation, given by Equation (3) [99] ;

$$z = \frac{(X-\mu)}{\sigma} \tag{3}$$

e - Margin of error expresses the maximum expected difference between the true population parameter and a sample estimate of that parameter. The margin of error of a sample dataset (N_s) of a given population (N_p) is given by Equation (4)[7] [99];

$$e = \sqrt{\frac{z^2 \times \sigma(1-\sigma) - \frac{N_S[z^2 \times \sigma(1-\sigma)]}{N_p}}{N_S}} \tag{4}$$

To be meaningful, the margin of error is qualified by a probability statement expressed as a confidence level (α) [99]. Confidence level indicates the percentage level of uncertainty with a statistic [99]. Generally, the larger the sample size, the more statistically significant it is, meaning there is less of a chance results of a survey happened by coincidence. A 100 % confidence level means there is no doubt that if the survey was repeated the same results would be returned. A 100 % confidence level doesn't exist in statistics, unless the entire population was surveyed — and even then it is unlikely that the survey was not open to errors or biases [100].

[7] Equation (1) rearraged in terms of 'e'

A confidence level for a given mean value (μ) of a population (N_p) can be calculated using Equation (5) [99];

$$\bar{X} \pm z\frac{\propto}{2} \times \frac{\sigma}{\sqrt{Np}} \qquad (5)$$

where $\bar{X}$ is the mean of the sample (N_s) and α is the desired percentage confidence level.

Based on Equation (5), a standard normal table or Z-table is a mathematical table that returns z-scores for desired confidence levels, an extract of which is shown in Table 3.

Table 3 Z-scores and desired confidence levels [98]

Desired Confidence Level (α)	z-score
80 %	1.28
85 %	1.44
90 %	1.65
95 %	1.96
99 %	2.58

"Acceptable" margins of error fall between 4 % and 8 % at a 95 % confidence interval [101].To ascertain whether the segmented sample population (N_s) of 50,236 detached is representative of the entire population (N_p) of 406,910, the margin of error at a 99 % confidence level (z-score 2.58 from Table 3) for each period of construction was calculated using Equation (4) with results shown in Table 2.

$$e = \sqrt{\frac{2.58^2 \times 0.5(1-0.5) - \frac{50,236\,[2.58^2 \times 0.5(1-0.5)]}{406,910}}{50,236}} \qquad (6)$$

A value of 0.5 (50 %) for standard deviation (σ) was chosen for input to Equation (4) as this is the worst-case scenario percentage so guaranteeing that the margin of error calculated is worst-case.

Table 2 shows EPCs to have been carried out on older dwellings less frequently than newer dwellings. This reflects older dwellings changing ownership less often, meaning that older dwellings are somewhat less represented than newer dwellings. Notwithstanding all margin of errors are acceptable.

Table 2 demonstrates that the sample number and percentage of detached dwellings in the empirical dataset mirror checks with the actual number and percentage of detached dwelling nationally. The relative sample sizes in the refined dataset are thus consistent with the national distribution of detached dwellings by period of construction published by Ireland's national statistics office [71, 76]. The segmented dataset is thus accepted as being representative of the detached dwelling stock-at-large.

2.3.2 Heating fuel source by period of construction

Whilst typically 2 in 3 (63 % see Figure 1) of the SyAv detached dwelling in Ireland is heated by oil, the balance, approximately 1 in 3 (31 % see Figure 1) of rurally located dwellings were heated by solid-fuel in 2006 [71]. The amount of dwellings heated by solid-fuel has reduced to an average 1 in 4 households (24 %) in 2016 [74]. The use of solid-fuel in Ireland is too high to average out in favour of simplification of the model. The relative proportions of heat fuel source by period of construction of EPC assessed dwellings are shown in Table 4.

As the data within the EPC dataset is shown to correlate with the distribution of detached dwellings nationally, it was expected that the large percentage (31 %[8] in 2006, 24 % in 2016) of solid-fuel dwellings returned by the CSO dataset would correlate with the number of solid-fuel heated dwellings returned by the EPC dataset. However, as shown in Table 4, the EPC dataset returns a weighted average of 8 % of rural detached dwellings heated by solid-fuel. This lower figure correlates with EPC data (6 % *all dwelling types* in Q4, 2017) published by the same statistical authority [102] and may, to some extent, be attributable to the older dwellings being somewhat less represented in the EPC dataset. As more data is added to the EPC database it is expected that this discrepancy will lessen. This is discussed further in Chapter 5 (Section 5.1). Unexpectedly, the EPC dataset also suggests a step-increase, after 1994, in the proportion of gas heated detached dwellings (see Table 4 and Figure 3)

[8] Of the 31% is 9 % "open-fire only" with 22 % being central heated by "stove/cooker"[39] Ahern, An investigation into the retrofitting of air source heat pumps into fabric improved, detached, oil centrally heated dwellings in rural Ireland, MSc., School of the built environment, Ulster University, 2010.

Table 4 Central heating fuel source by year of construction for detached rural dwellings in Ireland (as suggested by EPC dataset) [76]

		Period of Construction																			
		pre 1900		1900 - 1929		1930 - 1949		1950 - 1966		1967 - 1977		1978 - 1982		1983 - 1993		1994 - 1999		2000 - 2004		2005 - 2006	
Central heating fuel source	Coal (incl. Anthracite)	26	1%	76	2%	46	2%	57	1%	34	0%	34	1%	47	0%	19	0%	10	0%	1	0%
	Liquid Petroeum Gas (LPG)	45	2%	72	2%	42	1%	53	1%	141	2%	145	2%	383	4%	143	2%	255	2%	199	4%
	Electricity	198	11%	408	10%	232	8%	263	6%	241	3%	107	2%	218	2%	317	3%	343	3%	282	6%
	Oil	**1248**	**68%**	**2845**	**70%**	**2032**	**72%**	**3496**	**76%**	**6202**	**83%**	**5502**	**85%**	**8131**	**80%**	**6959**	**76%**	**8791**	**78%**	**3661**	**74%**
	Natural Gas	33	2%	67	2%	82	3%	223	5%	439	6%	356	5%	844	8%	1554	17%	1696	15%	748	15%
	Smokeless Coal	3	0%	13	0%	8	0%	8	0%	8	0%	4	0%	4	0%	4	0%	3	0%	1	0%
	Peat (incl.turf)	36	2%	48	1%	37	1%	57	1%	63	1%	44	1%	52	1%	11	0%	6	0%	2	0%
	Solid multi-fuel	***233***	***13%***	***518***	***13%***	***331***	***12%***	***400***	***9%***	***320***	***4%***	***263***	***4%***	***399***	***4%***	***174***	***2%***	***139***	***1%***	***23***	***0%***
	Wood (incl. wood pellets)	21	1%	27	1%	22	1%	22	0%	28	0%	26	0%	37	0%	27	0%	26	0%	54	1%
	Sample set N/%	1843	100%	4074	100%	2832	100%	4579	100%	7476	100%	6481	100%	10115	100%	9208	100%	11269	100%	4971	100%
	Proportion solid-fuel N/%	**319**	**17%**	**676**	**17%**	**443**	**16%**	**543**	**12%**	**446**	**6%**	**366**	**6%**	**523**	**5%**	**229**	**3%**	**179**	**2%**	**48**	**2%**

To validate the proportion of heating fuel source by period of construction recourse to the Census of Ireland, 2016 (N = 511,787), published by the Central Statistics Office (CSO) was sought (see Table 5). Referring to Table 5, the CSO data in 2016 correlates the high use of oil as a heat source (68 %), followed by solid-fuel (24 %) with peat (13 %) listed as the highest use solid-fuel. Notably, peat use in the EPC database is not recorded as being as significant as is indicated by the CSO dataset. This is because when a heat generator is capable of using more than one fuel source, the EPC Assessor classifies the fuel source as "solid multi-fuel". Multi-fuel selection is not an option in the CSO dataset. As shown in Figure 4, the SyAv fuel use in the EPC dataset, at 71 %, is solid multi-fuel. Use of gas in dwellings constructed after 1994 is not correlated by the CSO dataset.

The CSO data relating to solid-fuel use in Ireland, shown in Table 5, is used to characterise the RD as it is more statistically significant than the EPC data. Accordingly, the data relating to solid-fuel use in Table 5 is reclassified by DEAP period of construction as shown in Table 6 and Figure 5. Table 6 reveals 1 in 3 dwellings constructed up until 1966 to be heated by solid fuel, this, reduces to circa 1 in 4 between 1967 and 1993 and reduces to 1 in 5 between 2000 and 2006. The characteristics of the heating system particular to the proportion of the dwelling stock heated by solid fuel are accounted for in the aggregated stock model as described in Chapter 4. To simplify the stock model, where dwellings are heated by solid-fuel, the characteristics of solid-multi-fuel are employed. Characteristics of solid-multi-fuel systems are analysed in Section 4.2.

Figure 4 Detached rural centrally heated dwellings by fuel type (as suggested by EPC dataset) [76]

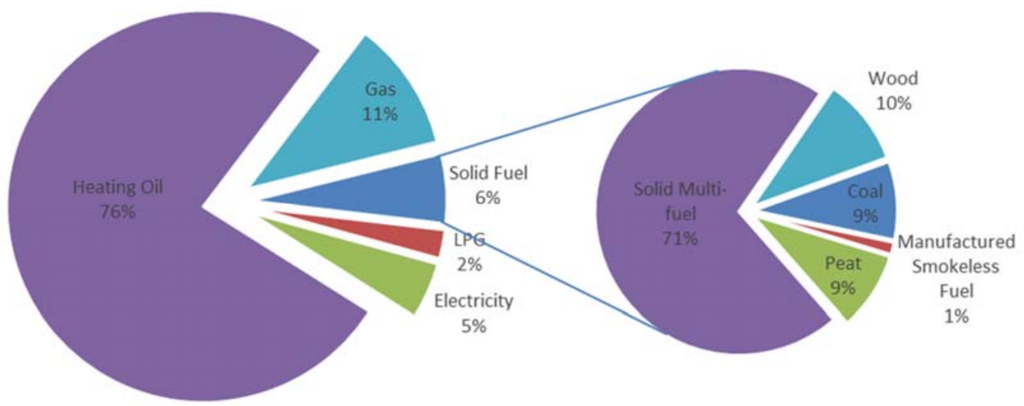


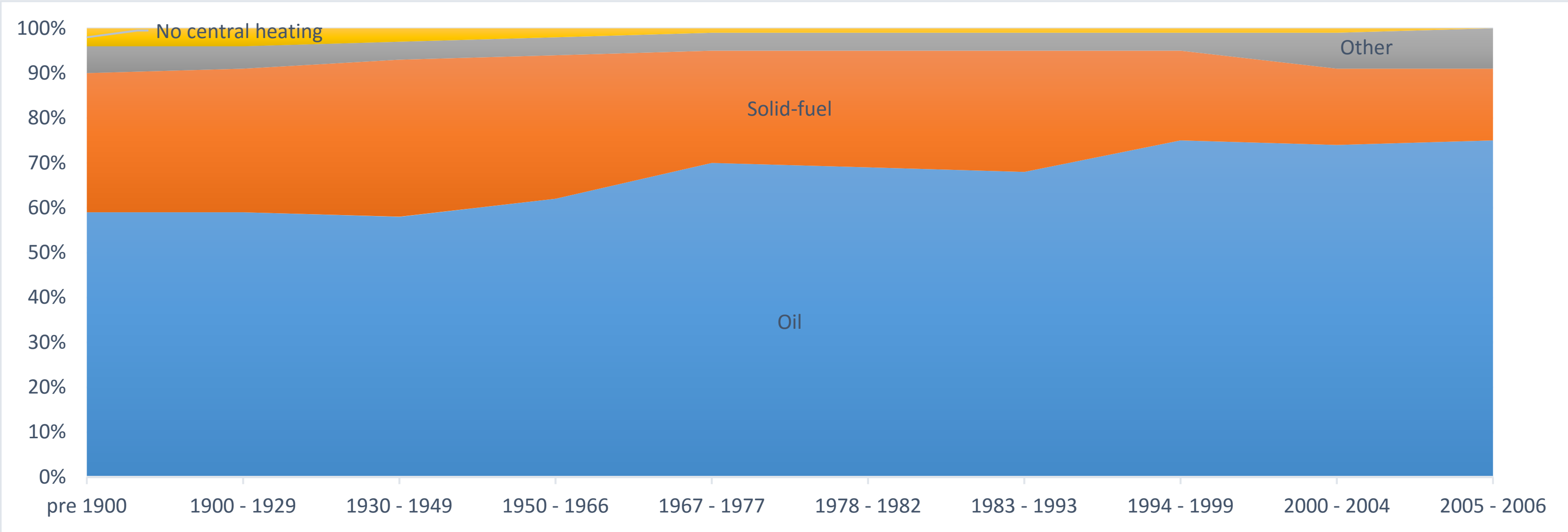
Table 5 Central heating fuel source by CSO period of construction, Census of Ireland 2016 [74]

		Period of Construction																	
		Before 1919		1919 to 1945		1946 to 1960		1961 to 1970		1971 to 1980		1981 to 1990		1991 to 2000		2001 to 2010		Not stated		Total	Average
Central heating fuel source	Coal (incl. anthracite)	6028	9%	3756	10%	2804	9%	1767	7%	4020	6%	4402	7%	3536	5%	4405	3%	680	6%	30718	6%
	Liquid Petroleum Gas (LPG)	516	1%	231	1%	139	0%	195	1%	620	1%	819	1%	590	1%	1260	1%	54	0%	4370	1%
	Electricity	1555	2%	688	2%	481	2%	424	2%	609	1%	443	1%	793	1%	4790	4%	244	2%	9783	2%
	Oil	**38662**	**59%**	**22280**	**58%**	**18294**	**60%**	**16881**	**67%**	**45919**	**71%**	**39442**	**66%**	**53069**	**75%**	**97024**	**74%**	**5986**	**52%**	**331571**	**68%**
	Natural Gas	449	1%	233	1%	203	1%	242	1%	604	1%	623	1%	863	1%	3319	3%	160	1%	6536	1%
	Peat (incl. turf)	**8978**	**14%**	**7487**	**20%**	**6194**	**20%**	**4011**	**16%**	**8956**	**14%**	**10389**	**17%**	**7969**	**11%**	**10776**	**8%**	**896**	**8%**	**64760**	**13%**
	Wood (incl. wood pellets)	5411	8%	2138	6%	1494	5%	974	4%	2540	4%	2659	4%	2560	4%	5453	4%	369	3%	23229	5%
	No central heating	3201	5%	1193	3%	678	2%	353	1%	574	1%	353	1%	318	0%	528	0%	149	1%	7198	1%
	Other fuels	428	1%	163	0%	146	0%	105	0%	265	0%	261	0%	332	0%	3635	3%	67	1%	5335	1%
	Not stated	364	1%	179	0%	141	0%	110	0%	286	0%	253	0%	264	0%	568	0%	2934	25%	2165	0%
	Total (all-fuels)/%	65592	100%	38348	100%	30574	100%	25062	100%	64393	100%	59644	100%	70294	100%	131758	100%	11539	100%	485665	100%
	Proportion solid-fuel Total/%	**20417**	**31%**	**13381**	**35%**	**10492**	**34%**	**6752**	**27%**	**15516**	**24%**	**17450**	**29%**	**14065**	**20%**	**20634**	**16%**	**1945**	**17%**	**118707**	**24%**

Table 6 Central heating fuel source by DEAP period of construction, Census of Ireland 2016 [74]

		pre 1900	1900 - 1929	1930 - 1949	1950 - 1966	1967 - 1977	1978 - 1982	1983 - 1993	1994 - 1999	2000 - 2004	2005 - 2006
Central heating fuel source	Oil	59%	59%	58%	62%	70%	69%	68%	75%	74%	75%
	Solid-fuel	31%	32%	35%	32%	25%	26%	27%	20%	17%	16%
	Other	6%	5%	4%	4%	4%	4%	4%	4%	8%	9%
	No central heating	4%	4%	3%	2%	1%	1%	1%	1%	1%	0%

Figure 5 Central heating fuel source by year of construction for detached rural dwellings in Ireland dataset, Irish National Census 2016 [74]



2.4 Analysis of microscopic data within EPC Dataset

"You can use all the quantitative data you can get, but you still have to use your own intelligence and judgment"

Toffler, A. [103]

This section is concerned with assessing the consistency and identifying and cleaning any errors in the microscopic EPC data before the data is verified as acceptable for use in the characterisation of the macroscopic reference dwellings.

2.4.1 Comment on default use in EPC assessments

During an EPC assessment and where accurately obtaining all of the required building envelope data would be excessively labour-intensive and/or invasive, national default values are sometimes employed. Default values are normally pessimistic to [14, 104];

- avoid offering a better than merited energy rating,
- allow the homeowner to know the energy advantage of carrying out retrofits,
- encourage the homeowner to maintain records of energy upgrades that inform EPCs, and
- encourage assessors to seek out information to improve the energy rating.

Since input data is often based on worst-case default [47, 51, 60, 105-109]; (i) thermal envelope characteristics, and (ii) operating conditions for *inter alia* external temperatures, internal loads, system efficiencies, prices and occupancy patterns, the results outputted by EPC methodologies can only offer an estimation of the actual building energy consumption. Indeed, there can be a major gap between the theoretical EPC rated prediction and actual measured [108] energy consumed in homes when occupied by real people [51, 105, 110].

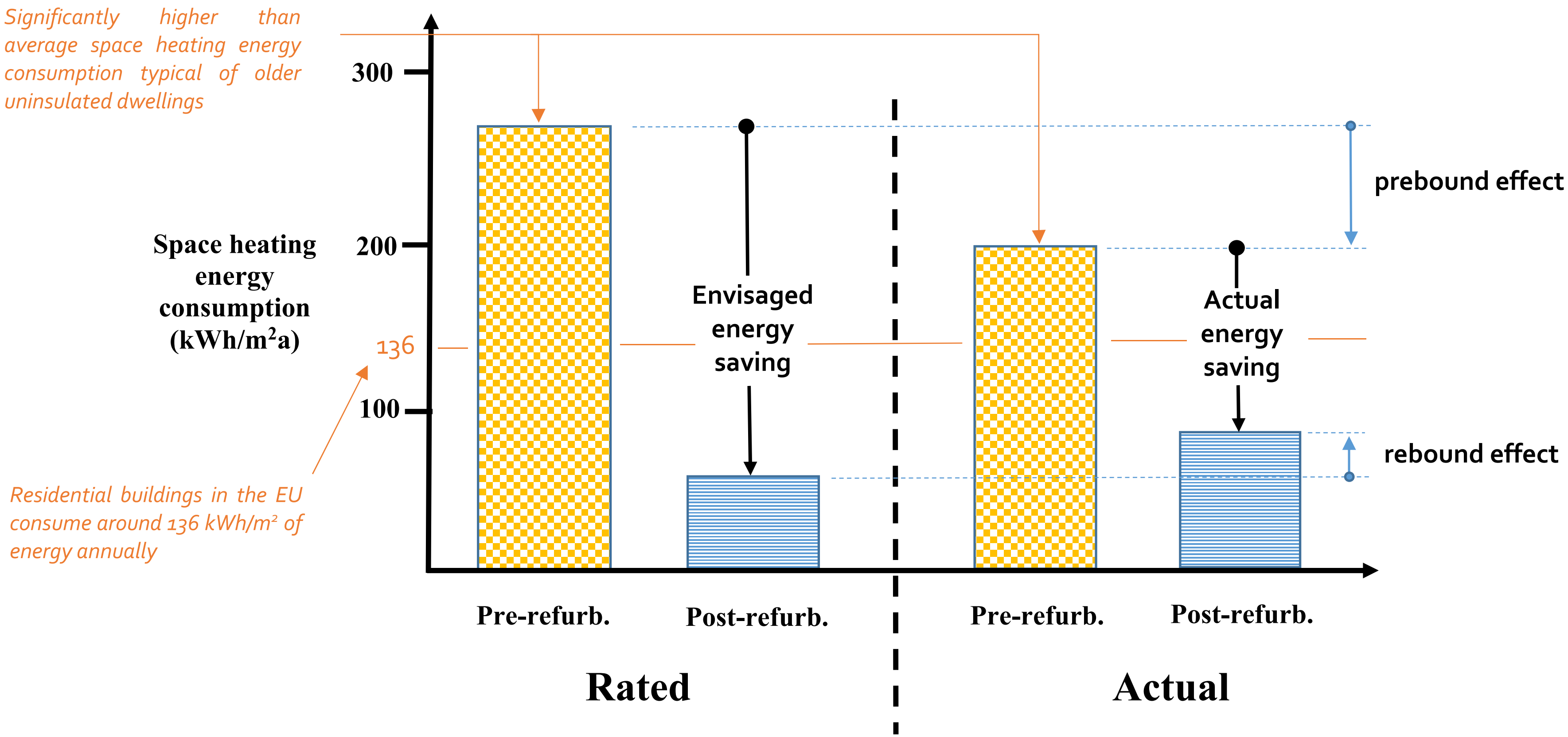
Referring to Figure 6 residential buildings in European Union (EU) consume around 200 kWh/m^2 of energy annually [65]. In the 27 EU member states in 2009 (EU 27), space heating consumed 68 % or 136 kWh/m^2/a of energy used in the residential sector [111]. Space heating energy consumption above 136 kWh/m^2/a thus represents above-average space heating energy consumption typical of less energy-efficient and likely older pre-refurbished dwellings.

Information on the characteristics of the dwelling is often more difficult to obtain in older than for recently constructed dwellings [14, 112]. If an improvement in the EPC is the basis for renovation, use of pessimistic default values may lead to higher than realisable (actual) pre and post energy refurbishment improvement expectations in the EPC rating [104, 105, 113], particularly for older pre-refurbishment dwellings. This 'prebound effect' is illustrated in Figure 6; wherein, theoretical predicted energy consumption tends to be overestimated for average and less energy-efficient dwellings (space heating consumption of 136 kWh/m^2/a or greater) [105] with occupants consuming 30 % less heating energy on average than the theoretical predicted EPC rating would imply [108].

Figure 6 also highlights how theoretical energy prediction tends to be underestimated when observing new or retrofitted dwellings (space heating consumption less 100 kWh/m^2/a or less); explained partly by the 'rebound effect' [114] where thermally-retrofitted dwellings make higher internal comfort temperatures more affordable leading to increased energy consumption ranging from 10 to 35 % [115], rather than reduced energy bills [33, 67, 105, 116-118].

In summary and as illustrated Figure 6, the combined prebound and rebound effects may limit EPC rated energy savings to be significantly less than envisaged, particularly for older, less energy-efficient as-built dwellings.

Figure 6 How the prebound and rebound effects may limit energy saving to be less than envisaged[9] [108]



[9] Actual values based on measured values [see Ref [108] M. Sunikka-Blank, R. Galvin, Introducing the prebound effect: the gap between performance and actual energy consumption, Building Research & Information, 40 (3) (2012) 260-273.]

Over an elapsed period, sufficient for heat transiently stored in the building fabric to be released into the building, a thermal transmittance coefficient or U-value of a building element correlates with the heat energy consumption of a dwelling. A default U-value characteristic should be based on empirical evidence. In the absence of such empirical data as shown in Table 7, base or as-built Irish thermal default U-values (similar to many other EU member states [112, 113]) are determined by [56, 72];

- building element type (roof, wall or floor),
- for pre-thermal regulation dwellings (pre-1978), the date of construction,
- for post-thermal regulation dwellings (1978 – 2006), prevailing draft or finalised building codes by period of construction - allowing a grace period of generally two to three years after a proposed change in draft or finalised regulations for a dwelling to be completed.

Table 7 Base-thermal-default U-values by period of thermal regulation in Ireland [119]

		Applicable Age Band	Base-default U-values (W/m^2K)		
			Roof	Wall	Floor
Date Regulation Introduced	N/A	<1978	2.3	2.1	1.2
	1976 (Draft)	1978-1982	0.4	1.1	0.6
	1981 (Draft)	1983-1993	0.4	0.6	0.6
	1991	1994-1999	0.35	0.55	0.45/0.6*
	1997	2000-2004	0.35	0.55	0.45/0.6*
	2002	2005-2006	0.25	0.37	0.37

* 0.45 = ground floor and 0.6 = exposed/semi-exposed floor

Ireland [70, 120] along with Italy [38], Spain [121] and Austria [122] use stock-aggregation methodologies to calculate residential stock energy consumption using as-built or base-default U-values applied to equally default dwelling typologies classified by period of construction.

2.4.2 Method of default U-value selection in EPC methodology

Dominant construction types are classified in DEAP [72] as either, masonry, timber or steel frame or insulated concrete form. 97 % of the case study dwelling type are classified as being of masonry construction [76]. The common masonry construction materials are stone, brick and concrete block. A dwelling classified by DEAP [72] as 'masonry' typically has a solid floor (but can be a suspended timber floor), insulated masonry external walls and internal walls that can either be plasterboard on timber/steel stud or masonry with plasterboard on dabs.

2.4.2.1 Walls

As illustrated in Figure 7, when full details on all wall layers are available from documentary evidence, DEAP requires EPC assessors to calculate and hence enter an actual U-value into the DEAP software. If however full details are not available, the assessor selects a wall-type and period of construction and DEAP selects a base-thermal-default U-value from Table 8. Through the removal of electrical sockets for example, installation of dry-lining is typically readily identified. If the assessor identifies dry-lining as present, the assessor adjusts the default U-value selected from Table 8 as shown in Table 9. There are thus numerous default U-values available for selection. If the assessor cannot identify the wall-type, the assessor selects wall-type "unknown" and the period of construction and DEAP will select a base-thermal-default from Table 8 and as listed in Table 7.

Figure 7 Derivation of wall U-values in DEAP [72]

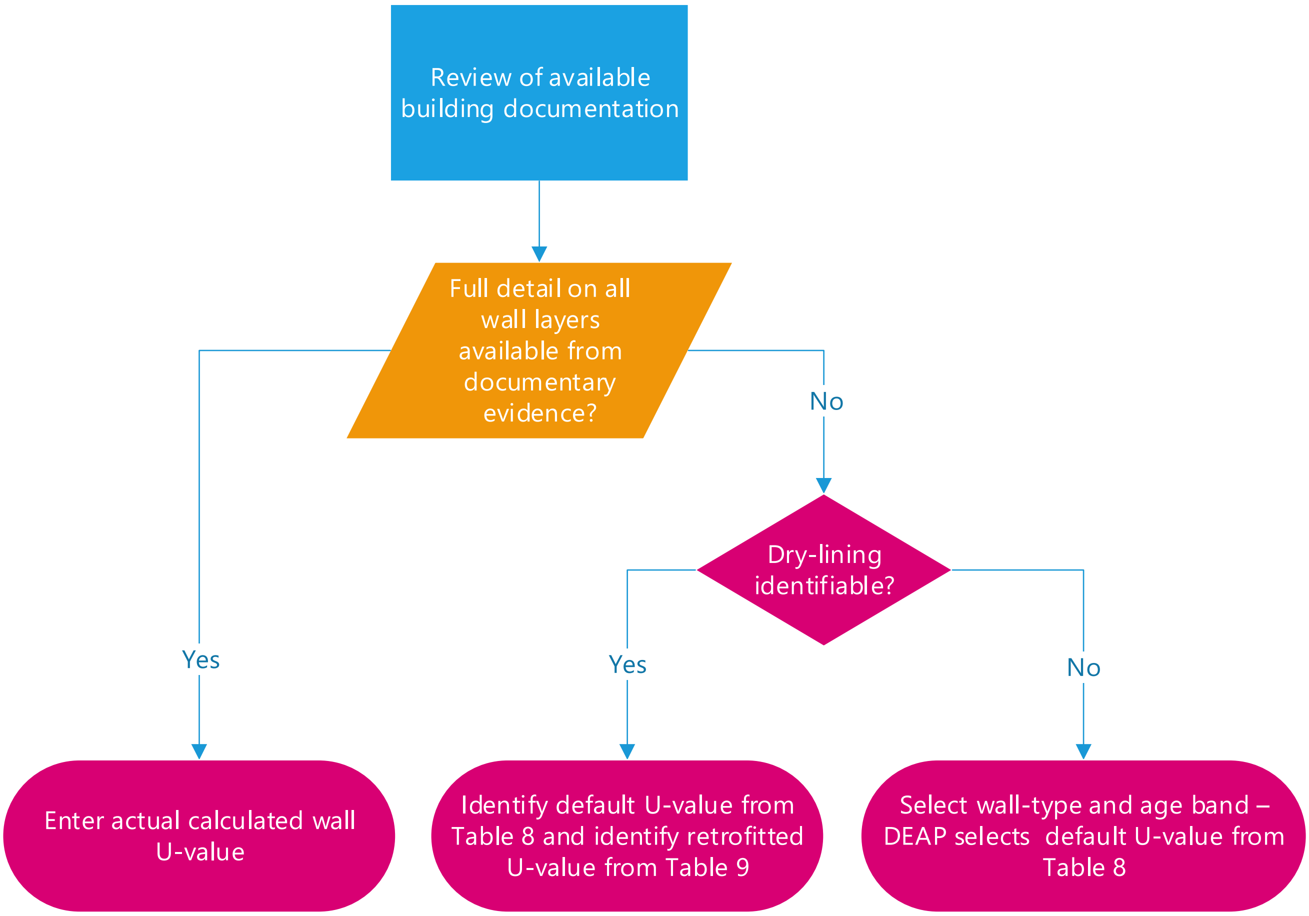


Table 8 Base-thermal-default wall U-values by wall type and period of construction [72]

		Period of Construction									
		Per-thermal regulation					Post-thermal regulation				
		< 1900	1900 - 1929	1930 - 1949	1950 - 1966	1967 - 1977	1978 - 1982	1983 - 1993	1994 - 1999	2000 - 2004	2005 - 2006
Wall Type	Stone	2.1	2.1	2.1	2.1	2.1	1.1	**0.6**	**0.55**	**0.55**	**0.37**
	225 mm solid brick	2.1	2.1	2.1	2.1	2.1					
	325 mm solid brick	1.64	1.64	1.64	1.64	1.64					
	300 mm cavity	2.1	1.78	1.78	1.78	1.78					
	300 mm filled cavity	0.6	0.6	0.6	0.6	0.6	0.6				
	solid mass concrete	2.2	2.2	2.2	2.2	2.2	**1.1**				
	concrete hollow block	2.4	2.4	2.4	2.4	2.4					
	timber frame*	2.5	1.9		1.1						
	Unknown	**2.1**	**2.1**	**2.1**	**2.1**	**2.1**					
	425 mm cavity wall*	1.73	1.51								
	425 mm filled cavity*	0.6									

Pre-thermal regulation dwellings are assumed in DEAP to have been constructed without insulation thus pre-thermal regulation "unknown" or base-default U-values are presumed pessimistically to be the same as that of uninsulated walls with a given construction.

Post-thermal regulations defaults are led by the prevailing building regulation of the time – Cross-reference Table 7

* Not typical construction types

Table 9 Default wall U-values by wall type, period of construction with dry-lining insulation upgrades [72]

		Plasterboard + 0 mm insulation	Plasterboard + 20 mm insulation	Plasterboard + 30 mm insulation	Plasterboard + 40 mm insulation	Plasterboard + 50 mm insulation	Plasterboard + 60 mm insulation	Plasterboard + 70 mm insulation
Original Base-default wall U-value from Table 8	**2.4**	1.53	1.12	0.91	0.77	0.67	0.59	0.53
	2.2	1.45	1.08	0.88	0.75	0.65	0.58	0.52
	2.1	1.41	1.05	0.87	0.74	0.64	0.57	0.51
	1.9	1.31	1.00	0.83	0.71	0.62	0.55	0.5
	1.78	1.25	0.96	0.81	0.69	0.61	0.54	0.49
	1.64	1.18	0.92	0.78	0.67	0.59	0.53	0.48
	1.1	0.87	0.72	0.63	0.56	0.5	0.46	0.42
	0.6	0.53	0.47	0.43	0.39	0.36	0.34	0.32
	0.55	0.49	0.44	0.4	0.37	0.34	0.32	0.3
	0.37	0.34	0.31	0.3	0.28	0.26	0.25	0.24

2.4.2.2 Roofs

The same procedure outlined in Figure 7 and as described for walls applies to the selection of default roof U-values indicated in Table 10.

Table 10 Default roof U-values by wall type, period of construction with insulation upgrades [72]

		Period of Construction				
		> 1900 - 1977	1978 - 1993	1994-1999	2000-2004	2005 - 2006
	Unknown	**2.3**	**0.4**	**0.35**	**0.35**	**0.25**
Insulation Thickness	None	2.3				
	12 mm	1.5				
	25 mm	1.1				
	50 mm	0.68				
	75 mm	0.5				
	100 mm	0.4				
	150 mm	0.26				
	200 mm	0.2				
	250 mm	0.16				
	>=300 mm	0.13				

Pre-thermal regulations dwellings are assumed in DEAP to have been constructed without insulation thus pre-thermal regulation "unknown" or base-default U-values are presumed pessimistically to be the same as that of uninsulated roofs.

2.4.2.3 Floors

The default floor U-value in DEAP [72] is calculated according to I.S. EN ISO 13370 [123] using the dwelling floor area and exposed perimeter (rounded to two decimal places). The ratio of ground floor perimeter to ground floor area is known as the P_f/A_{fg} ratio. I.S EN ISO 13370 offers three categories of ground classifications as shown in Table 11.

Table 11 Thermal conductivity for different ground types [123]

			Thermal conductivity λ_g W/mK
Category	1	Clay or silt	1.5
	2	Sand or gravel	2
	3	Homogenous rock	3.5

The following parameters are used by DEAP in the calculation of solid ground floors U-values as shown in Figure 8;

- Wall thickness (d_w) assumed at 300 mm,
- Soil type: default for sand or gravel [124] (ground thermal conductivity λ_g 2.0 W/mK)
- Internal surface thermal resistance R_{si} - 0.17 m^2K/W
- External surface thermal resistance R_{se} - 0.04 m^2K/W
- Thermal resistance of a solid-ground floor R_f - $(1/U_f)$ (m^2K/W) – Reference Table 12 for U_f values
- 50 mm screed
- All-over floor insulation of thickness as per Table 12.

As in the case of walls and roofs and as shown in Table 12, pre-thermal regulation floors are assumed [72] to have been constructed originally without any insulation.

Figure 8 Characteristic dimensions and total equivalent thickness of a solid-ground floor [124]

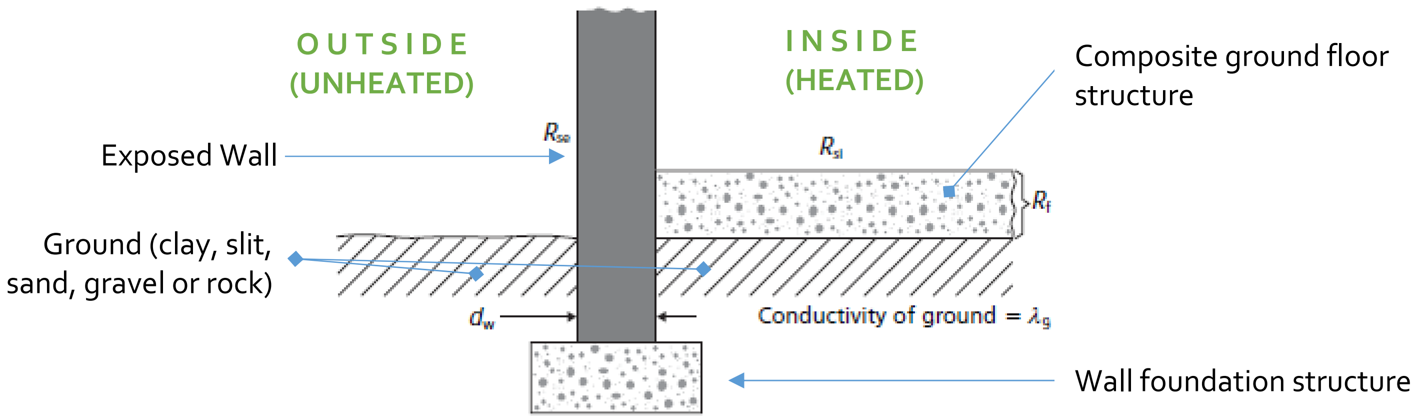


Table 12 Solid-floor default U-values by period of construction with assumed levels of insulation [72]

		Period of Construction			
		pre-1900 - 1977	1978-1993	1994-2004	2005-2006
		Insulation Thickness (mm)			
		None	12	35	50
Floor Perimeter to ground floor area (P_f/A_{fg}) ratio	0.1	0.27	0.23	0.19	0.17
	0.2	0.46	0.38	0.29	0.26
	0.3	0.61	0.48	0.36	0.31
	0.4	0.73	0.57	0.41	0.34
	0.5	0.84	0.64	0.44	0.37
	0.6	0.94	0.7	0.47	0.39
	0.7	1.02	0.74	0.49	0.4
	0.8	1.1	0.79	0.51	0.42
	0.9	1.16	0.82	0.52	0.43
	1 or more	1.23	0.85	0.54	0.44

Typical floor perimeter to ground floor area (P_f/A_{fg}) ratio for case study dwelling ranges between 0.37 and 0.52

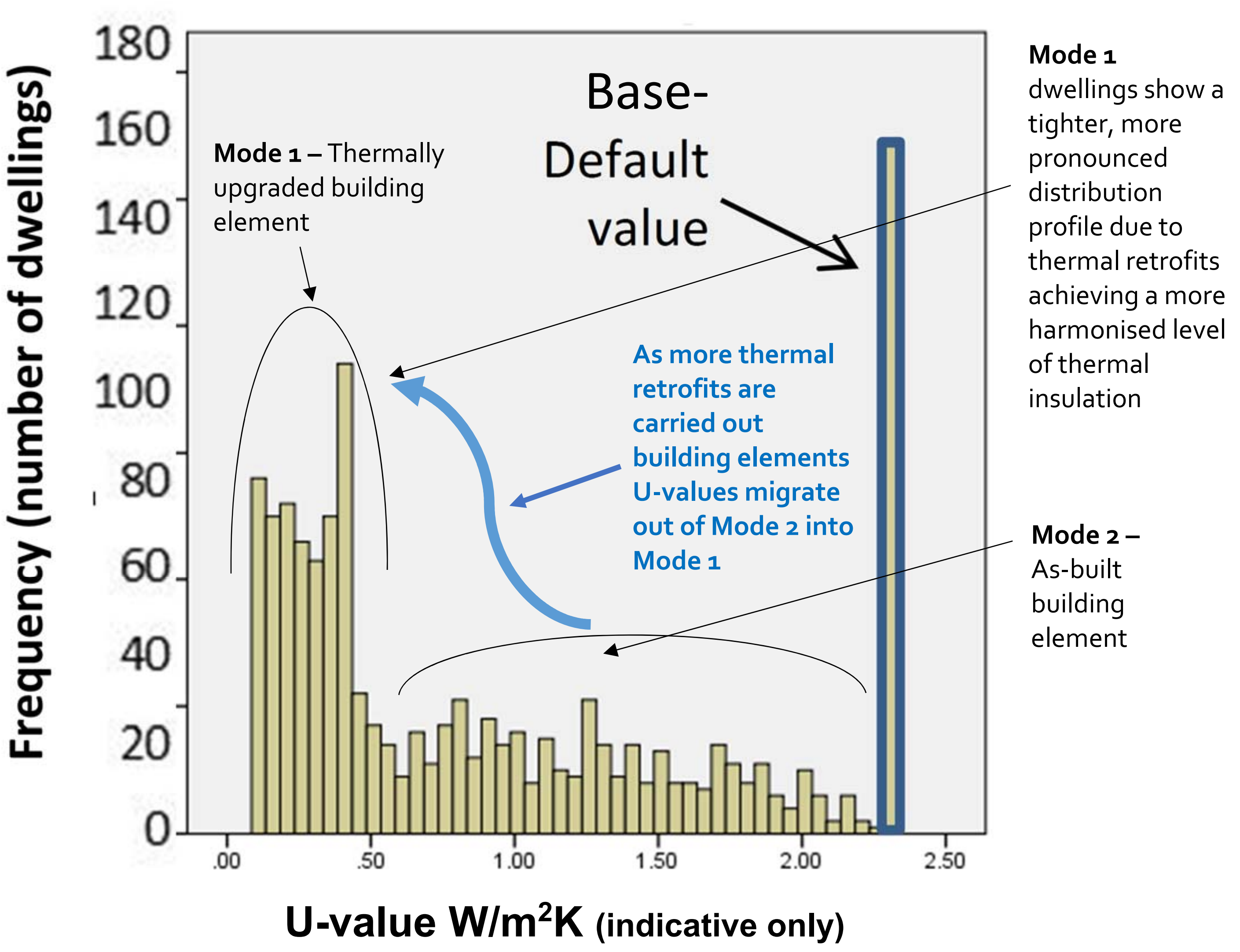
2.4.3 Typical thermal transmittance (U-value, W/m^{2}K) frequency distributions for case study dwelling

Figure 9 illustrates a typical U-value frequency distribution for a building walls or roofs by period of construction extracted from the Irish national empirical dataset analysed using SPSS® software as described in Appendix A [76]. Figure 9 reflects a typical distribution and is shown for illustrative purposes only, thus U-values shown on x-axis are indicative only. Figures 10 (a & b), 11 (a & b) and 12 (a & b) reflect the true distributions for walls, roofs and floors respectively. Figures 10 to 12 reveal the thermal characteristics of Ireland's walls and roofs to be bi-modally distributed. Referring to Figure 9:

- 'Mode 2' building elements reflect walls and roofs as constructed originally with corresponding thermal transmittance or U-values of circa 0.6 to 2.3 W/m^{2}K[10].
- 'Mode 1' dwellings are thermally upgraded building elements demonstrated by a lower U-value ranging between circa 0.1 to 0.59 W/m^{2}K.
- As more thermal retrofits are carried out building elements U-values migrate out of Mode 2 into Mode 1.

[10] Exact ranges determined in Chapter 3 using maximum likelihood estimation

Figure 9 Illustrative typical frequency distribution of wall and roof U-values [76]



Referring to Figures 10 to 12:

- Thermally upgraded or Mode 1 dwellings show a more pronounced distribution profile than Mode 2 dwellings yet to undergo significant thermal upgrades[8].
- The median values for Mode 1 dwellings are consistent with the range of U-values prescribed within the 2007 [125] and 2011 [126] Irish building regulations;
    - 0.21 (2011) to 0.27 (2007) W/m^2K for walls,
    - 0.16 (2011) to 0.22 (2007) W/m^2K for roofs.
- State funded energy refurbishments grants to the homeowner are available through the SEAI for [127];
    - walls that achieve a U-Value of 0.27 W/m^2K, and

  - roofs that achieve a U-value of,
    - 0.16 W/m²K for ceiling-level insulation, and
    - 0.2 W/m²K for rafter insulation.

  Peaks are observed consistently in the Mode 1 distributions relating to these values.
- In general, it is observed that the standard deviation[10] for Mode 2 tends to be greater than that of Mode 1, likely due to thermal retrofits giving more harmonised levels of thermal insulation.

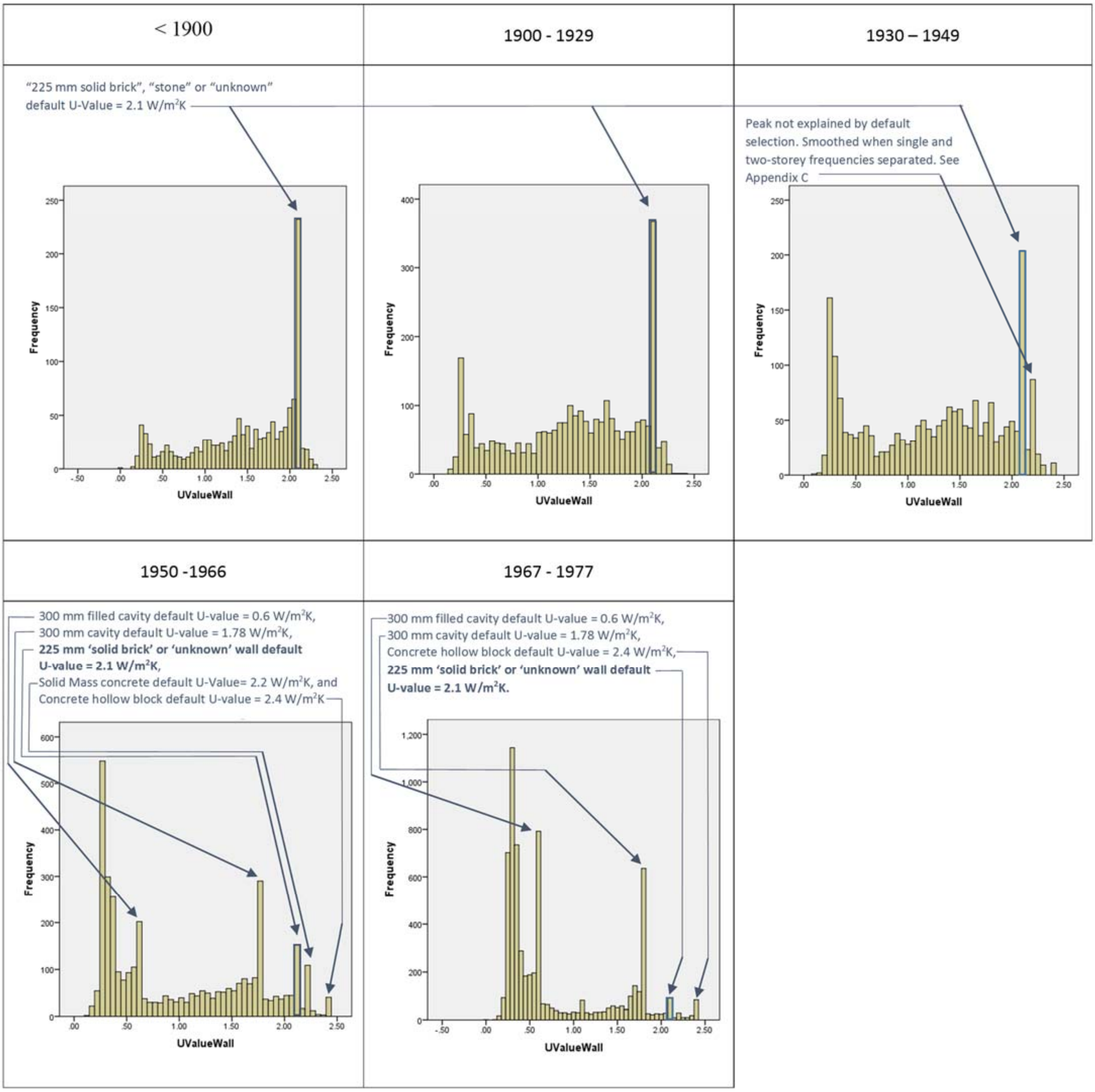
Unlike walls and roofs and as shown in Figure 12 (a & b), dwelling floors typically display a normal unimodal distribution, this is assumed to result from fewer thermal retrofits of floors arising from (i) the high cost of replacement floor coverings [128] and (ii) the difficulties of retrofitting floor insulation.

Statistically anomalous spikes or local optima are observed consistently in the data split-across time-periods in Figures 10 to 12, in both pre and post-regulation dwellings;

- in the tail of the Mode 2 empirical U-value distribution for exposed building elements such as walls (see Figure 10) and roofs (see Figure 11), and
- within the unimodal distribution of floor U-values (see Figure 12).

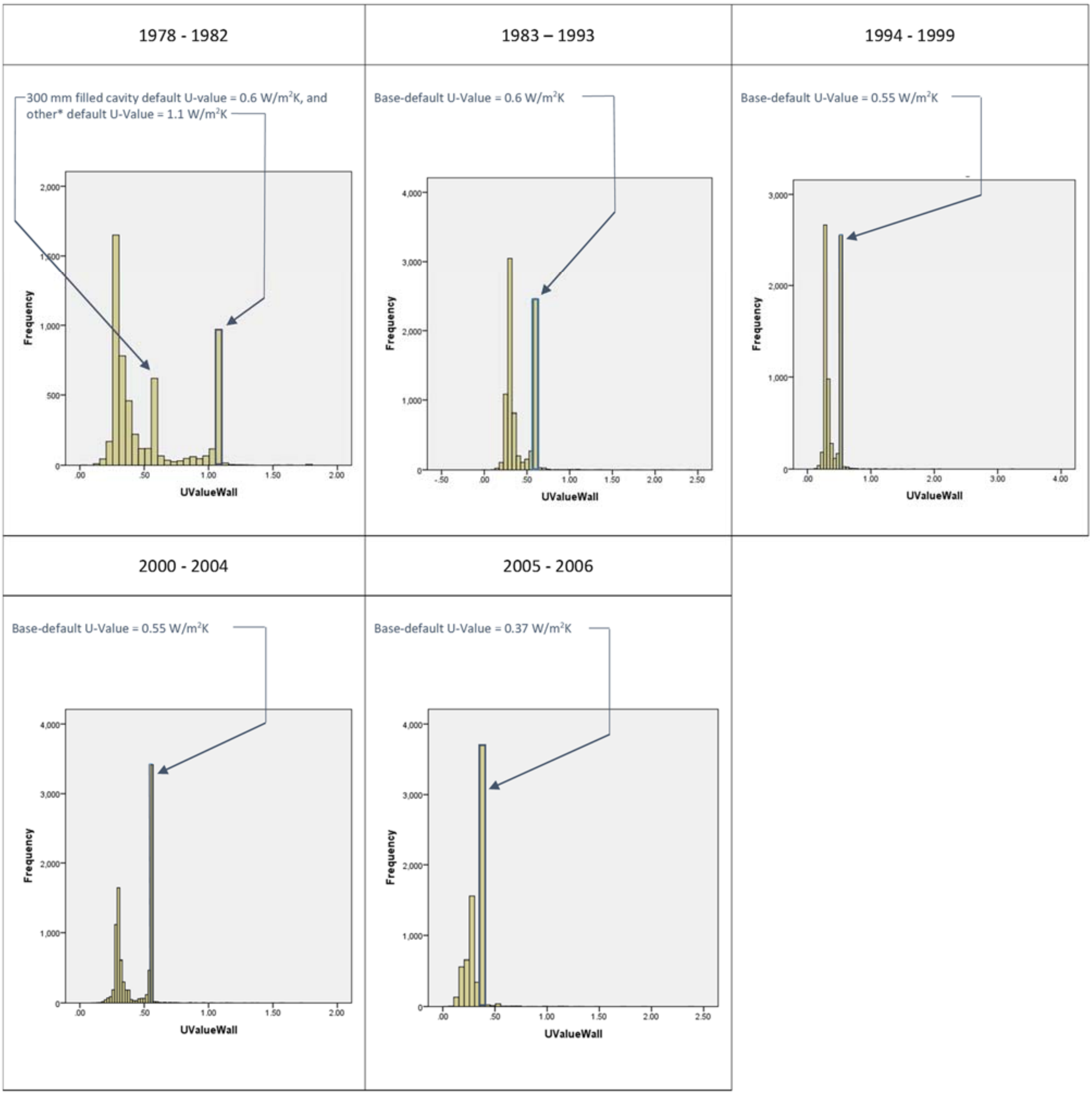
Analysis of Figures 10 to 12 reveal spikes in the empirical U-value distribution to result from default U-value selection. The phenomenon of default use is explored in the following sections 2.4.4 and 2.4.5.

Figure 10 (a) Default wall U-value analysis (single and two-storey) by period of construction for pre-thermal regulation detached rural dwellings [76]



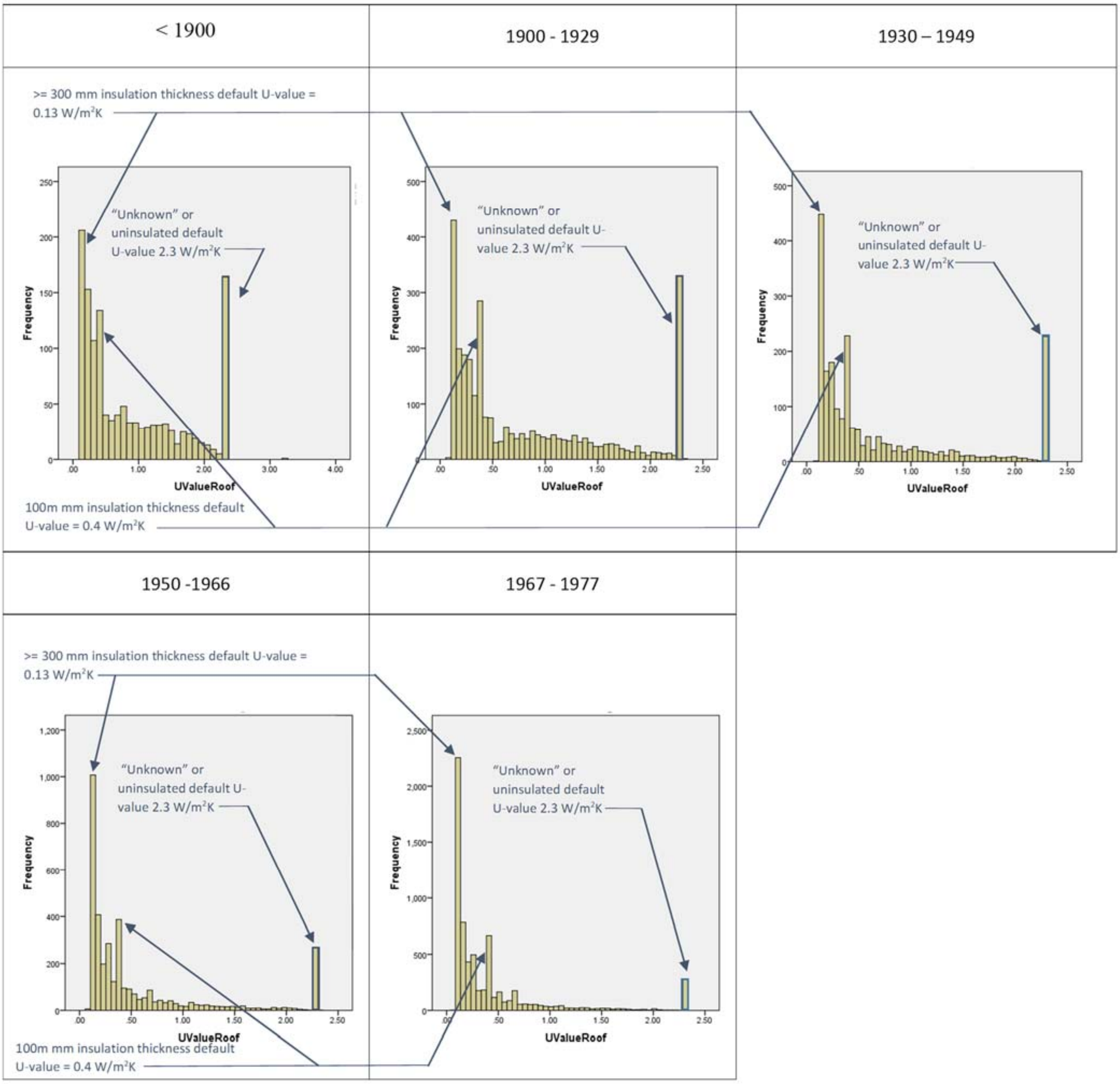
*** Cross-reference: Table 8 Default wall U-values by wall type and by period of construction**

Figure 10 (b) Default wall U-value analysis (single and two-storey) by period of construction for post-thermal regulation detached rural dwellings [76]



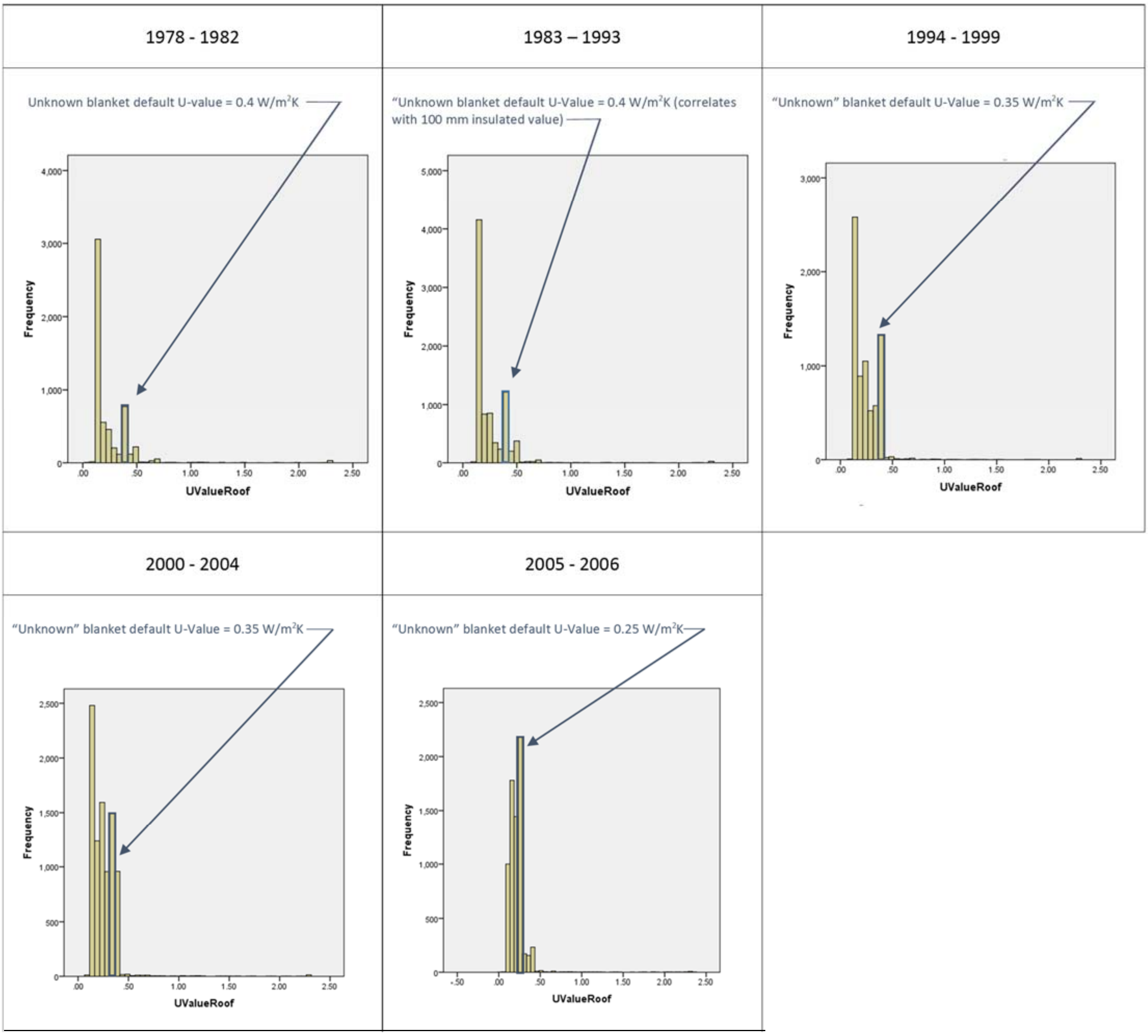
*** Cross-reference: Table 8 Default wall U-values by wall type and by period of construction**

Figure 11 (a) Default roof U-value analysis (single and two-storey) by period of construction for pre-thermal regulation detached rural dwellings [76]



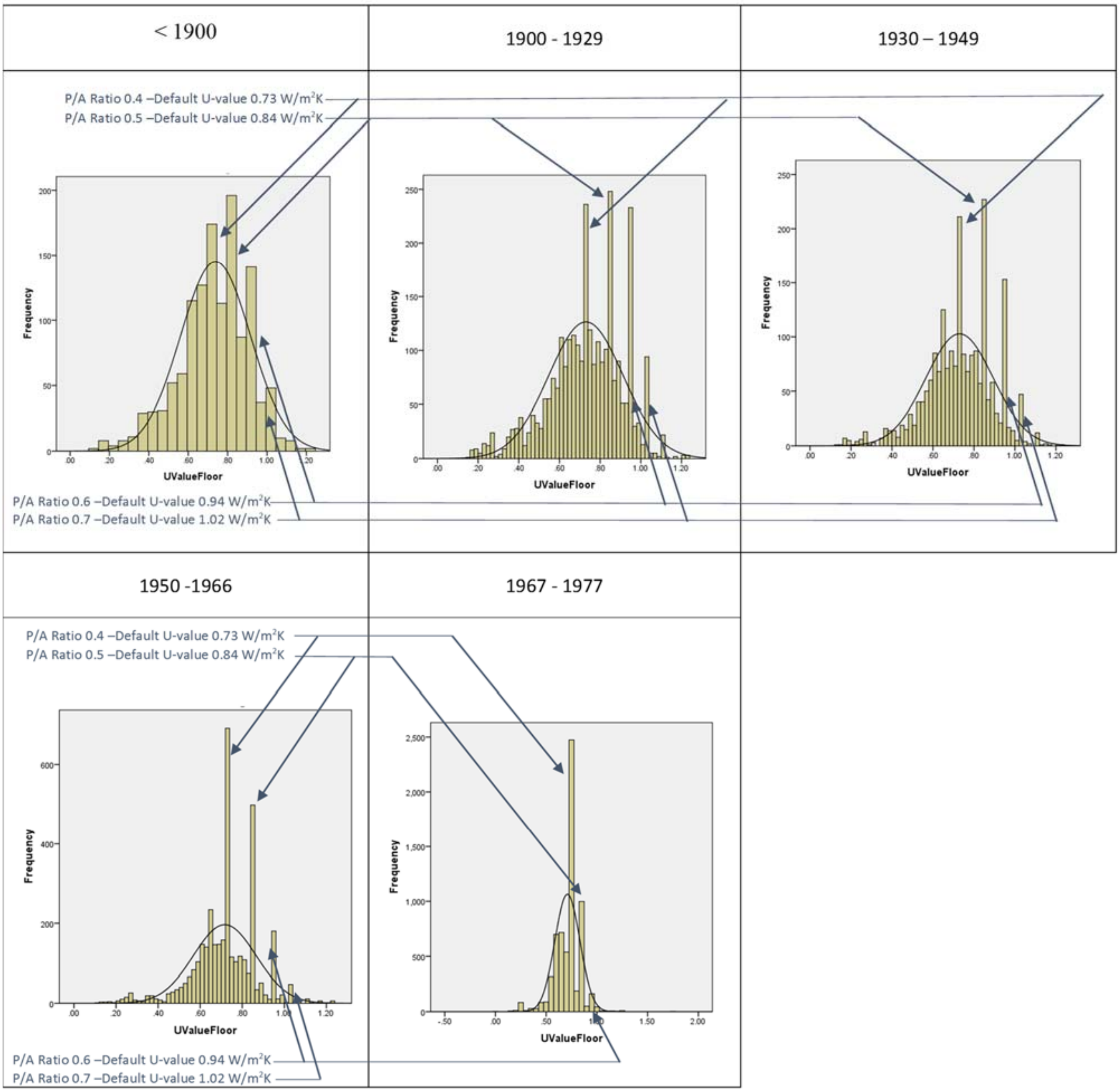
*** Cross-reference:Table 10 Default roof U-values by wall type and by period of construction**

Figure 11 (b) Default roof U-value analysis (single and two-storey) by period of construction for pre-thermal regulation detached rural dwellings [76]



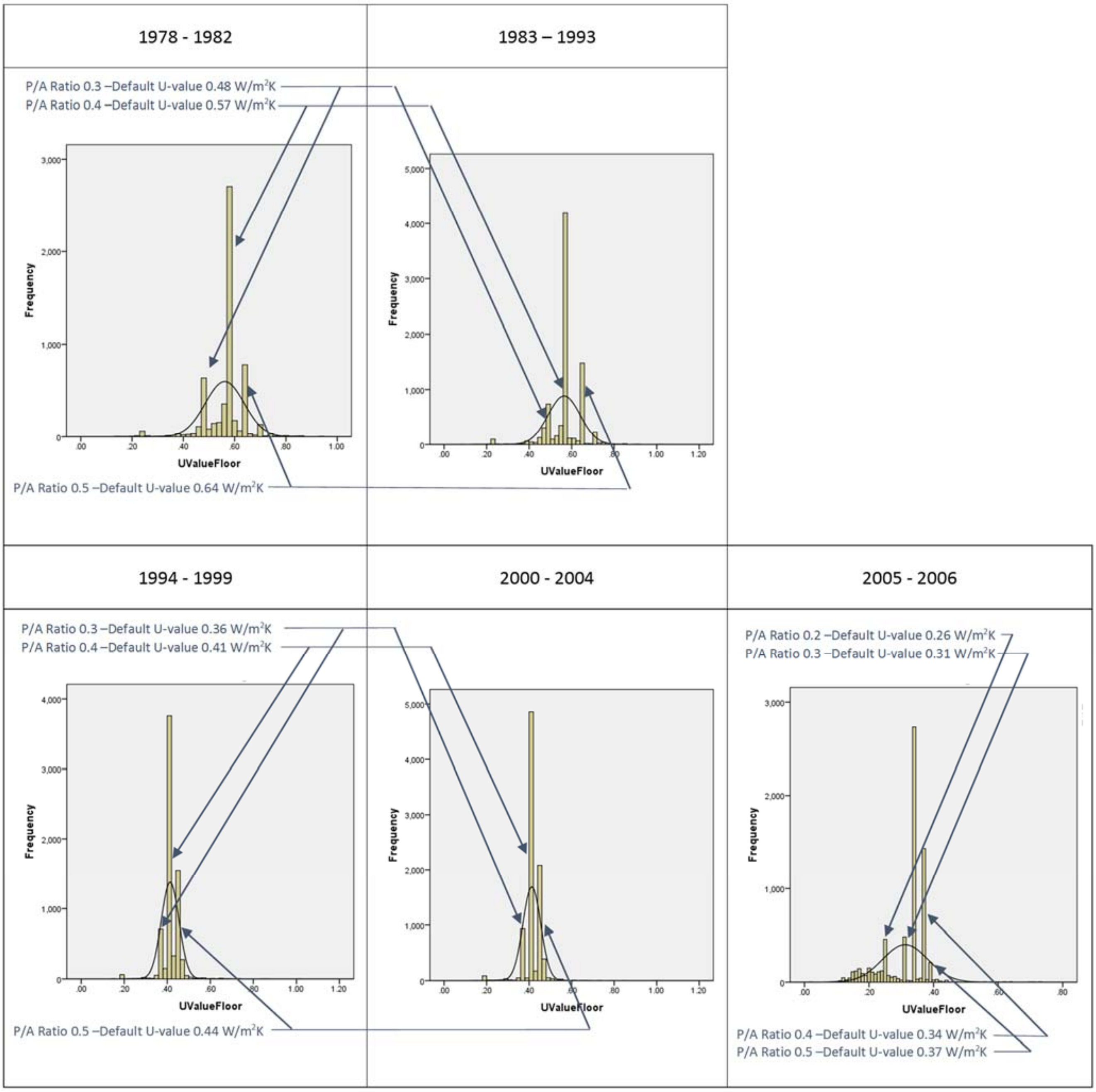
*** Cross-reference:Table 10 Default roof U-values by wall type and by period of construction**

Figure 12 (a) Default floor U-value analysis (single and two-storey) by period of construction for pre-thermal regulation detached rural dwellings [76]



*** Cross-reference:Table 12 Solid-floor default U-values by by period of construction with assumed levels of insulation**

Figure 12 (b) Default floor U-value analysis (single and two-storey) by period of construction for post-thermal regulation detached rural dwellings [76]



*** Cross-reference:Table 12 Solid-floor default U-values by by period of construction with assumed levels of insulation**

2.4.4 Commentary on default-selection within EPC dataset

As shown in Figures 10 and 11, statistically anomalous spikes in the empirical U-value distributions are demonstrated consistently across periods of construction. Wall or roof-type “unknown” is selected in preference to establishing the wall construction to calculate actual U-values. The consistency of this phenomenon, presenting across time-periods, suggests a structural error (as opposed to one-off outliers) in the data. It is apparent that assessors are often selecting the building-element-type “unknown” for walls and roofs leading to the ubiquitous presence of pessimistic base-default U-values within the EPC database.

Irrespective of the reason for over-selection of wall or roof-type “unknown”, the aggregate level of pessimistic base-default U-values within the EPC dataset leads to the dataset presenting an unrealistically pessimistic picture of the dwelling stock. The dataset should thus be cleaned of base-thermal-default U-values for walls and roofs as highlighted in Figures 10 and 11. The case for removal of base-thermal-default floor U-values is less convincing because;

a) without significant likely cost to the home-owner, floor construction details are difficult to establish retrospectively,
b) base-thermal-default U-values, as shown in Figure 12, are distributed reasonably throughout the unimodal empirical distribution,
c) there is a lack of information in the relevant literature [72, 120, 124, 129, 130] relating to floor construction.

The ease by which actual building element U-values can be established is explored in Section 2.4.5.

2.4.5 Vernacular construction characteristics of detached rurally-located dwellings in Ireland

"Vernacular architecture is a category of architecture based on localized needs and construction materials and reflecting local traditions"

Anon.

To allow comparison of base (as-built) thermal-default U-values often selected with the likely actual U-values for Irish rural dwellings, this section;

a) establishes vernacular construction characteristics of rural Irish dwellings,
b) determines the likely actual U-value arising for vernacular Irish dwellings,
c) compares base-thermal-default U-values from Table 7 with the likely actual U-values calculated.
d) compares base-thermal-default U-values for walls, roofs, and floors for a known building-element type, with the calculated U-value for the same construction.

2.4.5.1 Wall Characteristics

A government-sponsored review of the Irish dwelling stock was carried out by the Economic and Social Research Institute (ESRI) in 2001-2002 entitled 'The Irish National Survey of Housing Quality' (INSHQ) [131]. The INSHQ gathered detailed information on dwelling characteristics from a sample of over 40,000 households, conducted in spring 2001 [131]. A follow-on study carried out in 2010 [39] employed *inter alia* the INSHQ dataset to isolate and hence present the status of Ireland's predominant housing typology as reported in 2001. Figures 13 and 14 indicate respectively;

(i) wall types of detached housing in Ireland, and
(ii) the presence of cavity walls with and without insulation,

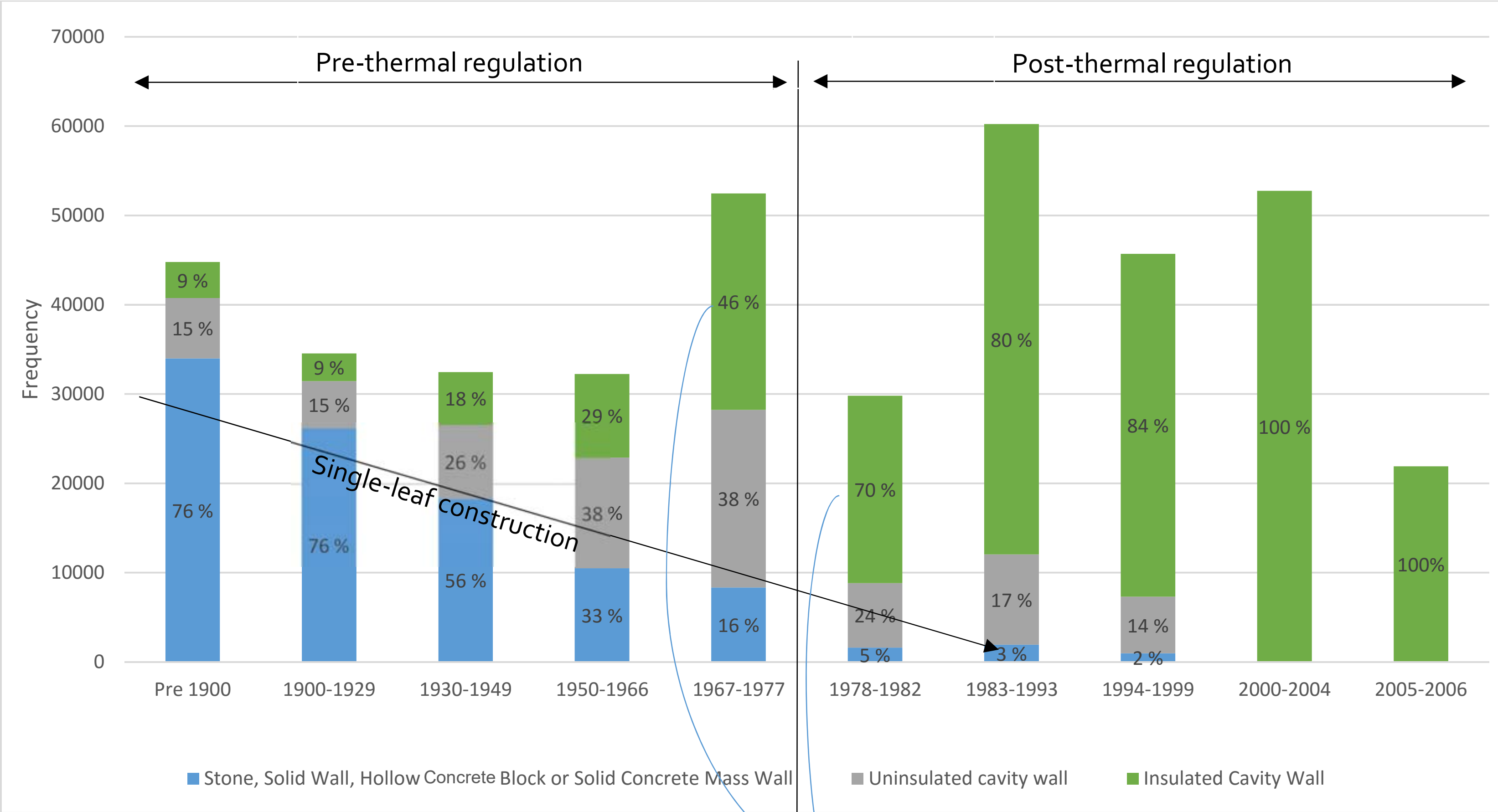
present in 2001.

Pre-thermal regulation dwellings are considered by DEAP to have been constructed originally [72]; (a) with no insulation, and (b) with single-leaf wall construction and are attributed an associated base-default U-value of 2.1 W/m^{2}K as shown in Tables 7 and 8. Contradicting this, the INSHQ data [131], depicted in Figures 13 and 14 [39] report pre-regulation dwellings to have significant numbers of cavity walls with the presence of cavity wall insulation increasing over time. The levels of insulation reported present in Irish dwellings in 2011, shown in Figures 13 and 14, suggest that the assertion in DEAP that pre-thermal regulation dwellings were constructed originally, without insulation, is incorrect or that homeowners;

i) constructed to better than regulation required at that time, or
ii) have carried out energy upgrades.

Referring to Figures 13 and 14, high levels of insulation are noted particularly in pre-thermal regulation dwelling walls constructed between 1967 and 1977. Due to being the largest, relative to other pre-thermal regulation dwellings, but with low levels of insulation; dwellings constructed during this time-period are considered to be the worst thermally performing dwelling [70]. This may have provided greater motivation to the homeowner to carry out thermal upgrades. The effect of the thermal building regulations when they came into force in the mid 1970's can be observed in Figure 13 with the presence of cavity wall insulation rising sharply from 46 % to 70 %.

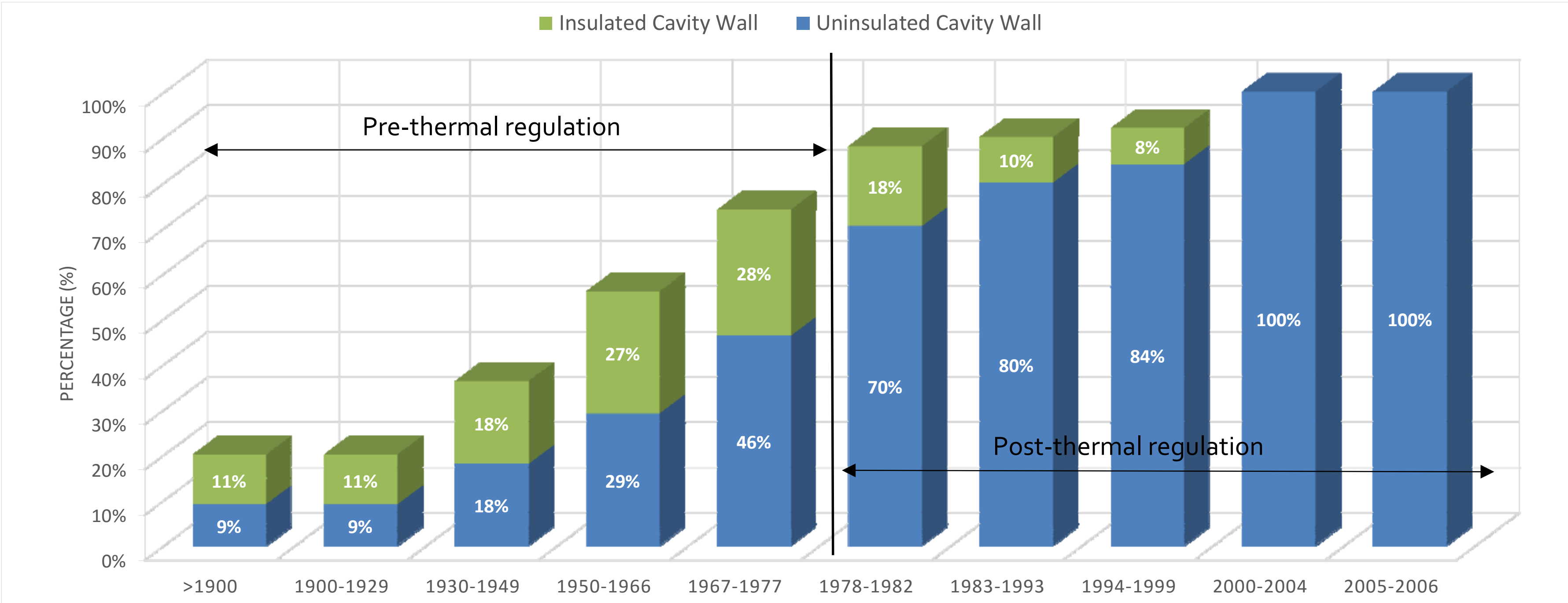
Figure 13 Wall type by period of construction for detached rural dwellings in Ireland in 2001-2002 [39, 131].



Pre-thermal dwellings are considered generally to have no insulation; however, significant levels of insulation were present in 2001-2002 indicating autonomous energy upgrades. This is especially noticeable in 1967 to 1977 walls; Due to being quite large but with low levels of insulation this house type is considered generally to be the worst thermally performing dwelling and that may have provided more motivation to the homeowner to carry out thermal upgrades

The effect of the thermal building regulations can be observed with cavity wall insulation jumping from 46 % to 70 %

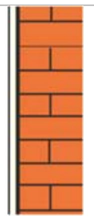
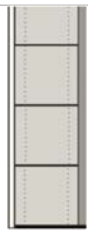
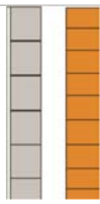
Figure 14 Prevalence of cavity and insulated cavity walls by period of construction in 2001 -2002 [39, 131]



The; a) predominant construction characteristics of dwelling walls in Irish vernacular rural housing, and b) the likely actual U-value arising are summarised in Table 13, full calculations and summary data are available in Appendix B. Referencing Table 13:

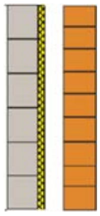
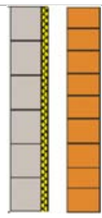
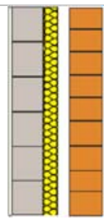
- In 18th century Ireland, brick was too expensive for use in rurally located vernacular housing (its use was limited to high status buildings such as castles and mansion houses) [132, 133]. Pre-1900 rural dwellings walls were therefore built typically of locally procured lime and sandstone [132, 133].
- Pre-1900 walls were normally rendered internally and externally with lime-based plasters but a stone finish was not uncommon [134, 135]. Masonry walls were designed traditionally using empirical slenderness ratios handed down the generations [136]. A pre-1900 stone cottage of typical wall height 4.5 m was constructed with a corresponding wall thickness ranging between 450 and 500 mm [136].
- Stone buildings were still popular in rural Ireland up to the 1930's however a more slender wall depth ranging from 300 to 400 mm became usual [129].
- In the period between 1900 and 1929, bungalows constructed of 225 mm solid brick became a feature of the rural Irish landscape [129, 136].
- Between 1930 and 1949, concrete was the favoured construction material and dwellings of this period were constructed typically with solid mass concrete walls [129, 136].
- Between 1950 and 1966, hollow-block walls were increasingly favoured over solid mass concrete; it is also during this time-period that cavity-wall construction became the dominant wall construction type accounting for over 50 % of the wall types in this construction period.
- The presence of insulation reported in 2001 was below 30 % [131]. Between 1966 to the present day the amount and quality of insulation is assumed to have been in-line with prevailing thermal building regulations.

Table 13 Predominant construction details for rural detached dwelling walls by period of construction [124, 129-131, 136, 137]

	Period of Constr-uction	Typical Dwelling	Details	Wall const'n typical	Likely actual U-value range calculated (W/m²K)	"Unknown" Base and / "known" default U-value from Table 8 (W/m²K)	Ref. Append-ix B for U-value calc.
Pre-thermal Reg.	Pre-1900 – 1930		Stone wall construction was common up until the 1930s. Wall depth ranged from 300 to 500 mm typically. Walls are usually rendered externally but stone finish is not uncommon. 13 mm lime plaster usual internally.		1.8 - 3.6 (depending on wall depth and presence of external render)	2.1/2.1	Tables B1-B4
	1900 - 1929		One-off bungalow with solid brick walls. Brick depth limited to 225 mm. Walls typically rendered externally with a 13 mm lime plaster internally.		1.58	2.1/2.1	Table B5
	1930-1949		One-off bungalow with 250 - 330 mm solid mass concrete wall, rendered externally with 13mm plaster internally.		2.4 to 2.65 depending on wall depth	2.1/2.2	Table B6-B7
	1950-1966		215 mm hollow block walls, rendered externally with 20mm cement/sand and plastered internally with 12 mm gypsum plaster. House type located in east coast areas in particular.		2.09	2.1/2.4	Table B8
			105 mm block, 75 mm cavity, 105 mm brick, no insulation, rendered externally with 13 mm plaster internally		1.58	2.1/1.78	Table B9

"Known" default value approximates calculated value

Table 13 (cont.) Predominant construction details for rural detached dwelling walls by period of construction [124, 129-131, 136]

	Period of Constr -uction	Typical Dwelling	Details	Wall constr'n typical	Likely actual U-value range calculated (W/m²K)	"Unknown" Base and / "known" default U-value from Table 8 (W/m²K)	Ref. Append-ix A for U-value calc.
Pre-thermal Reg.	1967-1977		Very common house construction in most of rural Ireland during the 1960s and 1970s. 105 mm block, 100 mm cavity part-filled with 50 mm **fibre insulation board** 105 mm brick.		0.54 - 0.59 depending on external render	2.1/0.6	Table B10 – B11
Post-thermal Reg.	1978-1982		105 mm block, 100 mm partially filled cavity part-filled with 50 mm **fibre insulation board**, 105 mm brick. Commonly found outside Dublin in neighbouring counties			1.1 / 0.6	
	1983-2004		50 mm of **polystyrene wall insulation board** was normally fitted during construction.		0.46	0.55 or 0.6*	Table B12
	2004 - 2006		70 mm of **mineral wool insulation** board was normally fitted during construction.		0.37	0.37 or 0.55*	Table B13

* singular default applies in line with thermal building regulations as shown in Table 7

"Known" default value approximates calculated value

2.4.5.2 Roof Characteristics

Similar to walls, pre-thermal regulation roofs are considered by DEAP [72] to have been constructed originally with no insulation and an associated base-default U-value of 2.3 W/m²K (see Table 7) [72, 124]. As shown in Table 14, a weighted average level of roof insulation of 82 % was present in 2001 – 2002. Notably, a high percentage was present in pre-thermal regulation dwellings [39, 131]. The high prevalence of roof insulation is attributed to the greater ease and lower cost associated with retrofitting wall insulation [131] as well as a successful state-funded attic-insulation incentive scheme of the 1980s [33] .

Table 14 Roof insulation by period of construction in 2001 - 2002 [39, 131]

			Roof insulation reported present %
Period of Construction	Pre-thermal regulation	Pre 1940	62
		1941-1970	78
		1971-1980	90
	Post-thermal regulation	1980-1996	95
		After 96	98
Frequency weighted average across periods of construction			**82**

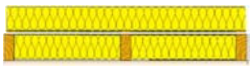
Within the European Intelligent Energy Europe (IEE) programme, the Typology Approach for Building Stock Energy Assessment (TABULA) project was undertaken between 2009 and 2012 by 13 EU MSs [53]. The objective of the project was *inter alia* to create a harmonised structure for European building typologies [53]. The building typologies report for Ireland [129] publishes roof construction characteristics as indicated in Table 15, notably with the inclusion of insulation in pre-thermal regulation dwellings, correlates with the INSHQ dataset [131]. Likely U-values were established as shown in Table 15 and as described in Appendix B.

Table 15 Predominant roof construction details for rural detached dwelling walls by period of construction [124, 129]

<table>
<tr><th></th><th>Period of Constr -uction</th><th>Typical Dwelling</th><th>Details</th><th>Roof construction typical</th><th>Likely actual U-value calculated (W/m²K)</th><th>"Unknown" Base and / "known" default U-value from Table 10 (W/m²K)</th><th>Ref. Append-ix B for U-value calc.</th></tr>
<tr><td rowspan="6">Pre-ther-mal Reg.</td><td>Pre-1900 – 1930s</td><td></td><td rowspan="6">50 mm of mineral wool between ceiling joists, roof space, tiling.</td><td rowspan="6"></td><td rowspan="6">0.71</td><td rowspan="6">2.3/0.68</td><td rowspan="6">Typical pitched roof constr'n (c); Table 3.5 CIBSE A [124]</td></tr>
<tr><td>1900 - 1929</td><td></td></tr>
<tr><td>1930-1949</td><td></td></tr>
<tr><td rowspan="2">1950-1966</td><td></td></tr>
<tr><td></td></tr>
<tr><td>1967-1977</td><td></td></tr>
</table>

"Known" default value approximates calculated value

Table 15 (cont.) Predominant construction details for rural detached dwelling walls by period of construction [124, 129]

	Period of Constr-uction	Typical Dwelling	Details	Roof construction typical	Likely actual U-value calculated (W/m²K)	"Unknown" Base and / "known" default U-value from Table 10 (W/m²K)	Ref. Appendix B for U-value calc.
Post-ther-mal Reg.	1978-1982		100 mm of mineral wool between ceiling joists, roof space, tiling.		0.42	0.4/0.4	Typical pitched roof constr'n (d); Table 3.5 CIBSE A [124]
	1983-1993						
	1994-2004		100 mm of mineral wool insulation between joists and 50 mm of mineral wool quilt over joists, roof space, tiling.		0.28	0.35/0.26	Typical pitched roof constr'n (e); Table 3.5 CIBSE A [124]
	2005 - 2006		100 mm of mineral wool insulation between joists and 100 mm of mineral wool quilt over joists, roof space, tiling.		0.21	0.25/0.21	Typical pitched roof constr'n (f); Table 3.5 CIBSE A [124]

"Known" default value approximates calculated value

2.4.5.3 Floor Characteristics

DEAP [72] is the only authoritative guide published, detailing typical composite floor constructions. The recent TABULA [120, 129] project characterised walls and roofs only. It is thus not possible to review default U-values quoted in DEAP in any detail.

I.S. EN ISO 13370 suggests a default for ground thermal conductivity (if the soil type is unknown) of λ_g 2.0 W/mK. This value appears to have been adopted as the standard in DEAP [72], however as shown in Figure 15, the predominant soil type in Ireland is homogenous rock namely limestone or sandstone. I.S. EN ISO 13370 states if the soil type is known, values for the actual location, averaged over a depth equal to the width of the building and allowing for the normal moisture content should be adopted in the calculation of ground floor U-values. Hard-core under slab is ignored.

CIBSE Guide A [124] Tables 3.15-3.17, quote default figures for solid ground floor U-values, an extract of which is shown Table 16. It is noted in Table 16 that U-values for ground floors on homogenous rock are substantially greater than slabs over sand or gravel, suggesting that the use of default ground floor U-values quoted in DEAP [72], will underestimate the heat loss through the ground in the majority of locations in Ireland.

Floor insulation was present in 22 % of Irish dwellings in 1996, 24 % in 1998 and 25 % in 2001 [138]. However, as the data published is not categorised by period of construction it does not facilitate this characterisation.

Figure 15 Geological Map of Ireland [139]

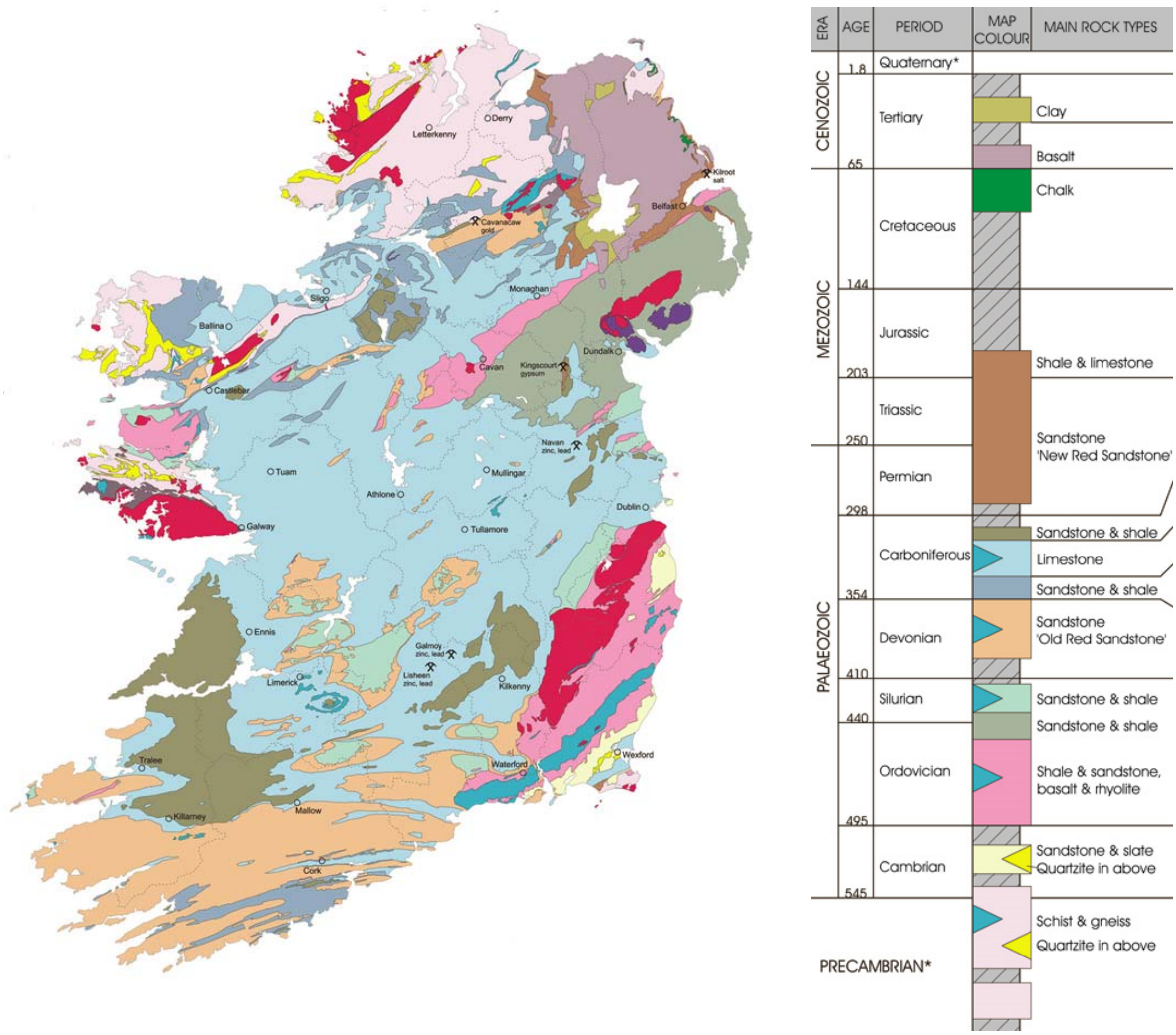


Table 16 Extract from CIBSE Guide A, Tables 3.15 to 3.17, relating to solid ground floors [124]

Typical floor perimeter to ground floor area (P_f/A_{fg}) patios for case study dwellings

Table 3.15 *U*-values for solid ground floors on clay soil (λ_g = 1.5 W·m⁻¹·K⁻¹)

Ratio p_f/A_{fg}	*U*-value (/ W·m⁻²·K⁻¹) for stated thermal resistance, R_f (/ m²·K.W⁻¹)			
	0	0.5	1.0	2.0
0.05	0.13	0.11	0.10	0.08
0.10	0.22	0.18	0.16	0.13
0.15	0.30	0.24	0.21	0.17
0.20	0.37	0.29	0.25	0.19
0.25	0.44	0.34	0.28	0.22
0.30	0.49	0.38	0.31	0.23
0.35	0.55	0.41	0.34	0.25
0.40	0.60	0.44	0.36	0.26
0.45	0.65	0.47	0.38	0.27
0.50	0.70	0.50	0.40	0.28
0.55	0.74	0.52	0.41	0.28
0.60	0.78	0.55	0.43	0.29
0.65	0.82	0.57	0.44	0.30
0.70	0.86	0.59	0.45	0.30
0.75	0.89	0.61	0.46	0.31
0.80	0.93	0.62	0.47	0.32
0.85	0.96	0.64	0.47	0.32
0.90	0.99	0.65	0.48	0.32
0.95	1.02	0.66	0.49	0.33
1.00	1.05	0.68	0.50	0.33

Table 3.16 *U*-values for solid ground floors on sand or gravel (λ_g = 2.0 W·m⁻¹·K⁻¹)

Ratio p_f/A_{fg}	*U*-value (/ W·m⁻²·K⁻¹) for stated thermal resistance, R_f (/ m²·K.W⁻¹)			
	0	0.5	1.0	2.0
0.05	0.16	0.14	0.12	0.10
0.10	0.28	0.22	0.19	0.16
0.15	0.38	0.30	0.25	0.20
0.20	0.47	0.36	0.30	0.23
0.25	0.55	0.41	0.33	0.25
0.30	0.63	0.46	0.37	0.26
0.35	0.70	0.50	0.39	0.28
0.40	0.76	0.53	0.42	0.29
0.45	0.82	0.56	0.43	0.30
0.50	0.88	0.59	0.45	0.31
0.55	0.93	0.62	0.47	0.31
0.60	0.98	0.64	0.48	0.32
0.65	1.03	0.66	0.49	0.33
0.70	1.07	0.68	0.50	0.33
0.75	1.12	0.70	0.51	0.34
0.80	1.16	0.72	0.52	0.34
0.85	1.19	0.73	0.53	0.35
0.90	1.23	0.75	0.54	0.35
0.95	1.27	0.76	0.54	0.35
1.00	1.30	0.77	0.55	0.35

Table 3.17 *U*-values for solid ground floors on homogeneous rock (λ_g = 3.5 W·m⁻¹·K⁻¹)

Ratio p_f/A_{fg}	*U*-value (/ W·m⁻²·K⁻¹) for stated thermal resistance, R_f (/ m²·K.W⁻¹)			
	0	0.5	1.0	2.0
0.05	0.27	0.21	0.18	0.15
0.10	0.45	0.34	0.28	0.22
0.15	0.61	0.43	0.35	0.26
0.20	0.74	0.51	0.40	0.28
0.25	0.86	0.58	0.44	0.30
0.30	0.97	0.63	0.47	0.32
0.35	1.07	0.68	0.50	0.33
0.40	1.16	0.72	0.52	0.34
0.45	1.25	0.75	0.53	0.35
0.50	1.33	0.78	0.55	0.35
0.55	1.40	0.80	0.56	0.36
0.60	1.47	0.82	0.58	0.37
0.65	1.53	0.84	0.59	0.37
0.70	1.59	0.86	0.60	0.37
0.75	1.64	0.87	0.61	0.38
0.80	1.69	0.89	0.62	0.38
0.85	1.74	0.91	0.62	0.38
0.90	1.79	0.92	0.63	0.39
0.95	1.83	0.93	0.64	0.39
1.00	1.87	0.95	0.64	0.39

U-values for ground floors on homogenous rock are substantially greater than slabs over sand or gravel

2.4.5.4 Window Characteristics

Default window U-values for double and single glazing are 3.1 W/m²K and 4.8 W/m²K respectively [72] . Employing *inter alia* the INSHQ dataset [131], a study of these case study dwellings was carried out in 2010 [39], this study established that:

- U-values for windows in existing dwellings are no longer strongly associated with dwelling age. For example 65 % of windows in dwellings constructed between 1941 and 1970 are double glazed.
- The statistical mean glazing U-value for a single and two-storey dwellings is 2.95 Wm²K and 2.91 Wm²K respectively.
- 72 % of these case study dwellings were found to be double-glazed in 2010.
- Predominant window frame material across all age bands is timber (40 %) or PVC (50 %) with the presence of steel (1 %) and aluminium frames (9 %) negligible.

High double glazing rates are likely as replacing old windows with energy efficient window systems;

(i) are known to increase the value of a property [17], and

(ii) have a significant impact of the overall energy efficiency of the dwelling [58].

In Ireland [72] and the UK [140] window systems installed or retrofitted prior to 2004 are not considered to have low-emissivity "Low E" glazing.

2.5 Validation of EPC Dataset

Figures 10 (a &b) and 11 (a & b) demonstrate the;

i) frequency of default U-value selection across periods of construction, and
ii) independence of default U-value selection to building element type,

whilst implying that building assessors are often selecting "unknown" wall types by period of construction, in preference to calculating actual elemental U-values, leading to Ireland's EPC methodology selecting pessimistic base-default U-values. The rationale for this assertion is evidenced particularly in;

(i) *Post-regulation dwellings* - Information on wall constructions in recently constructed dwellings should be more easily obtainable than for older dwellings, despite this "unknown" default U-values for walls and roofs are observed to be selected consistently. This is demonstrated particularly in roofs and walls constructed between 2005 and 2006, wherein the "unknown" base-default U-value's display the highest frequency in the distribution.

(ii) *Pre-thermal regulation dwellings walls constructed up and until 1949* - As shown in Figure 10 (a) and as described in Table 13, single-leaf stone-wall construction was typical in rural Ireland up and until 1949. By measuring wall depth, via an open window for instance, wall thickness can be established straightforwardly. Render and plaster finishes can be observed easily. The U-value for solid stone-wall construction can thus be calculated with relative ease yet Figure 10 (a) suggests an over-use of "unknown" base-default U-values during this time period.

(iii) *Pre-regulation dwelling roofs* - Insulation in roofs is typically easier to identify than in walls. As indicated in Table 7, the base-default U-value associated with an uninsulated roof is 2.3 W/m^2K, however we know from the INSHQ dataset [138], that 82 % roofs in this dwelling typology were insulated in 2001. Figure 11 (a) thus displays an inconsistent level of uninsulated roofs.

In all cases, base-default U-values associated with "unknown" wall-types, often chosen by assessors, are shown in Tables 13 and 15 to be strongly pessimistic. As more retrofit interventions are carried out in the housing sector, current "unknown" base-default U-values become less relevant to the real statistical distribution over time especially with respect to Mode 1 dwellings. Contrary to this, as shown in Tables 13 and 15, where the default U-value associated with a 'known' building element type is selected, the default U-value approximates the likely U-value calculated. To use a 'known' wall-type the dwelling assessor must have been able to establish evidence to support their assertion. It is thus appropriate to;

- remove "unknown" base-default U-values from the database, but accede
- default U-values associated with 'known' wall-type default U-values to remain[11].

This will;

- eliminate the structural data errors associated with outmoded base-thermal-default values,
- refine the dataset from the apparent overuse of base-default U-values, and
- represent better, the real statistical distribution of a dwelling stock.

Referring to Figures 10 (a &b) and 11 (a & b); median U-values for:

- Mode 2 dwellings correlate strongly with likely as-built U-values calculated in Tables 13 and 15.
- Mode 2 dwellings correlate with building regulations current at time of construction.
- Mode 1 dwellings correlate with,
    - the range of U-values prescribed within the 2007 [125] and 2011 [126] Irish building regulations, and
    - State funded incentivised energy refurbishments grants to the homeowner.

Data for Mode 2 or as-built dwellings is thus consistent with vernacular construction characteristics of Irish dwellings and data for Mode 1 dwellings is consistent with desired

[11] With the exception of pre-thermal regulation brick and stone walls constructed up and until 1949 wherein the known and unknown wall types have the same value

outcomes for state-funded retrofit incentives. Consequently, the microscopic data within the EPC dataset is accepted as plausible and representative of real-world scenarios.

As detailed in Section 2.2 data quality results from intrinsic characteristics of the data accuracy, coherence, compatibility, clarity and accessibility [80]. A summary of data quality checks and measures taken to ensure final data quality are listed in Table 17. Section 2.2 (ref: Table 1 and Figure 3) outlines checks for consistency of data with corresponding data validation levels, defined by Eurostat in [79, 80]. In summary and referring to Table 17; the data was checked for consistency within the elements of the dataset to validation level 1. Intra-datasets time-series checks via differing periods of construction;

(i) found the data to behave consistently to validation level 2, while also
(ii) confirming a structural error, and the requirement to clean the data of base-thermal default U-values.

Using data from other statistical authorities (see Table 17), and through intra-domain consistency checks, it was possible to confirm the quality of the data in the refined EPC dataset to data validation level 5. Validation level 5 is the highest level of data validation achievable as defined by Eurostat in [79, 80], so verifying data quality. Achieving data validation level combined with the fact that the data has undergone data cleaning implies (see Section 2.2) that the refined microscopic data in the EPC dataset is acceptable to characterise the reference dwellings into macroscopic information.

Chapter 4 expresses the methodological stages 3 and 4 relating to the characterisation of reference dwellings described in terms of operation, form (geometry), thermal and system characteristics. Chapter 4 also outlines how the reference dwellings characterised were aggregated to stock level. The following chapter, Chapter 3 explores the structural data error discovered during the data validation process identified as the 'default effect'. The implications of this default effect on the results of the EPC methodology and on the quality of data within the EPC dataset is discussed. The renovation status of the stock and the level of compliance with thermal building regulations is also assessed in the following Chapter 3.

Table 17 Summary of data quality checks and measures taken to validate EPC dataset

Valid-ation Level	Description	Statistical Authority and/or data provider	Action Taken to accept data as plausible	Reference
1	File was compiled by an authorised authority	SEAI	Review of SEAI audit and quality assurance mechanisms	Section 2.2.1
2	Intra-dataset time-series checks via differing time periods – data behaved consistently	Ahern - Segmented dataset	Structural error in the data established – base-thermal-default U-values removed in the case of walls and roofs	Section 2.4
	Defaults correlated with period of construction			
5	Intra-domain consistency check in respect of wall, roof and floor insulation levels	Consistent with INSHQ dataset [131]	Recommendation to review base-thermal-default assumptions in DEAP	Section 2.4
	Vernacular construction characteristics of dwelling thermal envelope established	INSHQ [131], TABULA [120, 129], CIBSE Guide A [124], literature [70, 132-134, 136, 138, 139]	Base-thermal-defaults removed as inconsistent with other data sources – 'known' thermal defaults not removed as consistent with other data sources and calculations	Section 2.5
			Figures 10 and 11 analysed to established consistency with vernacular construction details and state-funded incentivised retrofit schemes	

Chapter 3 – Introducing the Default Effect & Quantifying the Renovation Status of the Irish housing stock.

Thermal retrofits "cannot save energy that is not actually being consumed"

Sunikka-Blank et al. [108]

3.1 Introduction

This chapter uses the recently-published Irish national empirical energy performance certification database [76] to:

1) Assess the relationship of current base-thermal-default U-values relative to the empirical statistical distribution.
2) Indicate (a) the current condition of Irish housing stock, (b) building stock refurbishment trends, and (c) the extent of installation of dwelling thermal insulation.
3) Make recommendations for updated, contemporaneous base-thermal-default U-value's relative to the empirical statistical distribution.
4) Discuss the potential impact of base-thermal-default U-value selection on the validity of,
    i) energy performance certification, and
    ii) use of base-default U-values as key inputs to national building energy consumption models.
5) Highlight the potential contribution of base-thermal-default use to prebound effect in existing dwellings

The research reported in this chapter:

a) Appraises the necessity of use of pessimistic base-default U-values in energy labelling.
b) Assesses the level of thermal retrofits and thermal building regulation compliance for Ireland's predominant housing typology.
c) Recommends a statistically relevant selection point for base-default U-values.
d) Assesses the impact of base-thermal-default use on building performance certification quality.
e) Highlights inappropriate use of base-default U-values as energy model inputs.
f) Highlights how base-thermal-default use may influence uptake of residential upgrade measures.

3.1.1 Energy Performance Certification

Building energy classification allows inter-comparison of building energy use [51, 141]. Different approaches to calculating the energy classification of dwellings have been adopted across EU Member States [51, 104].

An EPC:

- Presents the calculated energy performance coefficient of the building on a scale of A (which should have the lowest fuel bills) to G [51].
- Uses the same scale A-to-G to define the building's greenhouse gas emissions.

In Ireland [142] and in the UK [143] publicly-available EPC methodologies are used to calculate the energy classification of dwellings. EPC methodologies at the national level need to have:

- Credibility and accuracy, so that, for a given climate, buildings with better labels should use less energy [51, 59, 106].
- Applicability to a wide variety of buildings balancing possible loss of accuracy with remaining representative [104].

- Clarity, so that users should be able to understand a) the overall result and b) the effect of choices (input) on the calculation result [104, 106].
- Reproducibility, so that for a specific building the underlying method used leads to the same result; irrespective of subjective or arbitrary choices and independent of the user [51, 104].
- Transparency to ensure the energy label of a given building is relevant and useful [51, 104, 106],
- Cost-effectiveness to avoid;
  - significantly adding to the cost of the label particularly compared to the impact of the certificate on the energy performance - obtaining the building data needed for an energy performance certificate must not be too labour intensive [104], and
  - poorly user-interfaced or complex simulation programs that require a high training level for the program user [144].

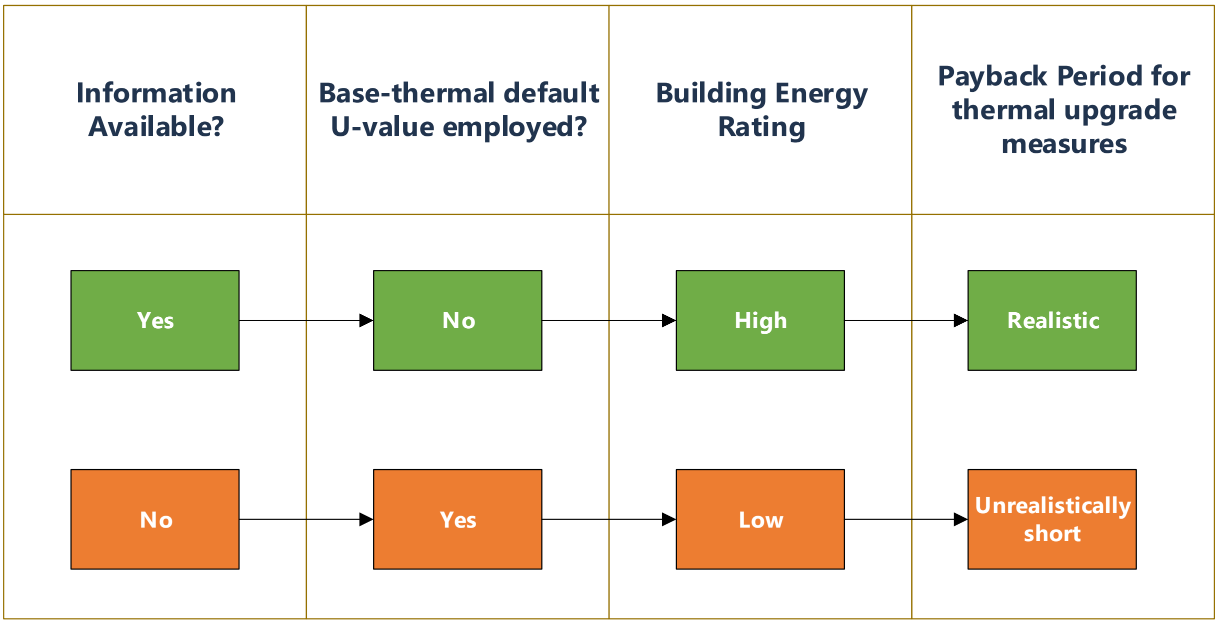
The EPC also informs an associated advisory report recommending feasible energy efficiency measures from both technical and economical perspectives [51, 106, 109]. The underlying premise being that building owners decisions are predicated on financial savings. Informing the household about cost-effective energy-saving measures is anticipated therefore to result in marked behavioural change to reduce their energy costs [145, 146]. However even when the majority of recommendations are economically advantageous, consumers are not generally persuaded to act rationally to adopt these measures [2, 145-147].

A barrier perceived to the credibility of EPC labels and advisory reports by homeowners is inaccuracy wherein the financial energy-savings are in reality smaller than estimated [110]. To overcome this, energy consumption associated with improving an EPC label after a specific energy saving intervention in a particular dwelling should reflect closely the actual decrease in energy consumption [62, 105]. The effectiveness of the rating therefore depends on the proper selection of default data [51, 60]. Where accurately obtaining all of the required building envelope data would be excessively labour-intensive and/or invasive, national base-default values are sometimes employed. Base-default values are normally pessimistic [14] so as to [104];

- avoid offering a better than merited energy rating,
- allow the homeowner to know the energy advantage of carrying out retrofits,
- encourage the homeowner to maintain records of energy upgrades that inform EPCs, and
- encourage assessors to seek out information to improve the energy rating.

An illustrative case of two identical buildings is presented in Figure 16 [104]. Where for one building, the data item is not observable on site or via documentary evidence, so a base-thermal-default is used. While for the other building the actual data available was used.

Figure 16 Building energy rating and payback periods for two identical buildings with and without information [104]



Information on the thermal characteristics of older dwellings is often more difficult to obtain than for recently constructed dwellings [14, 112]. If an improvement in the energy performance certification is the basis for renovation, use of pessimistic default values may lead to higher improvement expectations in the EPC rating [104, 105, 113]. Arkestijn and van Dijk (2010) [104] raised the policy-related question of whether it is equitable to give a worse energy rating simply because less information is available. Furthermore, if the lack of information associated with the building is to be penalised - how tough should the penalty be? In other words how pessimistic should the default value be?

3.2 Methodology to establish statistically relevant base-thermal-default values

3.2.1 How pessimistic should the default value be?

Default U-values should be employed when producing EPC's to;

(i) keep the cost of certification at an affordable level and,

(ii) aid the reproducibility and robustness of the method for situations where information is lacking.

When selecting a base-thermal-default U-values relative to the statistical distribution, the key issue is the potential impact of that selection point on the EPCs accuracy.

Assuming the empirical data to distribute normally[12] (variations equally likely to be below and above the mean), Figure 17 expresses and Table 18 describes, the probable validity of an EPC relative to a standardised normal frequency distribution of dwelling-stock element U-values by period of construction, articulated on a scale ranging from the very optimistic to the very pessimistic, expressed in terms of of standard deviations away from the mean. Both Table 18 and Figure 17 consider how the selection of:

a) '*Moderately optimistic*' to '*very optimistic*' (ranging from 0 to -3 standard deviations from the mean) default U-values are not desirable as it may act as a disincentive to carrying out thermal energy efficiency upgrades in the housing sector.

b) '*Very pessimistic*' (ranging from 2 to 3 standard deviations from the mean) default U-values are likewise not desirable due to the significant risk of;

[12] The validity of this assumption is explored Sections 3.2.2.1 and verified in Section 3.2.2.2 as well as in Appendix C

i. greatly overestimating the potential saving from retrofit intervention, and
ii. the creation of a very punitive system for existing dwellings where information is often difficult to obtain.

c) '*Realistic*' (zero standard deviations from the mean) statistically derived means will often lead to an underestimation of the potential to improve the energy performance rating.

'*Moderately pessimistic'* and '*pessimistic*' thus remain. Figure 17 shows how the use of:

a) '*Moderately pessimistic'* default U-values (ranging from the 50th to 84.1st percentile point or 0 to 1 standard deviations from the mean), results in a slight loss of validity and a better comparative energy performance rating of the two identical buildings examined in Figure 16, however there is significant risk of overestimating the potential savings from a retrofit intervention for dwellings occupying the 84.1st to 100th percentile point (15.9 % of the dwelling stock).
b) '*Pessimistic'* default U-values (ranging from the 84.1st to 97.7th percentile point or 1 to 2 standard deviations from the mean) will lead to a greater loss in validity than that of *moderately pessimistic* U-values, but only a slight risk of overestimating the potential savings from a retrofit intervention for dwellings occupying the tail of the distribution (6.7 to 15.9 % of the dwelling stock)

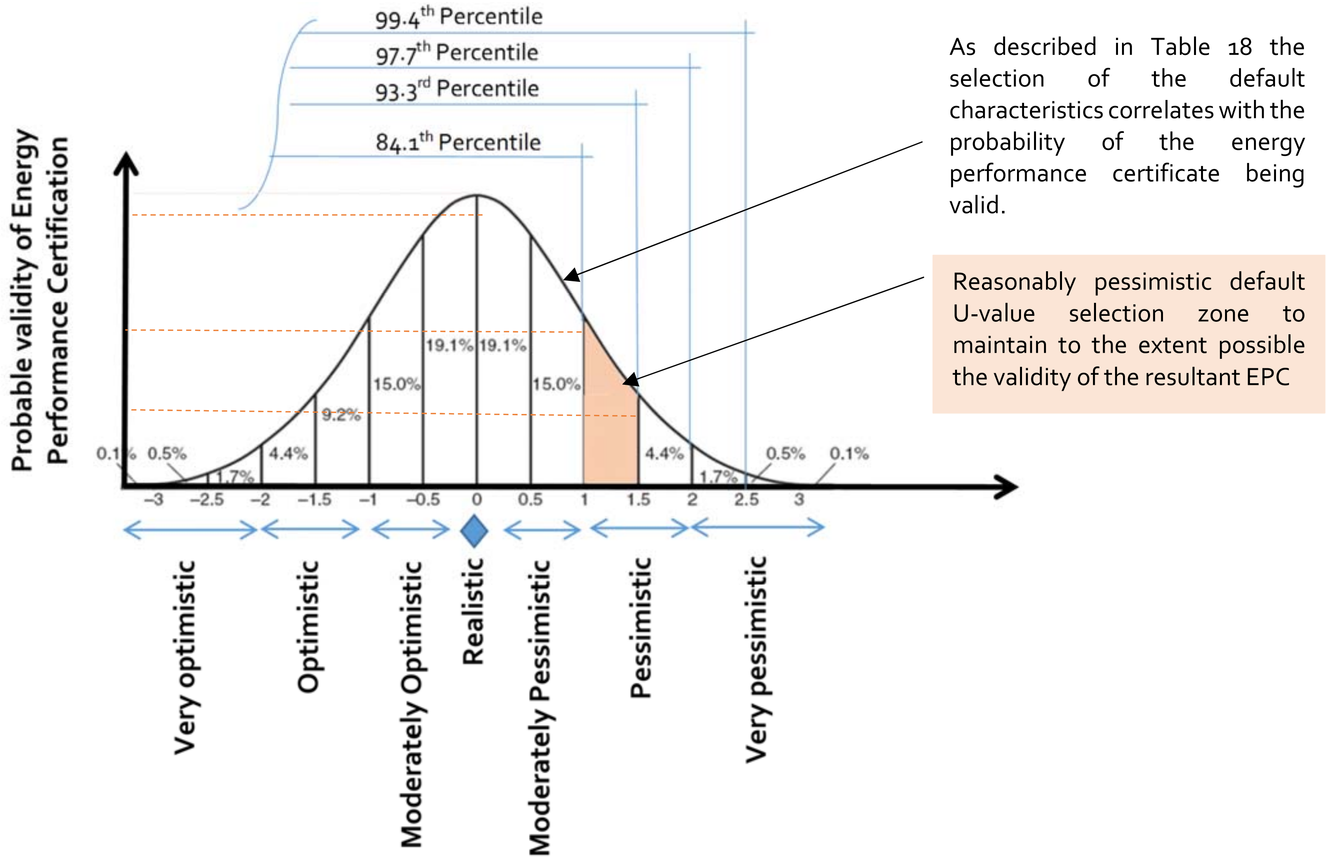
Referring to Figure 17, a '*reasonably pessimistic'* default U-value would lie between the 84.1th or 93.3rd percentiles. Selection of a default U-value in this zone will ensure a reasonable level of accuracy for the certificate but also allow the homeowner to perceive the energy advantage of carrying out thermal retrofits.

The 90th percentile point falls centrally between the 84.1th or 93.3rd percentiles, whilst also allowing a margin of error to stay within the desired zone. The refined dataset [76] was therefore analysed to calculate statistically relevant base-default U-values based on 90th percentile point of the distributions as described in the following Section 3.2.2.

Table 18 Implication of base-default U-value selection on Energy Performance Certification

Thermal Default	Very Optimistic	Optimistic	Moderately Optimistic	Realistic	Moderately Pessimistic	Pessimistic	Very Pessimistic
Loss of Validity Scale	Loss of Validity ← Significant		Slight	◆	Loss of Validity → Slight		Significant
Implication for Energy Performance Certification	Increasing loss of accuracy leading to an increasingly significant risk that, a) improvement measures could actually worsen the energy rating rather than make it better and, b) assessors and end-users might be less motivated to gather detailed information about the building where it is not readily available.			Using statistical means determined empirically shall significantly increase the statistical accuracy of the performance certificate however if the realistic value is too optimistic for the particular building being examined without information, it may lead to an underestimation of the potential to improve the energy performance rating	Increasing loss of accuracy leading to an increasingly significant risk of, a) the results returned by the process greatly overestimating the potential savings from the retrofit intervention and b) a punitive system, especially for existing buildings.		

Figure 17 Relationship of default U-value selection to quality aspects of energy performance certification relative to standard normal statistical distribution of a dwelling-stock element by period of construction



Standardised normal distribution of dwelling-stock element U-values by period of construction (W/m²K)

3.2.2 Maximum Likelihood Estimation (MLE) (of the parameters of the distribution)

In order to;

i) assess the relationship of current base-default U-values to the empirical statistical distribution, and
ii) assess the level of thermal retrofits and thermal building regulation compliance for Ireland's predominant housing typology, and
iii) make recommendations for updated base-default U-value's,

it is necessary to fit a bimodal distribution to the empirical data to;

a) establish the proportion of Mode 1 and Mode 2 dwellings by period of construction (see Figure 18),
b) ascertain the mean of Mode 1 and Mode 2 dwellings, 'Mean 1' and 'Mean 2' by period of construction (see Figure 18), and
c) plot the fitted cumulative distribution function (see Figure 24) to establish the 90th percentile point of the data (ref: Section 3.2.1).

3.2.2.1 Selection of distribution to fit empirical data

In statistics, measurement values are classed as continuous numerical data [148] and considered to be 'random' quantities [149]. Leito [149] offers an example of repeatedly pipetting 10 ml volumes to demonstrate how measurement quantities are random, stating that: "If a sufficiently large number of repeated measurements are carried out and if the pipetted volumes are plotted according to how frequently they are encountered then it becomes evident that although random, the values are still governed by some underlying relationship between the volume and frequency: the maximum probability of a volume is somewhere in the range of 10.005 and 10.007 ml and the probability gradually decreases towards smaller and larger volumes. This relationship is called distribution function."

The normal distribution function is used to analyse random quantities or data when there is an equally likely chance of a data point being above or below the mean for continuous data whose histogram fits a symmetrical distribution or bell curve [150]. If the curve is normal, no phenomenon is unduly skewing the process [150].

Where a measurement result is influenced simultaneously by many uncertainty sources and if the number of the uncertainty sources approaches infinity then the distribution function of the measurement result approaches the normal distribution, irrespective of the distribution functions of the factors/parameters describing the uncertainty sources [149]. In reality the distribution function of the result becomes indistinguishable from the normal distribution if there are between 3 to 5 (depending on situation) significantly contributing uncertainty sources [149]. This explains why measured quantities have a normal distribution typically and why the mathematical basis of measurement science and uncertainty estimation is based classically, on the normal distribution [149].

A thermal transmittance or U-value is the reciprocal of the thermal resistance coefficient 'R', given by Equation (7).

$$U = \frac{1}{R} \text{ (W/m}^2\text{K)} \tag{7}$$

The thermal resistance coefficient 'R' of a building element is given by Equation (8) and is a measure of resistance to heat flow through a given thickness of material, measured in meter squared Kelvin per watt (m^2K/W);

$$R = \frac{L}{\lambda} \text{ (m}^2\text{K/W)} \tag{8}$$

where;

L = thickness of material (m)

λ = thermal conductivity of material (W/mK)

For a composite structure, and as shown in Equation (9), the U-value is given by the reciprocal of the sum of the thermal resistances of the composite layers;

$$U = \frac{1}{\sum R} \text{ (W/m}^2\text{K)} \tag{9}$$

The sum of the thermal resistance coefficient 'R' (∑R) of a composite structure is given by Equation (10). Equation (10) demonstrates the sum of the resistances to include the resistance to heat flow of:

i) The sum of the various wall elements comprising the structure ($\sum R_{composite\ element}$);
ii) The boundary between the composite building element and air on both the;
   a. external (R_{se}), and
   b. internal (R_{si}) surfaces;
iii) An air gap (R_a) where present.

$$\sum R = R_{external\ surface} + \sum R_{composite\ elements} + R_a + R_{internal\ surface} \text{ (m}^2\text{K/W)} \tag{10}$$

where

$$R_{composite\ element} = \frac{L_{\ composite\ element}}{\lambda_{composite\ element}} \text{ (m}^2\text{K/W)} \tag{11}$$

An analysis of vernacular wall and roof characteristics is carried out in Section 2.4.5 (see Tables 13 and 14). U-value calculations associated with constructions detailed in Tables 13 and 14 are detailed in Appendix B. As shown in Appendix B, U-values are calculated by the assessor based on measured wall thicknesses and manufacturers declared U-values where available, otherwise assumed standardised thermal conductivities by composite element type are used.

To source information on thermal conductivities for common construction materials, DEAP [89] cites the following three resources;

(i) the Irish Building Regulations, 2008 [151],

(ii) IS EN 12524, 2000, Building materials and products – hygrothermal properties – tabulated design values[13] [152], or

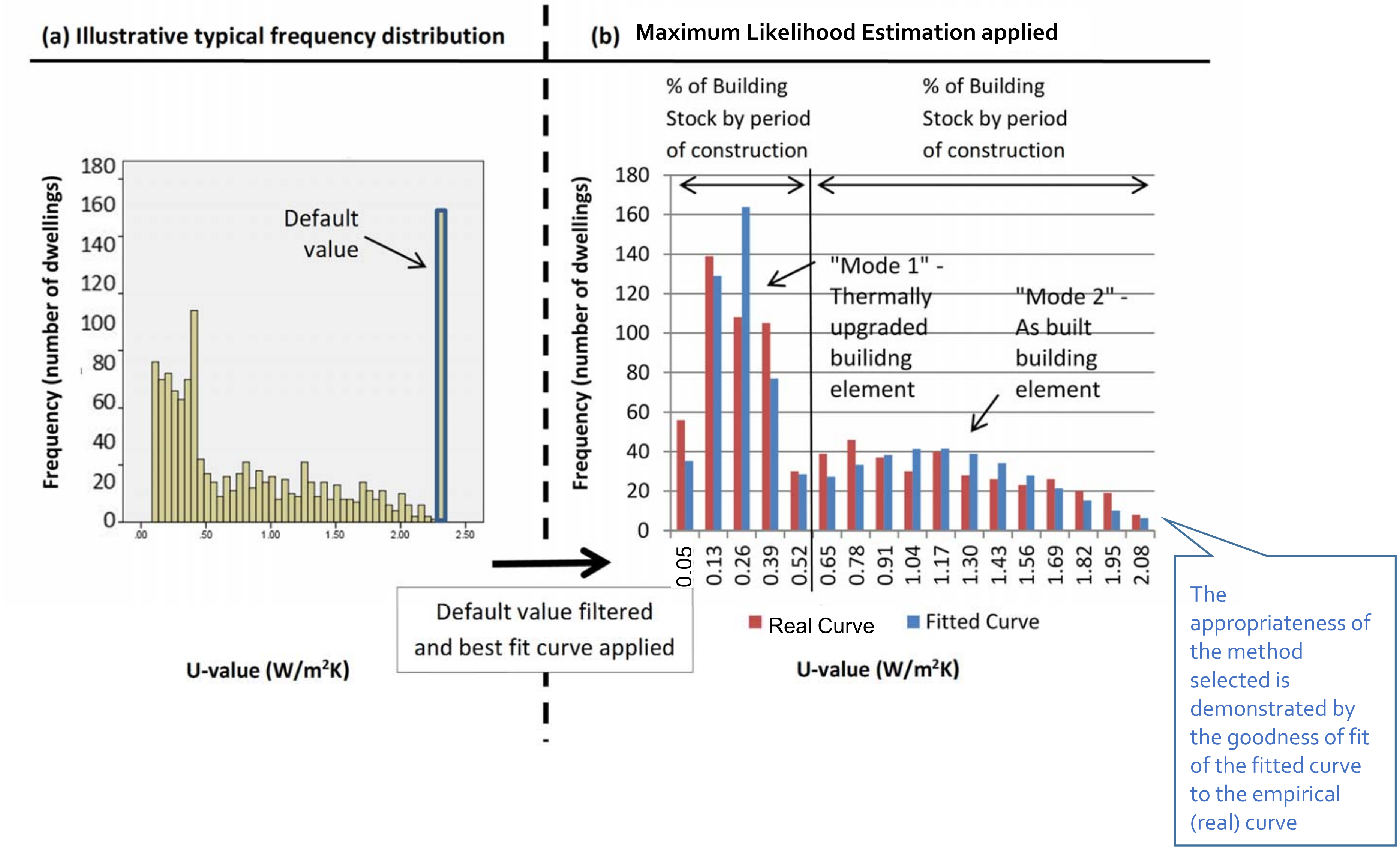
(iii) CIBSE Guide A [124].

CIBSE Guide A [124] is used to source data for U-value calculations in Appendix B wherein relevant exerts from the guide are shown. It can be seen from these exerts that the thermal conductivities of materials vary with assumed density and information source. Due a lack of specific information on the density and characteristics of its materials, a range of possible calculated **U** values is thus possible from the same wall classification.

As stated previously, where a measurement result is influenced simultaneously by 3 to 5 uncertainty sources then the distribution function of the measurement result likely approaches the normal distribution. It is expected therefore that measured values for thermal resistances (R-values) would distribute normally, it is not known however whether the reciprocal of the measured R-values (U-values) would also behave normally. Figure 18 (b) shows a normal distribution to be a reasonable fit to the data. It is possible that other distributions will fit the data better in certain cases. To ascertain this, and as detailed in the following Section 3.2.2.1.1, the "Find the Best Distribution" (FBD) function [153] from the MATLAB® [154] central file exchange was used.

[13] No longer current but cited in Irish building regulation guidance

Figure 18 (a & b) Illustrative typical frequency distribution and analysis of wall and roof U-value [76]



3.2.2.1.1 Likely distribution function to fit empirical dataset

The FBD function [153] in MATLAB® [154] was used to find the distribution function that fits the empirical data best. The FBD function [153] tests the following distributions; Generalized Pareto; Inverse Gaussian; Logistic; Log-logistic; Lognormal; Nakagami; Normal; Rayleigh; Rician; t location-scale; Weibull, Birnbaum-Saunders; Exponential; Extreme value; Gamma; Generalized extreme value, against data submitted.

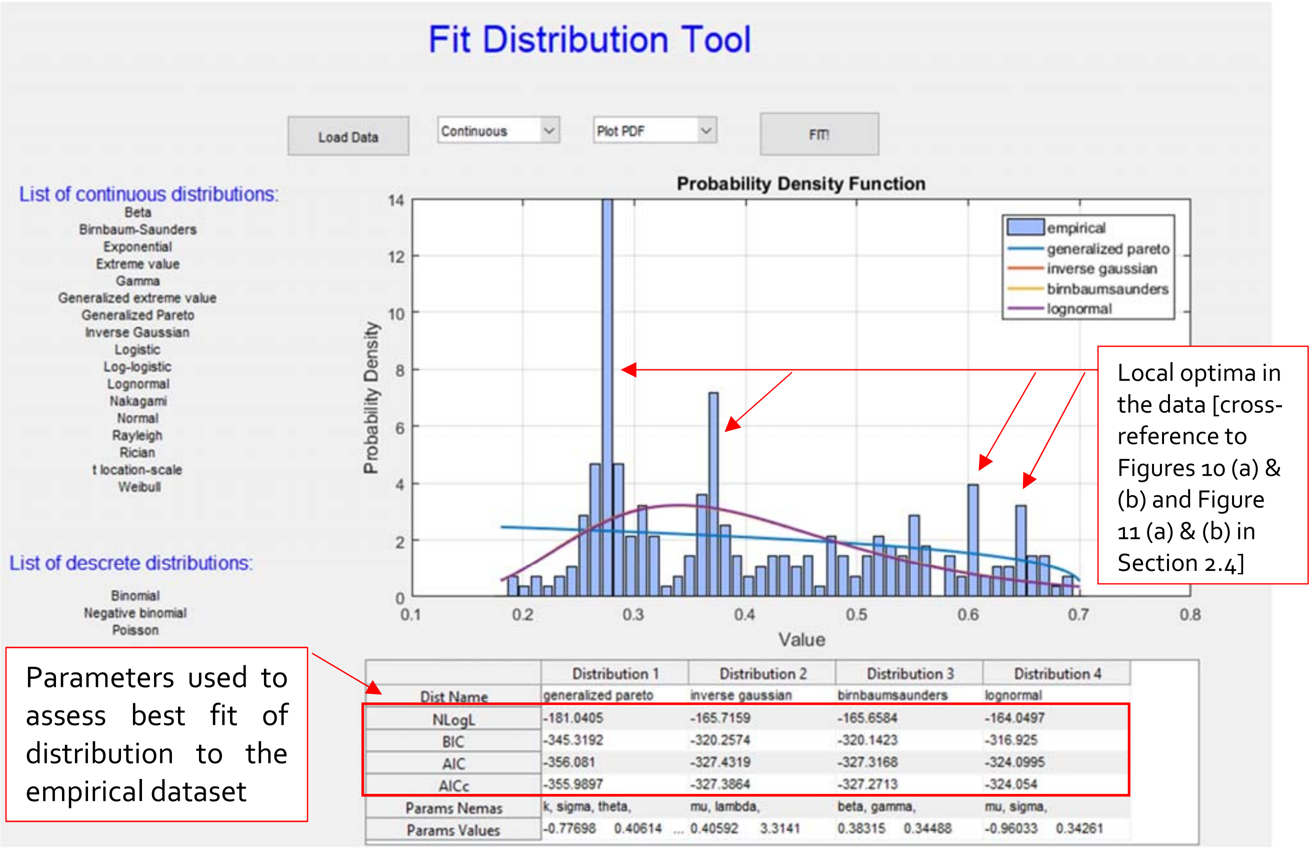
Figure 18 (a) shows the building envelope data in the EPC dataset to be distributed with an asymmetric bimodal characteristic. The FBD function [153] works on unimodal data only so it was necessary to split the empirical dataset into Mode 1 and Mode 2 data by dwelling element type, by period of construction. Distributions for single and two-storey roof and wall characteristics were selected randomly for two number:

- Pre thermal regulation dwellings (periods selected: 1900 and 1929, and 1967 and 1977); and
- Post thermal regulation dwellings (periods selected: 1978 and 1982, and 2000 and 2004).

The selection set resulted in 16 datasets. The dataset by dwelling element and period of construction was split manually into Mode 1 and Mode 2 dwellings resulting in 32 datasets as shown in Table C1 in Appendix C. Without the aid of an optimisation tool it is problematic to tell where Mode 1 distribution ends and Mode 2 distribution begins. The manual approach adopted therefore involved truncating the modes in an uncompromising manner while also adding subjectivity to the methodology that use of maximum likelihood estimation avoids.

The FBD function [153] uses the Negative of the log likelihood (NLogL), Bayesian information criterion (BIC), Akaike information criterion (AIC) as well as AIC with a correction factor for finite sample sizes to determine the best fit distribution to the data. When fitting models, it is possible to increase the likelihood by adding parameters, but doing so may result in overfitting. Both BIC and AIC attempt to resolve this problem by introducing a penalty term for the number of parameters in the model; the penalty term is larger in BIC than in AIC. As shown in Figure 19, all four parameters give very similar results in the cases tested.

Figure 19 Sample output from the "Find the Best Distribition" tool in MATLAB® (Sample shown, Mode 1, single story wall constructed between 1900 and 1929)



As shown in Figure 19, the FBD function ranks the top four distributions by best fit, Distribution 1 being the best fit. While the FBD function presents a best fit, it is evident from Figure 19 that none of the distributions shown represents a good fit to the data. To determine if the best-fit distribution returned by MATLAB® is a good fit to the empirical data, a chi-square goodness of fit test was carried out using the inbuilt function 'chi2gof' [155] in MATLAB® [154].

With parameters estimated from the data, the chi-square goodness-of-fit tests the hypothesis that the data sample comes from a specified probability distribution. The chi-square test statistic is of the form shown in Equation (12).

$$\chi^2 = \sum \frac{(\text{observed count} - \text{expected count})^2}{\text{expected count}} \quad (12)$$

If the computed test statistic (X^2) is large, then the observed and expected values are not close and the model is a poor fit to the data. The hypothesis test result is returned as H_1 or H_0. The null hypothesis (H_0) suggests that the measured data are random values generated from the fitted distribution (i.e. that the distribution is a "good fit"). The alternative hypothesis (H_1) is that the distribution is not a good fit. The probability (p value) of obtaining the measured values if the null hypothesis is true was calculated for the distributions listed in Table C1. Tests at 5 % level of significance is the accepted norm for a chi-square test [99]. If the returned p value ≥ 0.05 (5 %), there is no evidence to reject the null hypothesis. If the returned p value < 0.05 (5 %) there is evidence to reject the null hypothesis, or in other words, there is evidence to say that the data does not come from the distribution tested.

With the exception of a two-storey wall constructed between 2000 and 2004, there was no evidence that the data fitted any distribution in the 32 datasets tested. In the case of data set for a two-storey wall constructed between 2000 and 2004, it was determined that the log-logistic distribution fitted the data to a 1 % significance level, and even this is quite a poor fit.

The finding that no standard statistical distribution fits the data is assumed to arise from the fact that the empirical data is a mixture of 'measured' U-values and deterministic data in the form of 'known' U-values. The over-selection of deterministic 'known' U-values by the assessor, in favour of 'measured' U-values, leads to local peaks and noise in the data; highlighted in Section 2.4.3 (see Figures 10 (a & b) for walls and 11 (a & b) for roofs). Deterministic 'known' U-values are thus disrupting normal uncertainty factors usual to measurement values meaning that no distribution presents a good fit to the data.

To establish a likely distribution of 'measured' U-values if deterministic 'known' U-values were not present, a typical composite wall was simulated in Excel® as detailed in Section 3.2.2.1.2.

3.2.2.1.2 Likely distribution function of simulated 'measured' U-values

To establish a likely distribution of U-values arising from uncertainty factors inherent in measured values a common vernacular wall type was selected from Table 13 in Section 2.4.5 for analysis. As discussed in Section 2.4.5, solid limestone wall construction was common in Ireland up until the 1930's. As described in Table 13, this wall type has a depth that ranges 300 to 500 mm, is rendered externally usually (but stone finish not uncommon), and is usually plastered internally with a 13 mm lime plaster.

Based on the depth of the wall and the presence of render or plaster in conjunction with the assumed thermal conductivities of the composite materials listed in CIBSE Guide A [124], the U-value of a traditional limestone wall can be expected to range widely from 1.8 W/m²K to 3.6 W/m²k (ref: Tables B1 and B3 in Appendix B). As shown in Equation (13), the range is determined primarily by the depth (L in metres) of the wall, render and plaster (where present) and range of likely thermal conductivities possible (as given by CIBSE Guide A [124]);

$$\sum R's = R_{se}(0.04) + \frac{L_{render}[0\,m\ or\ (0.015\,m\ \ to\ 0.025\,m\,)]}{\lambda_{render}\left(0.18\frac{W}{mK}to\ 1.0\ \frac{W}{mK}\right)} + \frac{L_{limestone\,(0.3\,m\ to\ 0.5\,m)}}{\lambda_{limestone}\left(1.5\ \frac{W}{mK}to\ 2.9\ \frac{W}{mK}\right)} + \frac{L_{plaster}\ [0\,m\ or\ (0.01\,m\ to\ 0.025\,m)]}{\lambda_{plaster}\left(0.8\ \frac{W}{mK}\right)} + R_{si}(0.13)\ (\mathrm{m^2K/W}) \quad (13)$$

Within the ranges shown in Equation (13), the 'RAND' function in Excel® was used to generate random values for the thermal conductivities of the render and limestone and the depth of render and plaster. It was assumed arbitrarily that outside render is present in 60 % of walls with the remaining 40 % having a stone finish while internal walls have a stone finish 20 % of the time with lime plaster present 80 % of the time. For those walls that were assumed rendered and/or plastered, a normal distribution with six standard deviations (capturing 99.73 % of the data +/- 3σ of the mean) was used to distribute depth of the render and plaster within the ranges shown in Equation (13). Wall depth was stepped in 50 mm stages from 300 mm to 500 mm, it was assumed that each depth occurred uniformly 20 % of the time. The RAND function in Excel® was used to distribute values of each of the three composite wall layers randomly thereby simulating 10,000 possible wall configurations.

The simulated wall data was processed through the FBD function [153] in MATLAB® [154] wherein the Gamma distribution was suggested as the best fit to the simulated data, however, the goodness of fit result was not significant, with a p-value of 0.0136 (1.36 %). So while gamma is suggested as the best fit it does not represent a good fit to the data. It can thus be concluded that there is no distribution that fits the simulated U-value 'measurement' data to a 5 % significance level.

To establish a likely distribution for in-situ rather than simulated U-values measurements, a review of the literature was made. A study by Gori [156] in 2017, created a novel method for the estimation of thermophyscial properties of walls from short and seasonally independent in-situ surveys, fitted a lognormal distribution to thermal resistance values.

On the basis of:

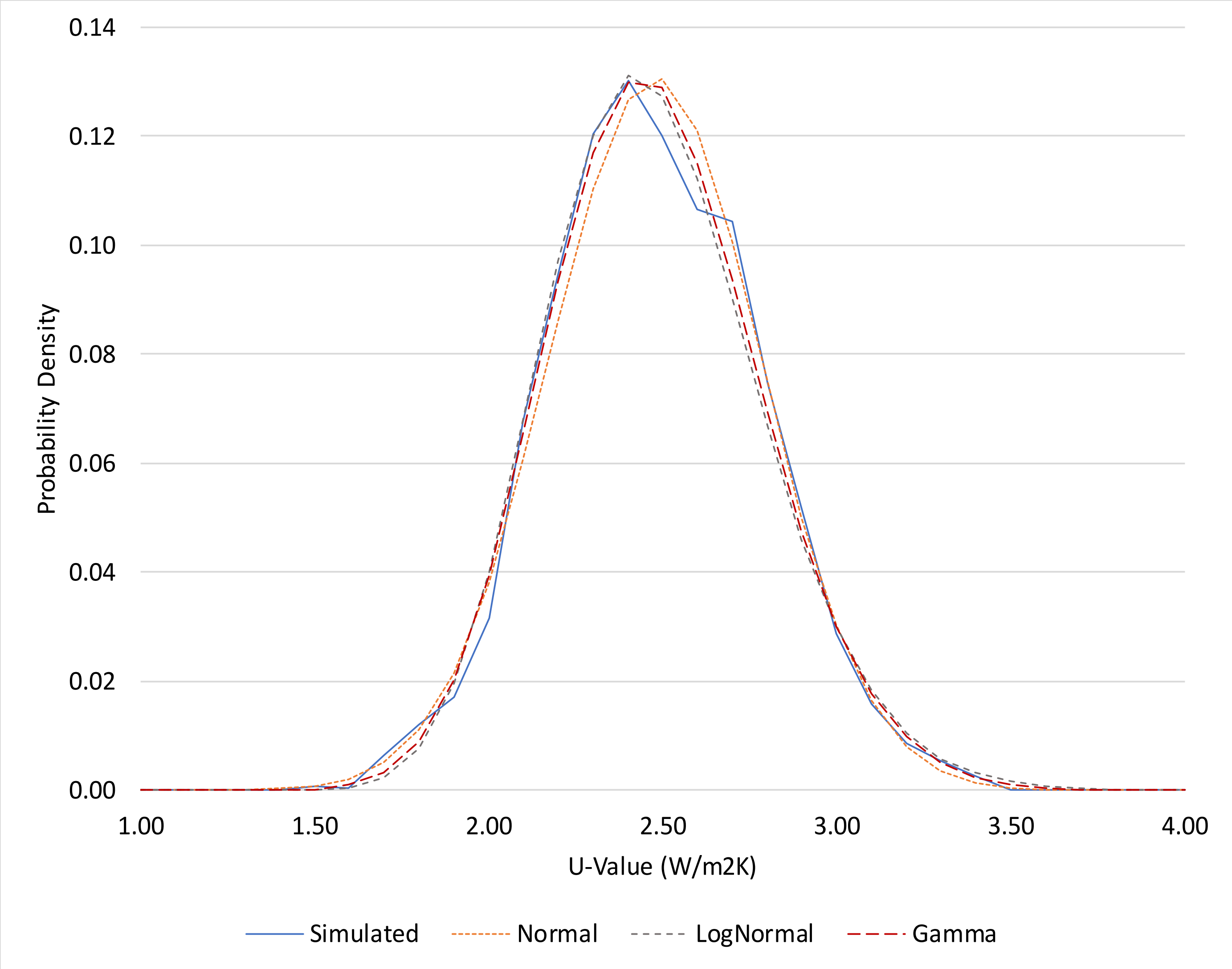
(i) An expectation of a normal distribution arising from uncertainly factors associated with measured data (if deterministic values are not present);
(ii) The suggestion of the;
   a) gamma distribution for the simulated U-value data in Excel® returned by MATLAB®, along with
   b) log-normal distribution for in-situ measurement of thermal resistance values by the literature;

the normal, lognormal and gamma distributions are fitted to the simulated data as shown in Figure 20.

It can be seen in Figure 20 that these distributions present reasonable fits to the simulated U-value 'measurements'. It is found that the lognormal and gamma distribution functions achieve a slightly better fit to the simulated data, than the normal distribution function, around the peak, but the normal distribution fits the 'measured' data slightly better in the tails of the distribution.

Choices between distributions should be made primarily, on the basis of important problem-specific requirements, while straightforward mathematical formulae describing features of distributions enable insight, interpretation and clarity of exposition, as well as improving computational speed and convenience [157]. In this context and in order to inform the selection of a suitable distribution to fit the empirical data, Section 3.2.2.1.3 assesses the likely impact of selecting different distributions on the results.

Figure 20 Normal, Lognormal and gamma fits to simulated U-value data for a sample wall (Period selected, pre-1900 to 1930)



3.2.2.1.3 Selection of distribution function to fit the empirical data

Understanding particular features of distributions is greatly enhanced if they correspond to specific parameters [157]. Figure 18 (a) shows the building envelope data in the EPC dataset to be distributed with an asymmetric bimodal characteristic. Figure 18 (b) describes the physical process causing the asymmetrical bimodal distribution validated in Section 2.4.3 against the phenomenon influencing the distribution, namely (i) building regulations at time of construction and (ii) state-funded energy refurbishment schemes.

This research is seeking to ascertain;

a) proportion of Mode 1 and Mode 2 and the 'Mean 1' and 'Mean 2' of dwellings by period of construction, and
b) 90^{th} percentile point of the data (reference section 3.2.1).

The assessment of a) necessitates fitting a bimodal distribution to the data while the assessment of b) requires an examination of the data points in the tail of the cumulative distribution function.

Unlike with the normal distribution the parameters of random variable (X), in this case U-values, transform when either the lognormal or gamma distribution is employed.

A lognormal distribution is a continuous probability distribution of a random variable whose logarithm is normally distributed. The two parameters (μ) and (σ) are location and scale parameters for the natural logarithm ln(X) of the U-values; (μ) thus represents the mean of the natural logarithim (LN) of the U-values. The median of a lognormal distribution is exp(μ), while its mean is $\exp(\mu+\sigma^2/2)$. The mean is larger than the median which indicates that the lognormal distribution is right skewed.

The gamma distribution is a two-parameter family of continuous probability distribution. When the random variable (X) is indexed by a function (I), the parameters of the gamma distribution that best fit the empirical data are parameterised in terms of a shape parameter (α) and scale parameter (β) given by Equations (14) and (15);

$$\alpha = \frac{Mean\ (X,I)^2}{Variance\ (X,I)} \tag{14}$$

$$\beta = \frac{Variance\ (X,I)}{Mean\ (X,I)^2} \tag{15}$$

The gamma distribution has a theoretical mean of ($\alpha\beta$) and theoretical variance of ($\alpha\beta^2$) while the standard deviation of a gamma distribution is given by ($\beta\sqrt{\alpha}$).

As the shape and scale parameters of the lognormal and gamma transform on distribution, it is not possible to compare the mean and modes of the normal, lognormal and gamma probability distribution functions directly (formulae for the theoretical means and standard deviations of the lognormal and gamma are used to compare results with the normal). A direct comparison can be made easily between the individual and independent data points of the empirical and fitted cumulative distribution functions. As this research is interested particularly in the 90th percentile point of the distribution, Table 19 compares the 90th percentile point of the normal, lognormal and gamma distributions for a sample dwelling by period of construction. Table 19 suggests that the normal distribution presents a marginally better fit to the data than the other distribution tested. Notwithstanding the difference is not significant in terms of the sensitivity required of the results.

The normal distribution has the advantage of remaining normal on transformation. This means its mean, median and mode are the same and the entire distribution can be specified using just two parameters, mean and variance. The characteristics of the normal distribution function simplifies the mathematics so enabling greater modelling convenience while also making the U-value distribution much easier to interpret and explain. Applying Occam's Razor principal, in that the simpler solution is the best one given that all other things are same [158], the normal distribution is thus selected as a reasonable fit to the empircal data.

Table 19 Comparison of the 90th percentile data point for the Empirical, Normal, Lognormal and Gamma cumulative distribution functions for a sample dwelling (period shown 1967 to 1977)

		Best fit 90th percentile data point			
		Empirical	Fitted		
			Normal	Lognormal	Gamma
Two storey	Wall	**1.78**	1.84	1.83	1.84
	Roof	**1.21**	1.21	1.08	1.18
	Floor	**0.85**	0.88	0.89	0.87
Single-storey	Wall	**1.78**	1.77	1.76	1.76
	Roof	**0.53**	0.53	0.53	0.60
	Floor	**0.84**	0.83	0.85	0.83

3.2.2.2 Fit of the normal distribution to the data

The Generalised Reduced Gradient (GRG) algorithm nonlinear solver tool in Excel® was used to determine the maximum likelihood estimates of the parameters for the best-fit curves to empirical distributions of large datasets [40]. Figure 18 (b) shows how a best-fit normal distribution was fitted to the empirical data using constraints as set out in Table 20.

Table 20 Constraints used within the Generalised Reduced Gradient (GRG) algorithm nonlinear solver in Excel®

Constraints	Mean 1	>=	0.1
	Standard Deviation 1	>=	0.01
	Mean 2	>=	Mean 1
	Standard Deviation 2	>=	0.01
	Proportion 1	<=	1 (100 %)
	Proportion 2	<=	0.1 (10 %)

For numerical stability of the calculation method, the sum of the log of the likelihood values was used. This avoided the product of the likelihoods being very small numbers leading to inaccuracies resulting from rounding of small numbers [99].

As the maximum likelihood uses individual data points, it is not dependent on the choice of histogram bin size. Histograms are used only to illustrate the goodness of fit [see Figure 18 (b)]. The choice of bin size was established from the average bin size returned by Sturges', Rice's and Scott's rules [99] given by Equations (16), (17) and (18);

Sturges' rule:

$$k = 1 + \log_2 N \quad (16)$$

Rice rule:

$$k = 2N^{\frac{1}{3}} = 2N^{0.333} \quad (17)$$

Scott's rule:

This specifies the bin (or interval) size, h:

$$h = \frac{3.5s}{N^{\frac{1}{3}}} \quad (18)$$

Outputs from the statistical methodology for all single and two-storey dwellings by dwelling element type are presented in the results section (Table 21 – Section 3.3.2) of this chapter. By way of example, Figure 23 illustrates methodology outputs for one and two storey dwellings constructed between 1967 and 1977 while Appendix C.2 contains the outputs for all dwelling elements by period of construction.

Figures 21 and 22 illustrate typical relationships of the empirical frequency distribution to the fitted normal distribution. It can be seen that the fitted normal curve smoothes the dataset to create an approximating function that attempts to capture important patterns in the data while leaving out the noise and discrete localised optima in the data. The fitted cumulative distribution function was thus used to establish the 90th percentile point of the distribution as shown in Figure 24.

Figure 21 Typical relationship of empirical to fitted frequency distribution for a dwelling element (Period shown, 1900 – 1929)

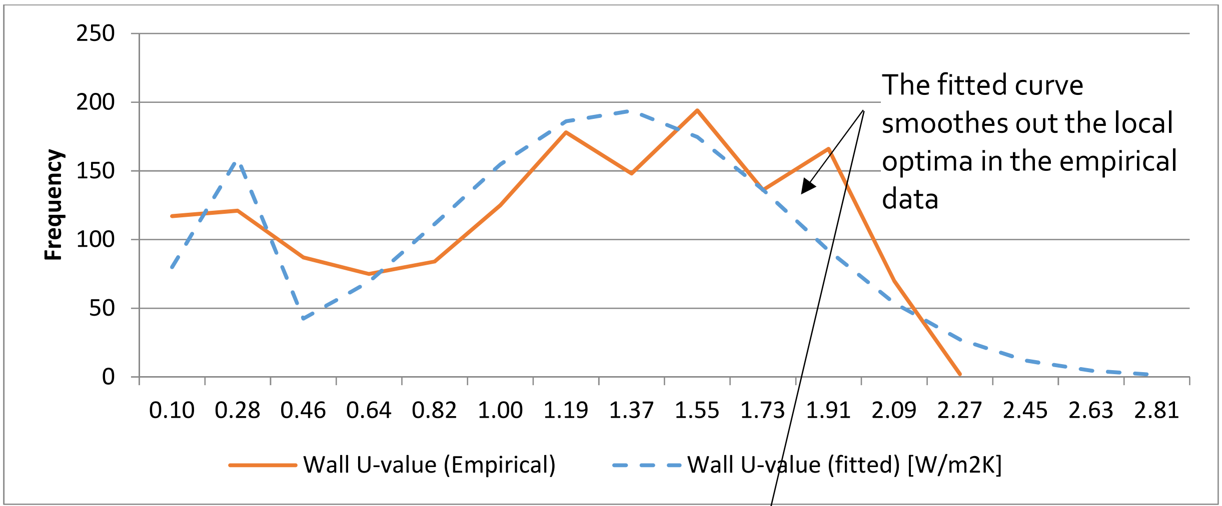


Figure 22 Typical relationship of empirical to fitted frequency distribution for a dwelling (Period shown, 1930 to 1949)

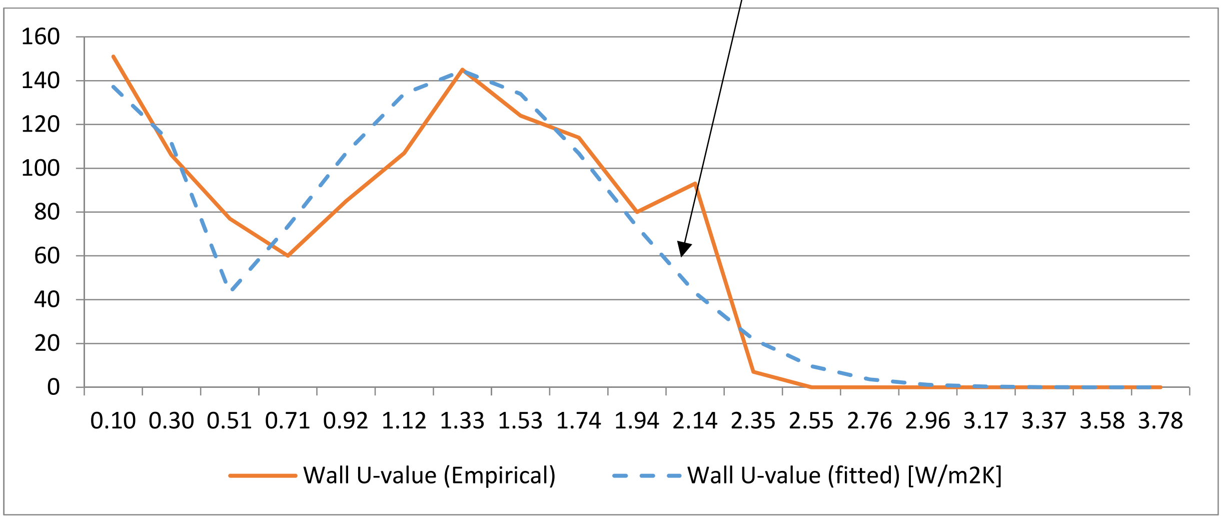
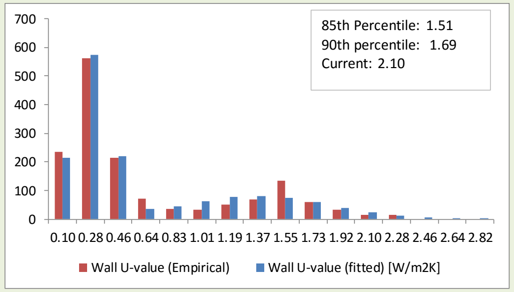


Figure 23 Typical methodology output for one and two storey detached dwellings by period of construction (Period shown, 1967 – 1977)

U-Value	Wall	Roof	Floor

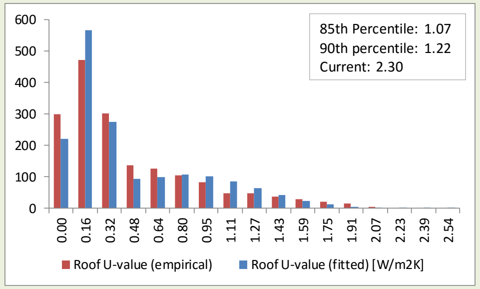
Two-storey

Wall



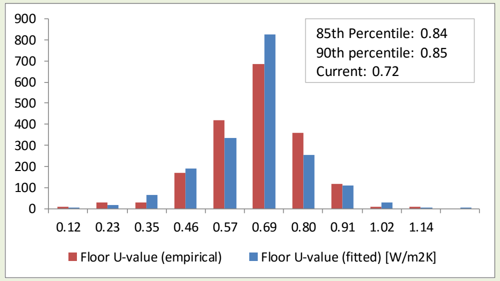
Mean (1)	0.37
Std Dev (1)	0.12
Mean (2)	1.44
Std Dev (2)	0.47
Proportion (1)	65%

Roof



Mean (1)	0.24
Std Dev (1)	0.11
Mean (2)	0.89
Std Dev (2)	0.45
Proportion (1)	56%

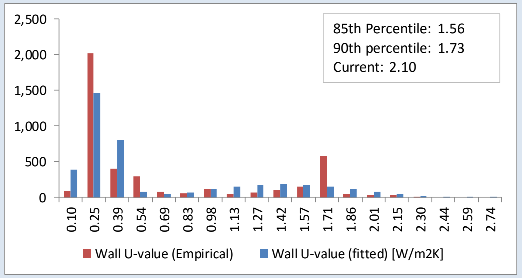
Floor



Mean (1)	0.71
Std Dev (1)	0.16
Mean (2)	0.73
Std Dev (2)	0.01
Proportion (1)	75%

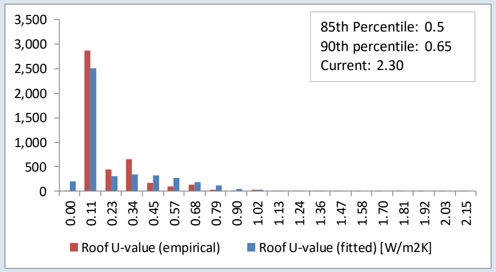
Single-storey

Wall



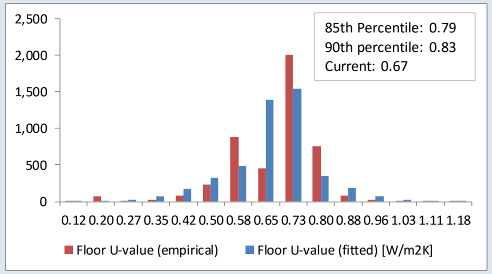
Mean (1)	0.35
Std Dev (1)	0.10
Mean (2)	1.50
Std Dev (2)	0.43
Proportion (1)	66%

Roof



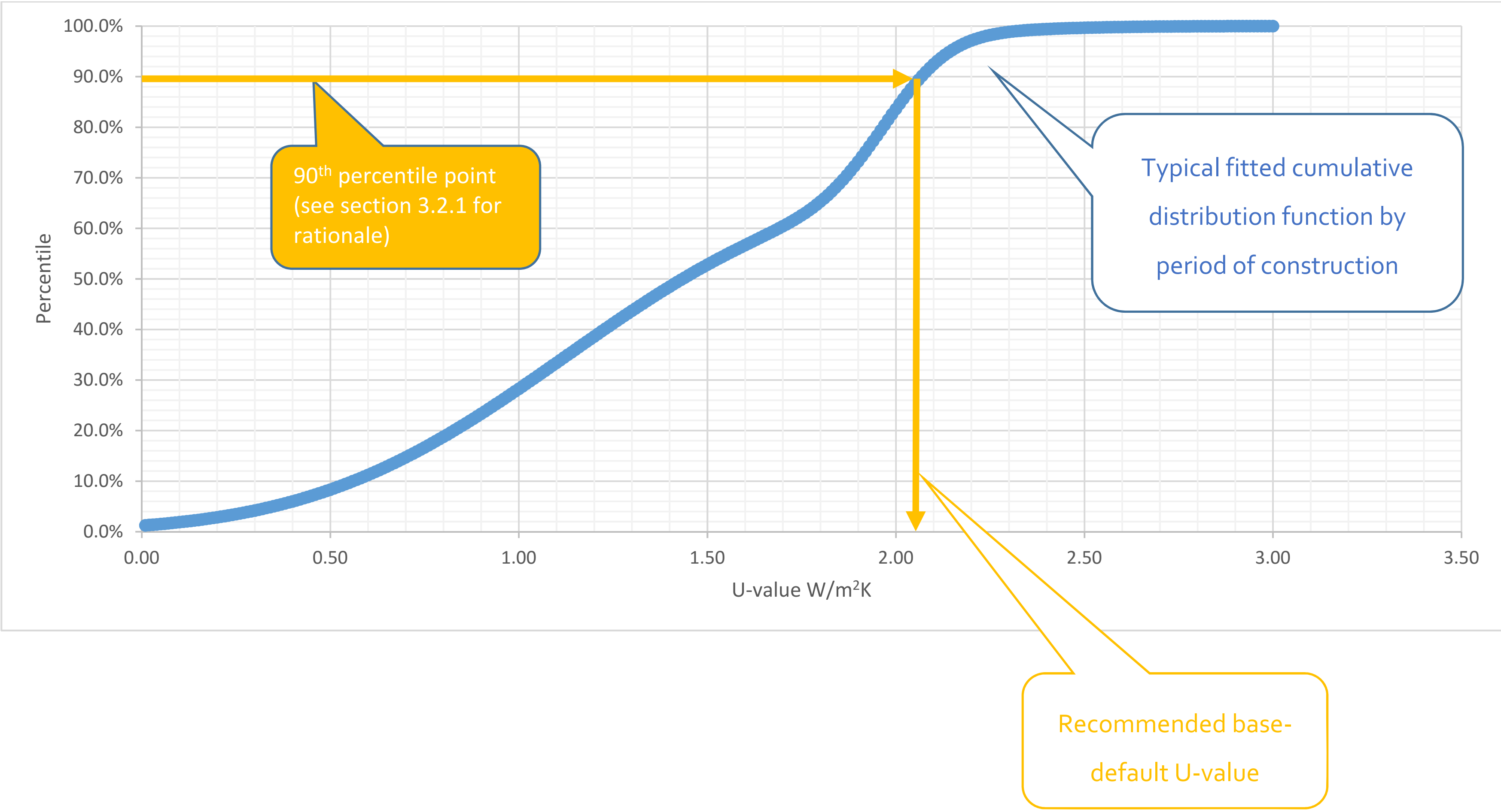
Mean (1)	0.13
Std Dev (1)	0.01
Mean (2)	0.41
Std Dev (2)	0.29
Proportion (1)	51%

Floor



Mean (1)	0.69
Std Dev (1)	0.15
Mean (2)	0.73
Std Dev (2)	0.01
Proportion (1)	60%

Figure 24 Basis of statistically derived base-thermal-default U-values established from 90th percentile point of the fitted cumulative distribution function



3.2.3 Statistical model validation and generalisability

3.2.3.1 Assumption of Bimodal Normality

The validity of selection of a normal distribution to fit the empirical data is verified through evaluating the individual empirical data points (U-values W/m²K) with fitted data points estimated by the maximum likelihood method. This analysis is shown in Tables C2 to C7 in Appendix C.3 wherein a sample set of the individual data points for the 50th, 75th, 80th, 85th and 90th percentile data points of the empirical and normal fitted distribution by dwelling element and by period of construction, resulting in 60 datasets, are matched. Tables C2 to C7 were assessed for goodness of fit. Highlighted in Tables C2 to C7 is any variance between the empirical and fitted data points that is greater than +/- 0.1 W/m²K. The fit of the normal distribution to the data was found to be;

- Good (maximum of one instance where variance greater than +/- 0.1 W/m^{2K}) in 82% of cases.
- Reasonable (two instances where variances greater than +/- 0.1 W/m²K) in 8.3 % of cases.
- Sub-optimal (three instances where variances greater than +/- 0.1 W/m²K) in 9.7 % of cases.

The analysis demonstrates:

- A reasonable to good fit in the vast majority (90.3 %) of cases;
- The data points of the normal fitted distribution to be equally likely to be below or above the empirical data points i.e. are normal.

The validity of the fit of the normal distribution is also discussed briefly in the context of the results (see Section 3.3.3)

3.2.3.2 Statistical model validation and generalisability

To develop a generalisable methodology to derive reference dwellings from an EPC dataset, it is necessary to evaluate the robustness of the statistical method. This will ascertain how well the model created predicts the probability distributions for dwelling envelope data not included in the original EPC dataset from which the model is built [159].

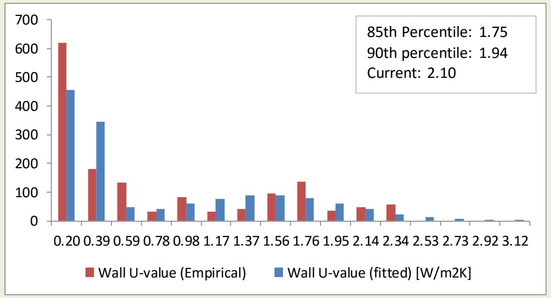
Use of the maximum likelihood method ensures that each model by period of construction and by building element type is mathematically optimised to best-fit the data from which it is derived. Thus, any performance indicator measured on the same sample used to fit the model is, through indicating the highest possible performance, biased in favour of the model [159]. Hence, when validating the model's ability to predict outcomes for future subjects, independent (external) data from the same or similar population to test the model should be used [159-161]. A new sample is used to assess the goodness-of-fit of the previously developed model by applying the model as it is to the new sample. Such external validation is the most stringent unbiased test for the model and for the data collection process [160].

Internal validation is used where it is not possible to obtain a new independent external sample from the same population or a similar one. One method for good internal validation of a model's performance is repeated data-splitting [160]. The EPC dataset was split in many ways; detached dwellings were isolated from the larger dataset, rural detached dwellings were isolated, dwellings were hence classified by number of stories, then by period of construction (10 No.) followed by dwelling element (wall, roof, floor etc.). The statistical model developed was applied repeatedly to each split dataset. The robustness of the method is demonstrated by consistent goodness-of-fit of the cumulative distribution function to the real data as shown in Figures 23 and Figures C1 to C10 in Appendix C.2.

To externally validate the methodology, an independent sample for a different housing typology from the same population was isolated from the original EPC dataset [76] employed in this work. To facilitate a comparison with Figure 23, semi-detached dwellings constructed in the same period were isolated within the dataset and the statistical methodology was applied to single and two-storey walls, roofs and floors. Referring to Figure 25, the methodology is considered to be validated externally as the:

i) Appropriateness of the method is defended by the goodness-of-fit of the fitted to the real curve for a different housing typology.
ii) Recommended defaults for walls and roofs for a different dwelling typology correlate with those recommended for the dwelling typology examined originally; corroborating the expectation that retrofit measures would be applied proportionately across the single-family dwelling stock-at-large.

Figure 25 Methodology output for one and two storey dwelling semi-detached rural dwellings by period of construction (Period shown, 1967 – 1977)

<table>
<tr><th>U-Value</th><th>Wall</th><th>Roof</th><th>Floor</th></tr>
<tr><td>Two-storey</td>
<td>
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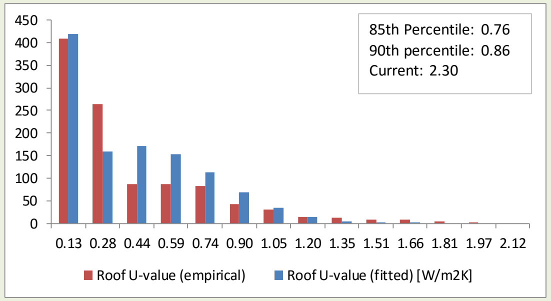
<td>
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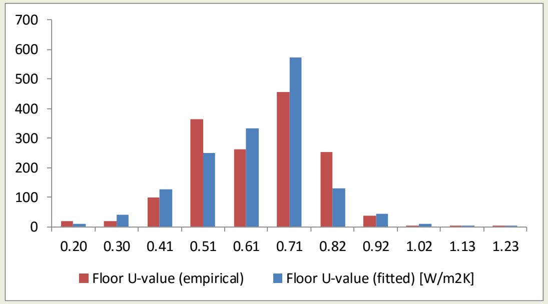
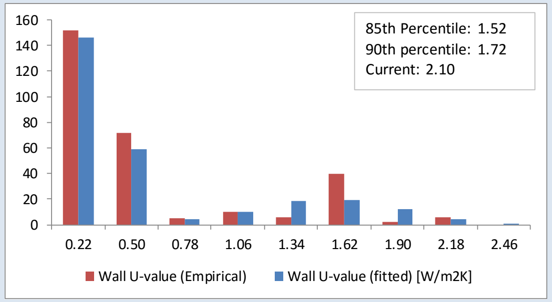
<td>
</td></tr>
<tr><td>Single-storey</td>
<td>
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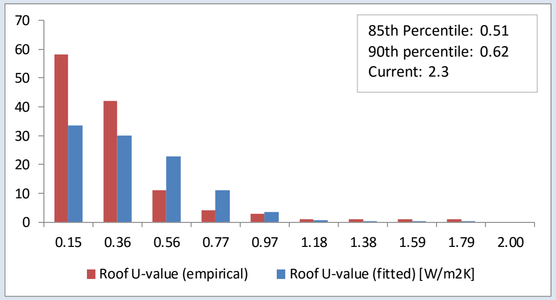
<td>
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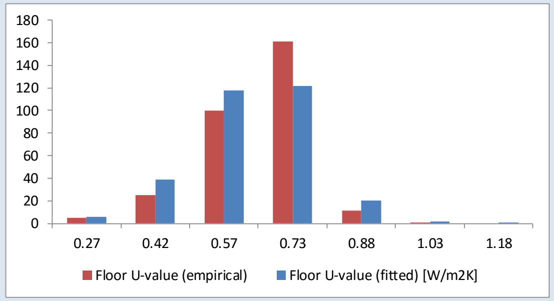
<td>
</td></tr>
</table>

3.3 Results

3.3.1 Position of current base-defaults relative to average empirically derived (real) U-values

Figures 26 and 27 show average wall and roof U-values found within the validated EPC database, along with corresponding base-thermal-default U-values by period of construction. Figures 26 and 27 highlight the large discrepancy between mean wall and roof U-values and the base-thermal-default U-values, particularly in pre-thermal regulation dwellings.

Referring to Figures 26 and 27, the gap between the base-thermal-default wall U-value and the real mean U-values in:

A. Pre-thermal regulation dwellings constructed pre-1900 up until 1982;
   - increases with time,
   - is greater in roofs than in walls, ranging from,
     - 1.5 W/m^{2}K to 1.9 W/m^{2}K for roofs, and
     - 0.6 W/m^{2}K to 1.1 W/m^{2}K for walls.
   - demonstrates that building energy assessors were often able to identify the presence of insulation in pre-thermal regulation dwellings.

B. Post-thermal regulation dwellings constructed from 1983 up until 2006;
   - decreases towards zero over time,
   - is greater in walls than in roofs, ranging from,
     - 0.65 W/m^{2}K to zero for walls, and
     - 0.1 W/m^{2}K to zero for roofs.
   - demonstrates that building energy assessors were often able to identify a large number of dwellings that were insulated to higher levels than were required by the prevailing thermal building regulations of the time.

The results correlate with the findings of INSHQ 2001-2002 [131] shown in Figures 13 and 14 and the more recent (2012) TABULA study [120, 129], to further suggest DEAP's [72] assertion that pre-thermal regulation dwellings were constructed originally, without insulation, is incorrect or that homeowners;

(i) constructed to better than regulation required at that time, or
(ii) have carried out energy upgrades.

Referencing Figures 26 and 27, a high level of insulation is noted in dwellings constructed between 1950 and 1977. These dwellings were found to have the worst heat loss characteristics within this typology, which may have provided greater motivation for the end-user to invest in upgrade measures [70].

Figures 26 and 27 demonstrate that the;

(i) strong association of a dwellings age with its energy efficiency is diminishing as retrofits in the sector are carried out, and
(ii) practice in Ireland [70, 120] along with Italy [38], Spain [121] and Austria [122] of using of pessimistic base-default thermal characteristics as inputs to national energy consumption models, will considerably overestimate the energy saving potential of the existing housing stock.

Figure 26 Average wall U-value in the default and empirical dataset over time [70, 76]

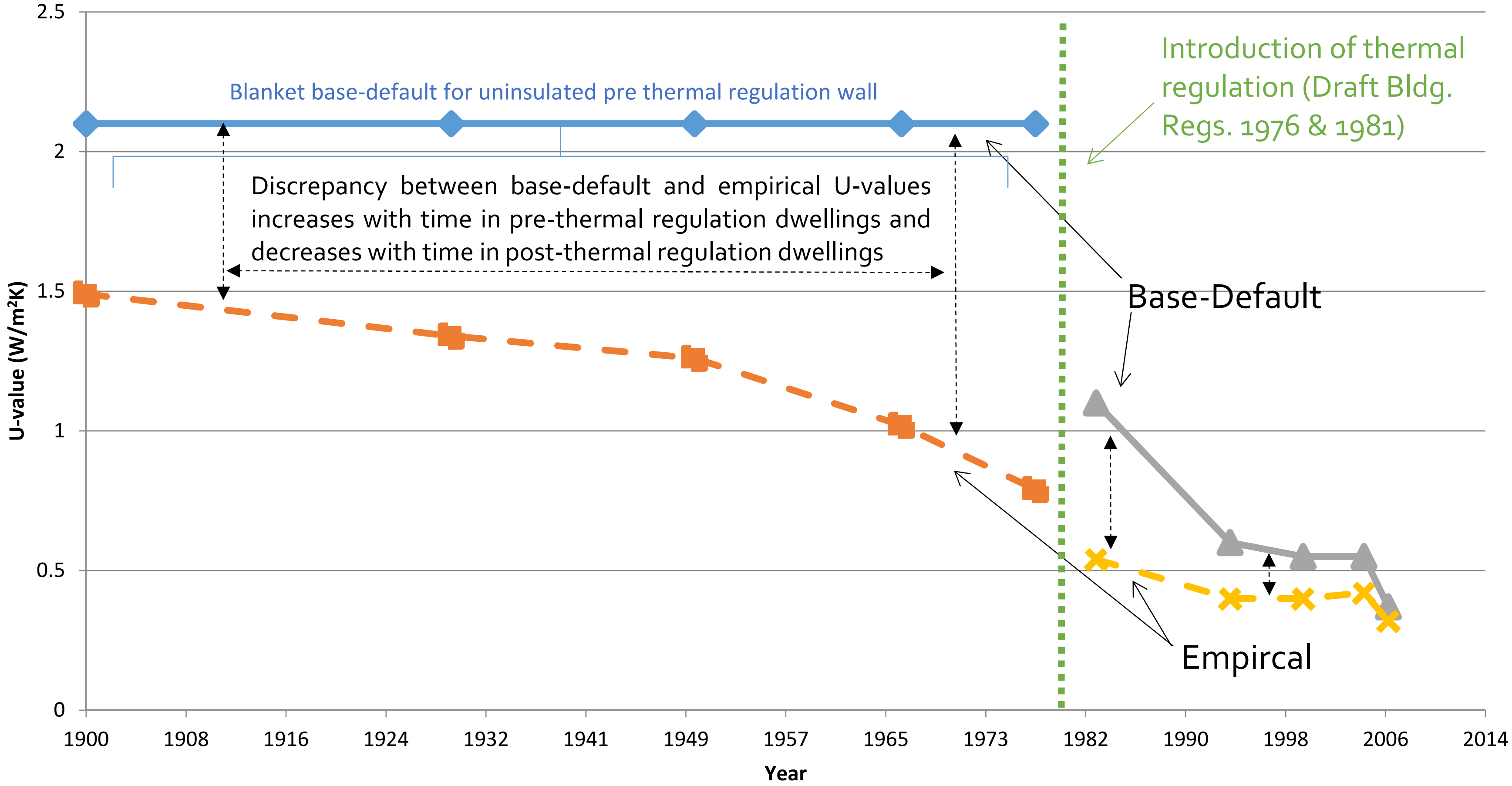
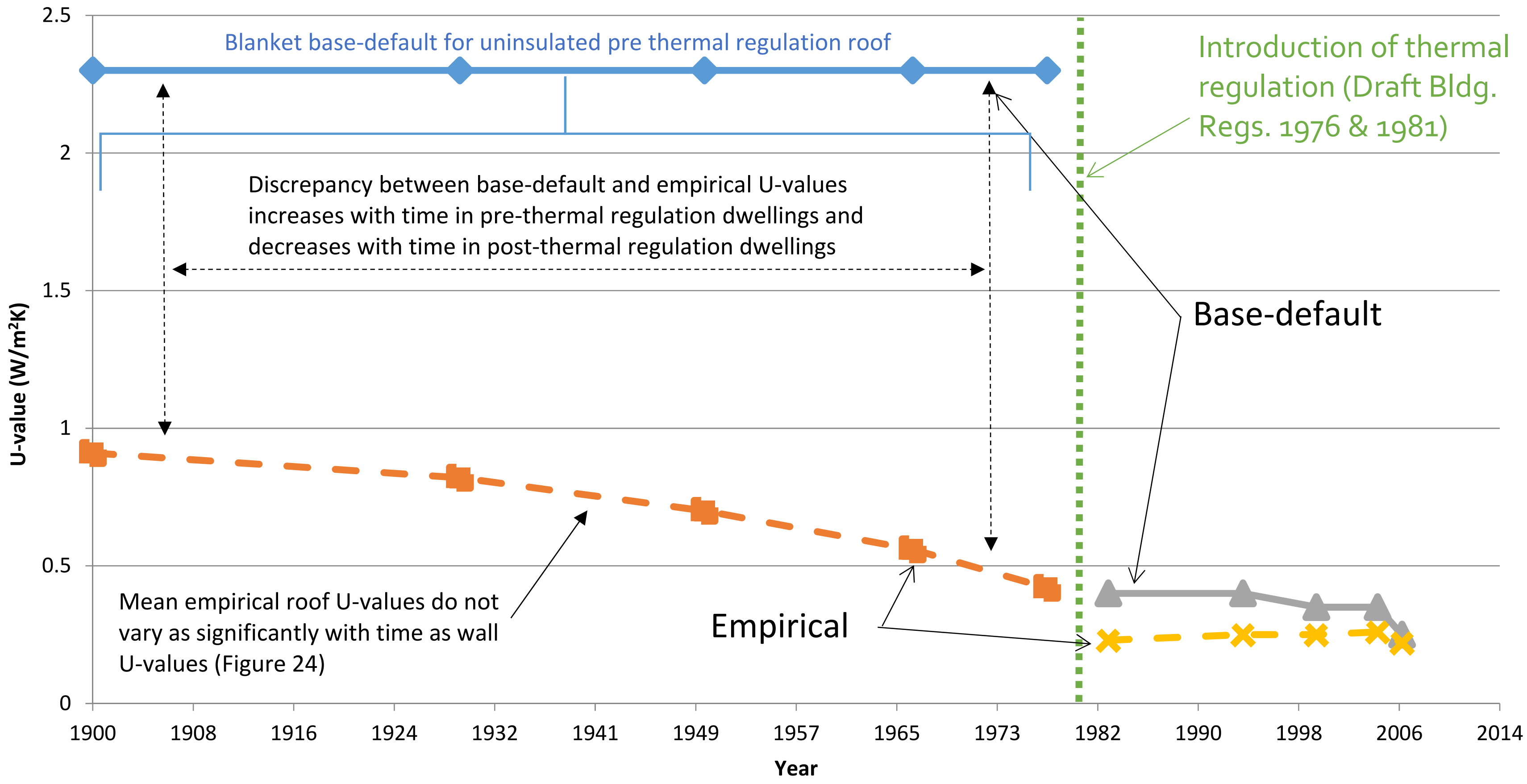


Figure 27 Roof U-value in the default and empirical dataset over time[70, 76]



3.3.2 Assessment of level of thermal retrofits and thermal building regulation compliance for Ireland's predominant housing typology

Assessment of the level of thermal retrofits and thermal building regulation compliance for Ireland's predominant housing typology is presented in Table 21 wherein the;

- proportion of Mode 1 (retrofitted) and Mode 2 (as-built) dwellings by period of construction [reference Figure 18 (b)],
- mean of Mode 1 and Mode 2 dwellings, 'Mean 1' and 'Mean 2',
- standard deviation of Mode 1 and Mode 2 dwellings,

is presented by dwelling element, by single and two-storey dwellings and by period of construction. Histograms for each dwelling element, by single and two-storey dwelling, by period of construction are presented in Appendix C.2 while the electronic media submitted with this work contains all calculation spreadsheets.

Referring to Table 21; mean roof U-values are generally lower than wall U-values; wall U-values range from;

- 0.29 to 1.97 W/m^2K for pre-thermal regulation dwellings, and
- 0.28 to 0.7 W/m^2K for post-thermal regulation dwellings.

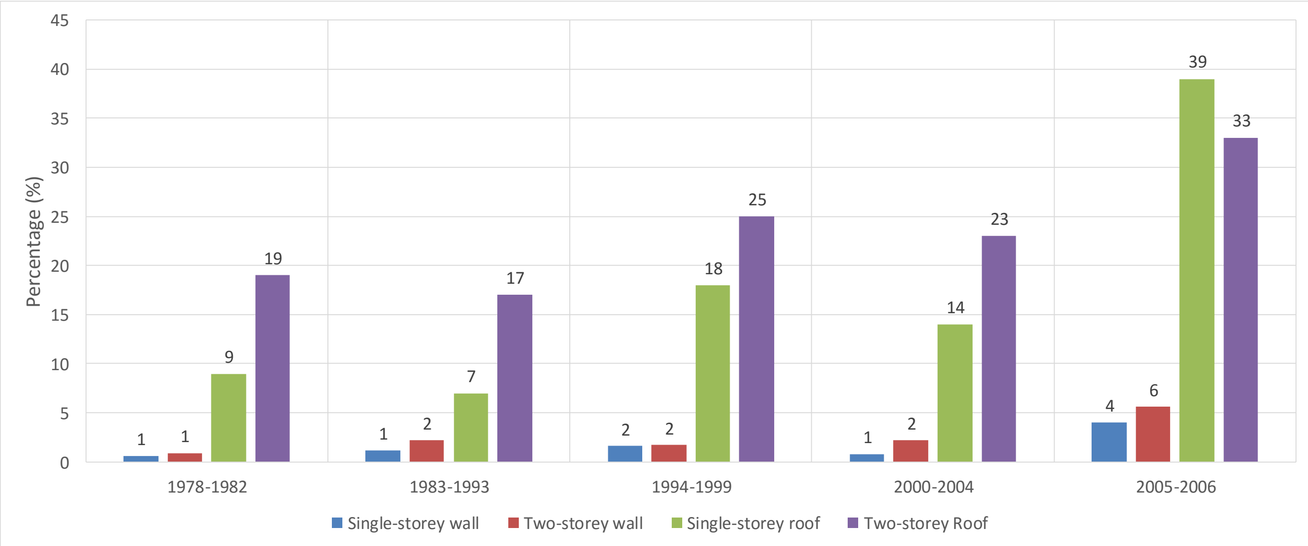
While roof U-values range from;

- 0.13 to 1.18 W/m^2K for pre-thermal regulation dwellings, and
- 0.13 to 0.96 W/m^2K for post-thermal regulation dwellings.

Max default for a post-thermal regulation dwellings roof is 0.49 $W/m^{2o}K$

The improved thermal characteristic of roofs is attributable to the relative ease and lower cost of retrofitting attic insulation compared to wall insulation. Conversely however, as shown in Figure 28 and highlighted in Table 21, it is noted that a large percentage of post-thermal regulation roofs are not compliant with the prevailing building regulations; this may be attributable to a lax adherence to building control measures during Ireland's housing construction boom that occurred in the period between the mid-1990's and mid-2000's [162].

Figure 28 Percentage of dwelling walls and roofs non-compliant with prevailing thermal regulations



Analysis of the means returned by the maximum likelihood method shown in Table 21 are analysed in Table 22, to find that;

- 46 % of walls (U-value range from 0.29 to 0.39[14] Wm²K) and 50 % of roofs (U-value range 0.13 W/m²K to 0.29 W/m²K) in pre-thermal regulation dwellings have undergone significant thermal retrofits, whilst
- 70 % of walls (U-value range from 0.28 to 0.31 Wm²K) and more than 84 % (U-value range from 0.13 to 0.26 Wm²K) of roofs in post-thermal regulation dwellings have either undergone energy efficiency upgrades or were constructed with better than maximum regulatory U-values.

Frequency-weighted stock averages find 58 % of walls (U-value range from 0.29 to 0.39[2] Wm²K) and 67 % (U-value range from 0.13 to 0.29 Wm²K) of roofs to be significantly refurbished or upgraded.

[14] With the exception of two storey pre-1900 dwellings at 1.13 W/m²K

Table 21 Summary of statistical methodology outputs characterising dwelling envelope characteristics by period of construction

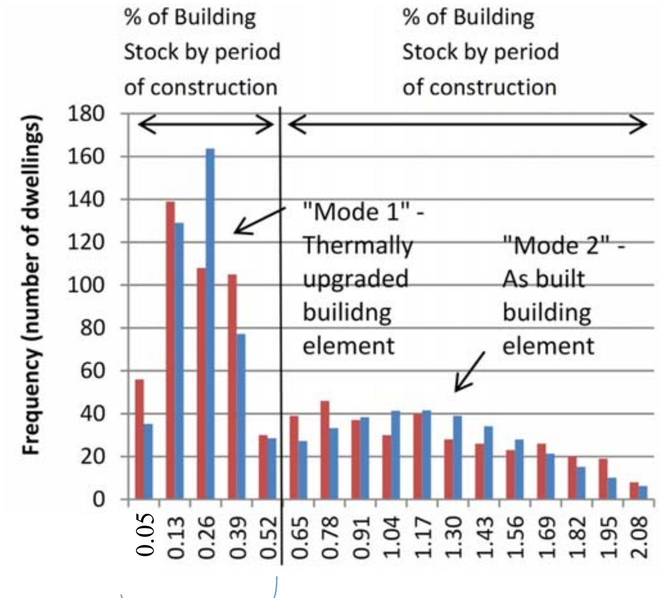
				Dwelling Envelope Element															
				Wall				Roof				Floor				Windows			
				Single-storey		Two-storey		Single-storey		Two-storey		Single-storey		Two-storey		Single-storey		Two-storey	
				Mode 1	**Mode 2**	**Mode 1**	**Mode 2**	**Mode 1**	**Mode 2**	**Mode 1**	**Mode 2**	**Mode 1**	**Mode 2**	**Mode 1**	**Mode 2**	**Mode 1**	**Mode 2**	**Mode 1**	**Mode 2**
Period of Construction	Pre-thermal building Regulations	>1900	% of the stock	17	83	70	30	56	44	49	51	17	83	94	6	71	29	75	25
			Mean	**0.39**	**1.53**	**1.13**	**1.97**	**0.22**	**0.98**	**0.29**	**1.18**	**0.53**	**0.80**	**0.73**	**0.73**	**2.86**	**4.69**	**2.89**	**4.73**
			Std. Dev	0.15	0.43	0.53	0.13	0.1	0.54	0.12	0.49	0.17	0.12	0.19	0.01	0.43	0.46	0.54	0.32
		1900-1929	% of the stock	15	85	15	85	27	73	52	48	10	90	94	6	56	44	59	41
			Mean	**0.31**	**1.39**	**0.31**	**1.42**	**0.13**	**0.67**	**0.28**	**1.14**	**0.37**	**0.76**	**0.73**	**0.84**	**2.88**	**2.88**	**2.88**	**2.88**
			Std. Dev	0.06	0.49	0.07	0.47	0.01	0.51	1.14	0.49	0.11	0.14	0.19	0.01	1.25	0.17	1.16	0.18
		1930-1949	% of the stock	19	81	30	70	27	73	59	41	10	90	85	15	44	56	42	58
			Mean	**0.29**	**1.43**	**0.38**	**1.47**	**0.13**	**0.57**	**0.28**	**1.06**	**0.48**	**0.76**	**0.7**	**0.9**	**2.84**	**3.40**	**2.82**	**3.29**
			Std. Dev	0.05	0.52	1.47	0.47	0.01	0.44	0.12	0.5	0.17	0.12	0.17	0.07	0.17	0.11	0.16	1.12
		1950-1966	% of the stock	41	59	42	58	36	64	59	41	82	18	88	12	29	71	28	72
			Mean	**0.31**	**1.26**	**0.33**	**1.3**	**0.13**	**0.49**	**0.25**	**0.99**	**0.72**	**0.73**	**0.7**	**0.73**	**2.76**	**3.29**	**2.76**	**3.2**
			Std. Dev	0.05	0.56	0.07	0.52	0.01	0.39	0.11	0.49	0.16	0.01	0.17	0.01	0.06	1.01	0.07	0.95
		1967-1977	% of the stock	66	34	65	35	51	49	56	44	60	40	75	25	15	85	11	89
			Mean	**0.35**	**1.5**	**0.37**	**1.44**	**0.13**	**0.41**	**0.24**	**0.89**	**0.69**	**0.73**	**0.71**	**0.73**	**2.70**	**3.11**	**2.7**	**3.03**
			Std. Dev	0.1	0.43	0.12	0.47	0.01	0.29	0.11	0.45	0.15	0.01	0.16	0.01	0.01	0.83	0.01	0.74
	Post- thermal building Regulations	1978-1982	% of the stock	54	46	57	43	52	48	95	5	45	55	13	87	51	49	52	48
			Mean	**0.3**	**0.6**	**0.31**	**0.7**	**0.13**	**0.2**	**0.24**	**0.77**	**0.54**	**0.57**	**0.52**	**0.58**	**2.82**	**2.82**	**2.83**	**2.83**
			Std. Dev	0.03	0.25	0.04	0.27	0.01	0.34	0.11	0.48	0.11	0.01	0.16	0.06	1.10	0.16	1.03	0.16
		1983-1993	% of the stock	70	30	65	25	71	29	98	2	45	55	10	90	45	55	36	64
			Mean	**0.29**	**0.46**	**0.3**	**0.49**	**0.13**	**0.35**	**0.25**	**0.96**	**0.55**	**0.57**	**0.49**	**0.58**	**2.84**	**2.84**	**2.87**	**2.87**
			Std. Dev	0.46	0.17	0.03	0.18	0.01	0.32	0.12	0.58	0.11	0.01	0.16	0.06	1.04	0.17	0.94	0.18
		1994-1999	% of the stock	79	21	65	25	60	40	99	1	92	8	10	90	50	50	17	83
			Mean	**0.29**	**0.44**	**0.29**	**0.43**	**0.13**	**0.33**	**0.26**	**0.88**	**0.41**	**0.41**	**0.41**	**0.42**	**2.77**	**2.85**	**2.61**	**2.84**
			Std. Dev	0.02	0.22	0.02	0.14	0.01	0.23	0.1	0.48	0.02	0.13	0.11	0.02	0.05	0.46	0.6	0.16
		2000-2004	% of the stock	75	25	63	27	49	51	99	1	38	62	25	75	44	54	46	54
			Mean	**0.29**	**0.39**	**0.29**	**0.43**	**0.13**	**0.31**	**0.26**	**0.96**	**0.39**	**0.41**	**0.4**	**0.42**	**2.63**	**2.74**	**2.59**	**2.75**
			Std. Dev	0.02	0.16	0.02	0.14	0.01	0.23	0.09	0.5	0.06	0.01	0.08	0.02	0.48	0.06	0.47	0.06
		2005-2006	% of the stock	93	7	94	6	84	16	98	2	45	55	39	61	63	37	66	34
			Mean	**0.28**	**0.48**	**0.29**	**0.49**	**0.19**	**0.46**	**0.22**	**0.71**	**0.32**	**0.34**	**0.34**	**0.34**	**2.06**	**2.75**	**2.08**	**2.73**
			Std. Dev	0.03	0.33	0.05	0.2	0.05	0.39	0.07	0.47	0.06	0.01	0.01	0.05	0.19	0.19	0.18	0.12

Non thermal-regulation compliant dwelling roofs – see Figure 26

Table 22 Percentage of walls and roofs which have been significantly or very significantly thermally retrofitted and/or upgraded by period of construction [76]

High percentage as reduction from Mean 2 to Mean 2 of 1.97 to 1.13 W/m²K respectively not as significant as for single storey counterpart of 1.53 to of 0.39

			Walls				Roofs			
			% Mode 1 dwellings		Frequency weighted average		% Mode 1 dwellings		Frequency weighted average	
			single-storey	two-storey			single-storey	two-storey		
Period of Constr-uction	Pre-thermal regul-ation	< 1900	17%	70%	49%	46%	56%	49%	52%	50%
		1900-1929	15%	31%	25%		27%	52%	42%	
		1930-1949	19%	30%	24%		27%	59%	47%	
		1950-1966	50%	49%	50%		36%	59%	50%	
		1967-1977	72%	66%	70%		51%	56%	54%	
	Post-thermal regul-ation	1978-1982	54%	57%	55%	70%	52%	95%	78%	84%
		1983-1993	70%	65%	68%		71%	98%	87%	
		1994-1999	79%	65%	72%		60%	99%	84%	
		2000-2004	75%	63%	68%		49%	99%	80%	
		2005-2006	93%	94%	94%		84%	98%	93%	
			Average across dwelling stock			58%	Average across dwelling stock			67%



In post thermal-regulation dwellings, high percentages evidence the large number of dwellings that were constructed to better than prevailing thermal building regulations; for instance in 2005 to 2006 two-storey walls Mean (1) is 0.29 when default is 0.37 W/m²K

*These figures appear low – however they represent very significant retrofits – 100 % of dwelling **means** are below current defaults – The difference between single and two-storey dwellings might be attributed to the fact that roof surface area on a single-storey building impacts the dwelling heat loss to a much greater extent than in the equivalent two-storey dwelling*

The distinction between Mode 1 and Mode 2 dwelling is more significant in pre-thermal regulation dwellings. For instance, in 1967 to 1977 dwellings, single storey Mean 2 to Mean 1 reduced from 0.6 to 0.3 W/m²K and two-storey Mean 2 to Mean 1 reduced from 0.7 to 0.31 W/m²K respectively – evidence of significant retrofits in pre-thermal regulation dwellings constructed between 1967 and 1977; 1950 to 1966 dwellings behave similarly

Mean (1)	**0.13**
Std Dev (1)	**0.01**
Mean (2)	**0.31**
Std Dev (2)	**0.23**
Proportion (1)	**49%**

3.3.3 Recommendation to revise base-default U-values

This section presents the results of the analysis of wall and roof thermal probability distributions, by period of construction, to recommend statistically relevant base-thermal-default U-values based on the 90th percentile point of the probability distributions, described in Section 3.2.1, using the method outlined in Section 3.2.2.

Due to the difficulty of retrofitting floor insulation in an occupied dwelling [70], and identifying the presence of floor insulation retrospectively, the empirical database [76] did not reveal any thermal upgrades of floors. Table 23 thus presents recommendations for walls and roofs only. The thermal performance of single storey and two-storey dwellings, with the same thermal characteristics, will differ owing to a different volume to surface area ratio so single and two-storey dwellings are distinguished.

Irish thermal base or as-built default U-values, similar to many other EU member states, were determined;

i) from the type and date of construction for pre-thermal regulation elements and;

- Walls – Recommendations for updated base-thermal-default U-values in Table 23 reasonably approximate the current default U-value of 2.1 W/m^{2}K. A small average reduction of - 11 % and - 8 % for two-storey walls is recommended.
- Roofs – Recommendations for updated base-thermal-default U-values in Table 23 deviate significantly from the current default U-value of 2.3 W/m^{2}K. An average reduction - 58 % for single-storey roofs and - 37 % for two-storey roofs is recommended. The difference between single and two-storey dwellings might be attributed to the fact that roof surface area on single storey dwellings affects the dwelling heat loss characteristic to a much greater extent than in the equivalent two-storey dwelling. This may have provided more motivation to the homeowner to carry out thermal upgrades to this element.

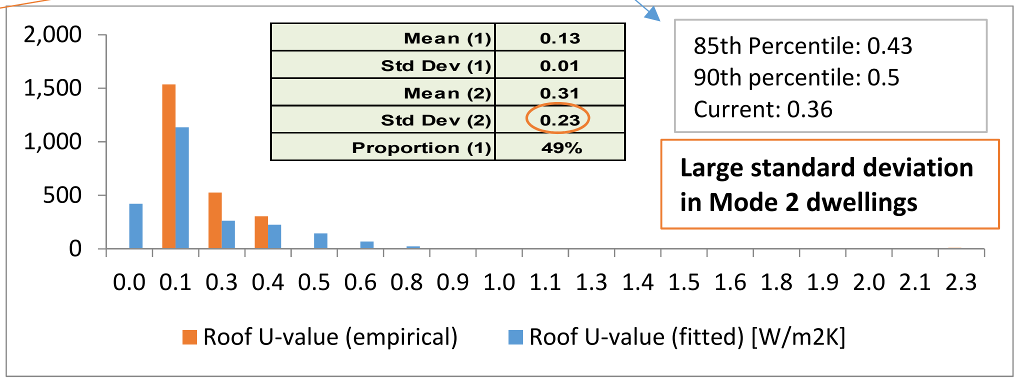
ii) by the maximum allowable U-value at time of construction for post-thermal regulation elements;

- Walls - Pre-thermal regulation single and two-storey walls behave similarly. However, post-thermal regulation, single-storey dwelling walls tend to perform better thermally than their two-storey counterpart. An average reduction of - 18 % to the current thermal default is recommended for single-storey detached dwellings while an average - 8 % reduction is recommended for two-storey walls. Dwellings constructed between 1978 and 1982 see the largest deviation of 28 % and 19 % for one and two-storey dwellings respectively, this may be attributable to the; (i) 1979 oil crisis making people more aware of the benefits of insulation and (ii) positive effect of the draft thermal building regulations published in the mid 1970's.
- Roofs – the methodology applied suggests an increase to current defaults for all post-regulation roofs but particularly for roofs constructed in the period from 1994 to 2006. This phenomenon is caused by lax adherence to thermal building regulations during Ireland's recent housing construction boom that occurred in the period between the mid-1990's and mid-2000's [162] causing histograms that appear positively skewed (see explanatory figure with Table 23); leading to higher than current defaults when recommended based on 90^{th} percentile. This would suggest that the lognormal or gamma distribution function might fit the data better in these cases however reference to the goodness of fit analysis carried out in Appendix C.3, the normal distribution applied through MLE tracks this phenomenon adequately via the application of large standard deviations. No adjustment to current defaults is therefore recommended for post-thermal regulation roofs.

Table 23 Recommendation of empirically derived wall and roof default U-values for detached Irish dwellings [76]

			Wall							Roof						
				Recommended single-storey default			Recommended two-storey default				Recommended single-storey default			Recommended two-storey default		
					% Difference			% Difference				% Difference			% Difference	
			Current Default U-value (W/m²K)	U-value (W/m²K)	by element	Weighted average by frequency of dwelling quantity	U-value (W/m²K)	by element	Weighted average by frequency of dwelling quantity	Current Default U-value (W/m²K)	U-value (W/m²K)	by element	Weighted average by frequency of dwelling quantity	U-value (W/m²K)	by element	Weighted average by frequency of dwelling quantity
Period of Construction	Pre-thermal regulation	>1900	2.10	2.03	-3%	-11%	2.06	-2%	-8%	2.30	1.37	-40%	-58%	1.60	-30%	-37%
		1900-1929	2.10	1.96	-7%		1.97	-6%		2.30	1.22	-47%		1.53	-33%	
		1930-1949	2.10	2.03	-3%		1.97	-6%		2.30	1.04	-55%		1.40	-39%	
		1950-1966	2.10	1.80	-14%		1.79	-15%		2.30	0.88	-62%		1.32	-43%	
		1967-1977	2.10	1.73	-18%		1.69	-20%		2.30	0.65	-72%		1.22	-47%	
	Post-thermal regulation	1978-1982	1.10	0.79	-28%	-18%	0.89	-19%	-8%	0.40	0.47	18%	28%	0.41	2%	8%
		1983-1993	0.60	0.53	-12%		0.58	-3%		0.40	0.47	18%		0.41	2%	
		1994-1999	0.55	0.45	-18%		0.50	-9%		0.35	0.48	37%		0.38	9%	
		2000-2004	0.55	0.43	-22%		0.51	-7%		0.35	0.50	43%		0.37	6%	
		2005-2006	0.37	0.33	-11%		0.36	-3%		0.25	0.34	36%		0.31	24%	

Lax adherence to thermal building regulations during Ireland's recent housing construction boom causes positively skewed histograms; reflected in higher than current defaults recommended based on 90th percentile – see Figure 28, Table 21 and Appendix C (Figures C8, C9 and C10) as well as goodness of fit analysis in Tables C2 to C7 for more detail



3.4 Discussion

Employing the data created in this study weighted against quantity of dwellings by DEAP [72] period of construction; a mean as-built U-value is estimated to apply across this dwelling typology as shown in Table 24. In Table 24, data for 2014 represents the results of this study. Table 24 is presented for discussion purposes only as:

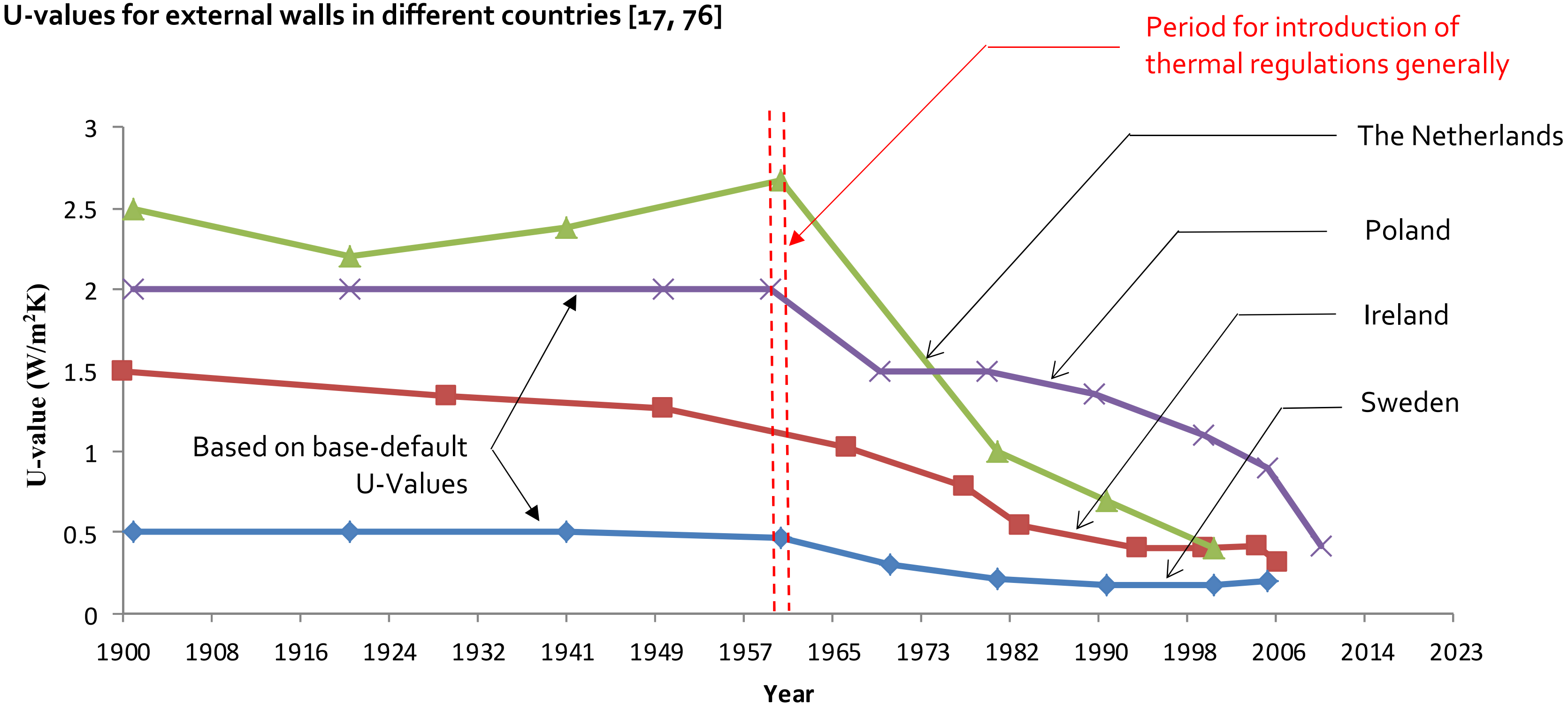
- The median level of thermal insulation is not expressly reported in the previous studies [70, 128, 131], it is thus not possible to determine an accurate mean U-value. It is noted that the percentage of roof insulation installed appears to have reduced from 82 % to 64 % between 2001 and 2014. This anomaly arises because this study is referencing lower levels of thermal transmittance U-values. Mean U-values achieved in 2014 are thus quoted for clarity although it must be noted, as outlined in Section 3.3.1, a significant thermal difference exists between pre and post-thermal regulation dwellings.
- It is unclear whether improved insulation levels rose due to; (i) newer more insulated stock being added to the overall stock, or (ii) whether the results are from retrofit interventions.
- Levels of insulation in floors are difficult to identify retrospectively, consequently, floor U-values are based typically on base-default U-values. Section 2.4.2.3 outlines how these base-default U-values have the potential to underestimate the heat loss through the ground floor slab.

Figure 29 compares the average wall U-values by period of construction [76] with available data for Sweden, The Netherlands and Poland [17]. The graph is presented for illustration only as the data for countries other than Ireland (i) includes all dwelling typologies, (ii) is not as contemporaneous as the data for Ireland, and is (iii) based on defaults. Nonetheless, Figure 29 shows Ireland to compare favourably with The Netherlands and Poland.

Table 24 Penetration of significant thermal upgrades in the detached Irish housing sector over time [76, 131]

		Walls		Roof		Double-glazed windows		Floor		Source
		%	Mean U-value (W/m²K)	%	Mean U-value (W/m²K)	%	Mean U-value (W/m²K)	%	Mean U-value (W/m²K)	
Year of Survey	2001	56	1.01	82	1.3	61	-	25¤	0.6	Ahern et al. (2013) [70] and INSHQ 2001-2002 [131] ¤ Healy and Clinch 2004 [128]
	2014	58	0.66	67	0.37	97	2.92	53	0.59	This research

Figure 29 U-values for external walls in different countries [17, 76]



The (i) extent of thermal retrofits and (ii) high degree of autonomous energy-efficiency improvements mean that the;

a) distinction between the thermal efficiency of pre-thermal regulation and post-regulation dwellings, whilst still valid, is lessening,
b) strong association of dwelling age and energy efficiency is diminishing as retrofits in the sector are carried out,
c) view that the majority of dwellings in Ireland are thermally sub-standard [130, 163] may no longer be true,
d) use of pessimistic base-thermal-default coefficients for the characterisation of a reference dwelling is not appropriate.

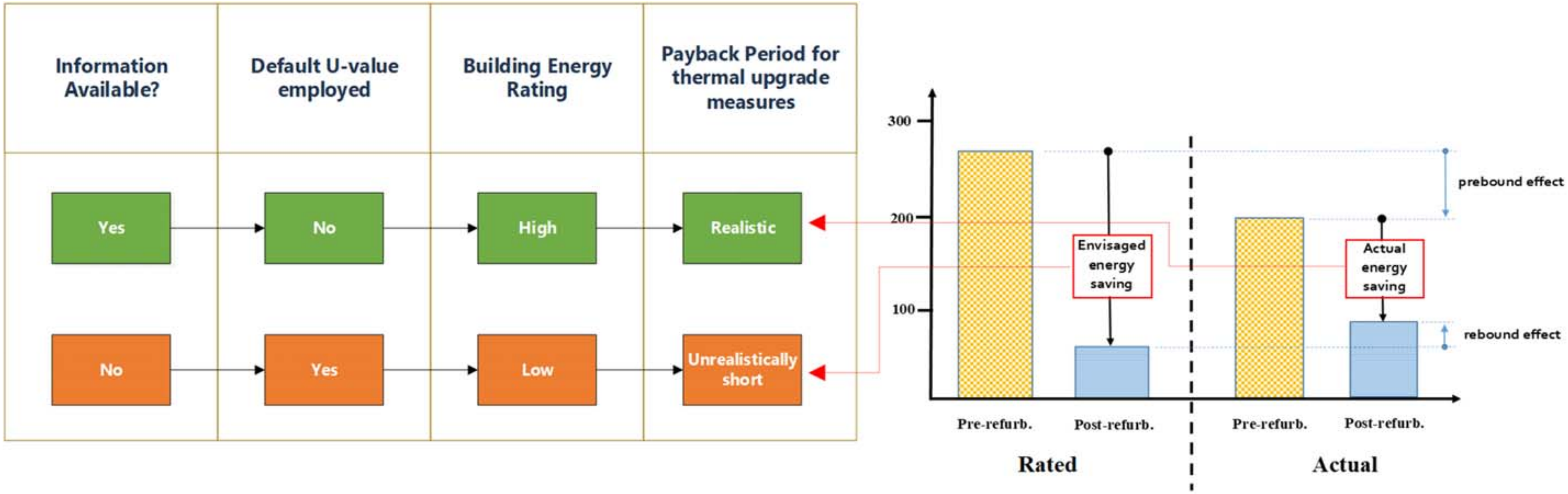
3.5 Recommendations

In Section 3.2.1, it was established that base-thermal-default U-values are necessarily pessimistic. Referring to Figure 30, as it is not possible to save energy that is not actually being consumed [108], it follows that where base-defaults are employed in an EPC methodology the program will return unrealistically short payback periods for refurbishment works in turn leading to EPC advisory reports lacking credibility by homeowners. This is an acknowledged barrier to the uptake of retrofit measures in a dwelling stock [110].

To, (i) remove this known barrier to the uptake of energy efficiency upgrades in the residential sector and, (ii) allow the end user to make a more informed decision on retrofitting strategies; reports of the assessor should;

- highlight how building element U-values were determined,
- how accurate they believe those values to be, and
- carry out a sensitivity analysis highlighting the impact their assumptions may have on the energy label and/or potential energy savings resulting from thermal retrofits.

Figure 30 Illustration of how use of defaults results in unrealistically short payback periods



Alternatively, homeowners could be offered a more likely, stochastically based, payback period for the refurbishment works. Payback periods, when base-thermal-defaults are employed are calculated as shown in Figure 31 (a). Referring to Figure 31 (a):

- When carrying out an estimation of the payback realisable through retrofit interventions, the desired retrofit U-values to be achieved occurs statistically, around the mean of Mode 1 dwellings, denoted (Y). The value for (Y) is thus known.
- Base-thermal-default U-values by period of construction, denoted (X), are employed where the wall U-value is "unknown".
- Shorter than realisable payback periods result from the unrealistic scale of improvement from the assumed pessimistic base-thermal-default U-value (X) to the refurbished U-value (Y).

Accordingly, it is recommended that where base-thermal-default U-values have been employed in a payback calculation that a more likely, stochastically based, payback period, as described in Figure 31 (b) also be offered to the homeowner. Referring to Figure 31 (b):

- Mean 'Mode 2' U-values, denoted (X'), by period of construction can be established by the methodology described in Section 3.2.2 of this work.
- It is recommended that these statistically derived (X') values replace the pessimistic default (X) value in the payback calculation to offer a more likely payback period to the homeowner.

The consequent realistic payback periods, increase the credibility of the advisory report associated with the EPC so enabling uptake of retrofit measures and energy efficiency in the dwelling stock.

Using algorithms to establish contemporaneous, statistically derived (X), (X') and (Y) U-values, the methodology proposed could be embedded in EPC databases thereby making the EPC database intelligent whilst also enabling real-time or live-stock modelling. This approach should be investigated as future research arising from this work as is further discussed in Chapter 8.

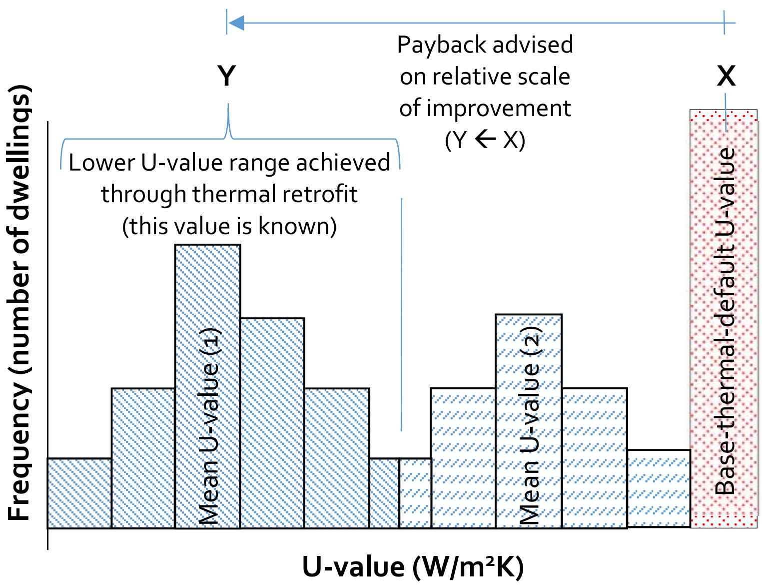
Figure 31 (a & b) Basis and recommendation for payback period calculation arising from thermal refurbishments when base-default U-values are used

Key

Mode 1 – Thermally refurbished building element

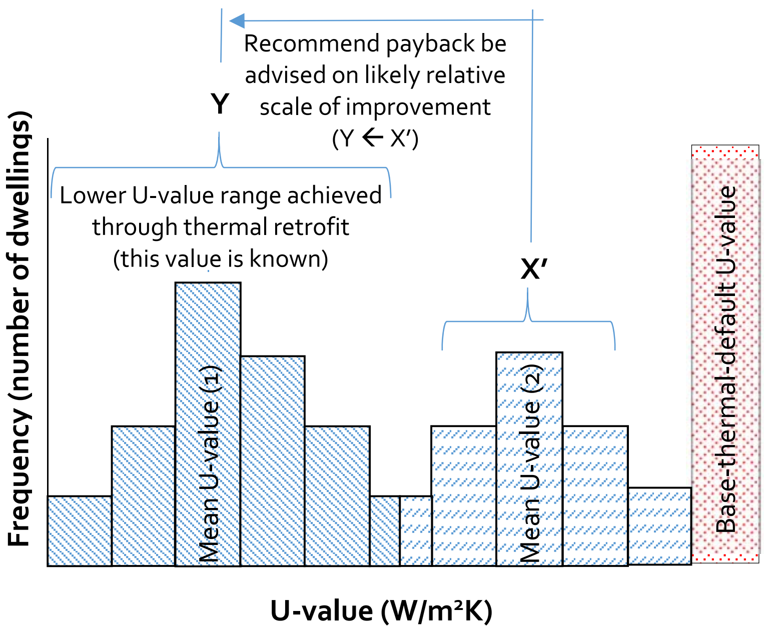
Mode 2 – As-built building element

(a) Basis of payback period calculation (X → Y)



As you cannot save energy that is not actually being consumed. When an outmoded pessimistic default value is used to calculate the payback period based on (X→ Y), there is a risk of greatly overestimating the potential saving from retrofit intervention...

(b) Recommended basis of payback period calculation (X'→Y)



...it is therefore recommended that along with payback period advised in (a) the homeowner is advised of a more likely payback period based on the Mean U-value of Mode 2 dwellings +/- 0.5 to 1 standard deviations or X'→ Y. The homeowner would be better informed about any proposed thermal retrofit intervention than if they just had the payback period calculated on the basis of X → Y

3.6 Conclusions

The level of thermal retrofits in the Irish residential sector in 2014 are assessed to find that significant levels of thermal retrofits are leading to;

i) a diminishing association between a dwelling's age and its energy efficiency,

ii) a positively shifting bi-modal distribution of thermal characteristics,

iii) base-default U-values chosen as described in Chapter 2 (Table 7), having become increasingly outmoded.

The use of outmoded base or as-built default U-values, to necessarily maintain the cost-effectiveness of EPC, decreases the accuracy and hence credibility of both the EPC and its associated advisory report. A perceived lack of certification accuracy by the homeowner inhibits investment in energy efficiency.

Adoption of pessimistic as-built base-thermal-default U-values under ranks the energy performance of circa 90 % of dwellings. It especially under ranks pre-regulation dwellings and, where used, is assumed to be a significant contributing factor to the prebound effect in dwellings and the energy performance gap of national residential energy consumption models (see Section 4.3.1 for confirmation).

This work derives validated generalisable methodologies to establish from an EPC dataset;

a) statistically relevant base-thermal-default U-values, as well as

b) the renovation state of the dwelling stock, whilst recommending

c) a more appropriate method of payback calculation when base-thermal-defaults are necessarily employed.

Use of the statistically derived default U-values established and/or the method for payback calculation proposed will help narrow the energy performance gap by increasing the accuracy and hence credibility of the EPC and its associated advisory report so enabling investment in energy efficiency for the residential sector.

Chapter 4 - Characterisation and Aggregation of Reference Dwellings to stock level

4.1 Introduction

"The goal is to turn data into information, and information into insight"

Fiorina, C [164]

This chapter uses the recently-published Irish national empirical energy performance certification database and other literature where appropriate [76] to:

1) Establish a suitable methodological approach for defining RDs from a large residential thermophysical empirical database.
2) Make transparent the process of characterising appropriate base-thermal-default-free RDs from an EPC dataset,
3) Create a stock model derived from largely default-free RDs that can be employed,
    i. as simplified inputs to a national cost-optimal energy refurbishment model,
    ii. to highlight the consequences of the use of base-default U-values in residential energy consumption models.
4) Formally present data prescribed within the EU Commission Delegated Regulation No 244/2012.
5) Validate the RDs and the stock model created.

The research presented in this chapter:

a) Discusses multi-collinearity between energy use factors in UK and Ireland dwellings stocks.
b) Confirms rationale of sub-segmenting housing typologies by system characteristics.

c) Details methodologies, both developed and employed, to characterise data applicable to the RD under the following subheadings; operation, form, envelope and system.
d) Highlights challenges around the characterisation of RDs from an EPC database but also more generally.
e) Contributes to a consensus on the definition of parameters for dwellings in Ireland but particularly for Ireland's predominant single-family housing typology.

As detailed in Chapter 1, the EU's main legislative tools aimed at reducing the energy consumption of buildings are the;

(i) 2010 Energy Performance of Buildings Directive (EPBD recast, 2010/31/EU), and
(ii) 2012 Energy Efficiency Directive (2012/27/EU).

EPBD Guidelines [52] require each EU member state to define and report a set of RDs that are representative of the typical national or regional dwelling stocks [43, 53, 54]. RDs across Europe are to be reported in compliance with the common reporting methodology; EU regulation 224/2012 [52]. This EU regulation [52] is designed to enable (i) transparent reporting, (ii) comparison of dwelling stocks across EU member states, and (iii) cost-optimal refurbishment interventions for the European housing stock to be developed. The RBs are used to model extrapolations consistent with those that would be produced if the detailed characteristics of the overall building stock were used [43, 53, 55].

As discussed in both Chapter 1 and Chapter 2, appropriate characterisation of the reference dwelling relies on high-quality empirical [11, 42, 56] and contemporaneous [56] data. Furthermore, to ensure that the research benefits the research community-at-large, the characterisation should be a result of a transparent and appropriate process [11, 42, 58].

As referred to previously, the building stock will be reflected more realistically when a higher number of RDs are used [52]. The effectiveness of use of RDs therefore depends on the;

i) number of building subcategories employed [60],
ii) level of detail pursued in defining the RD [54],

iii) validity of the information used to characterise the RD [54, 58],

iv) proper selection of default data and/or the terms of reference [43, 51].

4.2 Methodology

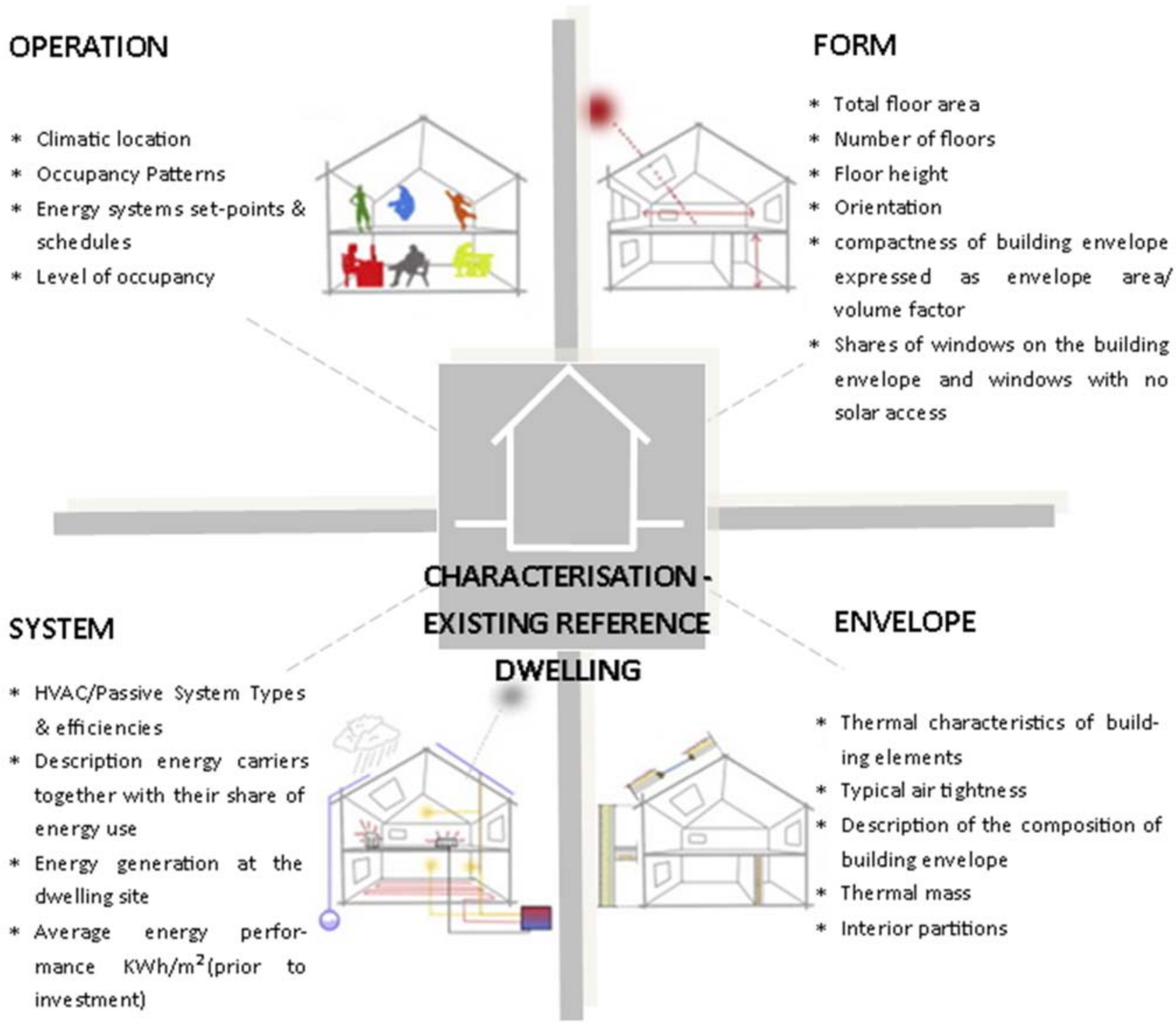
4.2.1 Overall Approach

Corgnati et al. (2013) [54] adapted a methodology for establishing RBs used by the US Department of Energy [165] to categorise the building data required to characterise RBs into four main categories; (i) form, (ii) envelope, (iii) system and (iv) operation. Here, the relevant EPBD directives [52, 55], adapt the methodology established by Corgnati et al. [54] for office buildings in Italy to apply to existing Reference Dwellings (RDs) as shown in Figure 32.

Referring to Figure 32, the approach adopted in this work is to employ a large, real empirical and contemporaneous sample dataset, described in Chapter 2, where available appropriate, to create SyAv reference dwellings representative of this dwelling typology at stock level. As discussed in Chapter 2, dwelling parameters are calibrated to an extent through dwelling audits. When information within the empirical database is unreliable, the composition of the reference dwelling is informed instead through available data and expert enquiries.

EPC energy performance assessment procedures generally provide all the detailed information pertaining to the building form, system and envelope as defined in Figure 32. Taking the performance gap together with the ubiquitous use of base-thermal-defaults outlined in Chapter 2, the methodology adopted ignores within the EPC dataset, aggregated data such as energy consumption figures, in favour of establishing disaggregated thermophysical data by period of construction [38, 49, 53, 166, 167].

Figure 32 Categorisation of characteristic data required to define reference dwelling for existing dwellings [52, 54, 55, 165]



The overarching approach is to define the reference dwellings by order of dominant thermophysical energy factors first; however as discussed in Chapter 1, multi-collinearity between factors makes it difficult to isolate which ones have the greatest influence on dwelling energy consumption [27, 28]. In Ireland and UK, some studies show heating system efficiencies, primary fuel types and heat source (system characteristics) to have the greatest influence on energy consumption of a dwelling [33-35] while others [11, 36] consider the building fabric to have the greatest influence. A study carried out in using base data for 12,500 gas centrally heated houses in 2009 [168], found the dominant factors, accounting for approximately 75 % of the observed variance in the energy performance rating of the home, to be heating system efficiency, external wall U-value and dwelling geometry.

4.2.1.1 Heating and Hot Water Systems

In 2016, as shown in Table 5, 68 % of the case study dwellings are centrally heated by oil boilers while 25 % use solid-fuel as a primary heat source accounting for 93 % of the case study dwellings. 1 % have no central heating, the balance of fuels are electricity (2 %), natural gas (1 %), Liquid Petroleum Gas (LPG) (1 %) and "other fuels" (1 %). Typically, the solid-fuel and oil boilers serve a radiator system [76]. Of those using solid-fuel two-thirds use a stove and/or cooker while a third use an open-fire with a back boiler [71].

To establish SyAv heating and Domestic Hot Water (DHW) heating system efficiencies for RDs, the EPC dataset was examined to establish SyAv heating and Domestic Hot Water (DHW) heating system efficiencies for RDs heated by oil and by solid-fuel as shown in Tables 25 and 26. Standardising and thus simplifying heating and DHW system characteristics in this manner mean the dominant parameters determining dwelling energy consumption of the dwelling relate to the (i) thermal characteristics associated with the dwelling envelope, (ii) dwelling envelope surface area, as well as (iii) operational (heating duration and set point temperature) characteristics.

Table 25 Synthetically Average (SyAv) space heating and DHW system characteristics for oil-heated RD [72, 76]

			Quantity	Unit	Description and/or source
Systems	Primary heating fuel		Oil		68 % RDs –see Table 5 [74]
	Secondary heating fuel		Coal		[76]
	Secondary heating proportion		10	%	[76]
	Efficiencies of space heating system	Primary heating generation η_b	81.2	%	[76]
		distribution	45.24	%	Boiler with uninsulated primary circuit (70.3% of the stock) [76].
		Primary system control and response category	1		71.2 % Control category 1[¤] and 98 % Heating System response category 1[¥] [76]
		Secondary heating efficiency	42	%	[76]
	Efficiencies of DHW system	Generation	81.56	%	56% Factory Insulated Tanks, 56% no electrical immersion used in summer [76].
		Distribution losses	45.24	%	[76]

¤ No time or thermostatic control of room temperature, programmer with no room thermostat, room thermostat only or programmer + room thermostat (Table 4e DEAP)

¥ Systems with radiators or underfloor heating - Table 4d DEAP [72]

Table 26 Synthetically Average (SyAv) Heating and DHW system characteristics for solid-fuel heated RD [72, 76]

<table>
<tr><th colspan="3"></th><th>Quantity</th><th>Unit</th><th>Description and/or source</th></tr>
<tr><td rowspan="9">Systems</td><td colspan="2">Primary heating fuel</td><td colspan="2">Solid-fuel Multi-fuel</td><td>24 % RDs – see Table 5 [74]</td></tr>
<tr><td colspan="2">Secondary heating fuel</td><td colspan="2">Solid-fuel Multi-fuel</td><td>[76] – see Figure 5</td></tr>
<tr><td colspan="2">Secondary heating proportion</td><td>10</td><td>%</td><td>[76]</td></tr>
<tr><td rowspan="4">Efficiencies of space heating system</td><td>Primary heating generation η_b</td><td>54</td><td>%</td><td>[76]</td></tr>
<tr><td>distribution</td><td>48</td><td>%</td><td>Boiler with uninsulated primary circuit [76]</td></tr>
<tr><td>Primary system control and response category</td><td colspan="2">1</td><td>69 % Control category 1¤ and 78 % Heating System response category 3¥ [76]</td></tr>
<tr><td>Secondary heating efficiency</td><td>42</td><td>%</td><td>[76]</td></tr>
<tr><td rowspan="2">Efficiencies of DHW system</td><td>Generation</td><td>61</td><td>%</td><td>31%/69 % Factory/ Loose jacket insulated tanks, 7% electrical immersion used in summer [76].</td></tr>
<tr><td>Distribution losses</td><td>6</td><td>%</td><td>[76]</td></tr>
</table>

¤ No time or thermostatic control of room temperature, programmer with no room thermostat, room thermostat only or programmer + room thermostat (Table 4e DEAP)

¥ Open fire with back boiler to radiators or Closed room heater with back boiler to radiators or Range cooker boiler (integral oven and boiler) or Range cooker boiler (independent oven and boiler) DEAP [72]

4.2.1.2 Heat loss through the building fabric

The heat loss through the building fabric relates to the thermal transmittance coefficients of dwelling to include;

a. planar elements (walls, floor and roof) expressed in watts per meter squared kelvin (W/m^2K) or U-values,
b. air-permeability of the fabric expressed in cubic metres per hour per square metre of envelope area (m^3/hm^2),
c. linear thermal bridges expressed in watts per meter kelvin (W/mK) which describes the heat loss associated with a thermal bridge not accounted for in the U-values of the plane buildings elements containing the thermal bridge, as well as
d. internal heat capacity, expressed as megajoules per meter-squared kelvin (MJ/m^2K), describes the dwelling's capacity to store heat within its structure.

Using a sample of RDs characterised later in this work, the 'BS EN 12831:2003 Heating Systems' steady-state heat loss design standard was used to estimate the relative percentage heat loss resulting from (a) planar (circa 80 to 90 %), (b) air permeability (circa 8 to 16 %), and (c) thermal bridging (circa 4 to 6 %) factors in detached dwellings. The dominant factor relating to heat loss is planar heat loss through the dwelling envelope, measured in W/K, calculated by totalling the sum of dwelling element surface area (m^2) multiplied by the dwelling element U-values (W/m^2k) for all exposed building elements.

4.2.1.3 Dwelling envelope surface area

Dwelling floor area and hence dwelling size and associated window ratios increase with time [70]. The length of thermal bridges increases correspondingly. Energy use pertaining to the surface area of the dwelling envelope planar elements as well as the length of its linear thermal bridges relates to the geometric characteristics of the dwelling or dwelling form. The development of these parameters in the reference dwellings is captured initially via classification by period of construction and hence similar architectural styles.

4.2.1.4 Reference dwelling definition process

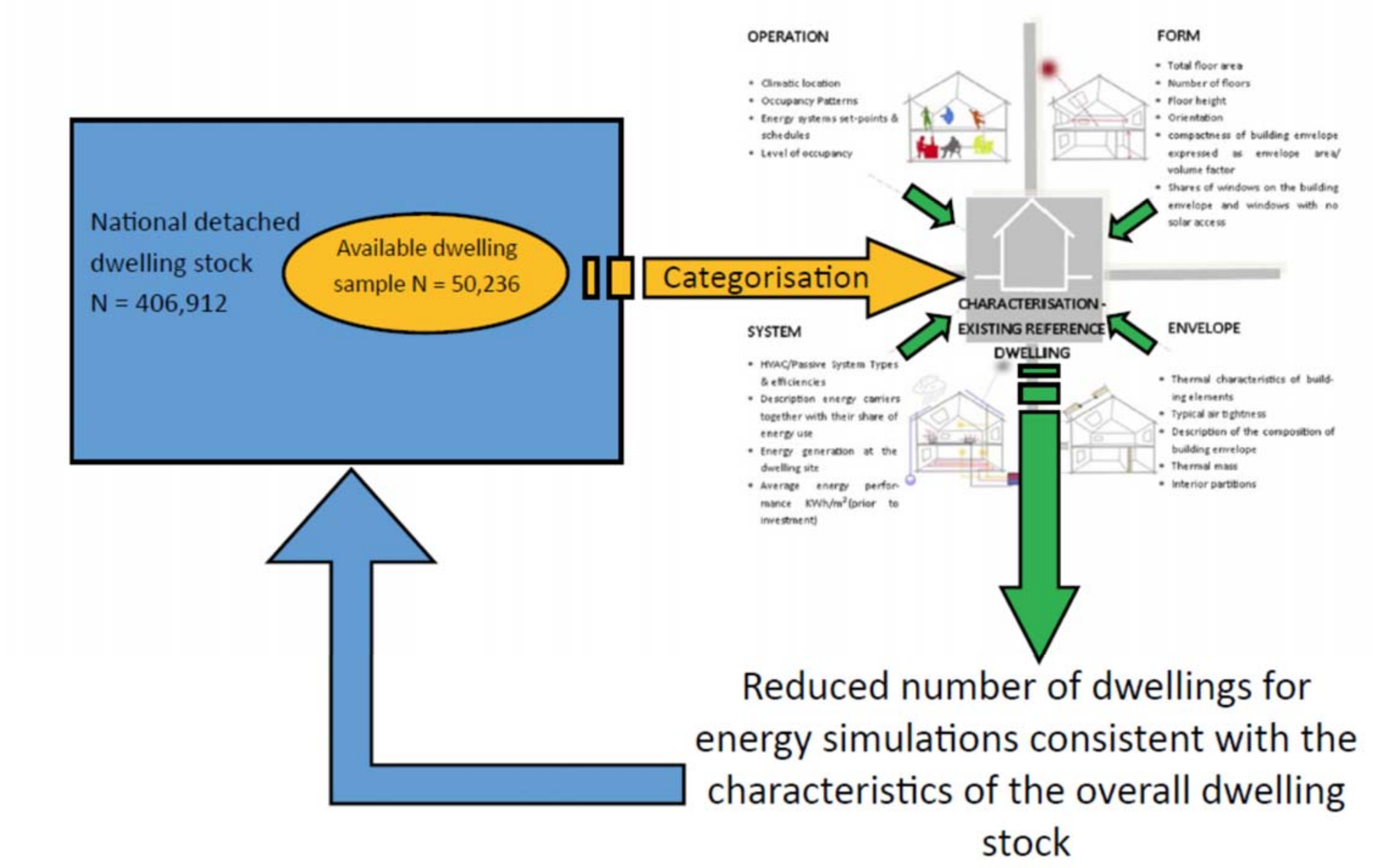
The following steps were used to define the reference dwelling;

1) Common heating duration, set-point temperatures and climatic conditions for the reference dwellings suitable for a one-fits-all energy model are established in Section 4.2.2.
2) Synthetically average occupancies by DEAP period of construction were also established in Section 4.2.2.
3) Synthetically average dwelling forms by DEAP and thus traditional periods of construction, were ascertained using maximum likelihood estimation of the microscopic data in the EPC dataset and as described in Section 4.2.3.
4) Mean 1 and Mean 2 thermal planar element U-values (W/m^2K) for Mode 1 and Mode 2 by were established for each dwelling element classified by DEAP by period of construction as outlined in Section 4.2.4.
5) To reduce the number of classification and hence reference dwellings so allowing the stock model to be less computationally intensive, the thermal data relating to planar elements established in step 4, by DEAP period of construction, was analysed for commonality. Likely due to thermal retrofits, commonality in the thermal characterisations of dwellings is observed across traditional construction periods.
6) Physical geometric characteristics, surface area of building envelope (m^2), window ratios (%) and length of thermal bridges (m) established in step 3, were reclassified to correlate with common thermal U-values classifications established in step 5.
7) Air-permeability characteristics and occupancy data were also reclassified to correlate with dominant planar element U-value classifications established in step 5.
8) Proportion of heating fuel use in Table 6 (Section 2.3) were reclassified to correlate with dominant planar element U-value classifications established in step 5.
9) Orientations and shares of windows with no solar access was estimated in Section 4.2.4

10) The clustered data was composed into SyAv reference dwellings.

The modelled energy use of the reference dwellings created can be modelled and hence employed as simplified inputs to hybrid bottom-up engineering stock energy consumption models as shown in Figure 33. Heating system characteristics, outlined in Tables 25 and 26, to be assigned to RDs in proportion applying (see summary results Table 37) at modelling stage.

Figure 33 Categorisation of disaggregated dwelling characteristics for use in a bottom-up hybrid residential energy consumption model



4.2.2 Operation

4.2.2.1 Climatic Location

The RD data established by this methodology are intended to be used to determine cost-optimal energy efficient refurbishments. To represent the energy savings that might be realised by particular interventions over the year it will be necessary to reference a statistical weather file. The International Weather for Energy Calculations (IWEC) contains "typical" weather files, in hourly time-steps, for a series of weather parameters suitable for use with building energy simulation programs [169]. The World Meteorological Organization (WMO) recommends that climate averages be computed over a 30-year period of consecutive records to smooth-out year-to-year variations. IWEC2 Weather Files (update of the original IWEC files) are available for twelve locations in Ireland with data spanning from 1983 to 2008 [170]. As shown in Figure 34 (a &b), the twelve IWEC 2 locations are mapped against;

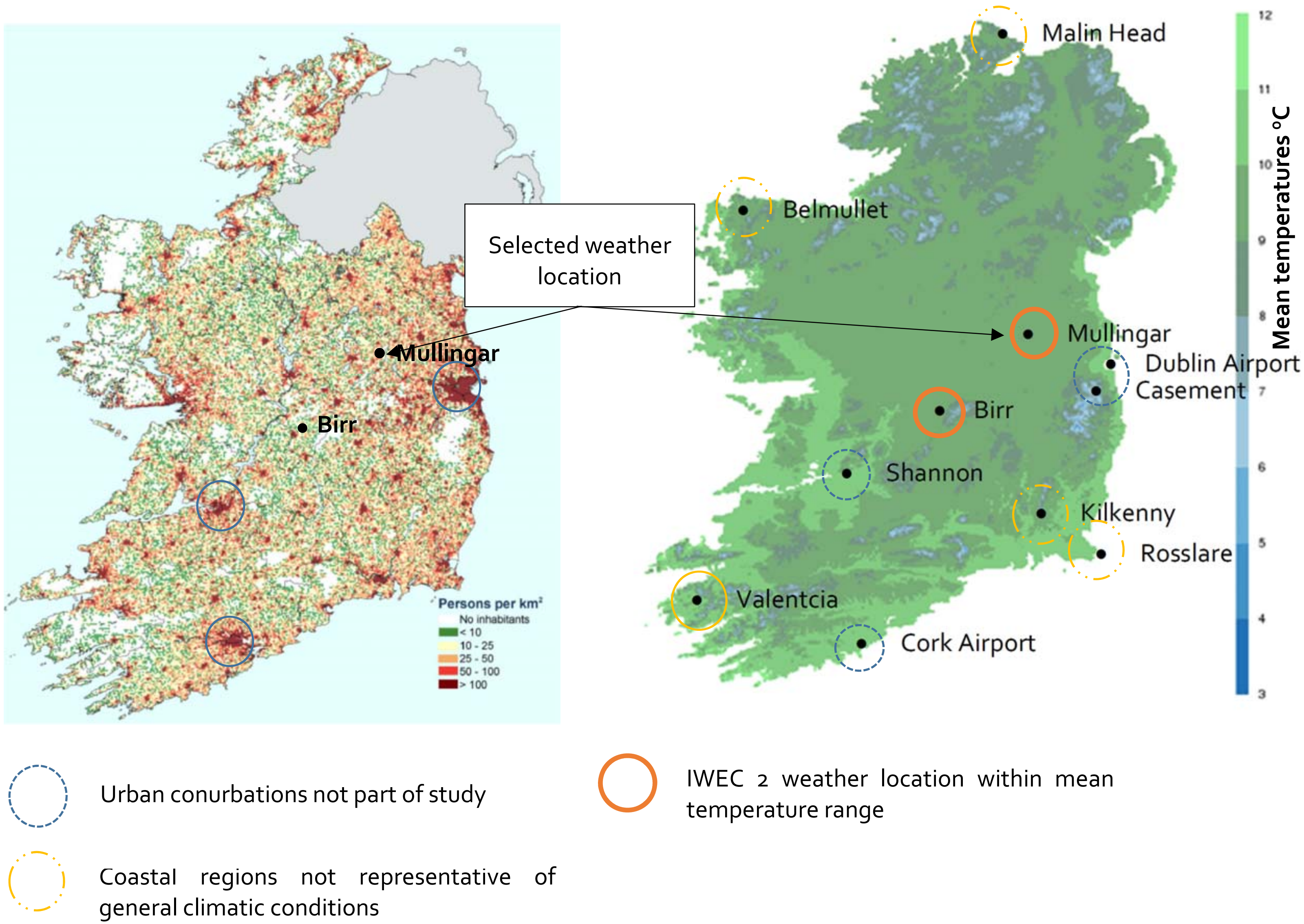
(i) population density of Ireland [Figure 34 (a)], and
(ii) the mean temperatures published by Ireland's meteorological body - Met Éireann [171] [Figure 34 (b)].

Ireland has a temperate climate with temperatures tending to be higher in the south-western areas and lower in the midlands and the northeast. However, the range of temperatures is modest [135]. As they do not represent the case study dwelling, IWEC 2 locations located in urban conurbations are discounted. IWEC 2 locations in coastal regions are discounted as they are not located within the mean temperature range indicated in Figure 32 (b). Two IWEC 2 locations (Birr and Mullingar) are representative of mean temperature range and rurally located dwellings. The Mullingar weather station is selected to provide a typical weather data file as it is located in a more representative densely populated region than Birr. Selecting one weather file to represent the island of Ireland provides a statistically average representative weather file required for a one-fits-all energy model.

Figure 34 (a & b) Population and temperature distribution in Ireland [171, 172]

a) Population denisty in terms of 1 km ^{2} grid cells, 2011

b) Twelve IWEC 2 locations available for Ireland mapped against mean temperatures for the period of 1981 to 2010



4.2.2.2 Operation & Occupancy Pattern, Set points and Schedules

A major determinant of domestic space heating energy use are heating demand temperatures (thermostat setting where thermostats are used) and heating duration [27, 57, 58, 173, 174].

In the UK, a widely used model for predicting home energy consumption is the Building Research Establishment Domestic Energy Model (BREDEM) that is consistent with the BS EN ISO 13790 standard [174]. The default assumption in the BREDEM model is that the whole dwelling is heated only during specific time periods, and the living area is heated to a higher temperature (usually of 3 °C) than the rest of the home during these periods [174]. The BREDEM module assumes set-point temperatures and heating durations as shown in Table 27.

Table 27 BREDEM, DEAP and assumed reference dwelling demand temperatures and schedules for space heating system [57, 72, 175, 176]

<table>
<tr><th colspan="4" rowspan="2"></th><th colspan="2">Mean Temperature (°C)</th><th colspan="2" rowspan="2">Heating Duration (hrs)</th></tr>
<tr><th>Living Room</th><th>Rest of Dwelling</th></tr>
<tr><td rowspan="7">Heating Period</td><td rowspan="3">BREDEM</td><td>Morning</td><td>07:00-09:00</td><td>21</td><td>18</td><td>2</td><td rowspan="2">9</td></tr>
<tr><td>Evening</td><td>16:00 – 23:00</td><td>21</td><td>18</td><td>7</td></tr>
<tr><td>Weekends</td><td>07:00 – 23:00</td><td>21</td><td>18</td><td>16</td><td>16</td></tr>
<tr><td rowspan="2">DEAP</td><td>Morning</td><td>07:00 – 09:00</td><td>21</td><td>18</td><td>2</td><td rowspan="2">9</td></tr>
<tr><td>Evening</td><td>17:00 – 23:00</td><td>21</td><td>18</td><td>7</td></tr>
<tr><td rowspan="2">Assumed for RD</td><td>Morning</td><td>06:45 – 09:00</td><td>18.3 [¤]</td><td>17 [#]</td><td>2 hrs 15 mins [α]</td><td rowspan="2">9 hrs 30 mins</td></tr>
<tr><td>Evening</td><td>15:45 – 22:00</td><td>19.9 [¤]</td><td>17 [#]</td><td>7 hrs 15 mins [α]</td></tr>
</table>

¤ [175] # [176] α See Figure 33 [175]

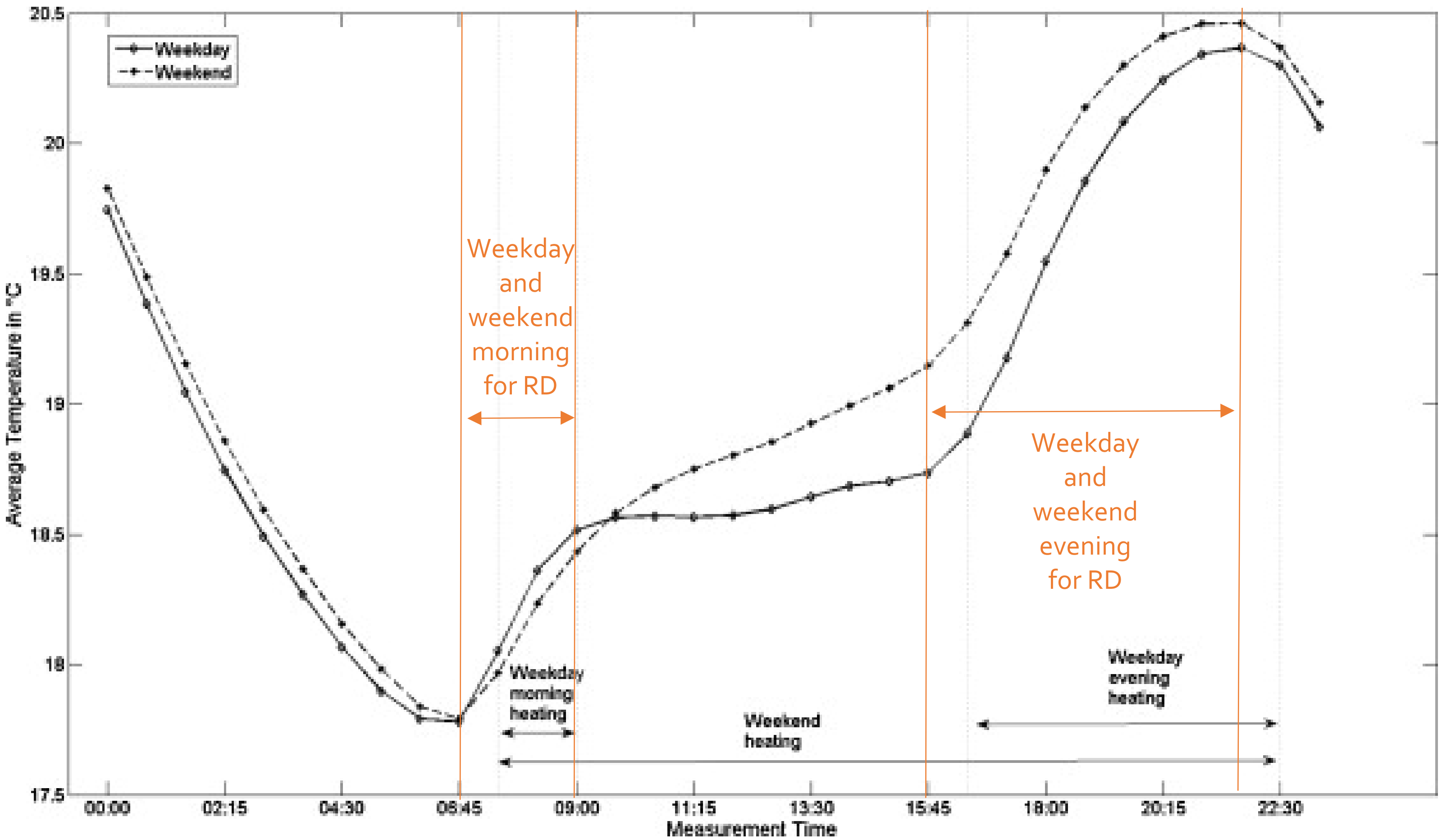
Recent empirical studies question the validity of both the BREDEM and DEAP data detailed in Table 27 finding:

- Standard assumptions of heating demand and heating duration do not reflect accurately, the heat consumption characteristics of dwellings in the UK and Ireland [34, 57, 174-176],
- A wide variety of heating patterns exist [57, 174-176],
- An average dwelling in England is heated for 8.4 hours/day, and detached dwellings, an average of 8.7 hrs per day [57],
- An average rest-of-home temperature of 17 °C [176] is usual in Irish dwellings.
- As shown in Figure 33 [175];
    - the average temperatures and heating duration of dwellings are generally independent of year of construction and day of the week,
    - living room temperatures are typically lower in the mornings than in the evenings,
    - living room temperatures of 21°C are rarely reached.

As shown in Table 27, Ireland's national DEAP methodology uses a standardised schedule that is independent of dwelling type representing a total heating period of 56 hours per week or 8 hrs/day of a 243-day heating season with no delineation between weekends and weekdays [176].

Statistically-average heating schedules and mean temperatures for an average year are required for a one-fits-all model of space heating consumption associated with detached dwellings. To mitigate savings taken back through increased comfort temperatures, an energy consumption model should ideally reflect empirical mean temperatures realised in the housing stock. To account for the longer running hours associated with detached housing specifically, the assumed demand temperatures and heating schedules for the RD are based on available empirical evidence as detailed in Table 27 and shown in Figure 35.

Figure 35 Average living room temperatures across all homes for weekdays (solid) and weekends (dashed). The dashed vertical lines indicate approximate heating times according to BREDEM [175] solid vertical lines indicate heating times assumed for RD.



4.2.2.3 Level of occupancy

Typical levels of occupancy for this case study dwelling by DEAP period of construction were published in [39] based national census statistics [71] for Ireland. The data was corrected in [39] to apply to DEAP periods of construction employed in this study as shown in Table 28.

Table 28 Level of occupancy in detached Irish dwellings by period of construction [39, 71]

		Total No. of Rural Detached House Constructed in that period	Total No. of Occupants	Average No. of Occupants	DEAP period of construction	Average No. of Occupants Corrected for DEAP Age Band
Period of Constr'n	before 1919	74,136	184,853	2.49	before 1900	2.49
	1919 to 1940	40,418	100,380	2.48	1900-1929	2.49
	1941-1960	36,488	94,018	2.58	1930-1949	2.53
	1961-1970	25,118	65,448	2.61	1950-1966	2.59
	1971-1980	65,554	199,210	3.04	1967-1977	2.88
	1981 -1990	60,593	216,589	3.57	1978-1982	3.25
	1991-1995	26,533	99,539	3.75	1983-1993	3.62
	1996-2000	46,844	169,906	3.63	1994-1999	3.67
	2001-2006	69,436	221,234	3.19	2000-2004	3.28
					2005-2006	3.19

As described in Section 4.2, the SyAv occupancies shown in Table 28 were subsequently weighted against the new thermal classifications established in Table 33 and Table 34 and are shown in summary result Table 37 in Section 4.3.

4.2.3 Form

4.2.3.1 Geometries

Statistically average dwelling geometries are established using realistic means found in the refined empirical database [76] using SPSS® software (see Appendix A for more detail). Dwellings geometries display typically, a normal distribution (see electronic media files submitted with this work). The thermal performance of single storey and two-storey dwellings with the same thermal characteristics will differ owing to a different volume-to-surface-area ratio. Single and two-storey geometries were therefore established. Typical geometries by period of construction are depicted in Figure 36 and described in Table 29. The development of geometric characteristics over time, listed in Table 29, is discussed in detail in Section 4.2.3

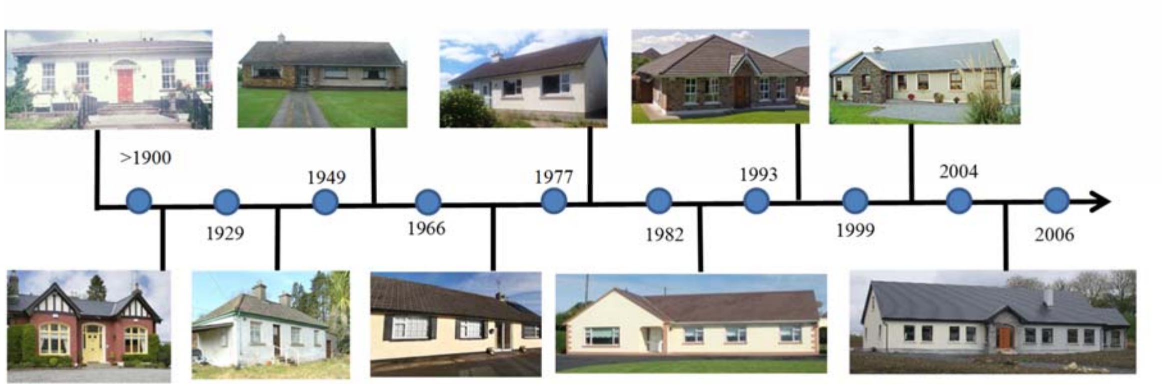
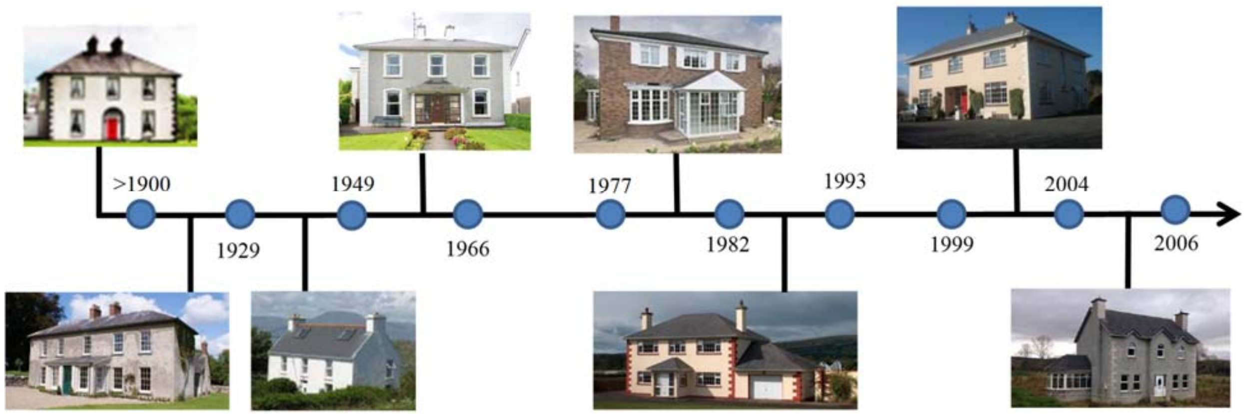
At a macroscopic level, detached Irish dwellings show a growth rate of 1.6 % and 1.34 % per annum in heated floor area for single and two-storey respectively, relative geometries have grown proportional to the increase floor area but have remained largely unchanged with time. The implications of rapidly growing floor areas are discussed in Section 4.5.

Referencing Table 29 the percentage of the façade occupied by windows[15], 'window ratio', at 13 % and 14 % in single storey and two storey dwellings respectively, was at its smallest in dwellings constructed pre-1900. At 26 % and 23 % in single storey and two-storey dwellings respectively, window ratios peaked in the late 1970's and early 1980's, dropping to 18 % in single storey dwellings and 20 % in two-storey dwellings by 2006.

Average geometries are calculated in Table 29 and depicted in Figure 36.

[15] applying to entire area of the window opening, including both frame and glazing

Figure 36 Timeline and average form of typical single and two-storey reference dwelling

Timeline of typical detached single-storey Irish dwelling	Average single-storey dwelling[16] (Ref: Average geometries listed in Table 28)
	 Window Ratio = 20 % Floor to ceiling height 2.56m
Timeline of typical detached two-storey Irish dwellings	**Average two-storey dwelling** **(Ref: Average geometries listed in Table 28)**
	 Window Ratio = 19 % Floor to ceiling height; GF = 2.53 m; FF = 2.12 m

[16] This geometry also pertains to a two-storey dwelling if attic converted to a habitable space applies when first floor height < 2.1 m – See Figure 35 (c)

Table 29 Characteristic form of reference dwellings by period of construction [176]

	Single-storey dwelling									Two-storey dwelling									
	Area (m^2)					Height (m)	%	(m^3)	Area/Vol.	Area (m^2)					Height (m)		%	(m^3)	Area/Vol.
Period of Construction	Wall	Roof	Floor	Window	Door	Ground floor height	Façade window Ratio	Volume	Compact-ness of building envelope	Wall	Roof	Floor	Window	Door	Ground floor height	First floor height	Façade window ratio	Volume	Compact-ness of building envelope
Pre 1900	104	95	94	14	2.87	2.60	13%	244	1.27	179	110	103	25	3.82	2.56	2.37	14%	508	0.83
1900-1929	100	94	94	14	2.89	2.57	14%	242	1.26	157	96	89	21	3.65	2.46	2.24	14%	418	0.88
1930-1949	100	96	96	15	3.2	2.60	15%	250	1.24	152	99	91	24	3.4	2.56	2.25	16%	438	0.84
1950-1966	102	103	102	19	3.2	2.62	18%	267	1.23	153	112	104	29	3.24	2.55	2.04	19%	477	0.84
1967-1977	101	121	121	25	3.2	2.53	25%	306	1.21	153	123	116	36	3.39	2.54	2.13	23%	542	0.80
1978-1982	102	127	128	26	3.25	2.53	26%	324	1.19	151	126	116	34	3.51	2.51	2.03	22%	527	0.82
1983-1993	102	126	126	24	3.19	2.52	24%	318	1.20	150	129	116	33	3.5	2.51	1.96	22%	519	0.83
1994-1999	104	127	127	24	3.42	2.52	23%	320	1.20	153	131	114	32	3.5	2.53	1.95	21%	511	0.85
2000-2004	110	139	137	25	3.65	2.54	23%	348	1.19	159	132	115	32	3.93	2.54	2.02	20%	524	0.84
2005-2006	153	150	149	27	3.74	2.57	18%	383	1.26	173	129	118	34	3.96	2.55	2.23	20%	564	0.81
Average	108	118	117	21	3.26	2.56	20%	300	1.23	158	119	108	30	3.59	2.53	2.12	19%	503	0.83

→ Cross-reference average single and two-storey dwelling models depicted in Figure 34

Peak window ratios

4.2.3.2 Validation of macroscopic dwelling form

In Chapter 2, the concept of coherence and comparability in terms of data validation is discussed. To achieve a high-level of validation, it is meaningful to test consistency and comparability across different statistical outputs (domains): in this case, the possibility to develop quality checks depends on the degree to which the different data collections make use of the same harmonised concepts (time-period classifications, definitions, etc.).

Referring to the average single and two-storey models shown in Figure 36 – it is seen that the aggregate geometries resulting, imitate closely real-world dwelling forms. They differ only in that they are a statistical composite of the features found within the case study dwelling typology.

Prior to the publication of the EPC dataset and in 2010, a study was carried out by Ahern *et. al* (2013) [70] wherein reference dwellings for this case study dwelling were characterised using the best data available at the time of study (2009). In the absence of an empirical database Ahern *et. al* employed data from the 2006 census collated by the Central Statistics Office (CSO) planning permission office, the smaller INSHQ dataset [138] described previously, as well as other data sources to inform the characterisation of the dwelling form.

An issue met by Ahern *et. al* was that the time-period classifications in DEAP differ from those quoted by the CSO, that also differ from those in the INSHQ dataset. Ahern *et. al* classified RDs by DEAP periods of construction so facilitating a comparison of data from different statistical providers.

4.2.3.2.1 Ground Floor areas

The CSO Planning Permission office holds data on floor areas from 1980 to the present day, however, it was only in 2001 that the CSO began to distinguish between 'all house types' and 'one-off' or detached type housing, prior to this all housing figures were grouped. Ahern *et. al* [70] reviewed available data in 2009 meaning, for detached housing particularly, there were 8 years of available data for ground floor areas [70]. Neither, the CSO or the INSHQ classified dwellings by number of storeys, however the INSHQ asked whether there was a staircase present in the home.

Ground floor areas were established by Ahern *et. al* [70] in the following manner:

1. By comparing the eight years of available data for the average floor-area of detached housing (2001 to 2009) to the average floor areas for 'all house types', the study established that detached housing was, on average, 28.45 % larger than the average of 'all house types'.
2. This size loading of 28.45 % was applied arbitrarily to average floor areas for 'all house types' available from 1980 to 2000.
3. The mean weighted average floor area by DEAP period of construction was hence calculated for houses constructed between 1980 and 2009.
4. For floor areas predating 1980, the research referred to the smaller INSHQ dataset that classified data into four time periods, pre-1940, 1941-1970, 1971 to 1990 and after 1990.
5. The mean weighted floor area for INSHQ age bands was established and then reclassified across DEAP age-bands.
6. The data was collated with the CSO data to estimate total floor areas.
7. Data from both the CSO and INSHQ was available from 1978 to 1999, it was thus possible compare data for this time period, establishing an acceptable 1.56 % difference.
8. To establish *ground* floor areas (as distinct from total floor area), it was necessary to establish whether the detached dwellings were single or two-storey. This data was not available from the CSO. The INSHQ asked respondents whether they had a staircase

present in the home; finding that 42 % of detached houses surveyed had a staircase whereas 58 % did not.

9. Using the weightings established in step 8, the average ground floor area for one (total floor area) and two-storey dwellings (total floor area divided by 2) were established.

In Figure 37, the ground floor areas calculated by the methodology outlined in Steps 1 to 9 are shown with the mean ground floor areas established from the EPC dataset. It can be seen that same data trends of increasing floor area with time are reflected in all datasets. However, the assumption made by Ahern *et. al*; that two-storey ground floor areas approximate the total floor area divided by 2, was inaccurate as the larger and more statistically significant EPC database suggests that ground floor areas for one and two-storey dwellings do not differ greatly. Referring to Figure 37, single and two-storey ground floor areas remained fairly static at circa 100 m^2 between dwellings constructed pre-1900 up and until the 1950s wherein ground floor areas began to grow. The vertical lines in Figure 37 represent DEAP periods of construction that are seen to correlate with step-growth-changes in ground floor areas. Referring to Figure 37, ground floor areas in:

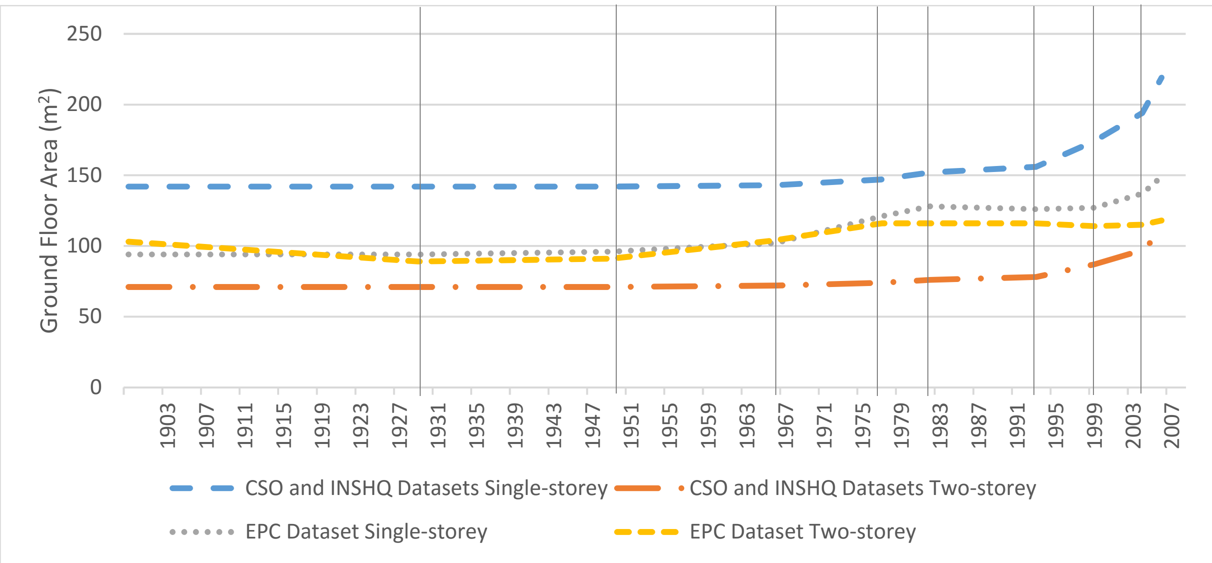
- Single storey dwellings grew from circa 100 m^2 in 1950 to circa 125 m^2 in 1982, followed by a relatively static growth period from 1983 to 1999 followed again by a period of growth from circa 125 m^2 in 2000 to 150m^2 in 2006.
- Two-storey dwellings grew from circa 90 m^2 in 1950 to circa 115 m^2 in 1976, followed by a relatively static growth period from 1977 to 2004 followed again by a slower period of growth from circa 115 m^2 in 2000 to 120 m^2 in 2006.

The data in the EPC dataset is considered more representative than the data characterised by Ahern *et. al* (2013) for the following reasons:

- Dwellings are classified by DEAP period of construction so no loss of accuracy resulted from the requirement to reclassify the data.
- Data for detached housing is available for all periods of classification from pre-1900 to 2006 with no requirement to infer data.

- Single and two-storey dwellings could be isolated in the dataset so broad percentages for single and two-storey dwellings as a percentage of the entire population were not applied.

Figure 37 Cross-domain comparison of mean ground floor areas (vertical lines represent DEAP periods of construction) [39, 76]



A different study on Irish housing carried out in 2001 [177] estimated the average ground floor area of a detached "Real Example Building" (*ReEx*) single-storey dwelling as being 130 m^2 and a two-storey as being 95 m^2, the larger EPC dataset suggests average single and two-storey ground floor areas to be 117 m^2 and 108 m^2 respectively.

4.2.3.2.2 Window Ratios

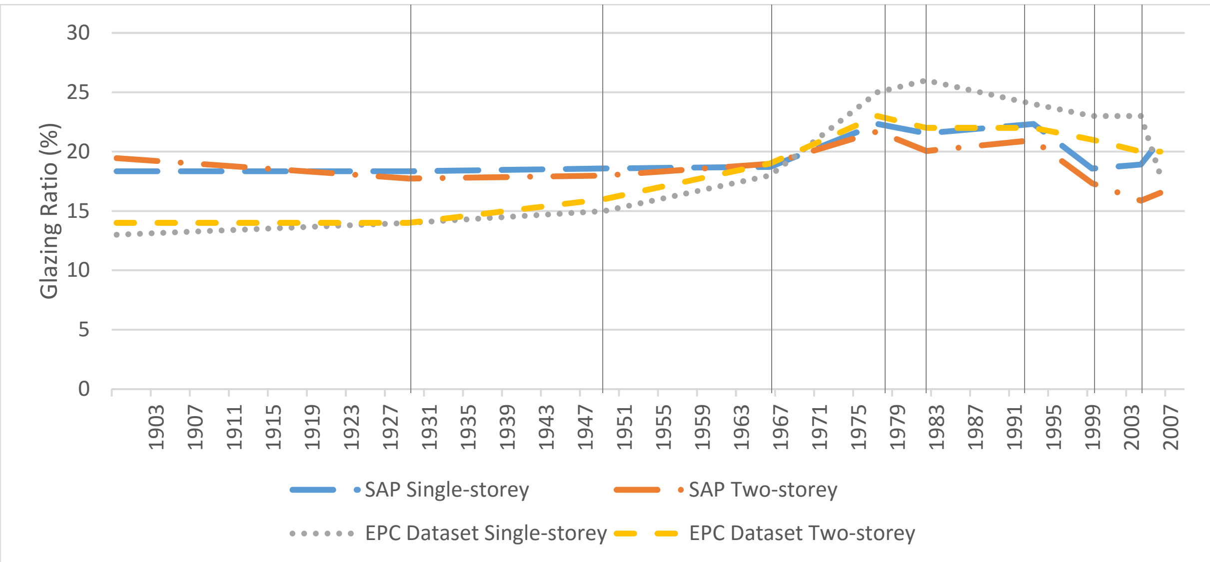
Prior to the publication of the EPC dataset no data for dwelling window ratios was available in Ireland. This issue was encountered by Ahern *et. al* [70] in the 2010 study. On the basis that vernacular architecture in the UK and Ireland were somewhat similar, Ahern *et. al* [70] characterised the reference dwellings using formulae contained in the UK EPC methodology (SAP) [178], listed in Appendix D. Figure 38 indicates that the average measured window ratios[17]

[17] applying to entire area of the window opening, including both frame and glazing

extrapolated from the EPC dataset correlates with standard formulae. The vertical lines in Figure 38 represent DEAP age bands that correlate with step-changes in window ratios. Window ratios for both single and two-storey dwellings are observed in Figure 38 to grow slowly from circa 13/14 % in dwellings constructed pre-1900 to circa 15/16 % in the 1950s. As was the case with ground floor areas, window ratios saw a rapid period of growth for both single and two-storey dwellings from circa 15/16 % in 1951 to 18/19 % in 1966. Referring to Figure 38:

- Single storey window ratios grew rapidly from circa 17 % in 1967 to a peak of 26 % in 1982, after this window ratios reduced to 23 % in 2004, reducing back to late-1960s levels of circa 17 % by 2006.
- Two-storey window ratios grew rapidly from circa 18 % in 1967 to a peak of 23 % in 1982, after this window ratios fell back to window ratios typical of the late-1960s levels of circa 20% in 2006

Figure 38 Synthetically average window ratios shown with window ratios arising for standard UK formulae (vertical lines represent DEAP period of construction) [76, 178]

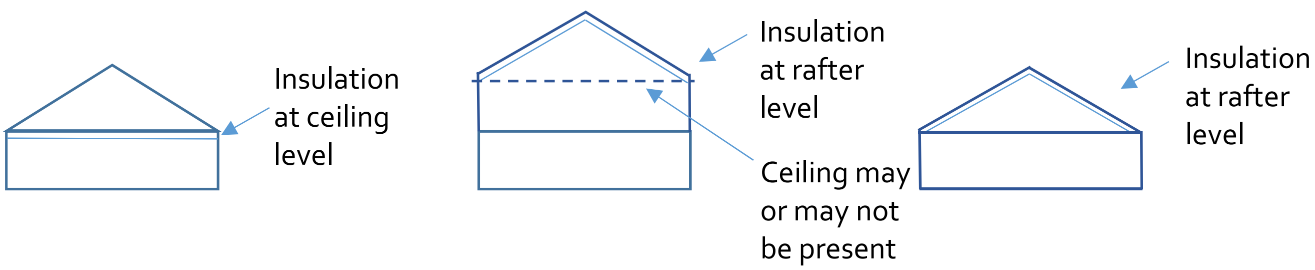


4.2.3.2.3 Roof area

Building energy assessors measure the roof 'at the thermal envelope' where the insulation is located. As shown in Figure 39 (a), a typical single storey Irish house with a pitched roof has insulation laid between (and possibly above) the ceiling joists, resulting in a flat 'roof' on the reference dwelling [179]. Figure 39 (b) and (c) depict two-storey dwellings. Figure 39 (c) depicts a single-storey dwelling where the attic is converted into a habitable space, recorded in DEAP as a separate storey. In two-storey dwellings and referring to Table 29, the roof area is larger than the floor area suggesting that the typical location of roof insulation in this dwelling type is in the rafters of the roof. The data relating to roofs in Table 29 behaves rationally and correlates with ground floor areas.

Figure 39 (a, b & c) Typical location of insulation in single and two-storey case study dwellings

(a) Single Storey **(b) Two-storey (Type 1)** **(c) Two-storey (Type 2)**



As shown in Figure 39 (b) and (c), to facilitate better the characterisation of the RD, it is recommended that two-storey dwellings be classified by type (1) or (2) in the EPC database.

4.2.3.2.3 Storey Height

A typical floor-to-ceiling storey height suggested in the Irish building regulations is 2.4 m [126]. The EPC dataset suggests;

- single-storey heights range from 2.52 m to 2.62 m with an average of 2.56 m.

- two- storey, ground floor heights range from 2.51 m to2.56 m with an average of 2.53 m, while first-floor storey heights range of 1.95 m to 2.37 m with an average of 2.12 m.

Where first floor ceiling heights are 2.1 m and below, it is assumed that the construction characteristic of the dwelling is in line with Figure 39 (c).

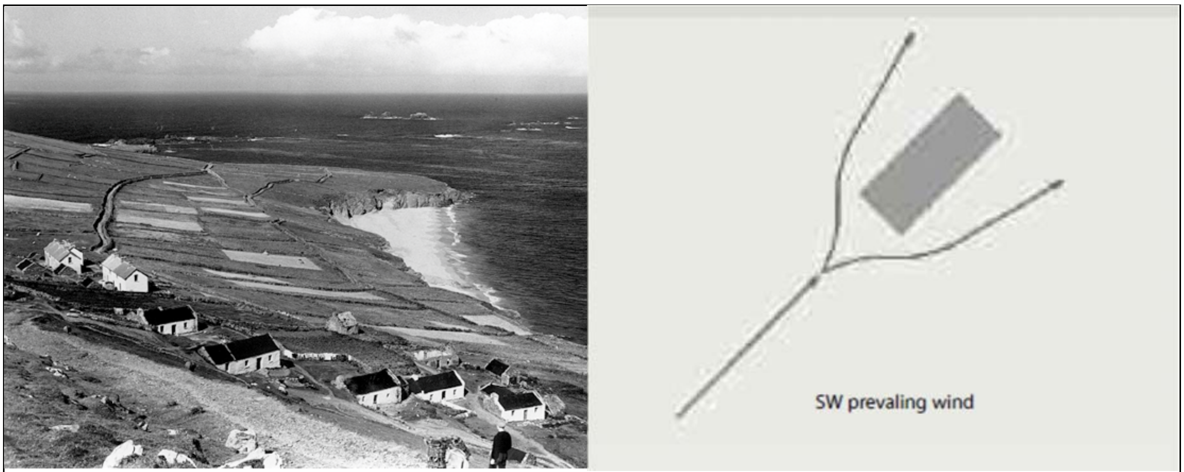
Irrespective of whether the construction form is of Type (a), (b) or (c), the geometric characteristics listed in Table 29 are scientifically correct and thus suitable as inputs to an energy consumption model.

4.2.3.3 Orientation and shares of windows with no direct solar access and wind conditions

In Ireland, about 40 % of the annual solar radiation is direct and 60 % diffuse [135]. In addition to photovoltaic electricity generation, the sun's energy can be used effectively, to passively (through glazing), and actively (through solar-thermal technologies), heat a dwelling whilst adding daylight. During the heating season, while heat can be gained from the sun, heat transfer through the building fabric and infiltration may lose more than is gained, particularly for glazing. Dynamic thermal modelling of an RD requires knowledge of the orientation of the dwelling and the shares of windows with and without solar access. Consequently, the common reporting mechanism for reference dwelling characteristics detailed within EU commission delegated regulation 244/2012 [55] requires percentage of windows with no direct solar access to be reported.

Ireland is an exposed island on the edge of the Atlantic Ocean with both high maximum and average wind speeds compared to most other European countries. Wind conditions across the island vary with pronounced differences on the coasts, on high ground and from the east to the west of the country. When wind speed across the external envelope of a building increases, the rate of heat transfer from the buildings surfaces also increases. Wind also affects heat gains or losses by infiltration due to increased pressure through openings in the building fabric. As shown in Figure 40, the benefits of shelter from wind has been traditionally well-understood [135], with dwellings often situated in the lee of a hill but avoiding hollows prone to frost [135]. Where natural features did not provide sufficient protection, shelter belts of trees were often planted [135].

Figure 40 Example of traditional orientation of dwellings in Ireland [135]



Vernacular Irish dwellings on Great Blasket Island situated in the lee of a hill with gables facing south westerly prevailing wind

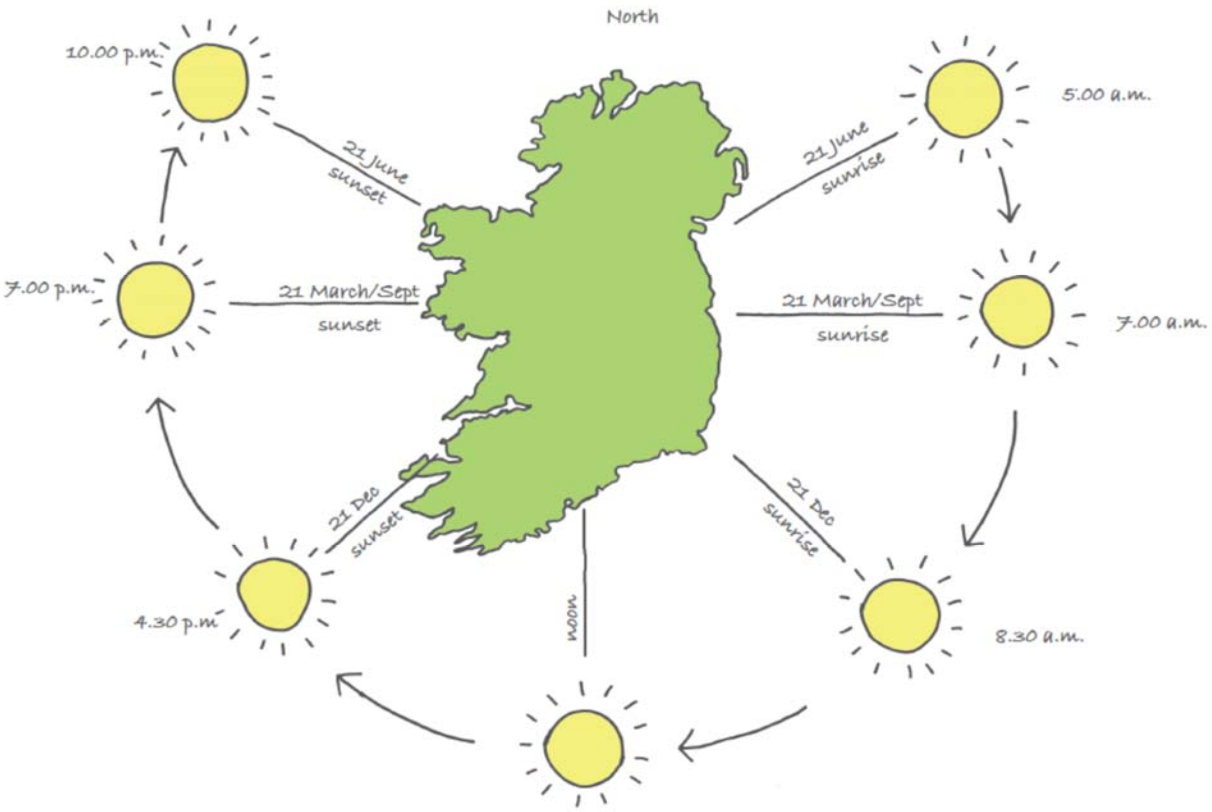
As shown in Figure 41, dwellings constructed more recently in rural Ireland typically parallel road frontage. This means that it is difficult to determine readily, a typical orientation representative of the dwelling stock.

Figure 41 Typical aerial photograph of rural Ireland [180]

4.2.3.3.1 Method of determining orientation and share of windows with no direct solar access

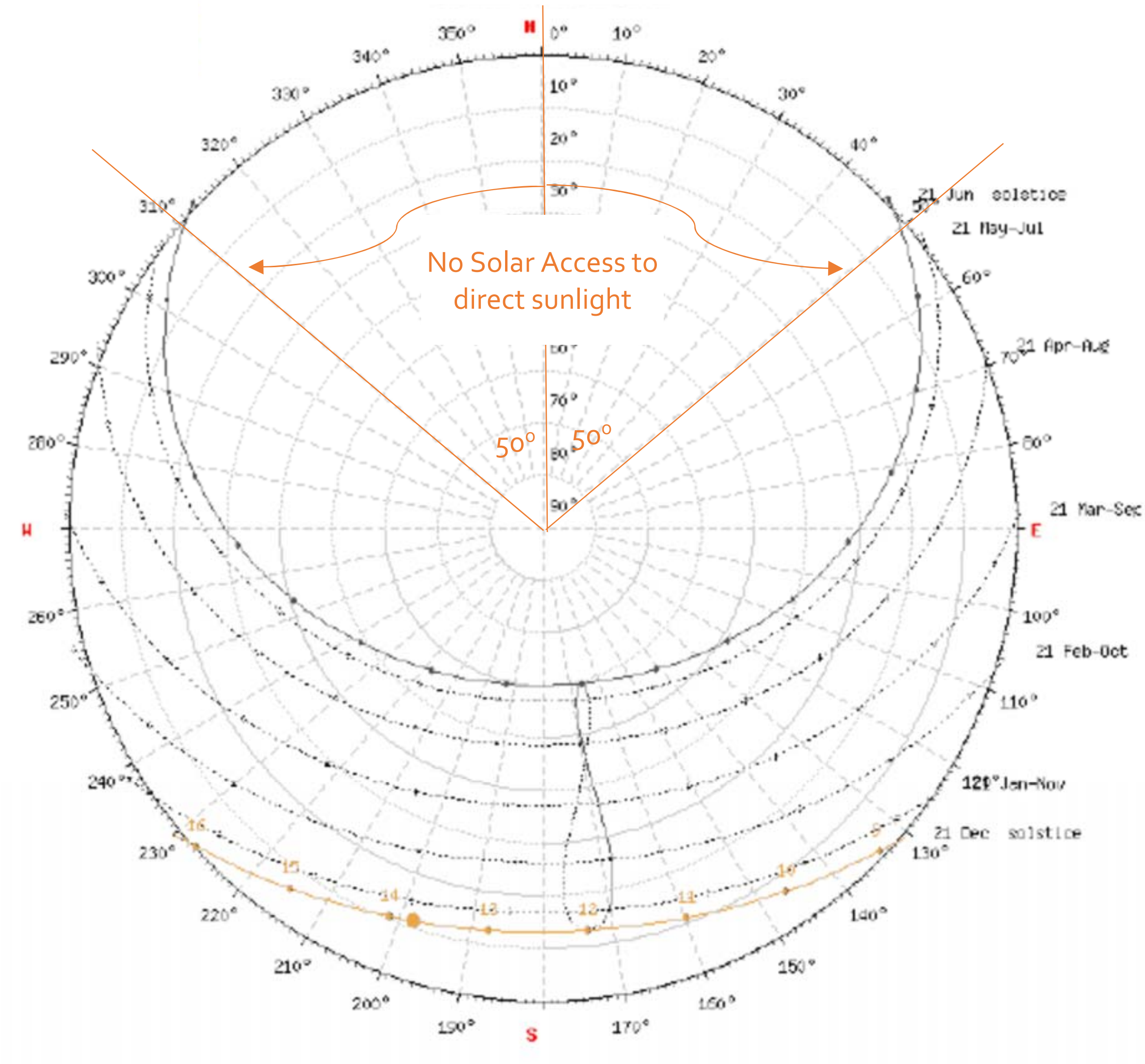
Solar access is the ability of a building to receive direct sunlight without obstruction from other buildings or impediments, not including trees [181]. A sun path diagram, for a particular location, indicates the position of the sun in the sky at any point in time, during the day and throughout the year and is used to determine solar access. Figure 42 shows a simplified sun-path diagram indicating approximate sunrise and sunset times in Ireland for different times of the year. Solar radiation is available in Ireland from approximately 5 am to 10 pm on the longest day of the year and from 8:30 am to 4:30 pm on the shortest day of the year.

Figure 42 Approximate sunrise and sunset times in Ireland for different times of the year [182]



As detailed in Section 4.2.1.1 Mullingar is chosen as the reference weather location for the reference dwellings. Figure 41 shows the detailed sun-path diagram for Mullingar (Latitude 53.53°N, Longitude -7.34 °W) sourced from [183]. Referring to Figure 43, no direct solar access exists circa 50° east and west of north.

Figure 43 Sun-path diagram for Mullingar, Co. Westmeath, Ireland (Latitude 53.53°N, Longitude -7.34 °W)



As stated, it is not possible, to determine readily, a typical orientation representative of a dwelling stock. The method for establishing percentage façade window area, applying to entire area of the window opening, including both frame and glass, with no solar access is shown in Figures 45 and 46 and as described below:

a) SyAv geometries established in section 4.2.3 and shown in Figures 44 (a) for single and Figure 44 (b) for two-storey dwellings were oriented (distributed) uniformly through the cardinal axes (N-S), (NE-SW), (E-W), and (NW-SE).

   Assuming no solar access 50° east and west of north and at each of the orientations the % of windows with no solar access was estimated as shown in Table 30.

Figure 44 (a & b) Synthetically Average (SyAv) single and two-storey dwelling forms

(a) single-storey or two-storey with attic conversion (type 2)	**(b) two-storey dwelling form (type 1)**
	
6 Windows; each 16.66 % of total window area % share of windows long wall = 33.32 % share of windows short wall = 16.66	18 Windows; each 5.5 % of total window area % share of windows long wall = 28 % share of windows short wall = 22

Figure 45 Method for establishing percentage of windows with no solar access for single storey and two-storey dwelling type 2

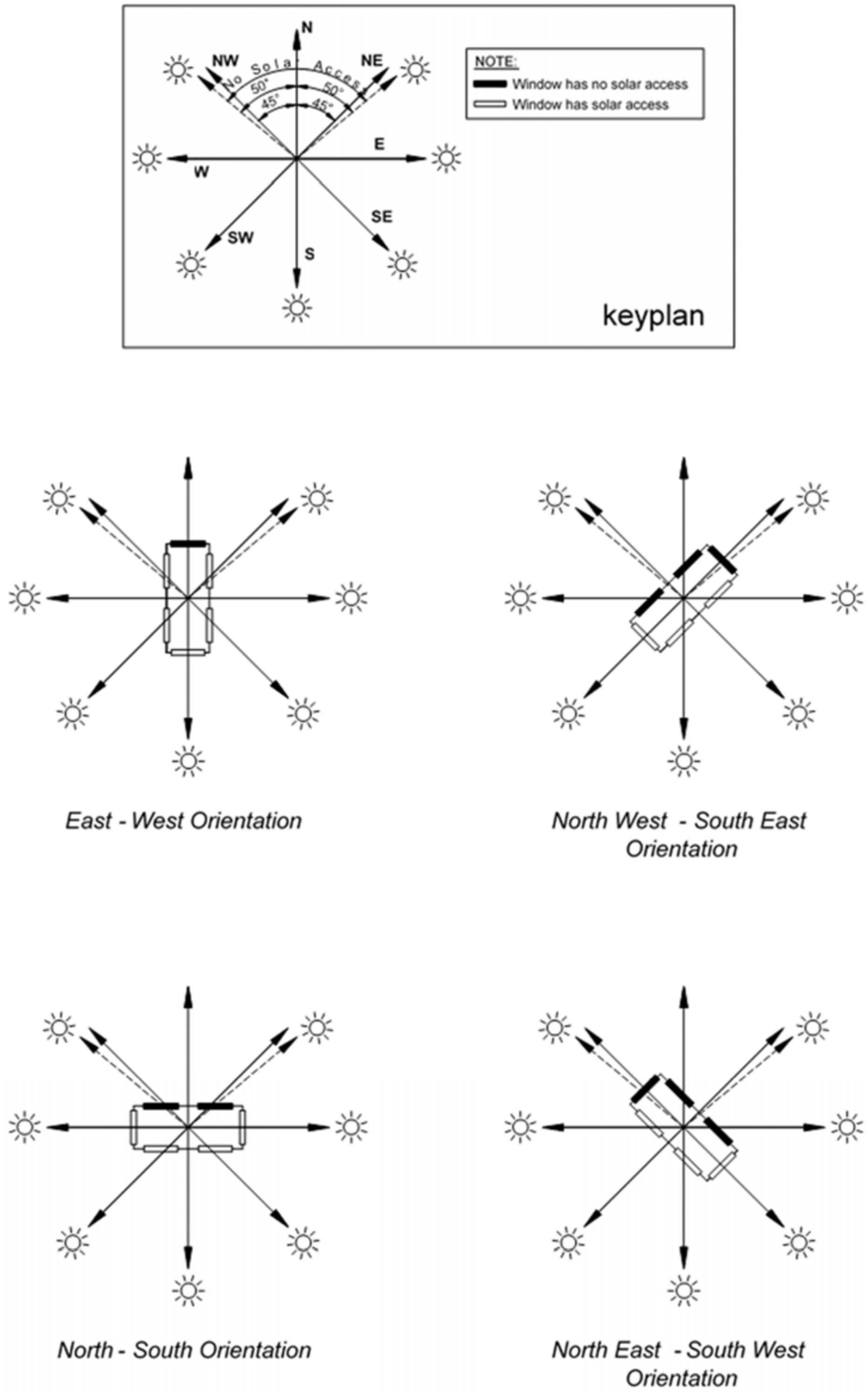


Figure 46 Method for establishing percentage of windows with no solar access two-storey dwelling type 1

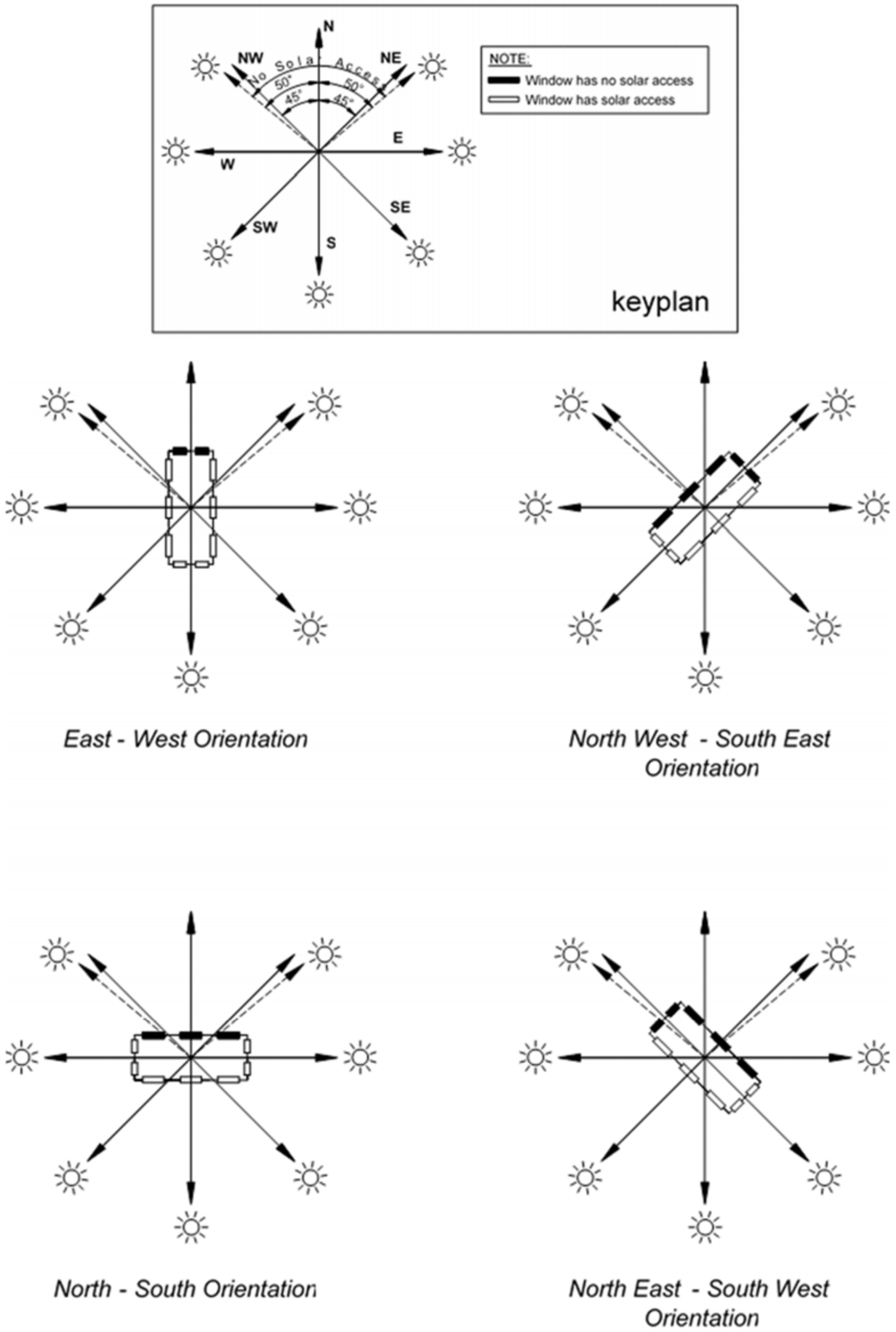


Table 30 Percentage share of windows with no solar access in detached Irish dwellings

		Quantity (N)	Single-storey & Two Storey (type 2)	Two-storey (type 1)
Orientation of long side of dwelling (Perimeter dimension 'x' Table 29)	N-S	(Quantity of reference dwelling by category)/4	17 %	22 %
	NE-SW		50 %	50 %
	E-W		33 %	28 %
	SE-NW		50 %	50 %

Referring to Table 30 and benefiting this characterisation there is no substantive difference in the share of windows with no solar access for single storey and two-storey dwellings Type 2 and two-storey dwellings Type 1 (reference Figure 39).

Recourse to the literature was made to correlate the validity of the assumptions made in this analysis. A study carried out in 2014 [184], in respect of 36 local authority urban housing schemes in Ireland, comprising 10,449 housing units, found the percentage orientations to be 29 %, 27 %, 23 % and 21 % north, south, west and east facing respectively. The results of that study suggest that houses developed traditionally, without solar orientation as a key design criterion, distribute reasonably uniformly. This approach will require further investigation with the objective of refinement in future research.

4.2.4 Envelope

4.2.4.1 Typical thermal transmittance coefficients by period of construction

As detailed in Chapter 2, Section 2.4, exposed dwelling elements U-values for walls and roofs such as walls, floors and windows, display generally bi-modal Normal distributions.

Statistical means for Mode (1) and Mode (2) dwellings, 'Mean 1' and 'Mean 2', for window, floor, roof and wall U-values were established by the maximum likelihood estimation method outlined in Section 3.2.2 and summarised in Table 21. The data in Table 21 is collated with the percentage of the actual dwelling stock nationally [71, 131] and is presented graphically in Figures 47 and 48 for single and two-storey dwellings respectively.

Current base-thermal-default U-values for floors, roofs and walls for single and two-storey dwellings shown in Figures 47 and 48 allow comparison with mean empirical values.

Window U-values are easily identified, base-thermal-default U-values for windows are thus not listed in Figures 47 and 48. Double-glazing typically has an averaged U-value of 3.1 W/m^2K and single glazing an averaged U-value of 4.8 W/m^2K [70, 76]. Large scale retrofitting of double glazed windows in detached dwellings over time is evidenced by the average U-value for a single and two-storey dwelling being 2.95 W/m^2K and 2.91 W/m^2K respectively. U-values for windows in existing dwellings are therefore no longer associated with dwelling age. Table S9 DEAP [72] quotes thermal-default window characteristics relating to double-glazed window U-values for wood/PVC framed windows as summarised Table 31.

Table 31 Thermal-default U-value characteristics of wood/PVC framed double-glazed windows

Low E coating	U-value (W/m²K)	Solar transmittance g-value	Comment
No	3.1	0.76	Air-filled 6 mm gap
Yes	2.2	0.72	Air-filled low E hard coat εn=0.15 12 mm gap

DEAP states that if the assessor cannot determine whether double glazing is low emissivity (εn) or not, it can be assumed that double glazing installed before 2004 is not low emissivity [72] .

The average U-values approximate the default U-value of 3.1 W/m²K suggesting that the majority of installed double-glazing is air-filled with a 6 mm gap with an associated solar transmittance "g-value" of 0.76. This g-value is adopted for the reference dwelling shown in summary result Table 38, Section 4.3

Figure 47 Mean (1) and (2) and default U-values for single-storey detached dwellings proportional to dwelling quantities by period of construction (see Table 21 for base data)

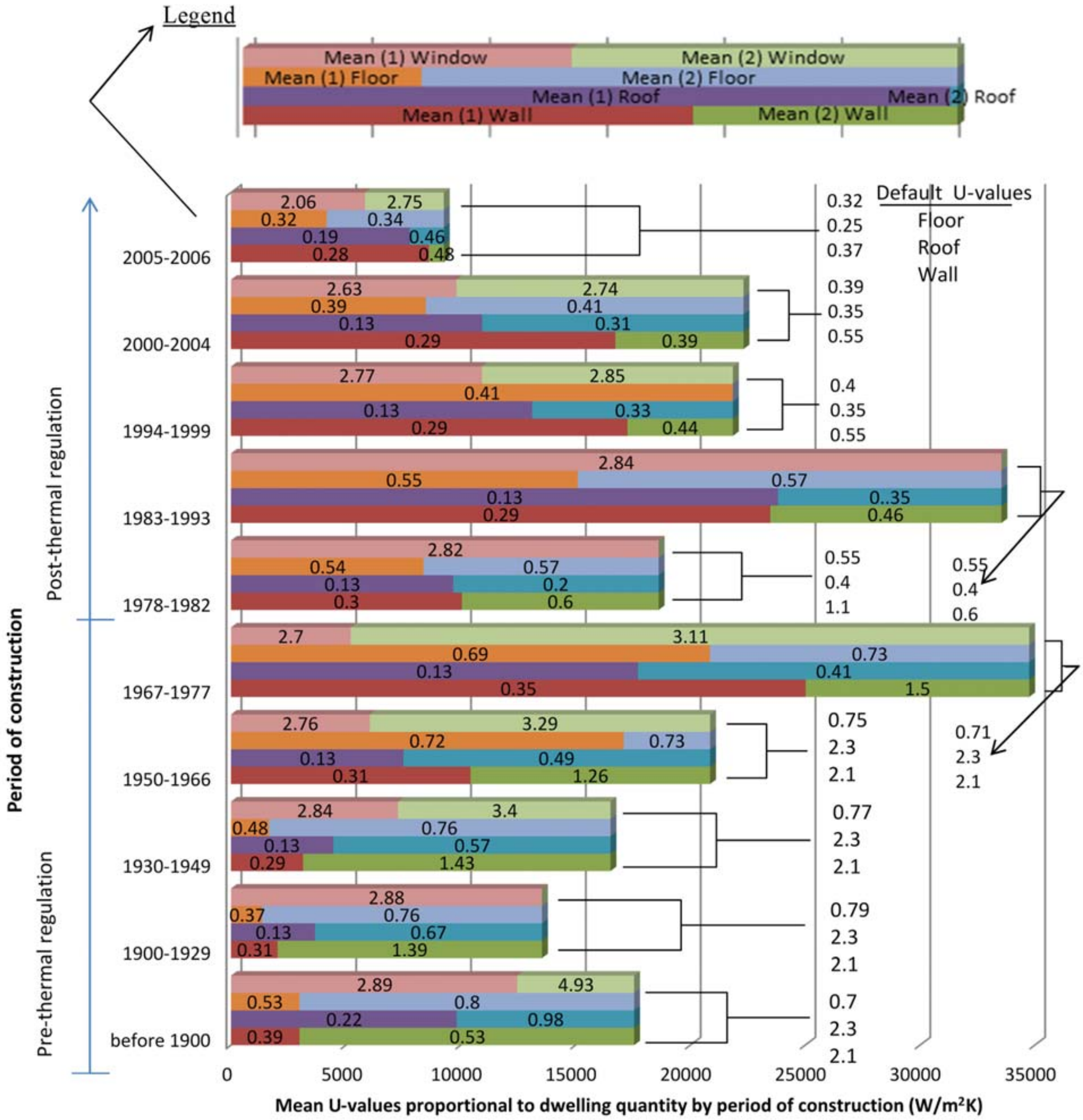
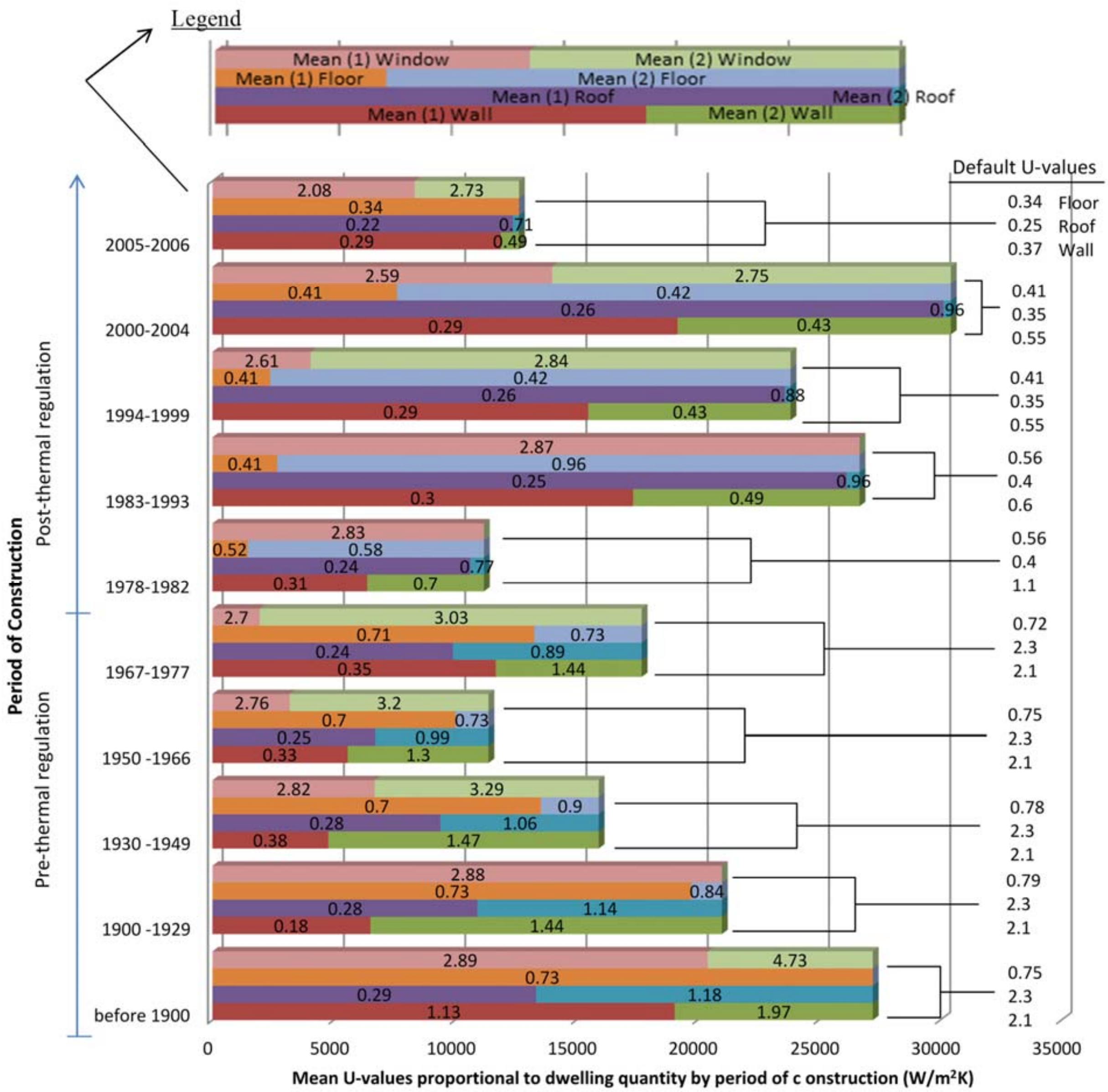


Figure 48 Mean (1) and (2) and default U-values for two-storey detached dwellings proportional to dwelling quantities by period of construction (see Table 21 for base data)



Each characterisation by period of construction (shown horizontally in Figures 47 and 48) is subcategorised vertically by common thermal characteristics, as described by Figure 49, to establish the thermal envelope characteristics for the RDs.

A minimum of 4 to a maximum of 5 categorisations per age category, [(a) to (d) or (e)], as shown in Figure 49, was required to accurately reflect the reference sample dataset by period of construction. This analysis resulted in a grouping of 45 single and 45 two-storey dwellings by period of construction as shown in Tables 32 and 33 respectively. Commonality in the thermal characterisations of dwellings is observed across traditional construction periods due to thermal retrofits.

Referencing Table 32 and 33:

- Observations of commonality were grouped manually, listed under the column 'category', these classifications were given a common number and colour;
    - 1S, x for single storey dwellings where x varies between 1 and 21, and
    - 2S, x for two-storey dwellings were x varies between 1 and 14.
- The appropriateness of these classifications were confirmed with the use of radial graphs shown in Tables 32 and 33. Each radial graph is denoted with the number in the 'category' column. For instance single-storey category 3 is denoted "Category 1S, 3" and two-storey category 9 is denoted "Category 2S, 9" and so on. Please note, singular or unique classifications are not depicted in radial graph format as no commonality and thus necessity to confirm classification existed.
- In this manner, thermal categorisations resulting from the statistical methodology were reduced from 45 to 21 for single-storey dwellings and from 45 to 14 two-storey dwellings.

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Figure 49 Segmentation of synthetically averaged bi-modal exposed thermal characteristics for dwelling elements by period of construction

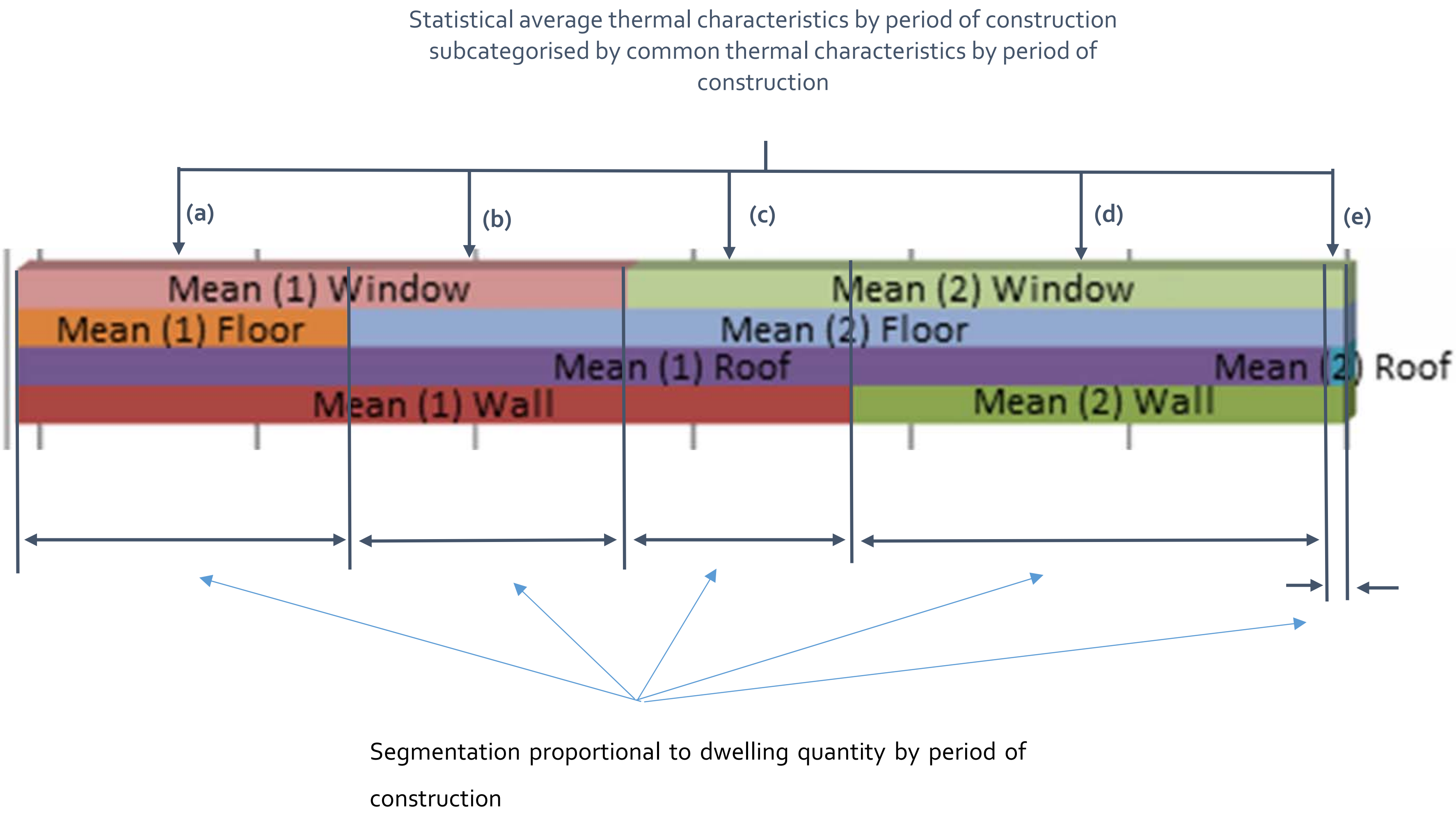


Table 32 Commonality analysis of statistical means across period of construction for single –storey (1S) dwellings – 45 No.

Period of Construction			Category 1S,x	Quantity		U-Value Window	Floor	Roof	Wall
Period of Construction	Post-thermal regulation	2005-2006	1	9268	4171	2.06	0.32	0.19	0.28
			1		1668	2.06	0.34	0.19	0.28
			2		1946	2.75	0.34	0.19	0.28
			3		834	2.75	0.34	0.46	0.28
			4		649	2.75	0.34	0.46	0.48
		2000-2004	2	22319	8481	2.63	0.39	0.13	0.29
			2		1339	2.63	0.41	0.13	0.29
			2		1116	2.74	0.41	0.13	0.29
			3		5803	2.74	0.41	0.31	0.29
			4		5580	2.74	0.41	0.31	0.39
		1994-1999	2	21856	10928	2.77	0.41	0.13	0.29
			2		2456	2.85	0.41	0.13	0.29
			3		3882	2.85	0.41	0.33	0.29
			4		4590	2.85	0.41	0.33	0.44
		1983-1993	5	33550	15098	2.84	0.55	0.13	0.29
			5		8387	2.84	0.57	0.13	0.29
			6		335	2.84	0.57	0.13	0.46
			7		9730	2.84	0.57	0.35	0.46
		1978-1982	5	18622	8380	2.82	0.54	0.13	0.3
			5		1304	2.82	0.57	0.13	0.3
			5		373	2.82	0.57	0.2	0.3
			8		8566	2.82	0.57	0.2	0.6
	Post-thermal regulation	1967-1977	9	34759	5214	2.7	0.69	0.13	0.35
			10		12513	3.11	0.69	0.13	0.35
			11		3128	3.11	0.69	0.41	0.35
			11		4171	3.11	0.73	0.41	0.35
			12		9733	3.11	0.73	0.41	1.5
		1950-1966	9	20862	6050	2.76	0.72	0.13	0.31
			10		1460	3.29	0.72	0.13	0.31
			11		2920	3.29	0.72	0.49	0.31
			12		6676	3.29	0.72	0.49	1.26
			12		3755	3.29	0.73	0.49	1.26
		1930-1949	13	16526	1653	2.84	0.48	0.13	0.29
			14		1487	2.84	0.76	0.13	0.29
			15		1322	2.84	0.76	0.13	1.43
			16		2809	2.84	0.76	0.57	1.43
			17		9255	3.4	0.76	0.57	1.43
		1900-1929	13	13544	1354	2.88	0.37	0.13	0.31
			14		678	2.88	0.76	0.13	0.29
			15		1625	2.88	0.76	0.13	1.39
			16		9887	2.88	0.76	0.67	1.39
		Before 1900	18	17555	2984	2.89	0.53	0.22	0.39
			19		6847	2.89	0.8	0.22	0.53
			20		2633	2.89	0.8	0.98	0.53
			21		5091	4.93	0.8	0.98	0.53
			Total	208861	208861				

Radial Diagrams of Categorisations

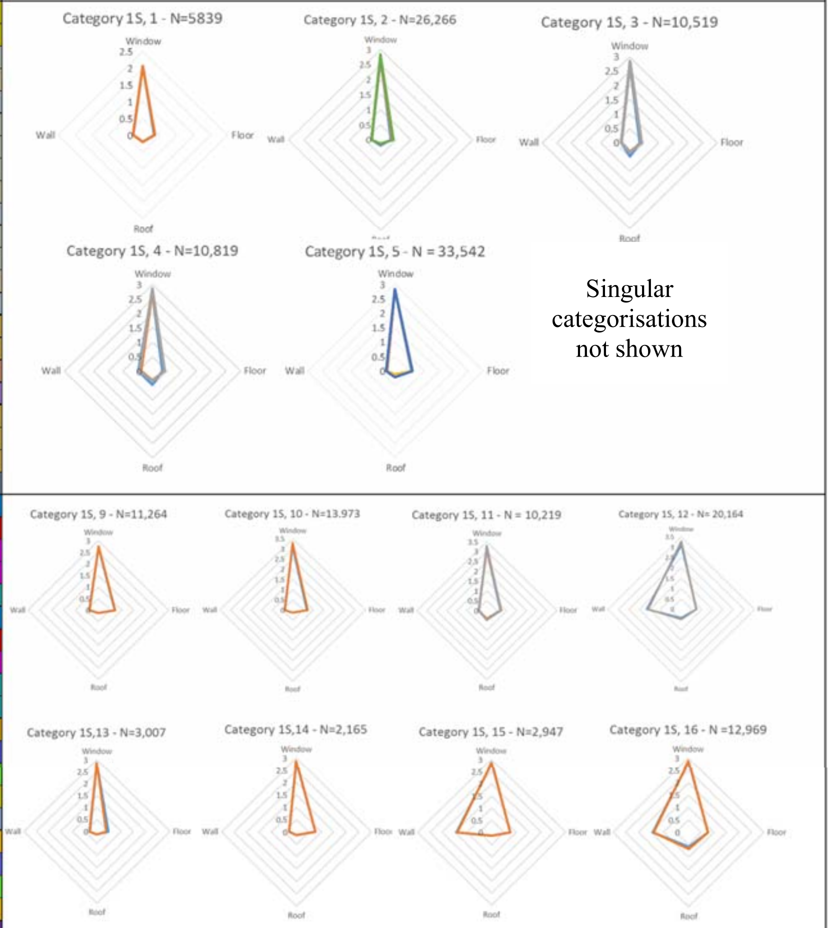
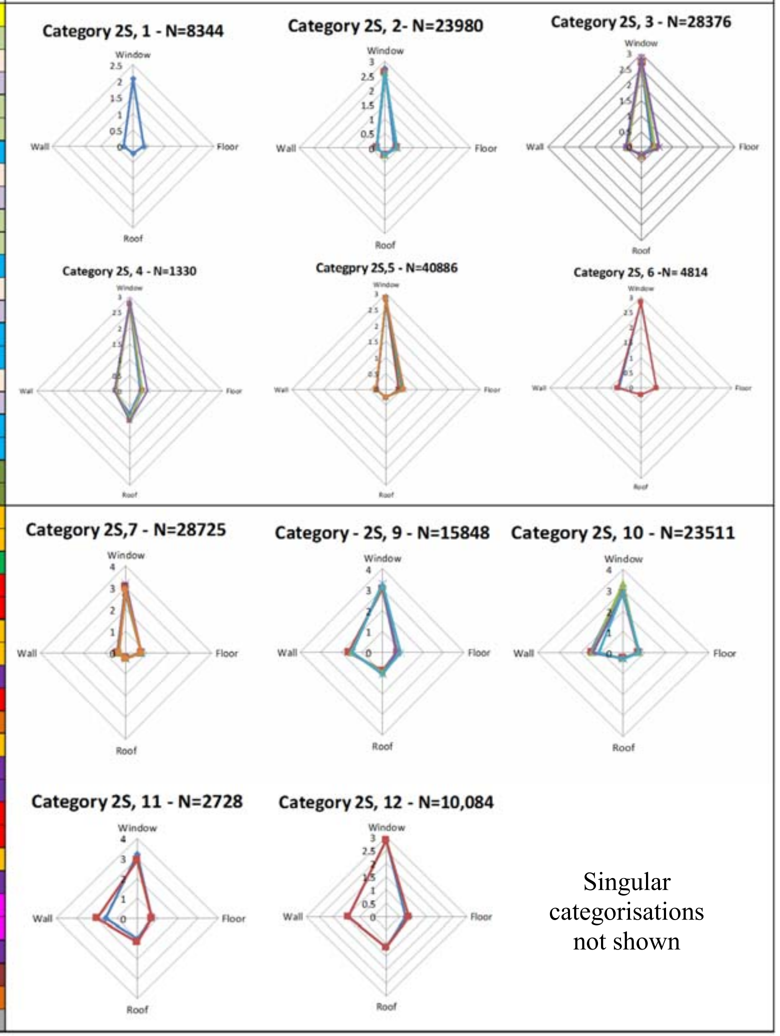


Table 33 Commonality analysis of statistical means across period of construction for two-storey (2S) dwellings – 45 No.

		Category 2S,x	Quantity		U-Value Window	Floor	Roof	Wall
Post-thermal regulation	2005-2006	1	12642	8344	2.08	0.34	0.22	0.29
		2		3539	2.73	0.34	0.22	0.29
		3		506	2.73	0.34	0.22	0.49
		4		253	2.73	0.34	0.71	0.49
	2000-2004	2	30455	7611	2.59	0.41	0.26	0.29
		2		6394	2.59	0.42	0.26	0.29
		5		5185	2.75	0.42	0.26	0.29
		3		10961	2.75	0.42	0.26	0.43
		4		304	2.75	0.42	0.96	0.43
	1994-1999	2	23838	2384	2.61	0.41	0.26	0.29
		2		1668	2.61	0.42	0.26	0.29
		5		11443	2.84	0.42	0.26	0.29
		3		8105	2.84	0.42	0.26	0.43
		4		238	2.84	0.42	0.88	0.43
	1983-1993	5	26683	2668	2.87	0.49	0.25	0.3
		5		14676	2.87	0.58	0.25	0.3
		3		8805	2.87	0.58	0.25	0.49
		4		534	2.87	0.58	0.96	0.49
	1978-1982	5	11195	1455	2.83	0.52	0.24	0.31
		5		4926	2.83	0.58	0.24	0.31
		6		4254	2.83	0.52	0.24	0.7
		6		560	2.83	0.52	0.24	0.77
Post-thermal regulation	1967-1977	7	17698	1947	2.7	0.71	0.24	0.37
		7		7964	3.03	0.71	0.24	0.37
		8		1770	3.03	0.71	0.89	0.37
		9		1592	3.03	0.71	0.89	1.44
		9		4425	3.03	0.73	0.89	1.44
	1950-1966	7	11382	3187	2.76	0.7	0.25	0.33
		7		2390	3.2	0.7	0.25	0.33
		10		1138	3.2	0.7	0.25	1.3
		9		3301	3.2	0.7	0.99	1.3
		11		1366	3.2	0.73	0.99	1.3
	1930-1949	7	15927	4778	2.82	0.7	0.28	0.38
		10		1913	2.82	0.7	0.28	1.47
		10		2706	3.29	0.7	0.28	1.47
		9		4141	3.29	0.7	1.06	1.47
		9		2389	3.29	0.9	1.06	1.47
	1900-1929	7	21008	6512	2.88	0.73	0.28	0.31
		10		4412	2.88	0.73	0.28	1.42
		12		8824	2.88	0.73	1.14	1.42
		12		1260	2.88	0.84	1.14	1.42
	Before 1900	10	27229	13342	2.89	0.73	0.29	1.13
		13		5718	2.89	0.73	1.18	1.13
		11		1362	2.89	0.73	1.18	1.97
		14		6807	4.73	0.73	1.18	1.97
		Total	198057	198057				

Radial Diagrams of Categorisations



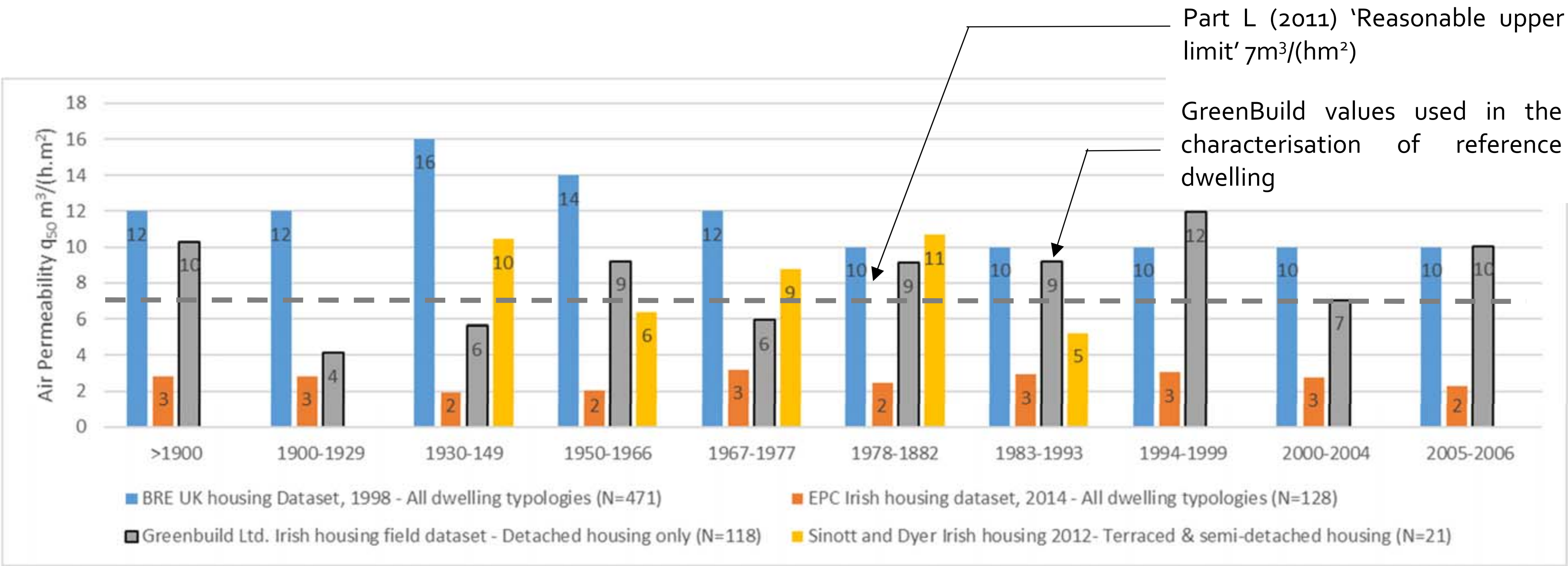
4.2.4.2 Air Tightness

Air permeability, expressed in cubic metres per hour per square metre of envelope area (m^3/hm^2) at 50 Pa pressure difference (q50), characterises air-tightness of the building fabric within Irish building regulations.

The Irish national EPC database contains data from dwellings having completed a pressurisation air-tightness test i.e. permeability test. The test is completed by installing a fan in the principal entrance doorway, sealing all fans, flues, chimneys, vents etc. and determining the airflow rate required to maintain a pressure of 50 Pa above outdoor air pressure. To give an estimate of the air change rate per hour at typical pressure differences under real operating conditions (ACH_{20}) the air permeability test result (q50) is divided by 20 for use in the DEAP software and this is how it is presented in the EPC database [76]and Figure 50.

With N=50,236, insufficient pressurisation data was returned from the refined dataset, an analysis was thus carried out on the larger dataset with N= 239,906, described in Appendix A, wherein all types of rural dwellings (detached, semi-detached, etc.) were examined. This returned data for only 128 dwellings or 0.05 % of the sample-set. The highest figure returned by the empirical dataset of 0.15 (ACH_{20}) suggests a permeability rate of 3.05 $m^3/(hm^2)$ at 50Pa. As shown in Figure 50, the reasonable upper limit of dwelling air permeability prescribed in the 2011 building regulations is 7 $m^3/(hm^2)$. At 3.05 $m^3/(hm^2)$ at 50Pa or less, permeability rates returned by the EPC dataset are much lower than expected. From an examination of the dataset, it was found that, in general, dwellings in which an air permeability test was carried out, typically had other measures installed that reduced the calculated overall energy consumption to below average. This indicates that end-users motivated to test for air tightness already had air-tight low-energy dwellings [185]. The infiltration rates returned by the empirical dataset were thus considered unrepresentative of the overall dwelling typology.

Figure 50 Comparison of air permeability datasets [70, 76, 186-188]



There is a paucity of published data relating to the real air-tightness charateristics of existing dwellings in UK and Ireland [187, 189]. A statistically small (28 dwellings) recent database for air tightness of Irish housing [187] focused on single-family residential semi-detached and terraced houses; 21 of which relate to pre-2006[18] dwellings. Only two large scale (>200) databases for air infiltration rates in pre-2006 UK dwellings are known, one held by British Gas covering 217 dwellings [190] and the other held by the BRE covering 471 dwellings [186]. The lack of data relating to air-tightness in Irish dwellings was encountered by Ahern *et. al* (2013) [70] when creating archetypal dwellings for detached dwellings in Ireland in 2010 who found:

- Published data from the British Gas database, while limited in detail, to correlate with BRE data [186].
- Most dwellings in the BRE air leakage database, as in the UK generally, are of semi-detached, terraced and apartment type construction.
- It was not possible to isolate typical infiltration rates for detached housing from the databases.

Assuming little difference between Irish and UK housing construction, Ahern *et. al.* (2013) [70] extrapolated the results from the cumulative distributions of 50 Pascal air change rates (ACH_{50}) for the 471 dwellings on the BRE database and reconfigured the data across DEAP age bands as shown in Figure 50. The infiltration rate of BRE tested homes was found to lie between 10 and 16 air changes per hour at 50 Pa pressure difference (ACH_{50}), the average of the BRE sample of dwellings was 14.8 ACH_{50} [191]. The BRE database suggests that the degree of air tightness of UK, and by assumption Irish Dwellings is low [70]. Using ACR_{50} divisors for one and two storey dwellings of 20.6 and 17 (Table 4.21 of CIBSE Guide A) [124] the air permeability of the existing detached Irish housing stock by period of construction was estimated [70] as shown in Figure 50.

GreenBuild Energy Rating and Building Information Services Ltd. have been carrying out air-tightness testing in Ireland since mid-2007, they have amassed air-tightness test data [188] relating to 187 Irish dwellings. GreenBuild issued this database to the author in June 2017 who

[18] Note: Case study RD classifications for dwelling constructed pre-1900 until 2006

isolated 118 (63 % of sample set) detached dwellings from the larger dataset. The dataset contains information on refurbished as well as as-built dwellings. It is noted that air-tightness results for the same dwelling typology constructed within the same period of construction are;

- varing widely, even for dwellings with similar construction characteristics,
- not necessarily lower for refurbished dwellings than for as-built dwellings,
- not related to wall-construction type (solid concrete, cavity block etc.),
- slightly better for post-thermal regulation dwelling than pre-thermal regulation dwellings.

The sample sizes by period of construction are statistically insignificant ranging from a minimum of six constructed between 2005 and 2006 to a maximum 25 between 2000 and 2004. Where the sample sizes are small, the addition of more data could change the average air-permeability rate by period of construction substantially. Moreover, it is often difficult for the assessor to ascertain the exact age of the dwelling. Dwellings are often classified as '1970s'. A dwelling classified as having been constructed in the 1970s could have been constructed pre-1977 or post-1978 thus changing its age classification. Notwithstanding, the GreenBuild dataset;

- is the largest dataset available for Irish housing in general and detached housing particularly,
- is shown in Figure 50 to compare reasonably well with the large BRE dataset.

It is considered therefore, to be the authoritative data-source on the air-permeability rates of detached housing in Ireland and is employed in the characterisation of the case study reference dwellings. The average rates established from the GreenBuild dataset were weighted against the thermal characterisations established in Section 4.2.4.1 and hence adopted for the characterisations of the SyAv RD as shown in summary result Tables 37 and 38 in Results Section 4.3.

4.2.4.3 Thermal Bridging

A thermal bridge is a proportion of a structure with a significantly higher thermal conductivity than is average in the dwelling [192]. They can occur in buildings because of (i) geometry e.g. a corner, (ii) structural requirements e.g., lintels, foundation, party wall, wall ties etc. and (iii) construction practice e.g. no edge insulation in ground floor. Thermal bridges are classified as [193]; a) repeating, b) non-repeating c) random, examples of which are shown in Figure 51.

The Y-value is the term used to describe the sum of all the non-repeating thermal bridging heat transfer coefficients (H_{TB}) divided by the total exposed area of the building envelope (A_{exp}), and is expressed as W/m^2K. The Y-value is a U-value 'penalty' added to the average U-value to account for the thermal bridges [193]. Linear thermal transmittance (ψ) (measured in W/mK) describes the heat loss associated with a thermal bridge not accounted for in the U-values of the plane buildings elements containing the thermal bridge. The transmission heat transfer coefficient associated with non-repeating thermal bridges is calculated as shown in Equations (19) and (20) [194]:

$$H_{TB} = \sum (\psi \times L) \text{ (W/K)} \qquad (19)$$

where L is the length of the junction/thermal bridge over which ψ applies. The value for Y can then be derived using [194];

$$H_{TB} = Y \times \sum A_{exp} \text{ (W/K)} \qquad (20)$$

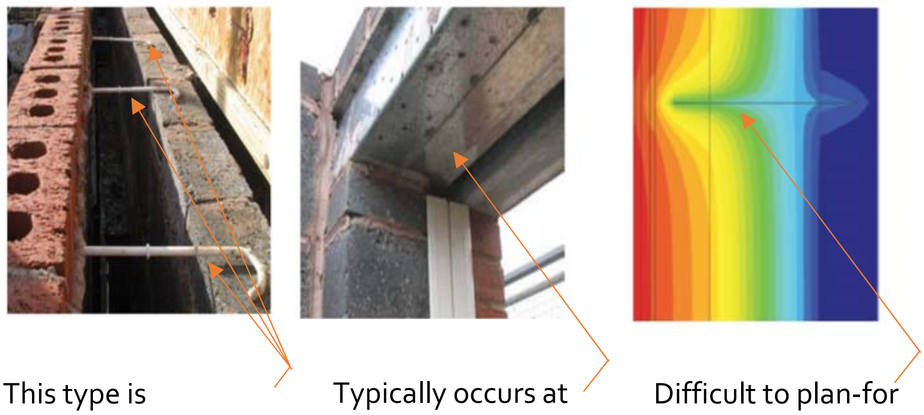
DEAP applies a global default Y-value 0.15 W/m^2K for all existing dwellings [195]. Studies have found that this figure can overestimate [196, 197] and sometimes underestimate [198] the heat loss from a dwelling due to thermal bridging and that it is not relevant to the building type [196] so must be calculated.

Figure 51 Classifications of thermal bridge[193]

Repeating

Non-repeating

Random



This type is predictable and should be accounted for when U-values are calculated.

Typically occurs at the junctions between plane building elements e.g. at wall/roof and wall /floor junctions and around openings

Difficult to plan-for – Could arise from a nail through a wall (as shown) or installation of a meter box for example

The calculation procedure to establish the linear thermal transmittance or Psi (ψ) value is outlined in BRE IP 1/06. Details should be assessed in accordance with the methods described in I.S. EN ISO 10217 [199]. These calculations of two-dimensional or three dimensional heat flow require the use of numerical modelling validated against I.S. EN ISO 10217 [199]. Validated values of ψ are available from the current (2011) Irish Building Regulations [126] for insulated walls, quoting values ψ-values for insulated envelopes classified as;

a) cavity wall,
b) external,
c) internal,
d) timber frame,
e) steel frame, or
f) hollow block.

The ψ-values quoted in the Irish building regulations [126] are dependent on U-value and are valid for two ranges (1 and 2 in Table 34) of maximum U-value (W/m^2K) for walls, roofs and floors only. To contextualise range 1 and 2 U-values, the maximum U-Values permitted under the current the regulation [126] are quoted in Table 34, it is noted that ψ-values quoted in the Irish building regulations are relevant to insulated new build or very significantly retrofitted dwellings only.

Table 34 Range of wall, roof and floor U-values relevant to ψ-values quoted in the Irish building regulations [126]

		Wall	Roof	Floor
Range of U-values relevant to ψ-values quoted in the Irish building regulations	1	0.21	0.16	0.21
	2	0.15	0.14	0.15
	Current (2011) Regulations [126]	0.21	0.16 (Pitched roof) to 0.2 (flat roof)	0.21

The regulations state that the aggregate percentage change from the respective Range 1 and 2 U-values should not exceed + 20 % for the Psi (ψ) value to be valid.

Analysis of the U-values detailed in Table 32 and Table 33 show the variance to exceed the 20 % limit in all cases. Thus, in the absence of an Irish dataset and on the assumption that the UK and Irish Housing Stock are similar [70], Psi (ψ) values were sourced from Table K1 of the UK Standard Assessment Procedure (SAP) [140] in accordance with Table 35. ψ values quoted in SAP, which are independent of U-value, tend to be higher than the Irish ψ values.

The SyAv geometries by period of construction listed in Table 29, were reclassified according to thermal classifications, established in Table 32 and Table 33, as shown in Table 35

(Ref: category 1S, x and 2S, x etc.). The likely length of thermal bridges junctions were calculated on the assumptions that;

(i) as shown in average depiction of typical single and two-storey dwellings in Figure 36, single-storey houses have a length twice the width and two-storey dwellings are square with a 25° pitched roof,

(ii) window heights and door widths are one metre wide,

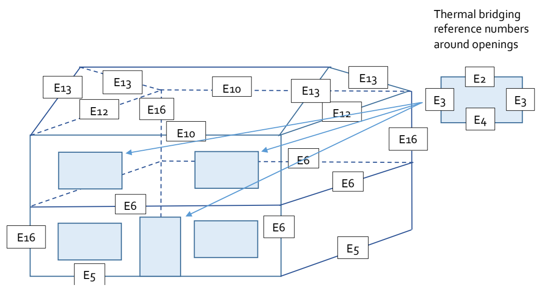
(iii) thermal bridging junctions, as depicted with Table 35, have a 200 mm extension on each end of junction E1/E2 and E4.

Equations (19) and (20) were used to calculate the likely Y-Value (W/mK) shown in Table 35. It is acknowledged that the Psi (ψ) values used in the calculations are somewhat default based and this is a limitation of this work. Notwithstanding, the Y-values calculated and adopted are based on a synthetically averaged (SyAv) detached building forms by period of construction and thus much less arbitrary than the global default Y-value of 0.15 W/m^2K employed by DEAP.

Table 35 Calculation of the thermal transmittance coefficient (Y-value) resulting from thermal bridges

Cross-reference Table 31 and 32

Category			Area (m^2)						Perimeter Dimensions (m)			Height (m)		Length (m) of Junction Detail x: Perimeter		Eaves -insul. at;		Gable - Insulation at;							
	1S/2S	x	Wall	Roof	Floor	Window	Door	A_{exp}	x	y	P/A Ratio	Ground floor height	First floor height	Grd. Flr	Int. Flr	Ceiling level	Rafter level	Ceiling level	Rafter level	Corners	Ope - Jamb	Ope - Lintels	Ope - Sills	Y-value W/m^2K	H_{TB} (W/K)
Post-thermal Regulation	1S,	1	153	150	149	27	3.74	334	24	6	0.41	2.57		61		49		6		10	29	29	17	0.08	26.0
		2	110	134	133	25	3.54	273	23	6	0.43	2.53		58		46		6		10	27	27	16	0.09	24.5
		3	111	135	134	25	3.57	275	23	6	0.43	2.53		58		46		6		10	27	27	16	0.09	24.6
		4	110	135	133	25	3.56	274	23	6	0.43	2.53		58		46		6		10	27	27	16	0.09	24.5
		5	102	126	127	25	3.21	256	23	6	0.44	2.52		56		45		6		10	27	27	16	0.09	24.2
		6	102	126	126	24	3.19	255	22	6	0.45	2.52		56		45		6		10	26	26	16	0.09	23.8
		7	102	126	126	24	3.19	255	22	6	0.45	2.52		56		45		6		10	26	26	16	0.09	23.8
		8	102	127	128	26	3.25	258	23	6	0.44	2.53		57		45		6		10	28	28	16	0.10	24.6
Pre-thermal Regulation		9	102	111	111	22	3.2	238	21	5	0.47	2.58		53		42		5		10	24	24	16	0.09	22.3
		10	101	119	119	24	3.2	247	22	5	0.46	2.54		55		44		5		10	26	26	16	0.09	23.4
		11	101	116	116	23	3.2	243	22	5	0.46	2.56	N/A	54		43	N/A	5	N/A	10	25	25	16	0.09	22.9
		12	102	112	111	22	3.2	239	21	5	0.47	2.58		53		42		5		10	24	24	16	0.09	22.3
		13	100	95	95	15	3.06	213	19	5	0.51	2.59		49		39		5		10	17	17	15	0.09	18.9
		14	100	95	95	15	3.1	213	19	5	0.51	2.59		49		39		5		10	17	17	15	0.09	18.9
		15	100	95	95	14	3.03	212	19	5	0.51	2.58		49		39		5		10	16	16	15	0.09	18.6
		16	100	94	94	14	2.96	211	19	5	0.52	2.58		48		39		5		10	16	16	15	0.09	18.5
		17	100	96	96	15	3.2	214	20	5	0.51	2.6		49		39		5		10	17	17	16	0.09	19.0
		18	104	95	94	14	2.87	216	19	5	0.52	2.6		48		39		5		10	16	16	15	0.09	18.5
		19	104	95	94	14	2.87	216	19	5	0.52	2.6		48		39		5		10	16	16	15	0.09	18.5
		20	104	95	94	14	2.87	216	19	5	0.52	2.6		48		39		5		10	16	16	15	0.09	18.5
		21	104	95	94	14	2.87	216	19	5	0.52	2.6		48		39		5		10	16	16	15	0.09	18.5
Post-thermal Regulation	2S,	1	173	129	118	34	3.96	340	11	11	0.37	2.55	2.23	43			22		13	19	41	41	34	0.08	28.8
		2	160	131	115	32	3.85	327	11	11	0.37	2.54	2.04	43			21		13	18	39	39	34	0.09	28.0
		3	155	131	115	32	3.67	322	11	11	0.37	2.53	1.99	43			21		13	18	39	39	33	0.09	27.9
		4	157	130	116	33	3.69	324	11	11	0.37	2.53	2.02	43			22		13	18	40	40	33	0.09	28.3
		5	152	129	115	33	3.56	318	11	11	0.37	2.52	1.98	43			21		13	18	40	40	33	0.09	28.3
		6	152	126	116	34	3.51	316	11	11	0.37	2.51	2.03	43			22		13	18	41	41	33	0.09	28.7
Pre-thermal Regulation		7	154	110	102	29	3.42	296	10	10	0.40	2.53	2.16	40		N/A	20	N/A	12	19	36	36	33	0.09	26.3
		8	153	123	116	36	3.39	315	11	11	0.37	2.54	2.13	43			22		13	19	43	43	33	0.09	29.3
		9	153	111	103	30	3.36	297	10	10	0.39	2.55	2.16	41			20		12	19	37	37	33	0.09	26.7
		10	168	105	98	24	3.68	301	10	10	0.40	2.54	2.31	40			20		12	19	31	31	33	0.08	24.4
		11	179	110	103	25	3.82	318	10	10	0.39	2.56	2.37	41			20		12	20	32	32	34	0.08	25.0
		12	157	96	89	21	3.65	278	9	9	0.42	2.46	2.24	38			19		11	19	29	29	33	0.08	22.9
		13	179	110	103	25	3.82	318	10	10	0.39	2.56	2.37	41			20		12	20	32	32	34	0.08	25.0
		14	179	110	103	25	3.82	318	10	10	0.39	2.56	2.37	41			20		12	20	32	32	34	0.08	25.0
													Psi (ψ) of Junction Detail x	0.16	0.07	0.06	0.04	0.24	0.04	0.09	0.05	0.3	0.04		
													Junction Detail Reference	**E5**	**E6**	**E10**	**E13**	**E12**	**E13**	E16	E4	E2	E3		



4.2.4.4 Internal heat capacity

There are two basic types of method for calculating the energy performance of buildings [40]:

(1) Quasi-steady-state methods, calculating the heat balance over a sufficiently long time (typically one month or a whole season). Dynamic effects can be accounted for by an empirically determined heat gain and/or loss utilisation factor [200].

(2) Dynamic methods, calculating the heat balance with short time steps (typically one hour) taking into account the heat stored in, and released from, the mass of the building.

Normative energy models quasi-steady state formulations of heat balance equations, based on CEN-ISO standards, are appropriate for modeling large sets of buildings efficiently [167]. DEAP thus employs method (1) using a calculation based on IS EN ISO 13790: 2004, now superseded by EN ISO 13970:2008 'Calculation of Energy Use for Space Heating and Cooling' [40], to assess a dwelling's capacity to store heat within its structure. In the quasi-steady-state methods, the dynamic effects of solar and internal heat gains are taken into account by introducing coefficients that correct for the effect of thermal inertia on [40, 72, 200];

a) heat loss/gain from a dwelling under intermittent heating conditions (IH), and

b) utilisation of free heat gains (UF).

The necessity to use such correction factors is illustrated in the case of a thermally heavyweight building as this type of structure;

(i) will maintain a higher internal temperature after heating ceases than a lighter structure. If the internal temperature rises due to overheating, the transmission and ventilation heat transfer from the considered zone will increase proportional to the change in temperature difference between internal and external temperature. The effect of thermal mass is accounted for either by introducing an equivalent internal temperature which deviates from the set point or by a correction on the calculated heat need. This is reflected in the DEAP [72] procedure in the form of a higher "intermittent heating" factor being applied.

(ii) has potential to store internal and solar heat gains [200] . A higher internal heat capacity structure retains heat released later to contribute to heating needs. For such cases, DEAP [72] uses a higher "utilisation factor" applied to 'free' heat gains.

The five thermal mass categories for a dwelling in DEAP [72] are; low, medium-low, medium, medium-high or high. A building is allocated to a category via the following steps;

(1) each opaque element type of the dwelling (walls, ceilings, floors, both external/ exposed and internal) are classed as either 'thermally light' or 'thermally massive',
(2) the ratio of total area of thermally massive elements to total floor area, 'AmAf', is then determined, and.
(3) the thermal mass category of the dwelling is then obtained by locating the 'AmAf' ratio in Table 35 closest to that calculated.

The thermal mass category returned by the dataset for Ireland's predominant housing typology is "medium" classified in Table 36 as having a utilisation and intermittent heating factor of 0.2 and 0.11 MJ/m²K respectively [76].

Table 36 DEAP correction factors associated with dwelling thermal mass categories [72]

		A_mA_f ranges		Heat capacity per unit floor area [MJ/m²K]	
		Low	High	UF	IH
Category	Low	<0.25	0.25	0.07	
	Medium-low	0.26	0.75	0.14	0.09
	Medium	0.76	1.5	0.2	0.11
	Medium-high	1.51	2.75	0.32	0.15
	High	2.76	>2.76	0.5	0.2

4.2.4.5 Validation of dwelling envelope thermal characteristics

4.2.4.5.1 Thermal Classifications

The base thermal transmittance of U-values (W/m²K) used in the creation of the thermal characterisations for the RDs were validated in sections 2.4 and 2.5. The validity of the information resulting from the classification of this base data is thus *de facto* validated. The validity of classifications are confirmed by way of the radial graphs shown in Tables 32 and 33.

4.2.4.5.2 Thermal Bridging Coefficients

The Y-value is the term used to describe the sum of all the non-repeating thermal bridging heat transfer coefficients (H_{TB}) divided by the total exposed area of the building envelope (A_{exp}), expressed as W/m²K as shown in Equation (21) below (Equation (20) rearranged in terms of 'Y')

$$Y = \frac{H_{TB}}{\sum A_{exp}} \; (W/m^2K) \tag{21}$$

H_{TB} coefficients for the case study dwelling explored in this work, described in Table 35, were found to range from 18.5 W/K to 28.8 W/K, averaging 24 W/K. As expected, low and high H_{TB} values correlate with low and high percentage window ratios and associated length lintels, sills, etc. Ranging from 211 m² to 332 m², and as discussed in Chapter 1, exposed surface areas (A_{exp}) values for detached Irish dwellings are relatively large. Referencing Equation (21), custom detached housing typological Y-values resulting from comparatively large A_{exp} divisors result in narrow range Y-values lying between 0.08 and 0.09 W/m²K (see Table 35)

There is little work reported on the use of calculated versus default Y-values in DEAP and SAP building energy simulations [198] facilitating a validation of thermal bridging heat transfer coefficients and there is no substantive work relating to detached dwellings particularly.

There is one study [198] in Ireland that looked at three ReEx terraced local authority reference dwellings with poorly performing archetypal construction details representing a total of 9173 dwellings built between 1930 and 1982 .House types 1 to 3 represented block-on-flat, cavity and pre-fabricated insulated composite cavity construction. An ISO-validated thermal bridge assessment software was used to quantify steady-state heat transfer relating to thermal bridges in two and three-dimensional planes pre and post dwelling envelope retrofit measures. External wall retrofit solutions were designed to reduce negative effects of localised thermal bridging through improved construction detailing, thereby reducing Psi (ψ) values and thus transmission heat transfer coefficient due to thermal bridging (H_{TB}) in line with Equation (19) [198]. The study quotes H_{TB} and Y-values for mid-terrace and end-of-terrace dwellings. Exposed surface areas (A_{exp}) for end-of-terrace would be closer to that of detached dwellings than mid-terrace dwellings. Thermal Bridging heat transfer coefficients for end-of-terrace dwellings were found to range from [198];

- 0.156 W/m²K (H_{TB} 23.43 W/K) to 0.263 W/m²K (H_{TB} 39.48 W/K) for block-on-flat solid wall dwellings pre-retrofit and 0.062 W/m²K (H_{TB} 9.36 W/K) to 0.066 W/m²K (H_{TB} 9.85 W/K) post retrofit,
- 0.211 W/m²K (H_{TB} 37 W/K) to 0.246 W/m²K (H_{TB} 43.13 W/K) for insulated and uninsulated cavity wall dwellings pre-retrofit to 0.066 W/m²K (H_{TB} 9.85 W/K) post retrofit.
- 0.179 W/m²K (H_{TB} 32.34W/K) to 0.102 W/m²K (H_{TB} 18.49 W/K) for composite cavity wall dwellings pre and post-retrofit.

H_{TB} values for end-of-terraced dwellings were found in [198] to range from 23.43 W/K to 43.13 W/K pre-retrofit and 9.36 W/K to 18.49 W/K post-retrofit. It is noted that thermal bridging coefficients change with wall construction type but also pre and post-retrofit. A_{exp} for the ReEx end-of-terrace dwelling ranged from 151 m² to 181 m² [198]. Corroborating the findings of other studies [192, 196, 197], and as expected, Y-values for detached dwellings would be lower than that of terraced dwellings.

The characterisations of the RDs are somewhat default based as;

(i) without detailed geometrical data relating to a particular dwelling, modelling efforts can at best only broadly estimate thermal bridging factors [198], and

(ii) the Psi (ψ) values used are somewhat default based.

Though these are limitations of this work, the Y-values calculated and adopted are (i) plausible and (ii) representative of the dwelling shape and the probable length of thermal bridging junctions and (iii) thus much less arbitrary than the global default Y-value of 0.15 W/m²K employed by DEAP. It is noted that the calculated values in Table 35, range from 40 % to 47 % lower than the DEAP [72] global default figure of 0.15 W/m²K, while H_{TB} values range from being 57 % to 64 % lower. This approach will require further investigation [61] with the objective of refinement in future research.

4.2.4.5.3 Air Tightness

It is not possible to cross-validate the GreenBuild dataset employed in this work satisfactorily, due to (i) paucity of data [28, 187, 189, 201] relating to the air-tightness in UK and Irish dwellings and (ii) air-tightness studies being carried out typically on small datasets [187, 202, 203], Notwithstanding, this GreenBuild dataset [188];

- is the largest dataset available for Irish housing in general and detached housing particularly,
- correlates with a large UK database.

It is thus considered the most authoritative data-source on the air-permeability rates of detached housing in Ireland and is employed in the characterisation of the case study RD.

4.2.4.5.4 Internal Heat Capacity

To facilitate EU MSs with suitable calculation methods so enabling the (i) EPBD, (ii) production of EPCs for buildings [204], and (iii) development of stock-energy models [167]; a set of European standards were developed by the European Committee for Standardisation (CEN). As part of this process, EN ISO 13790 'Calculation of Energy Use for Space Heating and Cooling' (EN ISO 13790, 2004), the international standard for the calculation of the energy use for space heating and cooling for residential and non-residential buildings was reviewed and updated to EN ISO 13790, 2005, since superseded by ISO 13790, 2008 [40].

By introducing a coherent set of procedures pertaining to boundary conditions assumptions applicable to both methods, the standard aims to create "a level playing field" for both simple (hourly and monthly quasi-steady state) and detailed (dynamic) methods [204]. Obtaining "a level playing field" is important for modelling large sets of buildings efficiently [167] and fulfilling the required attributes EPCs, discussed in Chapter 3, relating to transparency, robustness and reproducibility, and this is why simple methods are preferred [204].

Dynamic effects in simple methods are accounted for through the introduction of utilisation factors. Deviations due to simplification are considered "balanced inaccuracies" [204]. Balanced inaccuracies are weighted against uncertainties in dynamic calculations relating to specific boundary condition input data such as, system, occupancy, specific environment etc. [204].

In parallel with the development of EN ISO 13790, 2005, CEN TC89 WG6 developed validation cases for the method (CEN TC89 W.I. 17, 2005) [204]. When taking into account the need for these simplified methods in terms of transparency, robustness and reproducibility, the validation exercises demonstrated that (i) the uncertainties introduced are within acceptable bandwidths, and (ii) the simplified method is well suited to be used in both warm, moderate and cold European climates [204].

4.2.5 System

As discussed in section 2.3, in 2016, an average 3 in 4 of centrally heated RD's are heated by oil while 1 in 4 are heated by solid-fuel or oil. Proportions by DEAP period of construction are listed in Table 6. System characteristics for the two main fuels and thus SyAv RDs are as indicated in Tables 25 and 26 wherein data is presented to comply complying with EU Commission Delegated Regulation No. 244/2012 [55].

Renewable energy is not typically generated on site [76]. The dataset [76] suggests the average energy performance of the RDs ranges from 359 kWh/m² to 373 kWh/m² for single-storey dwellings and 315 kWh/m² to 332 kWh/m² for two-storey dwellings [205]. However, as these ratings are derived from the EPC database [76], they are not an actual rating but an asset rating [43, 47, 51, 60, 105-109] and thus not included in summary results Table 37 (Section 4.3). To get realistic figures of energy consumption the dwellings must be measured.

4.3 Results

The overall reference dwelling characterisations are summarised in Table 37. Results are reported as required as detailed in Commission Delegated Regulation (EU) No. 224/2012 [55] in Table 38.

Table 37 Characterisation of single (1S) and two-storey (2S) reference dwellings depicting Ireland's predominant housing typology

	Category	x	Quantity (N)		U-Value (W/mK) Window	U-Value Floor	U-Value Roof	U-Value Wall	Air permeability (m³/(h.m²))	Area (m²) Wall	Area Roof	Area Floor	Area Window	Area Door	Height (m) Ground floor height	Height First floor height	% Window Ratio	(m³) Volume	Surf. Area/Vol. Compact-ness of Building Envelope	Occupancy	Heating fuel source Oil	Heating fuel source Solid Fuel
Post-thermal Regulation	1S,	1	105616	5839	2.06	0.33	0.19	0.28	10	153	150	149	27	3.74	2.57	N/A	18%	382.93	1.26	3.19	75%	16%
		2		26266	2.72	0.40	0.13	0.29	10	110	134	133	25	3.54	2.53	N/A	23%	336	1.2	3.47	75%	19%
		3		10519	2.78	0.4	0.33	0.29	10	111	135	134	25	3.57	2.53	N/A	23%	340	1.2	3.42	75%	16%
		4		10819	2.79	0.41	0.33	0.42	10	110	135	133	25	3.56	2.53	N/A	23%	338	1.2	3.44	74%	18%
		5		33542	2.83	0.55	0.13	0.29	10	102	126	127	25	3.21	2.52	N/A	25%	320	1.2	3.51	75%	18%
		6		335	2.84	0.57	0.13	0.46	10	102	126	126	24	3.19	2.52	N/A	24%	318	1.2	3.62	68%	27%
		7		9730	2.84	0.57	0.35	0.46	10	102	126	126	24	3.19	2.52	N/A	24%	318	1.2	3.62	68%	27%
		8		8566	2.82	0.57	0.2	0.6	10	102	127	128	26	3.25	2.53	N/A	26%	324	1.19	3.25	69%	26%
Pre-thermal Regulation		9	103245	11264	2.73	0.71	0.13	0.39	13.07	102	111	111	22	3.2	2.58	N/A	21%	285	1.22	2.72	66%	29%
		10		13973	3.13	0.69	0.13	0.4	12.21	101	119	119	24	3.2	2.54	N/A	24%	302	1.21	2.85	69%	26%
		11		10219	3.16	0.71	0.43	0.39	12.57	101	116	116	23	3.2	2.56	N/A	23%	295	1.22	2.80	68%	27%
		12		20164	3.2	0.73	0.45	1.6	13.03	102	112	111	22	3.2	2.58	N/A	21%	286	1.22	2.73	70%	25%
		13		3007	2.86	0.43	0.13	0.3	14.02	100	95	95	15	3.06	2.59	N/A	15%	246	1.25	2.51	59%	34%
		14		2165	2.85	0.76	0.13	0.29	14.75	100	95	95	15	3.1	2.59	N/A	15%	248	1.25	2.52	58%	34%
		15		2947	2.86	0.76	0.13	1.41	13.79	100	95	95	14	3.03	2.58	N/A	14%	246	1.25	2.51	59%	33%
		16		12696	2.87	0.76	0.65	1.4	12.89	100	94	94	14	2.96	2.58	N/A	14%	244	1.26	2.50	59%	33%
		17		9255	3.4	0.76	0.57	1.43	12	100	96	96	15	3.2	2.6	N/A	15%	250	1.24	2.53	58%	35%
		18		2984	2.89	0.53	0.22	0.15	12	104	95	94	14	2.87	2.6	N/A	13%	244	1.27	2.49	59%	31%
		19		6847	2.89	0.8	0.22	0.53	12	104	95	94	14	2.87	2.6	N/A	13%	244	1.27	2.49	59%	31%
		20		2633	2.89	0.8	0.98	0.53	12	104	95	94	14	2.87	2.6	N/A	13%	244	1.27	2.49	59%	31%
		21		5091	4.93	0.8	0.98	0.53	12	104	95	94	14	2.87	2.6	N/A	13%	244	1.27	2.49	59%	31%
Post-thermal Regulation	2S,	1	104813	8344	2.08	0.34	0.22	0.29	10.00	173	129	118	34	3.96	2.55	N/A	20%	564	0.81	3.19	75%	16%
		2		21596	2.62	0.40	0.25	0.29	10.00	160	131	115	32	3.85	2.54	2.04	20%	528	0.84	3.34	74%	17%
		3		28377	2.81	0.47	0.26	0.45	10.00	155	131	115	32	3.67	2.53	1.99	21%	520	0.84	3.50	72%	21%
		4		1329	2.81	0.47	0.90	0.47	10.00	157	130	116	33	3.69	2.53	2.02	21%	527	0.83	3.47	72%	21%
		5		40353	2.84	0.51	0.25	0.30	10.00	152	129	115	33	3.56	2.52	1.98	21%	519	0.84	3.53	71%	24%
		6		4814	2.83	0.52	0.24	0.71	10.00	152	126	116	34	3.51	2.51	2.03	22%	527	0.82	3.25	69%	23%
Pre-thermal Regulation		7	93243.71	26778	2.92	0.71	0.26	0.37	13.13	154	110	102	29	3.42	2.53	2.16	19%	480	0.84	2.66	64%	30%
		8		1770	3.03	0.71	0.89	0.41	12.00	153	123	116	36	3.39	2.54	2.13	23%	542	0.80	2.88	70%	25%
		9		15848	3.17	0.74	0.98	1.56	14.06	153	111	103	30	3.36	2.55	2.16	19%	486	0.83	2.68	63%	31%
		10		23511	2.94	0.72	0.28	1.27	12.88	168	105	98	24	3.68	2.54	2.31	15%	476	0.84	2.50	65%	29%
		11		2728	2.89	0.73	1.18	1.97	14.00	179	110	103	25	3.82	2.56	2.37	14%	508	0.83	2.49	59%	31%
		12		10084	2.88	0.74	1.14	1.42	14.25	157	96	89	21	3.65	2.46	2.24	14%	418	0.88	2.49	62%	32%
		13		5718	2.89	0.73	1.18	1.13	12.00	179	110	103	25	3.82	2.56	2.37	14%	508	0.83	2.49	59%	31%
		14		6807	4.73	0.73	1.18	1.97	12.00	179	110	103	25	3.82	2.56	2.37	14%	508	0.83	2.49	59%	31%
Total			406910	406910																		

Table 38 Summary reference dwelling report complying with EU Commission Delegated Regulation 244/2012

		Quantity	Unit	Description and/or source
Primary energy conversion factors	electricity	2.19		[119, 206]
Carbon emission factors	electricity	0.473	$kgCO_2/kWh$	[119, 206]
	oil (kerosene)	0.257	$kgCO_2/kWh$	
	coal	0.341	$kgCO_2/kWh$	
Climatic conditions	location	Mullingar, Ireland		Section 4.2.1.1
	heating degree-days	2,389	HDD	Mullingar Weather Station - degree days below 15.5°C (occupied and unoccupied period); [171]
	source of climatic dataset	IWEC2 file		See Section 4.2.1.1
	terrain description	Rural		Nearby buildings not to be accounted for.
Geometry	length x width x height	Varies	m^3	Related to the heated/conditioned air volume, See Table 29
	number of floors	Varies		See Table 37
	S/V (surface-to-volume) ratio	Varies	m^2/m^3	See Table 37
	ratio of window area over total building envelope area	Varies	%	See Table 29
Orientation		Varies	N, S, E, W, NE, NW, SE, SW	See Section 4.2.2.2
Internal gains	building utilisation	Single-family houses		According to the building categories proposed in Annex 1 to Directive 2010/31/EU
	average thermal gain per occupants	93	$W/m^2/$ occupant	CIBSE Guide A [124]
	delivered lighting energy	1,149	$kWh/m^2/yr$	BER database [76]
	specific electric power of electric equipment	-	W/m^2	No information available

Table 38 Summary reference dwelling report (cont.) complying with EU Commission Delegated Regulation 244/2012

			Quantity	Unit	Source and/or description
Building Elements	average wall U-value		Varies	W/m²K	See Table 37
	average roof U-value		Varies	W/m²K	See Table 37
	Average window U-value		Varies	W/m²K	See Table 37
	living area as a % of total floor area		16	%	[76]
	thermal bridges	total length	Varies	m	See Table 37
		average linear thermal transmittance	Varies	W/mK	See Table 35
	thermal mass factors	Utilisation	200	J/m²K	See Section 4.2.3.4
		Intermittent heating	111	J/m²K	
	type of shading systems		Curtains		
	average g-value of glazing		0.76		Wood/PVC Double 6mm air-filled glazing average U-value 3.1 W/m²K Table S9 DEAP [72] and [70]
	% Windows Draught Stripped		94	%	[76]
	infiltration rate		Varies	m³/(hm²) at 50Pa	See Table 37

4.3.1 Quantifying the default related performance gap

To quantify the effect of thermal default use versus empirically derived thermal envelope data on the EPC rating of dwellings; four number pre and post thermal regulations RD's [2 x single storey (1S) and 2 x two storey (2S)], totalling eight RD's, were selected from Table 37 for input to the DEAP Methodology. RD's representing the highest quantity of dwellings (N) in Table 37 as shown Table 39. The selection set represents 206,183 dwelling's accounting for 50.7 % of the national detached dwelling stock.

Dwellings were modelled using empirical data derived in this study (reference Table's 35, 37 and 38) and hence remodelled assuming default thermal characteristics by assumed period of construction[19] (reference Table 7), the standard thermal bridging default Y-value of 0.15 W/m^2K was assumed for default RD's. To facilitate the comparison a singular north-east/south-west (NE/SW) orientation for the dwellings was selected randomly. Other model input assumptions as follows:

i. Double glazed windows with 10 % frame area;
ii. 300 litre DHW calorifier complete with cylinder thermostat;
iii. Lighting includes no incandescent lightbulbs;
iv. 21^{o}C internal temperature in the living room;
v. No sides of the dwelling were sheltered.

Referring to Table 39 and Figure 52, as expected, thermal default use resulted in increased rated primary energy consumption (kWhr/y) and CO2 emissions (kg/y) attributable to the dwelling. For dwellings with a NE/SW orientation the primary energy consumption associated with both the primary and secondary heating systems increases by 31 % for post-thermal regulation dwellings and 90 % for pre-thermal regulation dwellings when defaults are assumed. Thermal default use was found to increase the total rated primary energy consumption by 22 % in post thermal regulation dwellings and 70 % in pre-thermal regulation

[19] Categorisations in Table 38 span across traditional periods of construction used by DEAP methodology – period of construction with highest frequency of dwellings within a category was selected for default comparison.

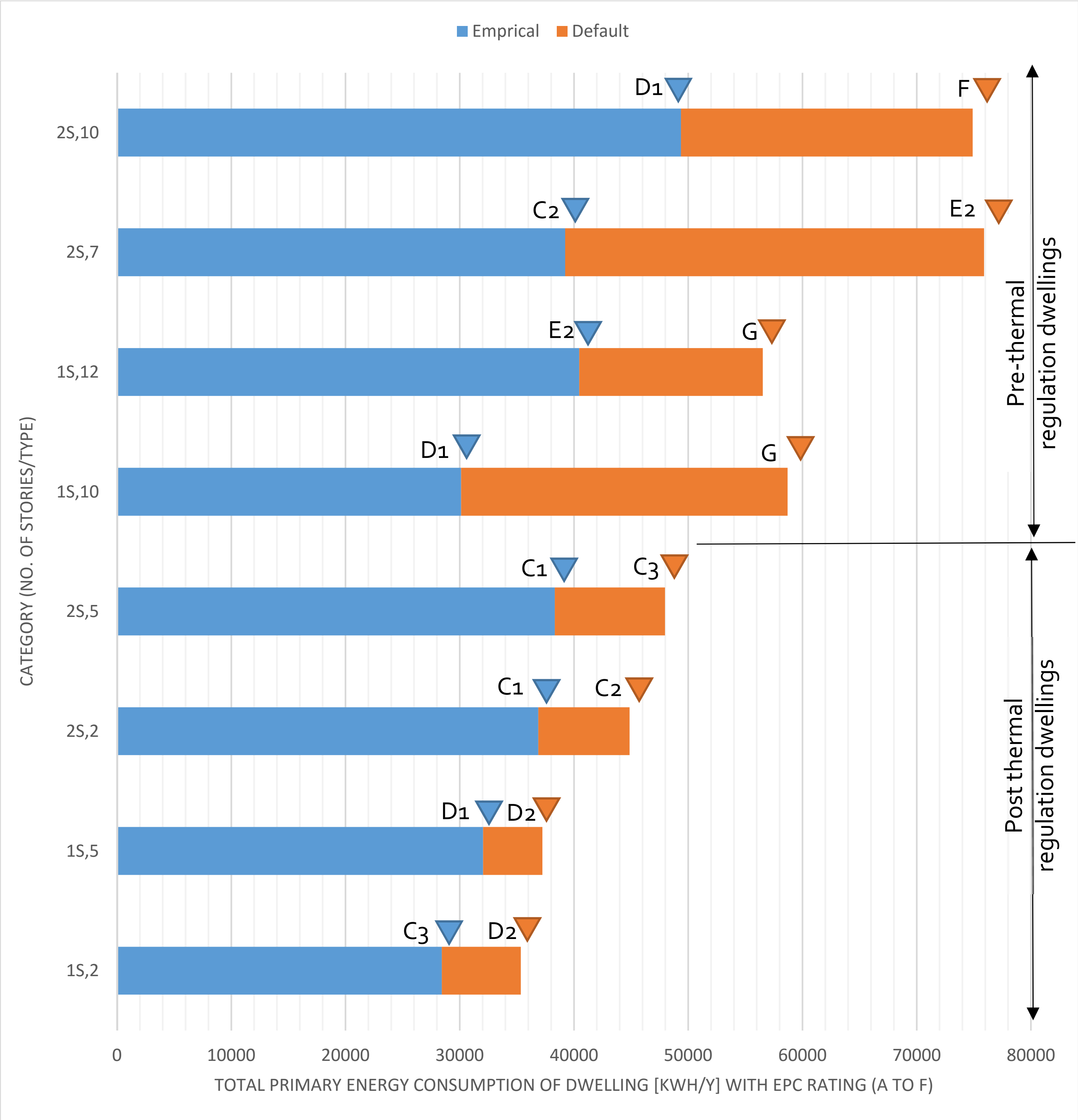
dwellings. Thermal default uses increased CO_2 emissions by a corresponding 23 % in post thermal regulation dwellings and 71 % in pre-thermal regulation dwellings.

As shown in Table 39 and Figure 52 use of thermal defaults will result in a significantly lower than merited energy rating, particularly for pre-thermal regulation dwellings.

Table 39 Summary of DEAP methodology outputs for selected empirical and default reference dwellings

				Primary Energy [kWh/y]											CO_2 Emissions [kg/y]					
	Category	Quanity (N)	Period of Construction	Main space heating system		Secondary space heating system		Main water htg. sys.	Pumps & Fans	Energy for lght'g	Total		per m^2 of floor area		Total		per m^2 of floor area		EPC Rating	
				E	D	E	D	E/D	E/D	E/D	E	D	E	D	E	D	E	D	E	D2
Post thermal regulation	1S,2	26266	2000-2004	16777	22516	3439	4610	5972	541	1708	28436	35347	213.81	265.77	7221	9033	54.29	67.92	C3	D2
	1S,5	33542	1983-1993	19951	24263	4086	4966	5845	541	1626	32049	37240	252.35	293.23	8175	9537	64.37	75.09	D1	D2
	2S,2	21596	2000-2004	21268	27905	4355	5710	7709	541	3012	36885	44877	160.37	195.12	9325	11420	40.54	49.65	C1	C2
	2S,5	40353	1983-1993	22468	30480	4600	6235	7709	541	3007	38325	47971	166.63	208.57	9703	12232	42.19	53.18	C1	C3
Pre thermal regulation	1S,10	13973	1967-1977	18584	42324	3807	8652	5671	541	1520	30124	58709	253.14	493.35	7680	15176	64.54	127.53	D1	G
	1S,12	20164	1950-1966	27401	40746	5607	8330	5493	541	1420	40461	56530	364.52	509.28	10400	14614	93.69	131.65	E2	G
	2S,7	26778	1967-1977	23837	54297	4879	11096	7303	541	2668	39228	75905	192.3	972.08	9968	19585	48.86	96.01	C2	E2
	2S,10	23511	Before 1900	32432	53636	6633	10961	7170	541	2600	49375	74907	251.91	382.18	12635	19330	64.46	98.62	D1	F

Figure 52 Total primary energy consumption and associated energy rating for selected empirical and default reference dwellings as calculated by the DEAP methodology



4.4 Discussion

Thermal default use results in significantly increased rated primary energy consumption (kWhr/y) and CO_2 emissions (kg/y) attributable to the dwelling when compared with empirical data established in this work. Pre-thermal regulation as-built thermal defaults assume no insulation is present in the dwelling envelope. The use of pessimistic thermal defaults combined with existence of significant levels of thermal retrofits in pre-thermal regulation dwellings, as outlined in section 2.4.5, leads to significantly increased (average of 90 % when compared to empirical data) in the rated primary energy associated with the dwelling heating system when pessimistic thermal defaults are employed. As thermal defaults for post-regulation dwellings are calculated assuming insulation to be present, the discrepancy in rated primary energy associated with the heating system, at an average of 31 %, while less than that of post-thermal regulation dwellings is still significant. The corresponding overall increase (when compared to empirical data) in total rated primary dwelling energy consumption, associated with thermal-default use, is 22 % in post-thermal regulation dwellings and 70 % in pre-thermal regulation dwellings. The associated increase in rated CO_2 emissions, at 23 % in post thermal regulation dwellings and 71 % in pre-thermal regulation dwellings mirrors rated primary energy consumption figures. Use of thermal defaults therefore results in a significantly lower than merited energy rating, particularly for pre-thermal regulation dwellings.

A previous study carried out by Ahern et. al. [70], included in Appendix E, characterised this case study dwelling in 2010. To simplify model inputs and as no singular resource pertaining to dwelling characteristics existed in 2010, the study [39, 70] created a base geometry based on a sampling of rural detached dwellings surveyed under the INSHQ [131] and the national census in 2006 [71]. Assuming similar characteristics of construction, base-thermal-default coefficients (see Table 7) were applied to this base geometry, by period of construction, creating 'default dwellings'. That study [70] created 20 RDs however these characterisations were based almost entirely on standard base-thermal-default characteristics thus lacking validity.

This research creates a set of 35 reference dwellings to characterise appropriately 406,918 dwellings averaging one RD per 11,626 dwellings. Use of this number of dwellings by quantity, shall best reflect the characteristics of Ireland's predominant housing typology and add to current knowledge.

Pre-regulation floors are assumed by DEAP to have been constructed originally without insulation. Analysis of P/A ratios in Table 29 and U-values Table 37 in conjunction with Table 12 reveal only 3 % of pre-thermal regulation floors to have floor insulation retrofitted (Categories 1S, 13 (N=3007) and 1S, 18 category (N=2984) – Table 27). The low-level of floor insulation are attributed to the high cost of replacement floor coverings [128] and the difficulty of retrofitting floor insulation.

Referencing Figure 36, it can be seen that while relative geometries have grown proportional to the increase in floor area, they have remained largely unchanged with time. Relatively homogenous geometry validates the methodological approach of classifying first by dominant thermal characteristics and then weighting geometry to the thermal classifications established.

4.5 Recommendations

It may be appropriate to reduce the 35 RD classifications created further. The difficulty in isolating factors which have the greatest influence on dwelling energy consumption is discussed in Section 4.2. The case study dwelling has common characteristics for heating systems efficiencies classified by predominant heating fuel type (oil or solid-fuel). Main variables influencing dwelling energy consumption thus relate to geometric and thermal characteristics of the building fabric. This work relates geometric characteristics weighted by thermal classifications. To reduce classifications further, a sensitivity analysis quantifying the relative impact of thermal variables on overall energy loads is recommended.

The average growth rate in European floor areas was 0.25 % per annum between 1997 and 2007 [65, 70]. The average growth rate for Irish dwellings in general over the same period is

1.3 % per annum [207]. With increasing trends in floor space, the energy demand associated with Irish dwellings is producing a phenomenon known as the 'size effect' [65, 70, 208]. At current average EU growth rates it is estimated that 20 % of energy efficiency progress for thermal uses has been offset, all things being equal, by the fact that dwellings are becoming larger [65]. Detached Irish dwellings show an growth rate of 1.36 % and 1.6 % per annum in heated floor area for single and two-storey respectively. Therefore, for the detached dwellings typology *all* of the energy efficiency gains achieved through thermal regulations of the housing sector are being offset by the size effect. To address this size effect in Irish dwellings, a policy measure which area weights the maximum average U-value (U_m) by reducing U_m in line with increasing building floor area (A_f) is recommended [70].

4.6 Conclusions

To derive simplified synthetically average base-default-free inputs to a bottom-up residential cost-optimality energy consumption model from an EPC dataset, a representative set of reference dwellings to comply with EU Commission Delegated Regulation No 244/2012 is created. 35 reference dwellings (RDs) are employed to characterise appropriately 406,918 dwellings averaging one RD per 11,626 dwellings. The number of characterisations could likely be reduced employing a sensitivity analysis to quantify the impact of thermal variables on overall energy loads. The characterisation of the reference dwelling detailed in this work is;

i. founded in real-world data and statistically significant datasets,
ii. appropriately characterised with a high level of detail,
iii. as contemporaneous as possible,
iv. based on the highest quality empirical or real data currently available,
v. contributes to a consensus on appropriate values for characterisation of an RD,
vi. commonly and transparently reported, compliant with EU Commission Delegated Regulation No 244/2012.

Thermal default use results in significantly increased rated primary energy consumption (kWhr/y) and CO_2 emissions (kg/y) attributable to the dwelling when compared with empirical data established in this work. Use of thermal defaults increases the total rated primary dwelling energy consumption by 22 % in post-thermal regulation dwellings and 70 % in pre-thermal regulation dwellings. The associated increase in rated CO_2 emissions at 23 % in post thermal regulation dwellings and 71 % in pre-thermal regulation dwellings, mirrors primary rated energy consumption figures. Use of thermal defaults therefore results in a significantly lower than merited energy rating, particularly for pre-thermal regulation dwelling.

Use of the appropriately characterised RDs as inputs to national residential energy consumption models shall best represent the energy saving potential of Ireland's predominant housing typology.

Chapter 5 - Limitations of this Study

"Errors using inadequate data are much less than those using no data at all"

Babbage, C [209]

5.1 Quality of the dataset

The EPC database employed [76] is the most comprehensive up-to-date real data on the Irish housing stock. However, it presents a favourable characterisation of the dwelling stock. Homeowners applying for any of the state-led grant schemes are obliged to get an energy performance certificate or building energy rating for the dwelling to qualify for a grant. 20.3 % of dwellings contained in the EPC database examined were because of their sale, 4 % from a private letting and 75.7 % were "unknown". SEAI publish statistics on the state-led grant schemes [210] however the data is not classified by dwelling type but by individual measures which include heating and renewable energy upgrades. The national statistics relating to upgrades of dwelling envelopes for *all* dwelling typologies in the Irish housing sector consistent with the EPC database are shown in Table 40.

Table 40 State-granted fabric energy-efficiency measures in the Irish housing sector for all dwelling typologies (rural and urban) by July 2014 [210]

Measures	Number of dwellings completed
Roof Insulation	112,992
Cavity	99,753
Dry-Lining Insulation	9,865
External Insulation	12,170
Total	234,780

It is not clear from Table 40 whether a household carried out more than one measure at a time. The total number of refurbished *dwellings* in the database is thus conservatively estimated at 112,992, on the bases that;

(a) it is unlikely that the homeowner carried out,

(i) external *and* cavity insulation,

(ii) wall insulation without also installing roof insulation,

(b) it is likely that the homeowner carried out,

(i) roof insulation separately, and

(ii) dry-lining along with cavity or external insulation.

The total number of dwellings in Ireland at the time of the last census in 2011 was 1,658,243. It is estimated that the percentage of homeowners, having availed of state-led grant schemes to upgrade the thermal fabric of their dwelling by July 2014 was likely 6.8 %. This seems reasonable as the number of dwellings having availed of the grant scheme by Oct 2016 is 193,432. The EPC database at the time of downloading consisted 463,582 dwellings. The estimated percentage of state-granted thermally refurbished dwellings in the database is likely 24 %; reduced from 50 % in 2010 [120]. Meaning that although EPC databases are continually growing they cannot yet be considered a scientific source of research data. EPCs need to be strictly categorised by their purpose, e.g. if they were required for sale or rental purposes, for public housing or for grant purposes thereby allowing researchers segregate data to make more representative.

The reference dwellings characterised in this study are more appropriate as they best reflect the characteristics of the overall detached dwelling stock. All other reference dwelling characterisations published in Ireland, as detailed in Table 41 are based on (i) outmoded base or as-built thermal default characteristics, (ii) smaller sample sizes, or (iii) indeterminate data.

Table 41 Previous characterisations of the Irish housing stock

		Data sources for characterisation	Data source for thermal characteristics	Extrapolated to Building Stock existing in…	No. of RDs created	Dwelling Type
Study	Dineen *et al.* (2015) [211]	EPC Database downloaded Aug. 2012/CSO 2011	EPC Database, default U-values not filtered. Default Y-value assumed	2011	175	All
	Livingston and Ross (2013)* [205]	EPC Database, Intelligent Energy Europe TABULA project	Default U-values derived from Building Regs, Default Y-value assumed	N/A	10	All
	Ahern *et al.* (2013) [70]	Multiple Datasources	Default U-values derived from Building Regs, Default Y-value assumed	2006	20	Detached, rural, oil heated dwellings only
	Badurek *et al.* (2012)¤ [120]	EPC Database 2010, CSO 2006	Default U-values derived from Building Regs, Default Y-value assumed	N/A	29	All
	Dineen & Ó'Gallachóir (2011) [64]	Default Values derived from Building Regulations for post-2007 stock and top-down approach based on historical data for pre-2017 dwellings	Default U-values derived from Building Regulations	Predicted to from base year 2007 to 2020	175	All
	Dineen & Ó'Gallachóir (2017) [212]	As per Dinnen & Ó'Gallachóir (2011)	Default U-values derived from Building Regulations	Predicted from base year 2011, Modelling period 2012-2020	175	All
	Moran *et. al* (2017) [213]	Homebound House Building Manual, 4th ed., 2004	Default Y-Values		8	South orientated semi-detached two storey
	Famuyibo (2012) [28]	Unavailable [214, 215]	Unknown	Pre 1960 - 2002	13	All house-types

Dwelling parameters are calibrated to an extent through dwelling audits. However, while dwelling assessors are required to act with integrity and diligence to ensure that each dwelling assessment is executed competently, as outlined in Section 2.4, it appears that assessors do not always carry out thermal assessments of the dwelling envelope as rigorously as they might.

The focus of this work was to carry out a systematic inquiry involving the practical application of available and relevant information to create a dwelling stock model derived from RDs in a transparent manner.

While it is preferential to use empirical data where available; where information within the empirical database was found to be questionable or unreliable, the composition of the reference dwelling is informed instead through available data and expert enquiries. This is not ideal as the quality of the characterisation relies heavily on the subjective judgment of the author or expert [167]. However, due to an acknowledged lack of information pertaining to the composition of dwelling stocks, this approach is accepted in the literature [22, 54, 55, 70, 97, 167]. The EPC database was not employed to characterise the reference dwellings for the following parameters;

- *Heating fuel proportion (Section 2.3.2)*

    Heating fuel proportion in the EPC dataset is found to be inconsistent with National census (CSO) data for Ireland. The CSO data is correlated by previous censuses and is more statistically significant than the EPC data. Accordingly, it is used to characterise the RD, to facilitate the characterisation, the data relating to solid-fuel use is reclassified across DEAP period of construction.

- *Thermal Bridges (Section 4.2.4.3)*

    UK SAP defaults correlating to established SyAv geometry were employed. It is acknowledged that the Psi (ψ) values used in the calculations are somewhat default based and is a limitation of this work. Notwithstanding the Y-values calculated and adopted are based on a statistically averaged detached building form by period of construction and thus much less arbitrary than the global default Y-value of 0.15

W/m²K employed by DEAP. Due to relatively large exposed surface areas, calculated Y-values are lower than the 0.15 W/m²K figure in all cases.

- *Air Tightness (Section 4.2.4.2)*

  The air-tightness results returned from the EPC dataset were questionable. A large contemporaneous air-tightness dataset was employed instead. The sample sizes by period of construction are statistically insignificant ranging from minimum of six dwellings constructed between 2005 and 2006 to maximum 25 dwellings between 2000 and 2004. Where the sample sizes are small, the addition of more data could substantially change the average air-permeability rate for differing periods of construction. As it is often difficult for the assessor to ascertain the exact age of the dwelling, dwellings are often classified, as '1970s' but could have been constructed pre-1977 or post-1978 thus changing the age classification. Notwithstanding, the GreenBuild dataset [188];

  - is the largest dataset available for Irish housing in general and detached housing particularly,
  - correlates with a large UK database.

  and is thus considered the most authoritative data-source on the air-permeability rates of detached housing in Ireland and is employed in the characterisation of the case study reference dwellings.

- *Orientation and Shading (Section 4.2.3.3)*

  Arbitrary distribution assumed based on established SyAv geometry

- *Operation & Occupancy Pattern, Set points and Schedules (Section 4.2.2.2)*

  Realistic internal temperatures for UK housing adopted for RD. "Rest of the house" temperature adopted from Irish study that had a relatively small sample size.

- *Level of Occupancy (Section 4.2.2.3)*

  Typical levels of occupancy are not published in the EPC dataset, so data published in the Central Statistics Office (CSO) [71] in Ireland is used. The data was corrected in [39] to apply to DEAP periods of construction employed in this study as shown in

Table 28. The occupancies established were subsequently weighted against the new thermal classifications created through this work (see Table 37).

5.2 Database refinement

Maximum likelihood estimation was used to fit a bi-modal normal curve to the empirical data as detailed in Section 3.2.2. The fitted curve is an approximating function that attempts to capture important patterns in the data while leaving out noise and discrete localised peaks. The approximating function creates SyAv data but assumes that data does not contain small-scale structure.

5.3 Weather Data

Applying a single weather file to the island of Ireland does not capture that temperatures tend to be higher in the south-western areas of the country and lower in the midlands and the northeast, however the range of temperature is modest [135].

5.4 Model Validation

A model can be defined as 'a representation of a real system or process' [216], the relevant measure of model quality is predictive accuracy, in other words, how close the model's predictions are to what actually occurs. While the data and the information resulting from the data used to create the stock model is validated to the extent possible, the only true way of validating the model would be to create the stock energy consumption model and hence to verify the outputs from this model with monitored energy and heat loss data. This is recommended as follow-on study to this work.

Chapter 6 – Summary Discussion & Recommendations

"I think you can have a ridiculously enormous and complex data set, but if you have the right tools and methodology then it's not a problem"

Koblin, A [217]

6.1 Creation of dwelling stock model

Using a predominant single-family housing typology as a case study dwelling, the overarching objective of this research is to define a methodology, to transparently create a dwelling stock model from a large empirical EPC database employing reference dwellings defined using a 'bottom-up' approach.

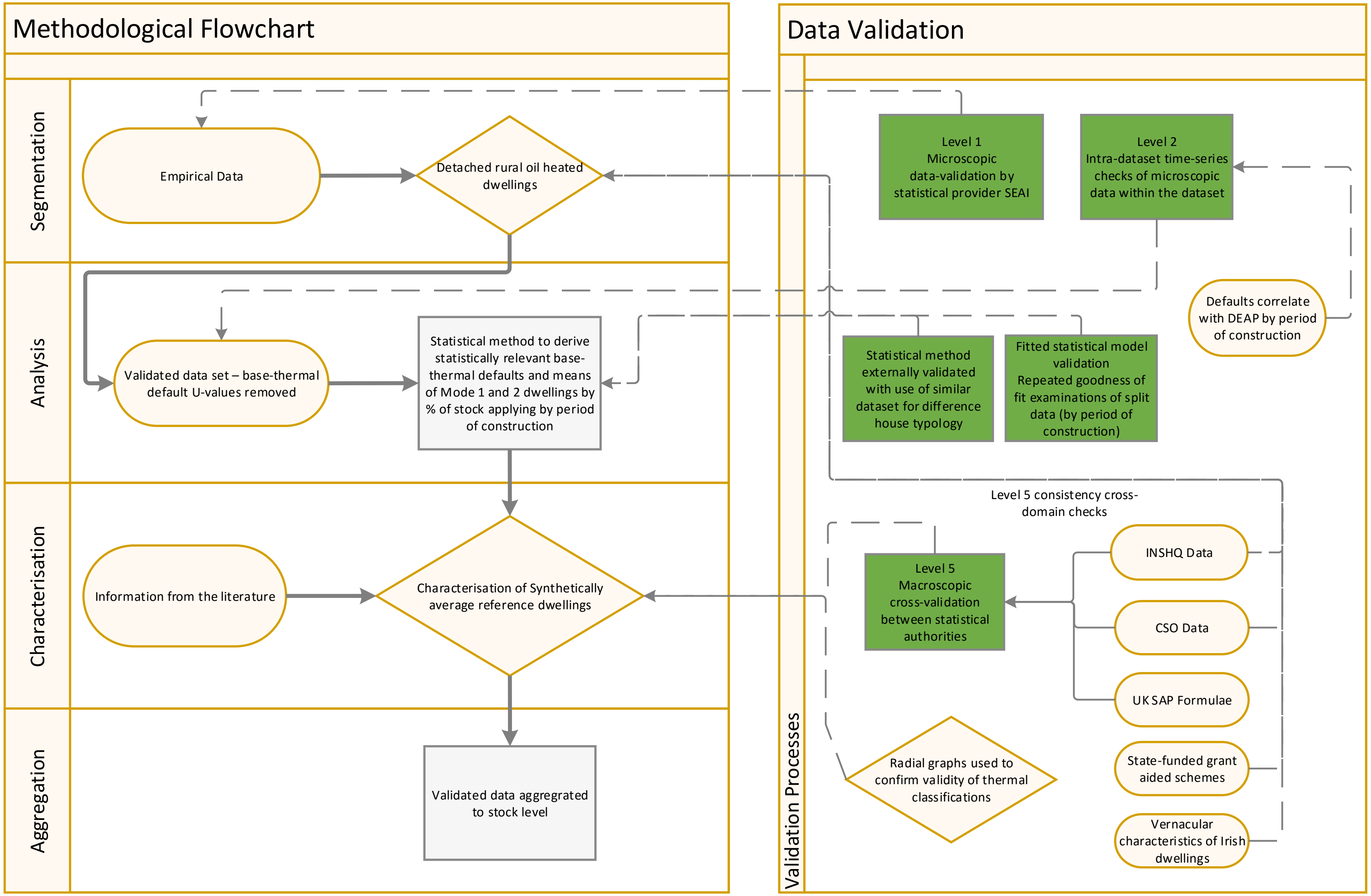
Ireland's predominant house typology, comprising 31 % of the pre-2006 stock, are rural detached, single-family dwellings. This dwelling typology was chosen as a representative case study reference dwelling as just over one third (34 %) of the EU 28 population lived in detached houses in 2013 [43]. Detached dwellings also have relatively high surface area to volume ratios and generally exhibit larger heat losses than other house types of the same construction period [51], and are therefore targeted particularly by energy-efficiency retrofit programmes [57, 67, 68]. Furthermore, 67 % of European housing was built prior to 1980 [69], before the introduction of meaningful thermal building regulations for the housing sector. Mirroring this, 70 % of Irish detached dwellings were constructed before the mid 1970's when constructional changes caused primarily by amendments to draft or actual building thermal regulations led to increased levels of thermal insulation [39, 43, 70-72]. Most houses in Ireland are thus considered to be thermally sub-standard [130, 218-220]. Indeed, Ireland's housing stock is currently identified in the literature [65, 163, 220] as being amongst the least energy efficient in Northern Europe.

The effectiveness of use of RDs depends on the validity of the information used to characterise the RD [54, 58]. The creation of a stock model through RDs follows four distinct methodological stages: 1. Segmentation, 2. Analysis, 3. Characterisation and 4. Aggregation. To ensure that RDs created in the work, represent correctly, the real world constructs to which they refer, and at each methodological stage, the data and the information resulting from the data is assessed to verify an acceptable level of data consistency before proceeding to the next stage. As described in Chapter 2, Eurostat [79, 80] outlines 6 levels of validation, levels 0 to 5, described in terms of consistency. The classification of validation levels presented implies a growing degree of complexity and a lesser 'control' of the data from one level to another. Figure 53, (i) summarises the validation techniques and (ii) outlines the validation levels achieved at the various methodological stages. Referring to Figure 53, at:

- Stage 1, the segmentation stage (see Section 2.3) - the segmented dataset used to develop the reference dwelling characterisations was found to be statistically significant while the segmentation was validated across domains and to level 5 using national census data.
- Stage 2, the analysis stage (see Section 2.4) – through repeated data-splitting across time-periods;
    - o the microscopic data was found to behave consistently whilst correlating with (i) INSHQ data, (ii) state-funded grant schemes, and (iii) vernacular housing characteristics established through a literature review,
    - o a structural data error, identified as the 'default effect' was established and this error was cleaned from the dataset.
- Stage 3, the characterisation stage (See Chapter 4), as the base microscopic data and the methods used to derive information resulting from the data are valid, it follows that the characterisation of reference dwellings ensuing are *de facto* valid. All the same, the reference dwellings characterised were reviewed for validity in the following ways;
    - o dwellings forms were analysed and found to be consistent with vernacular dwelling forms and with data from other statistical providers (level 5),
    - o the validity of the thermal U-value classifications was established via the use of radial graphs,

  - when information within the empirical database was found to be unreliable or lacking such is the case in respect of infiltration rates, thermal bridging coefficients and solar orientations. The composition of the reference dwelling is informed instead through available data and expert enquiries. The information employed was assessed for plausibility before being accepted as valid for use in the characterisation of the RD.
  - in conjunction with established construction characteristics, a CEN externally validated methodology [204] was used to generate the information relating to the internal heat capacity of the RDs.
- Stage 4, the aggregation stage, reference dwellings characterised were aggregated to stock level to correlate with national housing stock quantities.

Figure 53 Methodological and validation process flowchart



6.2 The Default Effect

Default values are necessarily pessimistic to encourage homeowners to maintain documentation relating to thermal retrofits and assessors to investigate construction details thoroughly. The necessity for pessimistic defaults needs to be balanced against ensuring a reasonable level of accuracy for the certificate while allowing the homeowner to perceive the energy advantage of carrying out thermal retrofits. Base-thermal-defaults used currently, were found in Chapter 2, to be outmoded or overly-pessimistic leading to a punitive system, particularly for older dwellings where information is often more difficult to obtain.

Pre-thermal regulation as-built thermal defaults assume no insulation is present in the dwelling envelope. The use of pessimistic thermal defaults combined with existence of significant levels of thermal retrofits in pre-thermal regulation dwellings, as outlined in section 2.4.5 and quantified in section 4.3.1, leads to significantly increased (average of 90 % when compared to empirical data), in the rated primary energy associated with the dwelling heating system. As thermal defaults for post-regulation dwellings are calculated assuming insulation to be present, the discrepancy in rated primary energy associated with the heating system, at an average of 31 %, while less than that of post-thermal regulation dwellings remains significant. The corresponding overall increase (when compared to empirical data) in total rated primary dwelling energy consumption, associated with thermal-default use, is 22 % in post-thermal regulation dwellings and 70 % in pre-thermal regulation dwellings. The associated increase in rated CO_2 emissions, at 23 % in post thermal regulation dwellings and 71 % in pre-thermal regulation dwellings mirrors rated primary energy consumption figures. Use of thermal defaults therefore results in a significantly lower than merited energy rating, particularly for pre-thermal regulation dwellings.

The presence of this structural error in the dataset suggests that despite SEAI's best efforts to ensure that assessments are carried out rigorously, and as outlined in Chapter 2, it appears that assessors do not always carry out thermal assessments of the dwelling envelope as scrupulously as they might. Thus, to mitigate 'the default effect', and as result of this work SEAI now "regularly monitor (overuse of base-thermal-defaults) as a risk amongst Assessors" and "Assessors who continue to carry out assessments in this way are going to keep being selected" for audit [92]. "At audit they can be told why they are being selected so it would be our (SEAIs) hope that Assessors would strive to get that extra evidence to give a more accurate asset rating of the home rather than resort needlessly to defaults" [92].

6.3 Generalisable Methodologies Developed

6.3.1 Method of determining statistically derived contemporaneous thermal-default U-values from an EPC dataset.

It was necessary to establish statistically relevant and thus representative base-thermal-default U-values to replace outmoded base-default U-values used currently. As described in Section 3.2.1 and Figure 17, assuming the empirical thermal dwelling envelope data to distribute normally (variations equally likely to be below and above the mean), a '*reasonably pessimistic'* statistically relevant zone for thermal-default selection was found to lie between the 84.1th or 93.3rd percentiles or 1 to 2 standard deviations from the mean. Selection of a default U-value in this zone will ensure a reasonable level of accuracy for the certificate but also allow the homeowner to perceive the energy advantage of carrying out thermal retrofits. The 90th percentile point falls centrally in this zone, whilst also allowing a margin of error to stay within the desired zone. The refined dataset resulting from the methodological stage 2 was analysed to calculate statistically relevant base-default U-values based on 90th percentile point of the thermal distributions by dwelling element and period of construction.

6.3.2 Method to ascertain renovation state of the housing stock from an EPC dataset

To ascertain the renovation status of the dwelling stock, it was necessary to establish means for retrofitted (Mode 1) and as-built (Mode 2) dwellings by percentage of the dwelling stock applying, by period of construction. Using maximum likelihood estimation a statistical model was developed. The model was also employed to recommend statistically relevant thermal-default U-values based on the 90th percentile point of the empirical data.

The appropriateness of the methodology selected is somewhat demonstrated by the repeated goodness of fit of the fitted curves to the empirical data. The use of the maximum likelihood method ensures that each model by period of construction and by building element type is mathematically optimised to best fit the data on which it is built. Through indicating the highest possible performance, any performance indicator measured on the same sample used to fit the model is biased in favour of the model [159]. Hence, when interested in validating the generalisability of the model to predict outcomes for future subjects, the use of independent (external) data from the same population or similar to fit and test the model is the most stringent and unbiased test for the model and for the data collection process [159-161]. A new sample for single-storey semi-detached dwellings was used to assess the goodness-of-fit of the previously developed model by applying the model as it is to this new sample. The statistical methodology was applied to single and two-storey walls, roofs and floors and was found to be generalisable to other housing typologies whilst also corroborating the expectation that retrofit measures would be applied proportionately across the stock.

6.3.3 Method to determine more realistic payback calculation arising from retrofit measures when a thermal-default U-value is necessarily employed.

As it is not possible to save energy that is not actually being consumed [108], it follows that where base-defaults are employed in an EPC methodology, the program will return unrealistically short payback periods for refurbishment works. To, (i) remove this known barrier to the uptake of energy efficiency upgrades in the residential sector and, (ii) allow the end user to make a more informed decision on retrofitting strategies; reports of the assessor should;

- highlight how building element U-values were determined,
- state how accurate they believe those values to be, and
- carry out a sensitivity analysis highlighting the impact their assumptions may have on the energy label and/or potential energy savings resulting from thermal retrofits.

Ideally, the homeowners would be offered a more likely payback period for the refurbishment works. It is recommended that where base-thermal-default U-values have been employed in a payback calculation and as described in Chapter 3, Figure 31 (b), that a more likely, stochastically based payback period also be offered. The consequent realistic payback periods increase the credibility of the advisory report associated with the EPC.

6.4 The renovation status of stock

Outputs from the model are renovation activity. In 2001, it is estimated that, [70, 131, 138];

- i) 56 % of walls were insulated at a mean U-values of 1.01 W/m^2K,
- ii) 82 % of roofs were insulated at a mean U-values of 1.3 W/m^2K,
- iii) 61 % of windows were double-glazed, and
- iv) 25 % of floors were insulated to a mean U-value of 0.6 W/m^2K.

In 2014, it is estimated that;

- i) 58 % of walls were insulated at a mean U-values of 0.66 W/m^2K,
- ii) 67 % of roofs were insulated at a mean U-values 0.37 W/m^2K,
- iii) 97 % of windows were double-glazed, and
- iv) 53 % of floors were insulated to a mean U-value of 0.59 W/m^2K.

The above listed values apply to detached dwellings only, however, on the expectation that retrofit measures are applied proportionately across the stock this figures are assumed indicative of the renovation status of the pre-2006 Irish dwelling-stock at large.

The average Irish dwelling in 2005 emitted 47 % more CO_2 than the average dwelling in the UK. Emissions were 92 % higher than the average for the EU-15 and 104 % more than the EU-27 [221]. The (i) extent of thermal retrofits and (ii) high degree of energy-efficiency improvements in Ireland contribute significantly [222] to;

- o household energy usage per square metre being 20 % below the UK average and 9 % below the EU 27 average in 2010, and
- o the average energy efficiency of Irish housing having improved by over 34 % between 1995 and 2011 (2.5 % per annum).

Whilst also meaning that;

- o the distinction between the thermal efficiency of pre-thermal regulation and post-regulation dwellings, whilst still valid, is lessening,
- o the strong association of dwelling age and energy efficiency is diminishing as retrofits in the sector are carried out, and
- o pessimistic 'as-built' base-thermal U-values are significantly outmoded.

Using average wall U-values by period of construction [76] established in this work, Irish dwellings in 2014 are shown to compare favourably with available data for the Netherlands and Poland [17]. This suggests that the long-held view that the majority of Irish dwellings are thermally sub-standard [65, 163, 220] may no longer hold true.

6.5 Policy Recommendations

The average growth rate in European floor areas was 0.25 % per annum between 1997 and 2007 [65, 70]. The average growth for Irish dwellings in general over the same period is 1.3 % per annum [207]. With increasing trends in floor space, the energy demand associated with Irish dwellings is producing a phenomenon known as the 'size effect' [65, 70, 208]. At current average EU growth rates it is estimated that 20 % of energy efficiency progress for thermal uses has been offset, all things being equal, by the fact that dwellings are becoming larger [65]. Detached Irish dwellings show a growth rate of 1.6 % and 1.34 % per annum in heated floor area for single and two-storey respectively. Therefore, for the detached dwellings typology *all* of the energy efficiency gains achieved through thermal regulations of the housing sector are being offset by the size effect. To address this size effect in Irish dwellings, a policy measure which area weights the maximum average U-value (U_m) by reducing U_m in line with increasing building floor area (A_f) is recommended [70].

One in four dwellings in Ireland in 2016 use solid-fuel from non-renewable resources as a heat source. A policy measure to encourage homeowners of solid-fuel heated dwellings to convert to renewable fuel resources is recommended.

6.6 Contribution to Knowledge

All other reference dwelling characterisations in Ireland, as detailed in Table 41, are based on (i) outmoded base or as-built thermal default characteristics, (ii) small sample sizes or indeterminate data. To address (a) the lack of transparent reporting, (b) to allow comparison of dwelling stocks across EU member states, and (c) to allow cost-optimal refurbishment interventions for the housing stock to be developed, the European Commission developed a common reporting methodology (Regulation No. (EU) 244/2012) for RDs. The focus of this work was to carry out a systematic inquiry involving the practical application of available and relevant information to create a dwelling stock model derived from RDs and to report the data in compliance with Regulation No. (EU) 244/2012.

35 reference dwellings (RDs) have been employed to characterise appropriately, 406,918 dwellings, averaging one RD per 11,626 dwellings. The number of characterisations could likely be reduced by employing a sensitivity analysis to quantify the impact of thermal variables on overall energy loads.

The characterisation of the reference dwelling detailed in this work is;

i. founded in real-world data and from a statistically significant dataset,
ii. appropriately characterised with a high level of detail,
iii. as contemporaneous as possible,
iv. based on the highest quality empirical or real data available currently,
v. contributes to a consensus on appropriate methods for the characterisation of an RD.
vi. commonly and transparently reported, compliant with EU Commission Delegated Regulation No 244/2012.

Use of these appropriately characterised RDs as inputs to national residential energy consumption models shall best represent the energy saving potential of Ireland's predominant housing typology. It will enable the quantification of the effect of default value use on the prebound effect in dwellings.

Chapter 7 – Conclusions

"Effective policy making starts with an accurate picture of the challenge"

Economidou et al. 2011 [17]

Energy analyses of dwelling stocks are defined by a stock model and an energy model. The stock model describes the development of the stock in terms of size, composition and renovation state, whereas the energy model includes average energy intensities of the various segments of the stock and assumed savings obtained when dwellings are renovated. Historically, building stock energy consumption models were informed by poor or outdated information leading to invalid information. There has also been a lack of documented transparency around model inputs.

Since it has been impractical to calculate optimal energy refurbishment interventions for every single building, the EPBD Guidelines requires each EU member state to define a set of reference buildings (RBs) that are representative of typical national or regional building stocks.

Using a representative single-family housing typology as a case study dwelling, the overarching objective of this research is to define a transparent generalisable methodology to create a stock model from a large empirical EPC database employing reference dwellings (RDs) defined using a 'bottom-up' approach. RDs are reported in compliance with EU Regulation No. 244/2012 common reporting methodology.

The level of thermal retrofits in Ireland is quantified, to find that 58 % of walls (U-value range from 0.29 Wm^2K to 0.39 Wm^2K) and 67 % (U-value range from 0.13 Wm^2K to 0.29 Wm^2K) of roofs had significant levels of insulation. This leads to;

i) a lesser association between a dwellings age and its energy efficiency,
ii) positively-shifting bi-modal frequency distribution of thermal characteristic, and
iii) current base-thermal-default U-values being increasingly and significantly outmoded.

It has been found that the adoption of pessimistic as-built base default U-values under-ranks the energy performance of circa 90 % of dwellings. It especially under ranks pre-regulation dwellings and, where used, is found to be a significant contributing factor to the prebound effect in dwellings and the energy performance gap of national residential energy consumption models.

This work has derived a validated generalisable methodology to establish statistically relevant base-thermal-default U-values. Use of the default U-values established will help narrow the energy performance gap by increasing the accuracy and hence credibility of the EPC and its associated advisory report. Moreover, to allow the end user to make a more informed decision on retrofitting strategies, reports of the assessor should;

- highlight how building element U-values were determined,
- how accurate they believe those values to be, and
- carry out a sensitivity analysis highlighting the impact their assumptions may have on the energy label and/or potential energy savings resulting from thermal retrofits.

Ideally, the homeowners could be offered a more likely payback period for the refurbishment works. It is recommended that where base-thermal-default U-values have been employed in a payback calculation that a more likely, stochastically based, payback period also be offered. The consequent realistic payback periods, increase the credibility of the advisory report associated with the EPC.

This work has developed generalisable methodologies that reduce the gap between the theoretical prediction and actual energy consumed in dwellings through characterising data more representative of national dwelling stocks. The work defines;

i) statistically relevant contemporaneous thermal base-default U-values,
ii) a stock model developed from largely-default-free synthetically averaged RDs,
iii) the renovation status of dwelling stock,
iv) a stochastically based payback calculation methodology to be used where pessimistic base-thermal-default U-values are necessarily employed.

Use of the statistically-derived empirical data created in this work will increase the accuracy and hence credibility of residential stock energy consumption models, the EPC and its associated advisory report and enable quantification of the;

d) energy saving potential of Ireland's predominant housing typology,

e) effect of base-thermal-default value use on the prebound effect in dwellings, and

f) overall national building energy consumption.

Chapter 8 – Future Study

"In the end you should only measure and look at the numbers that drive action, meaning that the data tells you what to do next"

Peinger, A

8.1 Energy Analysis of Irelands Predominant Housing Typology

Stock models enable energy analyses of the dwelling stock. The stock model created in this work is validated, to the extent possible and suitable for use as inputs to a residential stock energy model. An obvious future work, as shown in Figure 54, is to use reference dwellings created as simplified inputs to a bottom-up engineering stock energy model. True validation of the model can hence be achieved through comparing the outputs of the energy model with monitored energy and heat loss data.

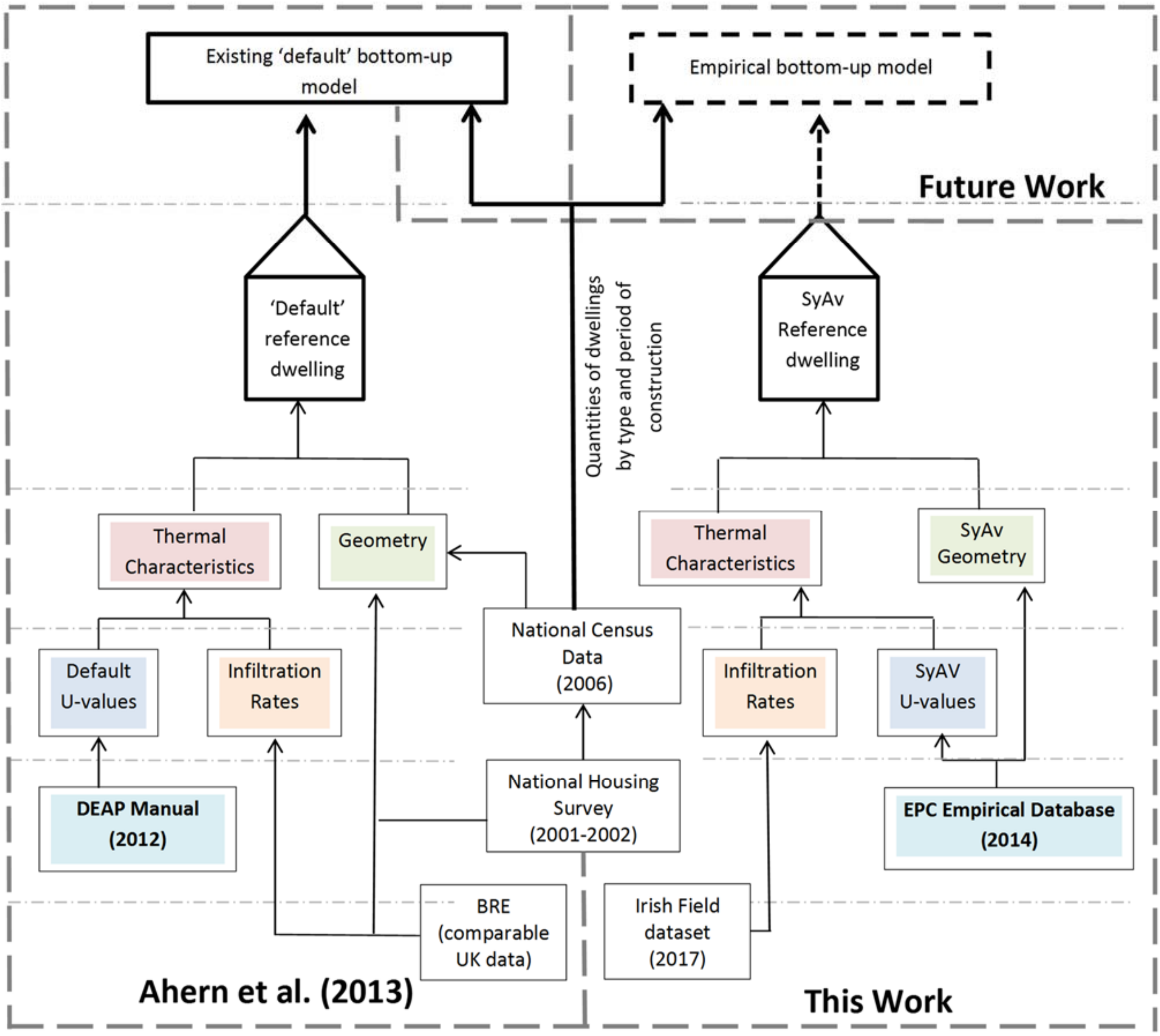
8.2 Quantifying the 'default effect' and its contribution to the 'prebound effect'

As shown in Figure 54 and as described in Appendix E (Section E.2), prior to the publication of the empirical database and due to a lack of statistical data, similar to the Irish TABULA project, RDs were created for Ireland's predominant house typology by Ahern *et al*. (2013) [39, 70] using base-default thermal characteristics.

In this work, a selection set of RD's for a singular orientation were inputted to the DEAP methodology to demonstrate the significantly increased rated primary energy consumption (kWhr/y) and CO_2 emissions (kg/y) attributable to default RDs when compared to empirical RD's.

It is recommended that the (i) full stock model of SyAv RD's (including all orientations) and (ii) base-default RDs created previously, be energy modelled and the outputs hence compared. In this way, it is possible to estimate the full effect of pessimistic thermal default U-value assumptions on the statistical accuracy of the energy performance label for existing dwellings and the potential impact of their selection on the prebound effect in dwellings.

Figure 54 Characterisation of a 'default' virtual and SyAv reference dwelling for Ireland's predominant housing typology [38]



8.3 Sensitivity analysis of energy consumption factors in dwellings

As discussed in Section 4.2, multi-collinearity between factors makes it difficult to isolate which have the greatest influence on dwelling energy consumption, [27, 28]. A sample of reference dwellings should be modelled to isolate which factors have the greatest influence on dwelling energy consumption. Model outputs should ideally, be validated against collected energy consumption data for detached dwellings. As the RDs are not actual dwellings but notional dwellings, characterised by a set of properties statistically detected in a category of buildings, correction factors would apply to correlate the outputs from the energy consumption model with actual energy consumption data from a sample of monitored dwellings. It would be useful to understand the range of correction factors arising and the causes determining that range.

It would be beneficial to identify a real dwelling mirroring the characteristics of mean geometrical and construction features of an RD, a "Real Average Building" (*ReAv*), and using the ReAv dwelling to validate the energy model but also to allow a sensitivity analysis of model inputs as part of the monitoring exercise. A sensitivity analysis to the use of statistically derived SyAv mean U-values to models is also recommended.

8.4 Intelligent EPC database

The methodologies developed can be employed to create a stock model of other housing typologies in Ireland and across Europe derived from EPC databases. The creation of stock models will inform renovation activity and allow monitoring and comparison of dwelling stocks across Europe, thereby enabling insight-driven decisions and informed policy.

Generation of stock-models from large datasets relies heavily on laborious manual data analysis. Increased automation would liberate information more readily from large data-rich EPC databases whilst also improving data accuracy.

Ideally, the methodologies developed in this work would be automated within EPC databases enabling them to transform automatically processed data into useful information, thereby making EPC databases artificially intelligent. The work of this case study could be used to gain trust in the accuracy of automated data analysis.

Continual analysis of the data by a database engine would enable EPC databases to reflect a live-stock model of a national dwelling stock; producing empirically derived housing typologies, by period of construction, by percentage of the dwelling stock applying. Intelligent EPC databases could readily, contemporaneously and accurately inform a national residential energy consumption model. The database engine could also be used to:

i) Clean the database of base-thermal-defaults.
ii) Detect and prevent the input of erroneous data through identifying and ranking information that positively correlates with defined attributes of unscrupulous activities. EPC administrators can learn from their audit history to detect new data patterns and increase the validity of the dataset thereby allowing them to focus more on exception-handling and service quality.
iii) Inform validation rules to maintain the quality of the database.
iv) Monitor changes in patterns in the data so indicating renovation activity and trends over time but also the effectiveness of certain policy interventions across defined time-periods.
v) Ascertain statistically derived base-default U-values as well as mean Mode 1 and Mode 2 U-values to inform more validly EPCs and payback calculations so narrowing the energy performance gap while increasing the credibility of the information produced.

The validated information resulting can be used to enable insight-driven decisions on how to maintain compliance, identify opportunities for policy interventions, and deflect risk without investing time to research.

8.5 The 'size effect' in Irish dwellings

To address this size effect in Irish dwellings, creation of a policy measure that area weights the maximum average U-value (U_m) by reducing U_m in line with increasing building floor area (A_f) [70] is recommended.

8.6 Research to close data-information gaps

This research found a lack of information pertaining to;

i) Operation of dwellings - Statistically average heating schedules and mean temperatures for an average year are required for a one-fits-all model of space heating consumption associated with detached dwellings. To mitigate savings taken back through increased comfort temperatures, an energy consumption model should ideally reflect empirical heating schedules and mean temperatures realised in the housing stock. Empirical studies to date, carried out on small samples, suggest heating schedules and mean temperatures vary by dwelling typology. It is recommended that an appropriate sample set of each dwelling typologies be monitored to determine the range of temperatures and heating schedules realised in the housing stock. This work could be potentially be facilitated by SEAI through the EPC assessment process.

ii) Air-tightness in dwellings - there is a paucity of published data relating to the real air-tightness charateristics of existing dwellings in both the UK and Ireland – it is recommended that as part of an EPC assessment process that an air-tightness test of the dwelling become mandatory.

iii) Thermal Bridging – Linear thermal transmittance (ψ) (measured in W/mK) describes the heat loss associated with a thermal bridge not accounted for in the U-values of the plane building elements containing the thermal bridge. Psi (ψ) values in this study were sourced from the UK SAP guidelines as Psi values quoted in the Irish regulations are linked with U-values that were not representative of the empirical U-values evidenced in the housing stock. It is recommended that a greater number of Psi values, linked to representative U-values be made available within the Irish Building Regulations.

iv) Orientation – to facilitate dynamic energy modelling of the dwelling stock – it is recommnended that assessors input the orientation of the front (longside) of the dwelling.

v) Classification of two-storey dwellings – A single-storey dwelling where the attic is converted into a habitable space is recorded in DEAP as a separate storey. To facilitate better, the characterisation of reference dwelling it is recommended that two-storey dwellings by classified by type (single-storey with an attic conversion or as-built as a two-storey dwelling) in the EPC database.

vi) Floor U-values - DEAP [72] is the only authoritative published guide detailing typical composite floor constructions. This research suggests that the use of default ground floor U-values quoted in DEAP [72] will underestimate the heat loss through the ground in the majority of locations in Ireland. It is recommended that a study be carried out to determine empirical floor U-values and that the default floor U-value in DEAP be reassessed.

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Appendices

Appendix A – SPSS analysis methodology

EPCs in Ireland are generated through a methodology embodied in the national Dwelling Energy Assessment Procedure (DEAP) software programme administered on behalf of the state by the Sustainable Energy Authority of Ireland (SEAI). SEAI made this detailed national empirical dataset publicly available in 2014 [75]. As shown in Figure A1, 463,582 dwellings representing 31.7 % of the total dwelling stock constructed up to 2006 received an EPC by August 2014 were downloaded from the SEAI website into Excel® [76].

As shown in Figure A1, 25 % (N=116,354) of the dwellings within the database are detached dwellings; this figure mirrors the percentage of detached dwellings nationally (28 % in 2006 census – see Figure 1). 60 % of detached dwellings within the database are rurally located an average of 76 % (19 % nationally) of which are heated by fuel oil [76]; at 18 % nationally (see Figure 1), this distribution also mirrors the percentage of detached dwellings nationally. 97 % of detached dwelling are either single or two-storey with only 3 % being three-storey or greater, while 98 % are naturally ventilated [76].

Rural, single and two-storey, oil centrally-heated and naturally-ventilated dwellings, accounting for 18 % of the dwelling stock nationally, represent consistently strongly across periods of construction, and are thus the predominant and hence statistically average dwelling type in Ireland. Accordingly dwellings consistent with these prevalent characteristics were isolated from the larger dataset as shown in Figure A1. Dwellings carrying a 'provisional' certificate were also filtered. As shown in Figure A1, this resulted in a sample of 50,236 dwellings representing 12.35 % of the detached dwelling typology nationally.

Figure A1 Selection process for comparative empirical dataset of sample size 'N_s'

- All dwelling typologies
- N = 463,583

- Detached dwellings only
- N =116,354

- Detached rurally located dwellings (includes three and four storey dwellings)
- N = 69,952

- One and two storey detached rurally heated dwellings
- N =67,857 (97 %)

- Oil heated, rurallly located detached dwellings
- N = 54,863

- Oil heated,rurally located, naturally ventilated detached dwellings to 2014
- N = 53,610

- Oil heated, rurally located, naturally ventilated detached dwellings limited to 2006, provisional certificates removed
- N= 50,236

The SPSS® programme is used to analyse descriptive statistics as shown in Figure A2. To cross-tabulate information, SPSS® requires data to be classified numerically as shown in Figure A3 and A4. Thus, to allow analysis by dwelling age, each period of construction was ascribed a number as shown in Table A1 and as shown in Figures A2 and A3.

The thermal performance of single storey and two-storey dwellings with the same thermal characteristics will differ owing to a different volume to surface area ratio. Results should thus be presented for single and two-storey dwellings by period of construction. Single-storey dwellings are thus ascribed a numerical value of one and two-storey dwellings a numerical quantity of 2 and this is handled as shown in Figure A5. Quantities of dwellings represented in the empirical dataset are shown in Table A2, on average 47 % of dwellings analysed were single storey and 53 % two-storey.

Table A1 Frequency of detached dwellings in representative empirical dataset compared with actual dwelling frequency by period of construction [71, 76]

Period of Construction		Numerical reference for SPSS analysis	Frequency in empirical dataset	
			N	%
Post-thermal regulation	2005-2006	1	3693	17%
	2000-2004	2	8867	17%
	1994-1999	3	7080	15%
	1983-1993	4	8375	14%
	1978-1982	5	5695	19%
Pre-thermal regulation	1967-1977	6	6559	13%
	1950-1966	7	3662	11%
	1930-1949	8	2110	7%
	1900-1929	9	2901	8%
	< 1900	10	1294	3%
Total/% of Total			50236/100%	

Figure A2 Analysing descriptive statistics in SPSS®

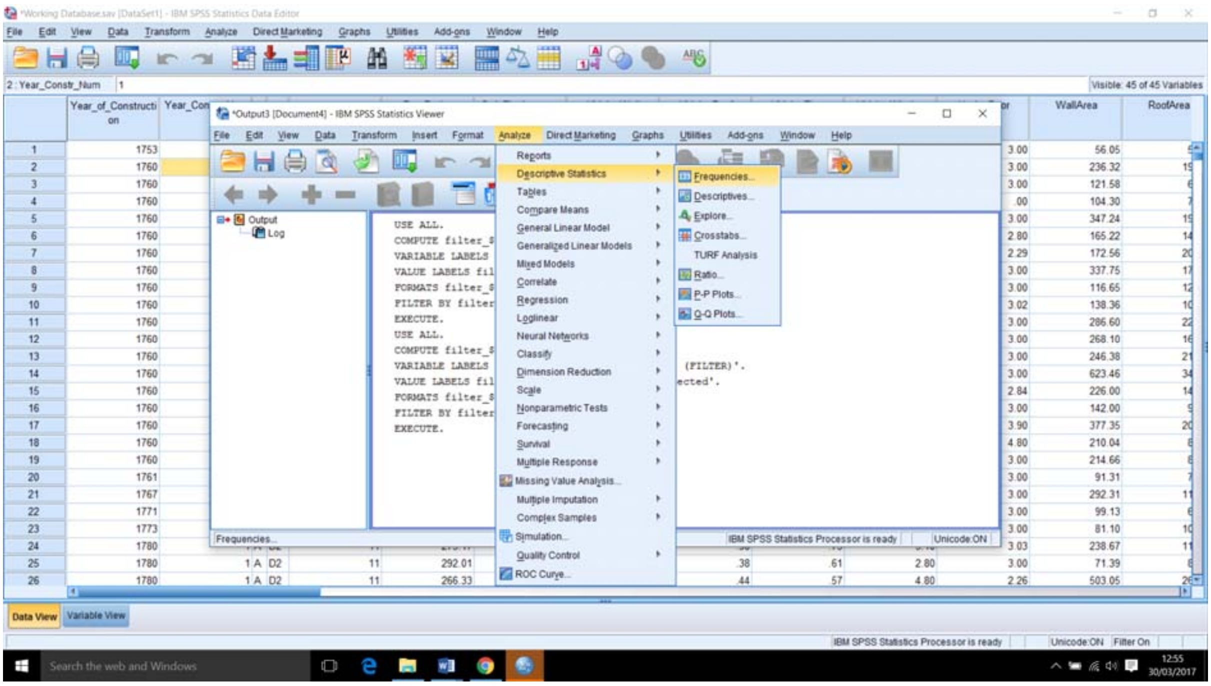


Figure A3 Step 1 - Selecting cases to analyse specific data by period of construction in SPSS®

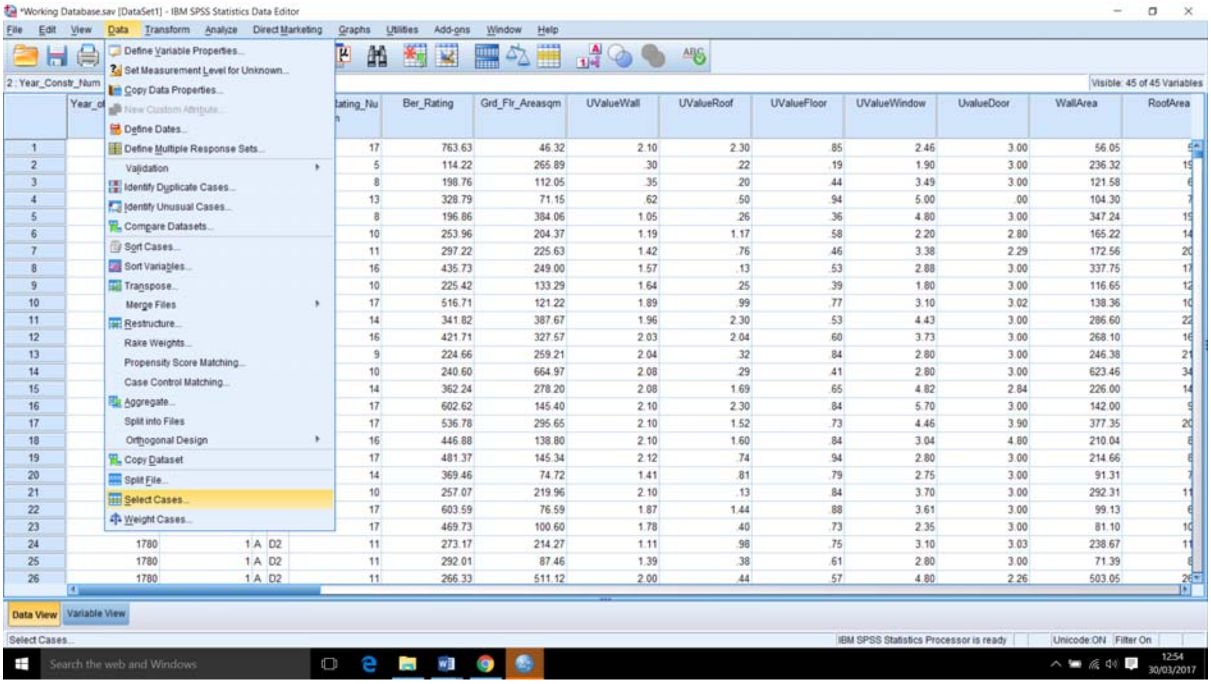


Figure A4 Step 2 - Selecting period of construction by numerical reference in SPSS®

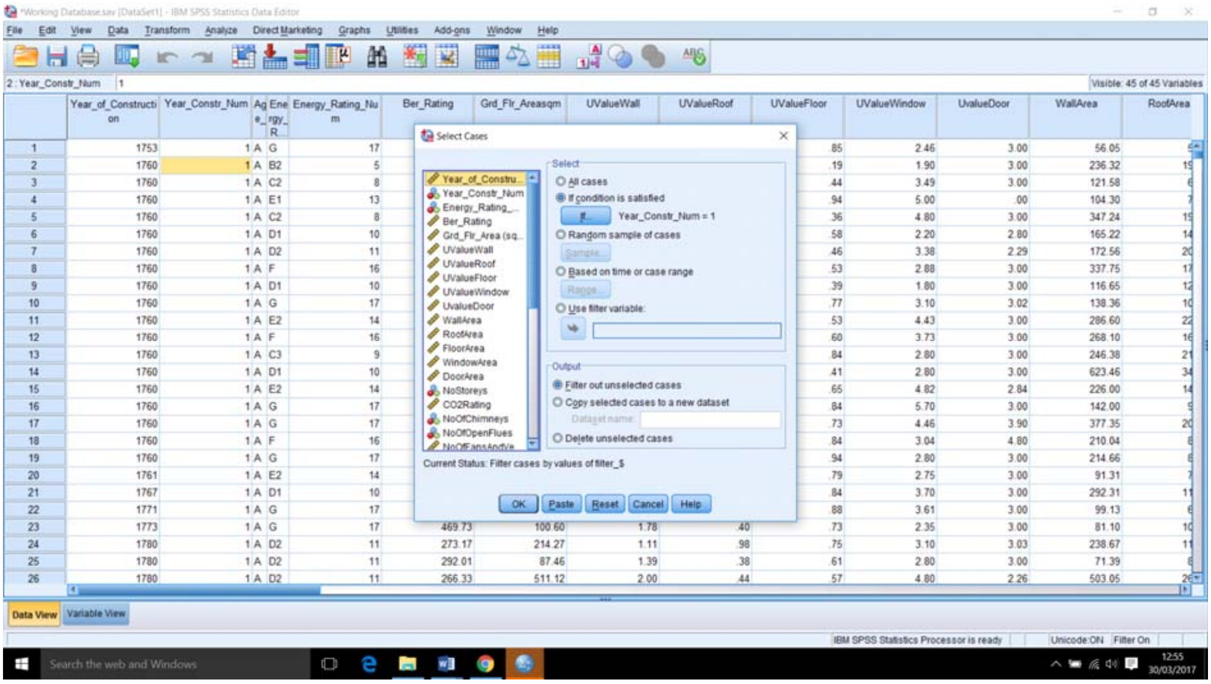


Figure A5 Step 3 - Selecting cases to analyse specific data by period of construction and number of stories in SPSS®

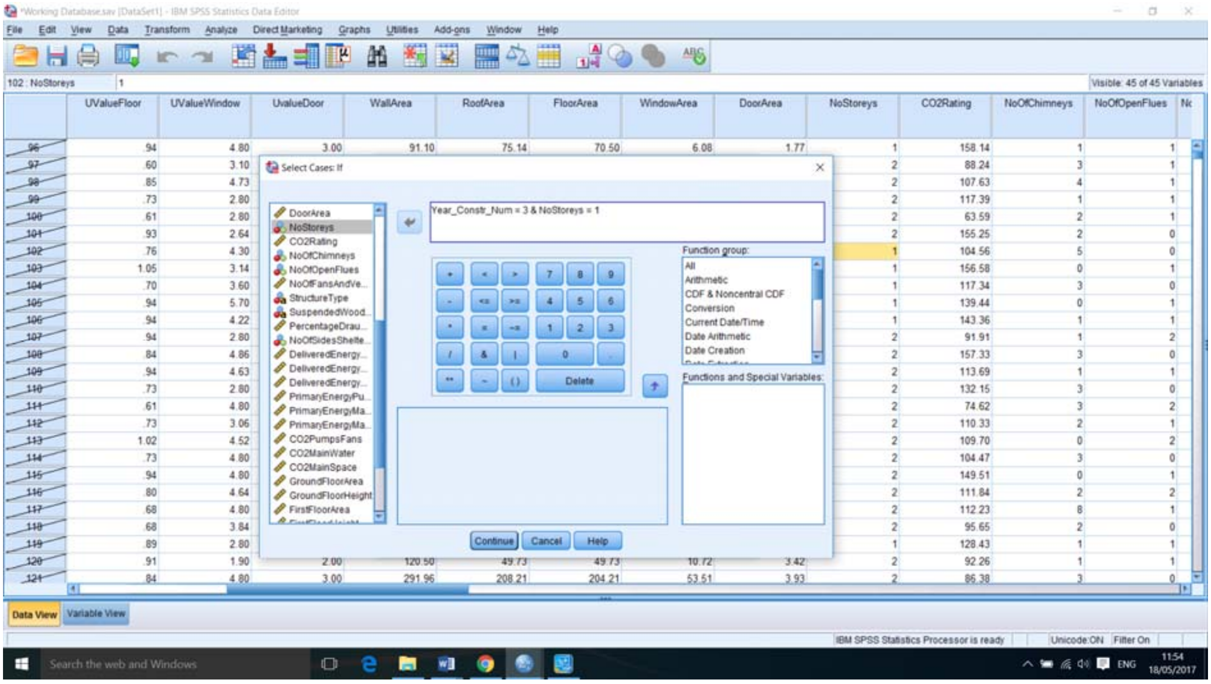


Table A2 Frequency of single and two-storey dwellings in the empirical dataset by period of construction [71]

			Single Storey		Two Storey	
			Quantity	%	Quantity	%
Period of Construction	< 1900	1294	505	39%	789	61%
	1900-1929	2901	1131	39%	1770	61%
	1930-1949	2110	1076	51%	1034	49%
	1950-1966	3662	2380	65%	1282	35%
	1967-1977	6559	4329	66%	2230	34%
	1978-1982	5695	3531	62%	2164	38%
	1983-1993	8375	4690	56%	3685	44%
	1994-1999	7080	3398	48%	3682	52%
	2000-2004	8867	3724	42%	5143	58%
	2005-2006	3693	1551	42%	2142	58%
	Total	**50236**	**26316**	**52%**	**23920**	**48%**

Appendix B – Manual default U-Value calculations

Calculation of likely U-values

Table B1 300 mm non-rendered, plaster-finished, stone wall U-value

		Source (CIBSE Guide A)	Thickness (mm)	Thermal Conductivity (W/mK)	Thermal resistance (m^2K/W)	U-Value (W/m^2K)
Element	Outer Surface	Table 3.10			0.04	
	Limestone	Table 3.38	300	2.75	0.11	
	Plaster	Table 3.38	0	0.8	0.00	
	Inner Surface	Table 3.9			0.13	
Composite building element				Σ R =	0.28	
	350 mm uninsulated non-rendered plaster-finished limestone wall					**3.6**

* Interpolated from Table 3.38 CIBSE Guide A (see Pg. 213) assuming typical Density 2690 kg/m^3 [223]

Table B2 350 mm rendered, plaster-finished, stone wall U-value

		Source (CIBSE Guide A)	Thickness (mm)	Thermal Conductivity (W/mK)	Thermal resistance (m^2K/W)	U-Value (W/m^2K)
Element	Outer Surface	Table 3.10			0.04	
	Outside Render	Table 3.37	19	0.8	0.02	
	Limestone	Table 3.38	350	2.75	0.13	
	Plaster	Table 3.38	13	0.8	0.02	
	Inner Surface	Table 3.9			0.13	
Composite building element				Σ R =	0.34	
	350 mm uninsulated rendered plaster-finished limestone wall					**3.0**

Source Data - CIBSE Guide A [124]

Table 3.48 Values of surface and airspace resistance used in calculation of thermal properties of typical constructions

Structure	External surface resistance / $m^2 \cdot K \cdot W^{-1}$	Internal surface resistance / $m^2 \cdot K \cdot W^{-1}$	Airspace resistance / $m^2 \cdot K \cdot W^{-1}$
External walls	0.04	0.13	0.18
Party walls and internal partitions	0.13	0.13	0.18
Roofs:			
— pitched	0.04	0.10	0.16
— flat	0.04	0.10	0.16
Ground floors	0.04	0.17	0.21
Internal floors/ceilings	0.13	0.13	0.18

Calculation of likely U-values (cont.)

Table B3 500 mm rendered, plaster-finished, stone wall U-value

		Source (CIBSE Guide A)	Thickness (mm)	Thermal Conductivity (W/mK)	Thermal resistance (m^2K/W)	U-Value (W/m^2K)
Element	Outer Surface	Table 3.48			0.04	
	Outside Render	Table 3.37	25	1	0.03	
	Limestone	Table 3.38 a	500	1.5	0.33	
	Plaster	Table 3.38 b	25	0.8	0.03	
	Inner Surface	Table 3.48			0.13	
Composite building element				Σ R =	0.56	
	500 mm uninsulated rendered plaster-finished limestone wall					**1.8**

Table B4 500 mm non-rendered, plaster-finished, stone wall U-Value

		Source (CIBSE Guide A)	Thickness (mm)	Thermal Conductivity (W/mK)	Thermal resistance (m^2K/W)	U-Value (W/m^2K)
Element	Outer Surface	Table 3.48			0.04	
	Limestone	Table 3.38 a	500	2.75	0.18	
	Plaster	Table 3.38 b	13	0.8	0.02	
	Inner Surface	Table 3.48			0.13	
Composite building element				Σ R =	0.37	
	500 mm uninsulated plaster-finished limestone wall					**2.7**

Source Data (cont.)- CIBSE Guide A [124]

Table 3.38 a Thermal conductivity, density and specific heat capacity: inorganic, porous materials — *continued*

Material	Condition/test (where known)	Source	Thermal conductivity / $W \cdot m^{-1} \cdot K^{-1}$	Density / $kg \cdot m^{-3}$	Specific heat / $J \cdot kg^{-1} \cdot K^{-1}$
Masonry (continued):					
— mediumweight	Dry	T	0.54	1550	840
— quarry-stones, calcareous	Dry	T	1.40	2200	840
Miscellaneous materials:					
— aggregate	Undried	D	1.8	2240	840
— aggregate (sand, gravel or stone)	Oven dried	A	1.3	2240	920
— building board, tile and lay-in panel		A	0.058	290	590
— calcium silicate brick		S	1.50	2000	840
— granolithic		E	0.87	2085	840
— mud phuska	At 50°C	I	0.52	1620	880
— tile bedding		E	1.40	2100	650
— tile hanging		C	0.84	1900	800
Roofing materials:					
— built-up roofing		D	0.16	1120	1470
— roof tile		C	0.84	1900	800
— tile, terracotta		T	0.81	1700	840
Soil:					
— alluvial clay, 40% sands		I	1.21	1960	840
— black cotton clay, Indore		I	0.61	1680	880
— black cotton clay, Madras		I	0.74	1900	880
— diatomaceous, Kieselguhr or infusorial earth	Moisture content 9%	E	0.09	480	180
— earth, common		E	1.28	1460	880
— earth, gravel-based		E	0.52	2050	180
Stone:					
— basalt		T	3.49	2880	840
— gneiss		T	3.49	2880	840
— granite		T	3.49	2880	840
— granite, red		E	2.9	2650	900
— hard stone (unspecified)		T	3.49	2880	840
		S	2.9	2750	840
— limestone		E	1.5	2180	720
		S	2.9	2750	840
	At 50°C	I	1.80	2420	840
— marble		S	2.9	2750	840
	Dry	T	2.91	2750	840
	Moist	T	3.49	2750	840
— marble, white		E	2	2500	880
— petit granit (blue stone)	Dry	T	2.91	2700	840
	Moist	T	3.49	2700	840
— porphyry		T	3.49	2880	840
— sandstone		E	1.83	2200	710
		T	3	2150	840
		T	1.3	2150	840
		S	5	2150	840

Calculation of likely U-values (cont.)

Table B5 225 mm rendered, plaster-finished, solid brick wall U-Value

		Source (CIBSE Guide A)	Thickness (mm)	Thermal Conductivity (W/mK)	Thermal resistance (m^2K/W)	**U-Value (W/m^2K)**
Element	Outer Surface	Table 3.48			0.04	
	Outside Render	Table 3.37	19	0.8	0.02	
	External Brickwork	Table 3.1	225	0.77	0.29	
	Plaster (lime)	Table 3.38 b	13	0.8	0.02	
	Inner Surface	Table 3.48			0.13	
Composite building element				Σ R =	0.50	
	225 mm uninsulated plaster-finished solid-brick wall					**1.99**

Table B6 250 mm Solid mass concrete, rendered and plaster-finished wall U-value

			Thickness (mm)	Thermal Conductivity (W/mK)	Thermal resistance (m^2K/W)	**U-Value (W/m^2K)**
Element	Outer Surface	Table 3.48			0.04	
	Outside Render	Table 3.37	19	0.8	0.02	
	Solid Mass Concrete	Table 3.1	250	2.06	0.12	
	Plasterboard (stand.)	Table 3.48	13	0.21	0.06	
	Inner Surface	Table 3.48			0.13	
Composite building				Σ R =	0.38	
	Solid Mass Concrete					**2.65**

Source Data (cont.)- CIBSE Guide A [124]

Table 3.47 Properties of materials used in calculation of thermal properties of typical constructions

Material	Density / $kg \cdot m^{-1}$	Thermal conductivity / $W \cdot m^{-1} \cdot K^{-1}$	Specific heat capacity / $J \cdot kg^{-1} \cdot K^{-1}$
Masonry materials:			
— sandstone	2300	1.8	1000
— brick (exposed)	1750	0.77	1000
— brick (protected)	1750	0.56	1000
— no-fines concrete	2000	1.33	1000
— concrete block (dense) (exposed)	2300	1.87	1000
— concrete block (dense) (protected)	2300	1.75	1000
— precast concrete (dense) (exposed)	2100	1.56	1000
— precast concrete (dense) (protected)	2100	1.46	1000
— cast concrete	2000	1.33	1000
— cast concrete	1800	1.13	1000
— lightweight aggregate concrete block	600	0.20	1000
— autoclaved aerated concrete block	700	0.20	1000
— autoclaved aerated concrete block	500	0.15	1000
— screed	1200	0.46	1000
— ballast (chips or paving slab)	1800	1.10	1000
Surface materials/finishes:			
— external render (lime,sand)	1600	0.80	1000
— external render (cement,sand)	1800	1.00	1000
— plaster (dense)	1300	0.57	1000
— plaster (lightweight)	600	0.18	1000
— plasterboard (standard)	700	0.21	1000
— plasterboard (fire-resisting)	900	0.25	1000
Insulation materials:			
— mineral wool (quilt)	12	0.042	1030
— mineral wool (batts)	25	0.038	1030
— expanded polystyrene (EPS)	15	0.040	1450
— extruded polystyrene	40	0.035	1400
— polyurethane foam	30	0.025	1400
— urea formaldehyde (UF) foam	10	0.040	1400
— blown fibre	12	0.040	1030

Calculation of likely U-values (cont.)

Table B7 330 mm Solid mass concrete, rendered and plaster-finished wall U-value

			Thickness (mm)	Thermal Conductivity (W/mK)	Thermal resistance (m^2K/W)	**U-Value (W/m^2K)**
Element	Outer Surface	Table 3.48			0.04	
	Outside Render	Table 3.37	19	0.8	0.02	
	Solid Mass Concrete	Table 3.1	330	2.06	0.16	
	Plasterboard (stand.)	Table 3.47	13	0.21	0.06	
	Inner Surface	Table 3.48			0.13	
Composite building				Σ R =	0.42	
				Solid Mass Concrete		**2.40**

Source Data (cont.)- CIBSE Guide A [124]

Table 3.38 b Thermal conductivity, density and specific heat capacity: inorganic, porous materials

Material	Condition/test (where known)	Source	Thermal conductivity $/ W{\cdot}m^{-1}{\cdot}K^{-1}$	Density $/ kg{\cdot}m^{-3}$
Asbestos-related materials:				
— asbestos cement		S	1.02	1750
— asbestos cement building board		D	0.6	1920
— asbestos cement decking		C	0.36	1500
— asbestos cement sheet	Conditioned	C	0.36	700
— asbestos fibre	At 50°C	I	0.06	640
— asbestos mill board	At 50°C	I	0.25	1400
Brick		D	0.72	1920
		D	1.31	2080
— aerated		S	0.30	1000
— brickwork, inner leaf		C	0.62	1700
— brickwork, outer leaf		C	0.84	1700
— burned		S	0.75	1300
		S	0.85	1500
		S	1.00	1700
— mud	At 50°C	I	0.75	1730
— paviour		E	0.96	2000
— reinforced	At 50°C	I	1.10	1920
— tile	At 50°C	I	0.8	1890
Cement/plaster/mortar:				
— cement		D	0.72	1860
— cement blocks, cellular		T	0.33	520
— cement fibreboard, magnesium oxysulphide binder		A	0.082	350
— cement mortar		S	0.72	1650
	Dry	T	0.93	1900
	Moist	T	1.5	1900
— cement/lime plaster		S	0.8	1600
— cement panels, wood fibres	Dry	T	0.08	350
	Moist	T	0.12	350
		T	0.12	400

Calculation of likely U-values (cont.)

Table B8 Concrete hollow block, rendered and plaster-finished wall U-value [137]

		Source	Thickness (mm)	Thermal Conductivity (W/mK)	Thermal resistance (m^2K/W)	U-Value (W/m^2K)
Element	Outer Surface	[211]		Data not published in study		
	Outside Render (cement/sand)	[211]	20			
	Conrete hollow block (40 + 135 + 40) (see Figure B1)	[211]	215			
	Plasterboard (gypsum)	[211]	12			
	Inner Surface	[211]				
Composite building element				Σ R =	0.48	
				Concrete hollow block wall		**2.09**

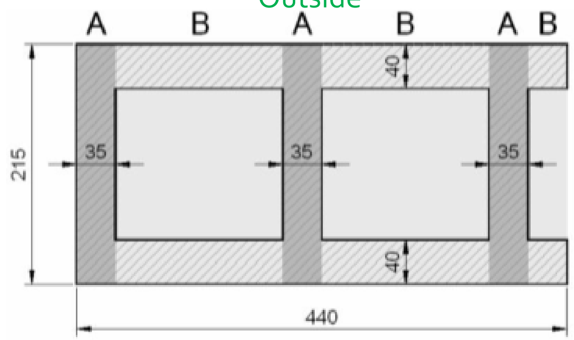
Table B9 Brick/dense concrete block, uninsulated, rendered, cavity wall U-value

		Source (CIBSE Guide A)	Thickness (mm)	Thermal Conductivity (W/mK)	Thermal resistance (m^2K/W)	U-Value (W/m^2K)
Element	Outer Surface	Table 3.48			0.04	
	Outside Render	Table 3.37	19	0.8	0.02	
	External Brickwork	Table 3.47	105	0.77	0.14	
	Cavity	Table 3.48			0.18	
	Dense concrete block	Table 3.47	105	1.75	0.06	
	Plasterboard (stand.)	Table 3.47	13	0.21	0.06	
	Inner Surface	Table 3.48			0.13	
Composite building element				Σ R =	0.63	
	300 mm uninsulated brick/dense concrete block cavity wall					**1.58**

Source Data (cont.) - [137]

As shown in Figure B1 - Concrete webs connect each side of a hollow block creating a non-uniform wall structure. Assuming that heat flows in straight lines perpendicular to the element's surface, there are two heat flow paths; (A) through the concrete webs, and (B) through the cavities.

Figure B1 – 215 mm Irish hollow block concrete wall section [137]



Finite element analysis is well suited to calculating heat transfer through non-uniform structures. The Irish concrete block is 215 mm thick typically, comprising a 135 mm^2 air-filled cavity bounded internally and externally by a 40 mm concrete webs and bridged internally by 35 mm concrete (see Figure B1). A study [137] employed THERM®, a two-dimensional finite element modeller, available from the Lawrence Berkeley National Laboratory (LBNL) [224] to model two-dimensional heat transfer through a typical Irish concrete block detailed in Table B8. The study calculated the overall thermal resistance of a typical Irish hollow block to be 0.48 m^2K/W with a corresponding overall U-value of 2.09 W/m^2K.

Calculation of likely U-values (cont.)

Table B10 Brick/dense concrete block, partially insulated, non-rendered, cavity wall U-value

		Source (CIBSE Guide A)	Thickness (mm)	Thermal Conductivity (W/mK)	Thermal resistance (m^2K/W)	U-Value (W/m^2K)
Element	Outer Surface	Table 3.10			0.04	
	External Brickwork	Table 3.1	105	0.77	0.14	
	Cavity	Table 3.9			0.18	
	Insulation Board	Table 3.47	50	0.04	1.25	
	Blockwork (protected)	Table 3.47	105	1.75	0.06	
	lasterboard (standard)	Table 3.47	13	0.21	0.06	
	Inner Surface	Table 3.9			0.13	
Composite building element				Σ R =	1.86	
	300 mm partially-insulated brick/block cavity wall					**0.54**

Table B11 Brick/dense concrete block, partially insulated, rendered, cavity wall U-value

			Thickness (mm)	Thermal Conductivity (W/mK)	Thermal resistance (m^2K/W)	U-Value (W/m^2K)
Element	Outer Surface	Table 3.48			0.04	
	Outside Render	Table 3.37	19	0.8	0.02	
	External Brickwork	Table 3.47	105	0.77	0.14	
	Insulation Board	Table 3.47	50	0.04	1.25	
	Brickwork	Table 3.37	105	1.75	0.06	
	Plasterboard (standard)	Table 3.47	13	0.21	0.06	
	Inner Surface	Table 3.48			0.13	
Composite building element				Σ R =	1.70	
	300 mm insulated cavity wall					**0.59**

Source Data (cont.)- CIBSE Guide A [124]

Table 3.1 Thermal conductivity of homogeneous masonry materials at 'standard' moisture content

Material	Dry density / $kg.m^{-3}$	Thermal conductivity / $W{\cdot}m^{-1}{\cdot}K^{-1}$ Protected	Exposed	Material
Brick (fired clay)	1200	0.36	0.50	Pyro-processed colliery material concrete
	1300	0.40	0.54	
	1400	0.44	0.60	
	1500	0.47	0.65	
	1600	0.52	0.71	
	1700	0.56	0.77	
	1800	0.61	0.83	Pumice aggregate concrete
	1900	0.66	0.90	
	2000	0.70	0.96	
Brick (calcium silicate)	1700	0.77	1.05	
	1800	0.89	1.22	
	1900	1.01	1.38	
	2000	1.16	1.58	
	2100	1.32	1.80	
	2200	1.51	2.06	Autoclaved aerated concrete
Dense aggregate concrete	1700	1.04	1.12	
	1800	1.13	1.21	
	1900	1.22	1.31	
	2000	1.33	1.43	
	2100	1.46	1.56	
	2200	1.59	1.70	
	2300	1.75	1.87	Other lightweight aggregate concrete
	2400	1.93	2.06	
Blast furnace slag concrete	1000	0.19	0.20	
	1100	0.24	0.25	
	1200	0.27	0.29	
	1300	0.32	0.35	
	1400	0.38	0.41	
	1500	0.45	0.48	
	1600	0.53	0.56	
	1700	0.60	0.65	

Note: these data have been derived from the values for the 90% fractile given in BS EN 1745[19] for the : value for mortar may be taken as 0.88 $W{\cdot}m^{-1}{\cdot}K^{-1}$ (protected) and 0.94 $W{\cdot}m^{-1}{\cdot}K^{-1}$ (exposed).

Calculation of likely U-values (cont.)

Table B12 Brick/dense concrete block, partially insulated, rendered, cavity wall U-value

			Thickness (mm)	Thermal Conductivity (W/mK)	Thermal resistance (m^2K/W)	U-Value (W/m^2K)
Element	Outer Surface	Table 3.48			0.04	
	Out. Render (cement,sand)	Table 3.47	19	1	0.02	
	External Brickwork	Table 3.47	105	0.83	0.13	
	Partially filled cavity (expanded polystrene EPS)	Table 3.47	50	0.04	1.25	
	Brickwork	Table 3.37	105	0.19	0.55	
	Plasteboard (standard)	Table 3.47	13	0.21	0.06	
	Inner Surface	Table 3.48			0.13	
Composite building element				Σ R =	2.18	
				300 mm partially insulated cavity wall		**0.46**

Table B13 Brick/dense concrete block, partially insulated, rendered, cavity wall U-value

			Thickness (mm)	Thermal Conductivity (W/mK)	Thermal resistance (m^2K/W)	U-Value (W/m^2K)
Element	Outer Surface	Table 3.48			0.04	
	Outside Render	Table 3.37	19	0.8	0.02	
	External Brickwork	Table 3.47	105	0.83	0.13	
	Filled Cavity (mineral wool)	Table 3.47	70	0.04	1.75	
	Brickwork	Table 3.37	105	0.19	0.55	
	Plaster	Table 3.38	13	0.19	0.07	
	Inner Surface	Table 3.48			0.13	
Composite building element				Σ R =	2.69	
				300 mm insulated cavity wall		**0.37**

Source Data (cont.)- CIBSE Guide A [124]

Table 3.50 Thermal properties of typical roof constructions — *continued*

Construction	Transmittance U / $W \cdot m^{-2} \cdot K^{-1}$	Admittance Y / $W \cdot m^{-2} \cdot K^{-1}$	Admittance ω / h
3 Pitched roofs (insulated at ceiling level)			
(*a*) 12.5 mm plasterboard, no insulation, roof space, tiling	2.30	2.05	0.6
(*b*) 12.5 mm plasterboard, 25 mm mineral wool quilt between ceiling joists, roof space, tiling	1.10	1.11	1.6
(*c*) 12.5 mm plasterboard, 50 mm mineral wool quilt between ceiling joists, roof space, tiling	0.71	0.85	2.6
(*d*) 12.5 mm plasterboard, 100 mm mineral wool quilt between ceiling joists, roof space, tiling	0.42	0.72	3.7
(*e*) 12.5 mm plasterboard, 100 mm mineral wool quilt between ceiling joists, 50 mm mineral wool quilt over joists, roof space, tiling	0.28	0.70	4.5
(*f*) 12.5 mm plasterboard, 100 mm mineral wool quilt between ceiling joists, 100 mm mineral wool quilt over joists, roof space, tiling	0.21	0.68	4.5
(*g*) 12.5 mm plasterboard, 100 mm mineral wool quilt between ceiling joists, 150 mm mineral wool quilt over joists, roof space, tiling	0.17	0.68	4.7
(*h*) 12.5 mm plasterboard, 100 mm mineral wool quilt between ceiling joists, 200 mm mineral wool quilt over joists, roof space, tiling	0.14	0.72	4.8

Standard roof construct-ions

Appendix C – Statistical analysis of dwelling envelope characteristics

C.1 Manual truncation of bimodal data to enable analysis of sample set of empirical distribution to enable analysis the 'Find the Best Distribution' Tool in MATLAB®

Cross-reference Section 3.2.2.1.1 for explanatory text

Table C1 Mode 1 and Mode 2 U-value ranges for two number randomly selected pre and post thermal regulation dwellings

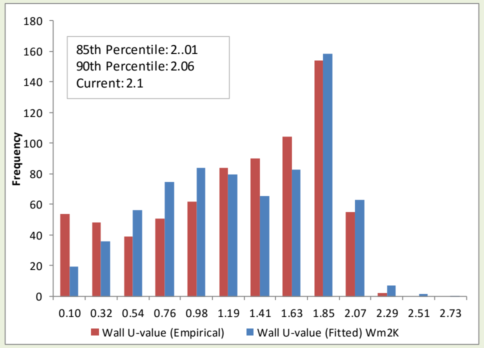
							Range of Empircal Distribution Mode 1 and Mode 2			
			House type	One Storey **(1S)**/ Two-storey **(2S)**	**R**oof/**W**all	Category	Mode 1		Mode 2	
Period of Constr.'n	Pre-thermal regulation	1900 - 1929	B	2S	W	B2SW	0.16	0.64	0.66	2.34
			B	1S	W	B1SW	0.18	0.7	0.71	2.4
			B	2S	R	B2SR	0.09	0.53	0.54	2.27
			B	1S	R	B1SR	0.08	0.43	0.44	2.33
		1967 - 1977	E	2S	W	E2SW	0.12	0.77	0.78	2.4
			E	1S	W	E1SW	0.15	0.66	0.67	2.4
			E	2S	R	E2SR	0.09	0.48	0.49	2.22
			E	1S	R	E1SR	0.09	0.25	0.26	2.24
	Post-thermal regulation	1978 - 1982	F	2S	W	F2SW	0.19	0.37	0.38	1.78
			F	1S	W	F1SW	0.12	0.32	0.33	1.78
			F	2S	R	F2SR	0.13	0.63	0.64	2.3
			F	1S	R	F1SR	0.08	0.24	0.25	2.3
		2000-2004	I	2S	W	I2SW	0.11	0.37	0.38	1.71
			I	1S	W	I1SW	0.1	0.32	0.33	1.55
			I	2S	R	I2SR	0.09	0.4	0.41	2.3
			I	1S	R	I1SR	0.09	0.25	0.26	2.3

C.2 Statistical methodology outputs by period of construction

Figure C1 Statistical analysis of dwelling envelope thermal frequency distributions for dwellings constructed pre-1900

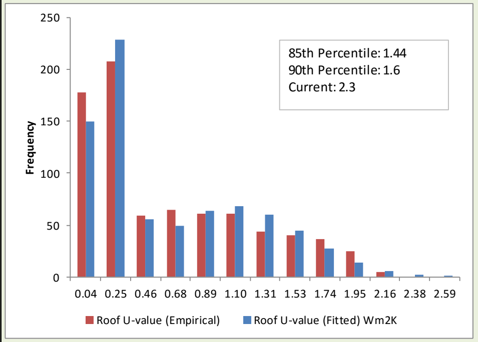
U-Value: Two-storey

Wall



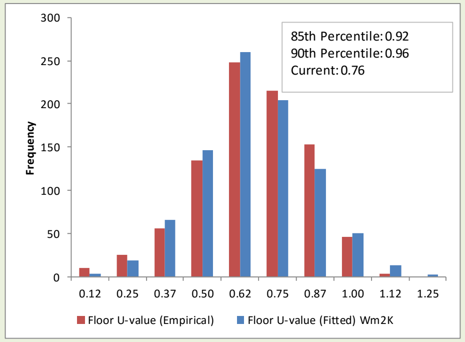
Mean (1)	1.13
Std Dev (1)	0.53
Mean (2)	1.97
Std Dev (2)	0.13
Proportion (1)	70%

Roof



Mean (1)	0.29
Std Dev (1)	0.12
Mean (2)	1.18
Std Dev (2)	0.49
Proportion (1)	49%

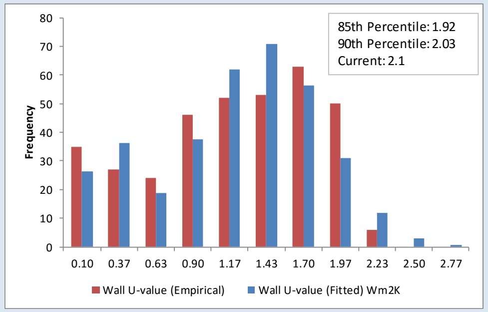
Floor



Mean (1)	0.73
Std Dev (1)	0.19
Mean (2)	0.73
Std Dev (2)	0.01
Proportion (1)	94%

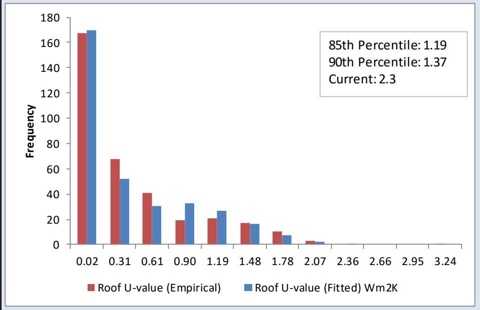
U-Value: Single-storey

Wall



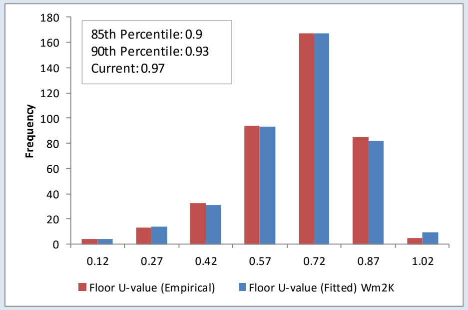
Mean (1)	0.39
Std Dev (1)	0.15
Mean (2)	1.53
Std Dev (2)	0.43
Proportion (1)	17%

Roof



Mean (1)	0.22
Std Dev (1)	0.10
Mean (2)	0.98
Std Dev (2)	0.54
Proportion (1)	56%

Floor



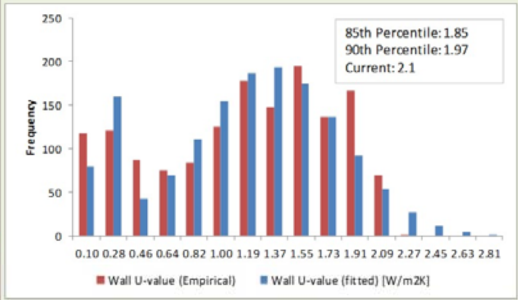
Mean (1)	0.53
Std Dev (1)	0.17
Mean (2)	0.80
Std Dev (2)	0.12
Proportion (1)	17%

Figure C2 Statistical analysis of dwelling envelope thermal frequency distributions for dwellings constructed between 1900 and 1929

U-Value	Wall	Roof	Floor

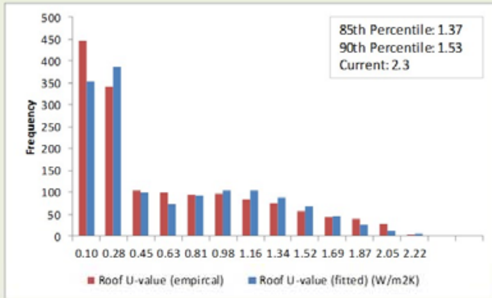
Two-storey

Wall



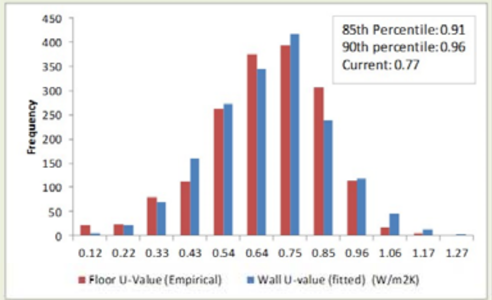
Mean (1)	0.31
Std Dev (1)	0.07
Mean (2)	1.42
Std Dev (2)	0.47
Proportion (1)	15%

Roof



Mean (1)	0.28
Std Dev (1)	0.11
Mean (2)	1.14
Std Dev (2)	0.49
Proportion (1)	52%

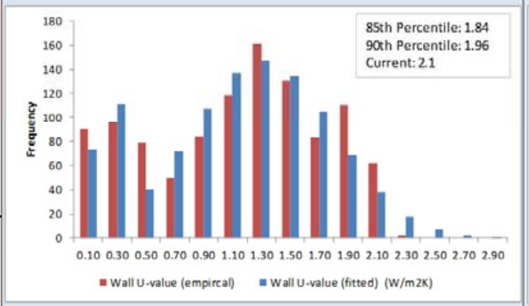
Floor



Mean (1)	0.73
Std Dev (1)	0.19
Mean (2)	0.84
Std Dev (2)	0.01
Proportion (1)	94%

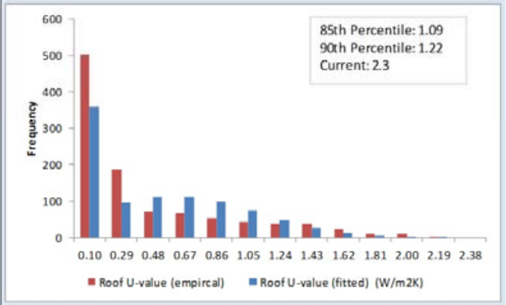
Single-storey

Wall



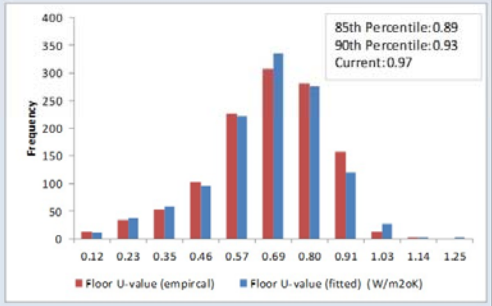
Mean (1)	0.31
Std Dev (1)	0.06
Mean (2)	1.39
Std Dev (2)	0.49
Proportion (1)	15%

Roof



Mean (1)	0.13
Std Dev (1)	0.01
Mean (2)	0.67
Std Dev (2)	0.61
Proportion (1)	27%

Floor



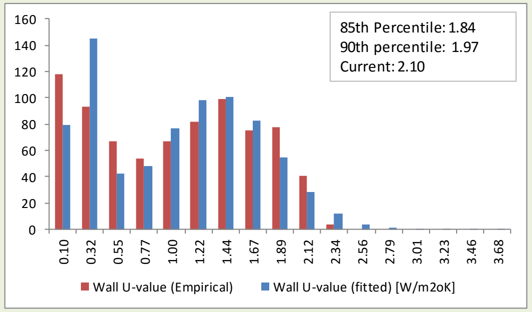
Mean (1)	0.37
Std Dev (1)	0.11
Mean (2)	0.76
Std Dev (2)	0.14
Proportion (1)	10%

Figure C3 Statistical analysis of dwelling envelope thermal frequency distributions for dwellings constructed between 1930 and 1949

U-Value	Wall	Roof	Floor

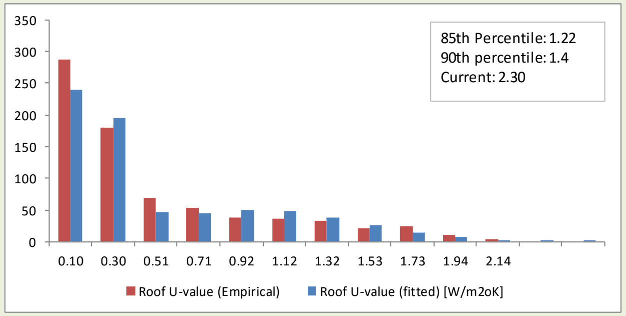
Two-storey

Wall



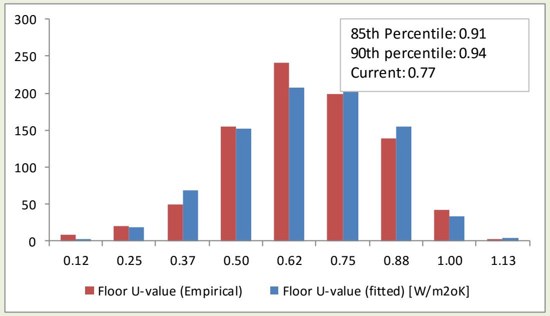
Mean (1)	0.38
Std Dev (1)	0.12
Mean (2)	1.47
Std Dev (2)	0.47
Proportion (1)	30%

Roof



Mean (1)	0.28
Std Dev (1)	0.12
Mean (2)	1.06
Std Dev (2)	0.50
Proportion (1)	59%

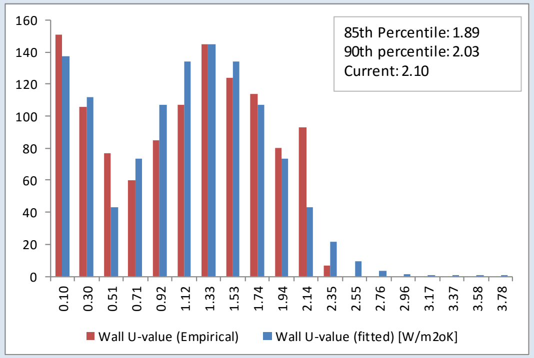
Floor



Mean (1)	0.70
Std Dev (1)	0.17
Mean (2)	0.90
Std Dev (2)	0.07
Proportion (1)	85%

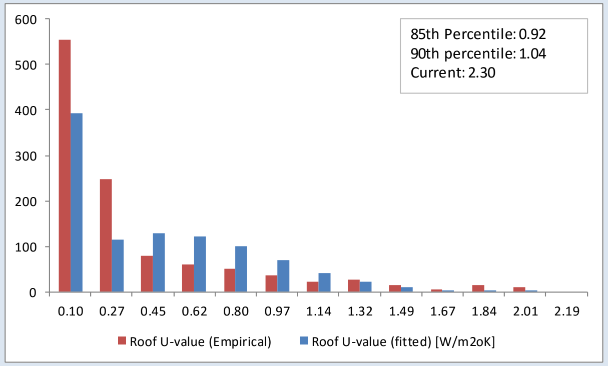
Single-storey

Wall



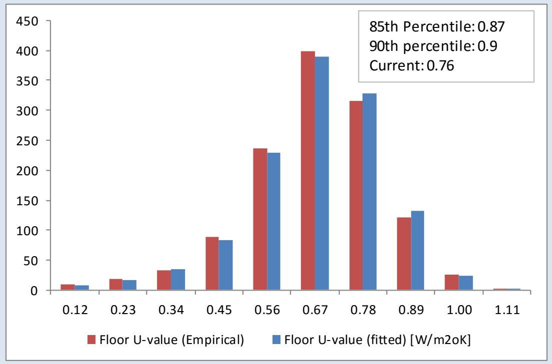
Mean (1)	0.29
Std Dev (1)	0.05
Mean (2)	1.43
Std Dev (2)	0.52
Proportion (1)	19%

Roof



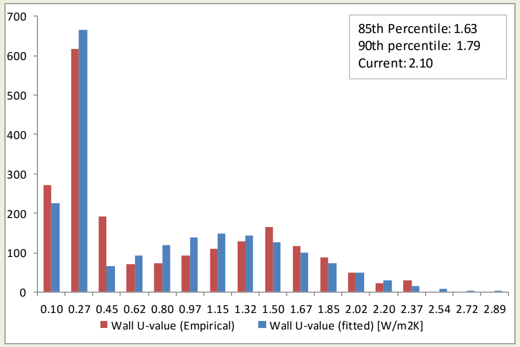
Mean (1)	0.13
Std Dev (1)	0.01
Mean (2)	0.57
Std Dev (2)	0.44
Proportion (1)	27%

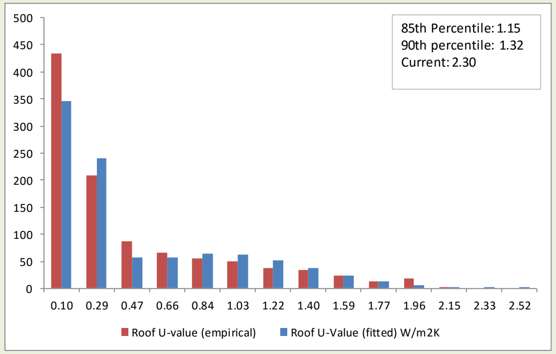
Floor

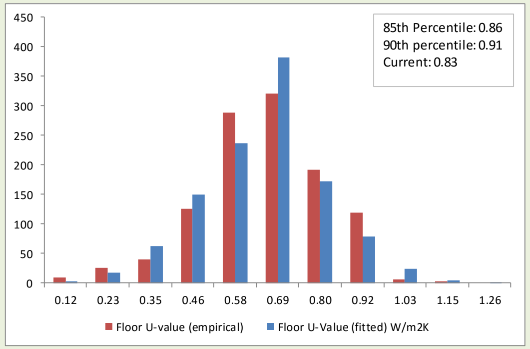


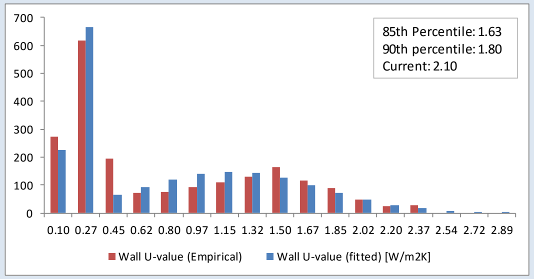
Mean (1)	0.48
Std Dev (1)	0.17
Mean (2)	0.76
Std Dev (2)	0.12
Proportion (1)	10%

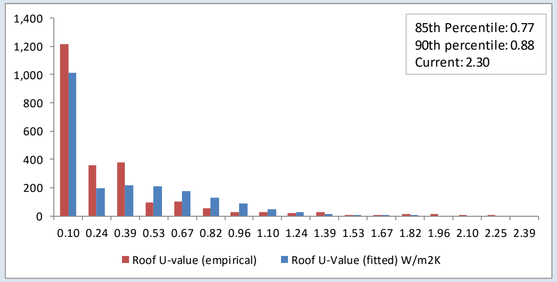
Figure C4 Statistical analysis of dwelling envelope thermal frequency distributions for dwellings constructed between 1950 and 1966

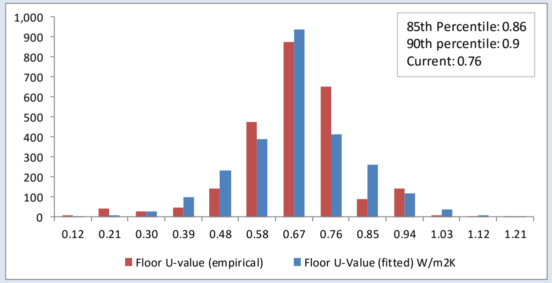
<table>
<tr><th>U-Value</th><th>Wall</th><th>Roof</th><th>Floor</th></tr>
<tr><td>Two-storey</td>
<td>

<table>
<tr><td>Mean (1)</td><td>0.33</td></tr>
<tr><td>Std Dev (1)</td><td>0.07</td></tr>
<tr><td>Mean (2)</td><td>1.30</td></tr>
<tr><td>Std Dev (2)</td><td>0.52</td></tr>
<tr><td>Proportion (1)</td><td>42%</td></tr>
</table></td>
<td>

<table>
<tr><td>Mean (1)</td><td>0.25</td></tr>
<tr><td>Std Dev (1)</td><td>0.11</td></tr>
<tr><td>Mean (2)</td><td>0.99</td></tr>
<tr><td>Std Dev (2)</td><td>0.49</td></tr>
<tr><td>Proportion (1)</td><td>59%</td></tr>
</table></td>
<td>

<table>
<tr><td>Mean (1)</td><td>0.70</td></tr>
<tr><td>Std Dev (1)</td><td>0.17</td></tr>
<tr><td>Mean (2)</td><td>0.73</td></tr>
<tr><td>Std Dev (2)</td><td>0.01</td></tr>
<tr><td>Proportion (1)</td><td>88%</td></tr>
</table></td></tr>
<tr><td>Single - storey</td>
<td>

<table>
<tr><td>Mean (1)</td><td>0.31</td></tr>
<tr><td>Std Dev (1)</td><td>0.05</td></tr>
<tr><td>Mean (2)</td><td>1.26</td></tr>
<tr><td>Std Dev (2)</td><td>0.56</td></tr>
<tr><td>Proportion (1)</td><td>41%</td></tr>
</table></td>
<td>

<table>
<tr><td>Mean (1)</td><td>0.13</td></tr>
<tr><td>Std Dev (1)</td><td>0.01</td></tr>
<tr><td>Mean (2)</td><td>0.49</td></tr>
<tr><td>Std Dev (2)</td><td>0.39</td></tr>
<tr><td>Proportion (1)</td><td>36%</td></tr>
</table></td>
<td>

<table>
<tr><td>Mean (1)</td><td>0.72</td></tr>
<tr><td>Std Dev (1)</td><td>0.16</td></tr>
<tr><td>Mean (2)</td><td>0.73</td></tr>
<tr><td>Std Dev (2)</td><td>0.01</td></tr>
<tr><td>Proportion (1)</td><td>82%</td></tr>
</table></td></tr>
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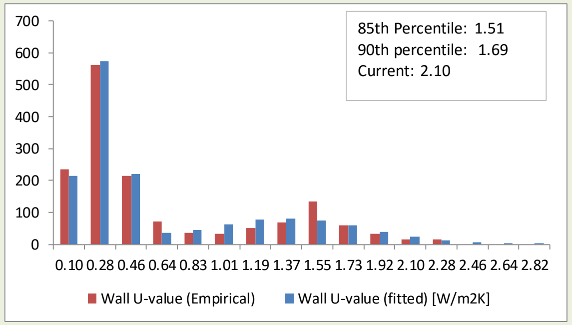
Figure C5 Statistical analysis of dwelling envelope thermal frequency distributions for dwellings constructed between 1967 and 1977

U-Value	Wall	Roof	Floor

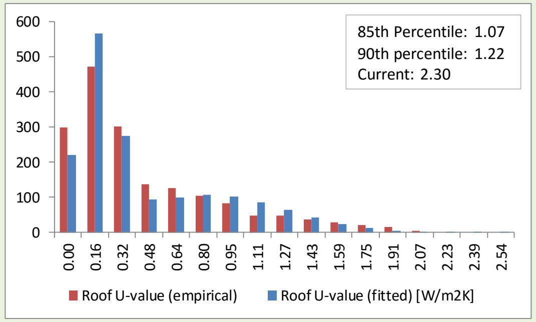
Two-storey

Wall



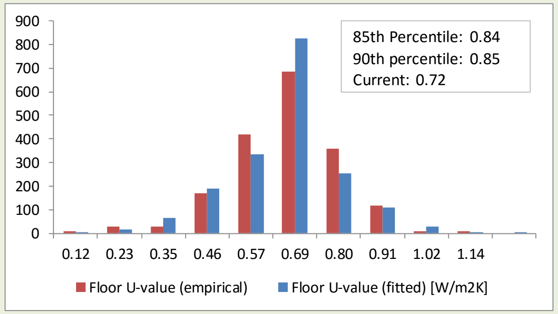
Mean (1)	0.37
Std Dev (1)	0.12
Mean (2)	1.44
Std Dev (2)	0.47
Proportion (1)	65%

Roof



Mean (1)	0.24
Std Dev (1)	0.11
Mean (2)	0.89
Std Dev (2)	0.45
Proportion (1)	56%

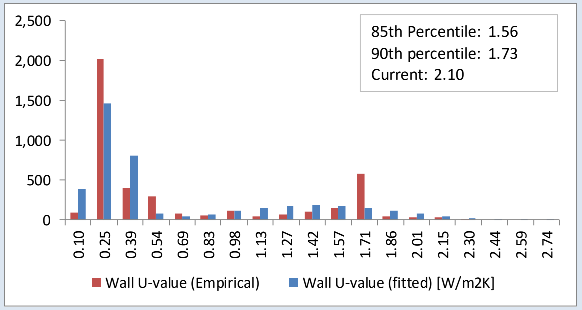
Floor



Mean (1)	0.71
Std Dev (1)	0.16
Mean (2)	0.73
Std Dev (2)	0.01
Proportion (1)	75%

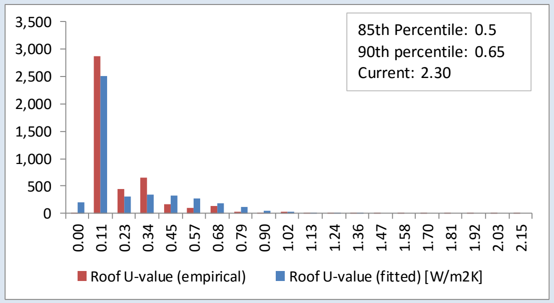
Single-storey

Wall



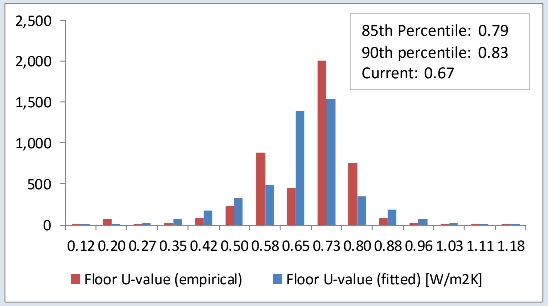
Mean (1)	0.35
Std Dev (1)	0.10
Mean (2)	1.50
Std Dev (2)	0.43
Proportion (1)	66%

Roof



Mean (1)	0.13
Std Dev (1)	0.01
Mean (2)	0.41
Std Dev (2)	0.29
Proportion (1)	51%

Floor



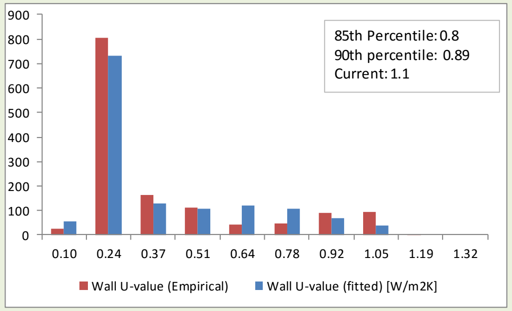
Mean (1)	0.69
Std Dev (1)	0.15
Mean (2)	0.73
Std Dev (2)	0.01
Proportion (1)	60%

Figure C6 Statistical analysis of dwelling envelope thermal frequency distributions for dwellings constructed between 1978 and 1982

U-Value	Wall	Roof	Floor

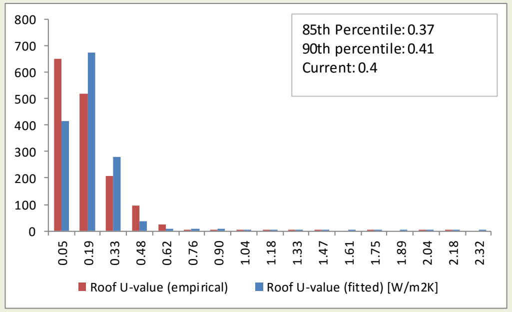
Two-storey

Wall



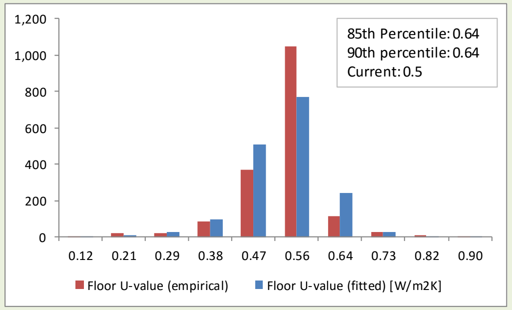
Mean (1)	0.31
Std Dev (1)	0.04
Mean (2)	0.70
Std Dev (2)	0.27
Proportion (1)	57%

Roof



Mean (1)	0.24
Std Dev (1)	0.11
Mean (2)	0.77
Std Dev (2)	0.48
Proportion (1)	95%

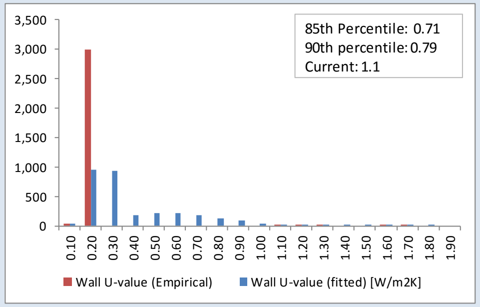
Floor



Mean (1)	0.52
Std Dev (1)	0.16
Mean (2)	0.58
Std Dev (2)	0.06
Proportion (1)	13%

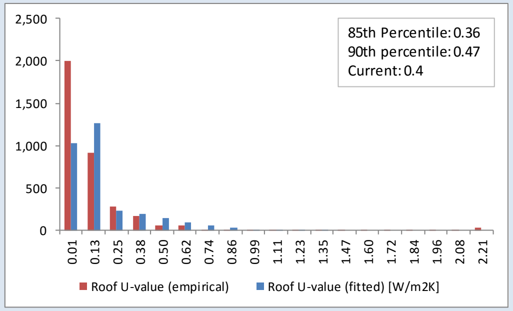
Single-storey

Wall



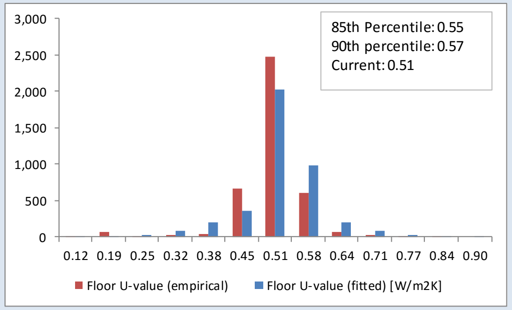
Mean (1)	0.30
Std Dev (1)	0.03
Mean (2)	0.60
Std Dev (2)	0.25
Proportion (1)	54%

Roof



Mean (1)	0.13
Std Dev (1)	0.01
Mean (2)	0.20
Std Dev (2)	0.34
Proportion (1)	52%

Floor

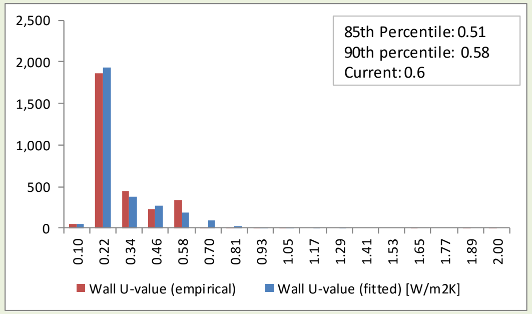


Mean (1)	0.54
Std Dev (1)	0.11
Mean (2)	0.57
Std Dev (2)	0.01
Proportion (1)	45%

Figure C7 Statistical analysis of dwelling envelope thermal frequency distributions for dwellings constructed between 1983 and 1993

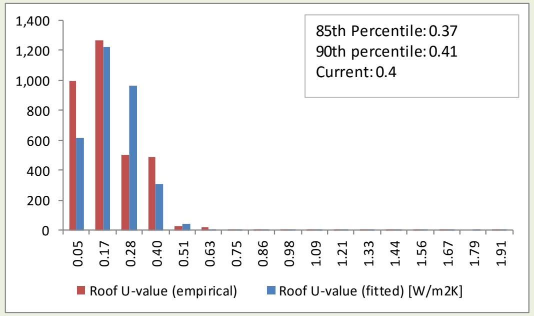
U-Value: Two-storey

Wall



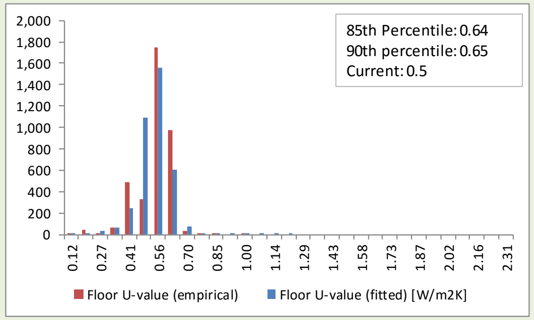
Mean (1)	0.30
Std Dev (1)	0.03
Mean (2)	0.49
Std Dev (2)	0.18
Proportion (1)	65%

Roof



Mean (1)	0.25
Std Dev (1)	0.12
Mean (2)	0.96
Std Dev (2)	0.58
Proportion (1)	98%

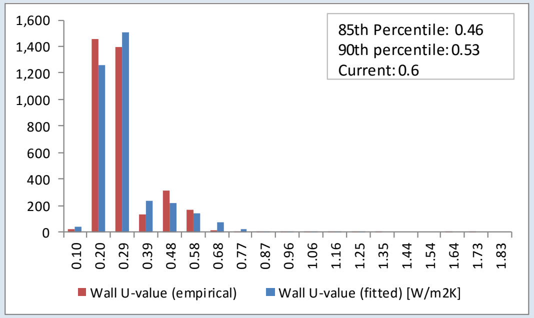
Floor



Mean (1)	0.49
Std Dev (1)	0.16
Mean (2)	0.58
Std Dev (2)	0.06
Proportion (1)	10%

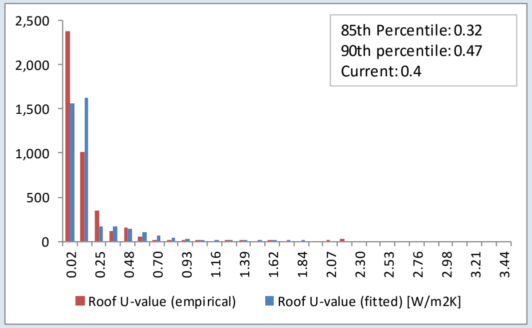
U-Value: Single-storey

Wall



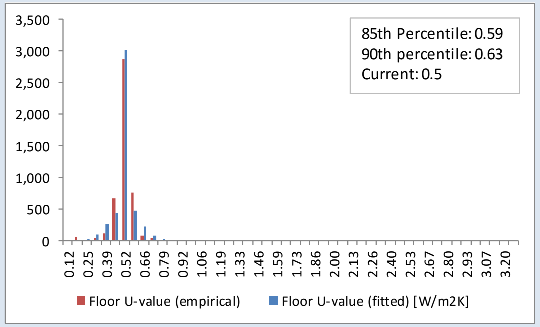
Mean (1)	0.29
Std Dev (1)	0.02
Mean (2)	0.46
Std Dev (2)	0.17
Proportion (1)	70%

Roof



Mean (1)	0.13
Std Dev (1)	0.01
Mean (2)	0.35
Std Dev (2)	0.32
Proportion (1)	71%

Floor



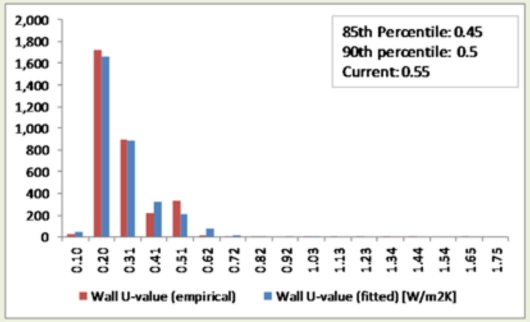
Mean (1)	0.55
Std Dev (1)	0.11
Mean (2)	0.57
Std Dev (2)	0.01
Proportion (1)	45%

Figure C8 Statistical analysis of dwelling envelope thermal frequency distributions for dwellings constructed between 1994 and 1999

U-Value	Wall	Roof	Floor

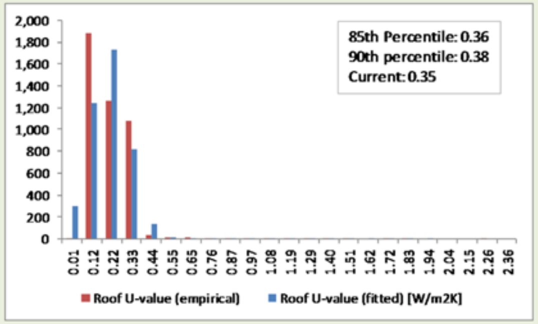
Two-storey

Wall



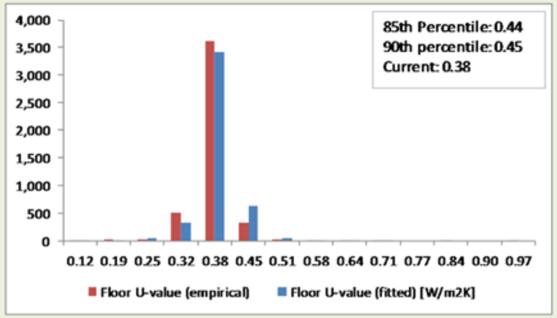
Mean (1)	0.29
Std Dev (1)	0.02
Mean (2)	0.43
Std Dev (2)	0.14
Proportion (1)	65%

Roof



Mean (1)	0.26
Std Dev (1)	0.10
Mean (2)	0.88
Std Dev (2)	0.48
Proportion (1)	99%

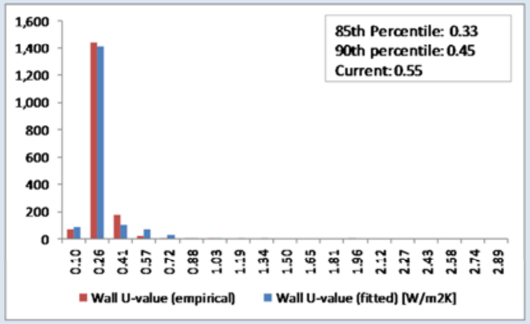
Floor



Mean (1)	0.41
Std Dev (1)	0.11
Mean (2)	0.42
Std Dev (2)	0.02
Proportion (1)	10%

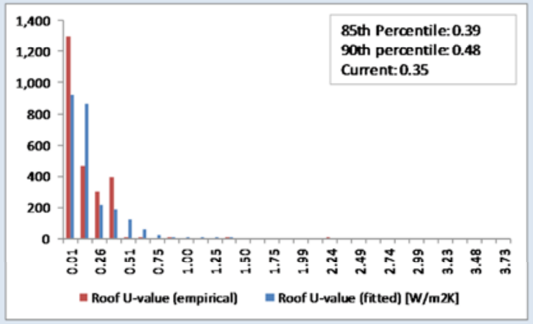
Single-storey

Wall



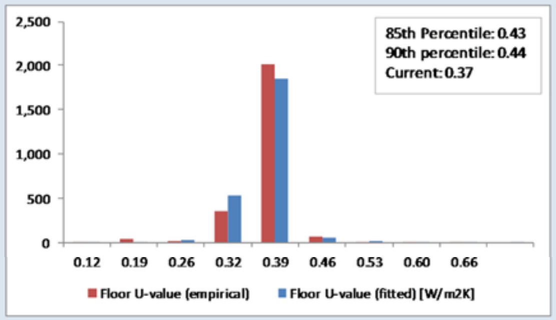
Mean (1)	0.29
Std Dev (1)	0.02
Mean (2)	0.44
Std Dev (2)	0.22
Proportion (1)	79%

Roof



Mean (1)	0.13
Std Dev (1)	0.01
Mean (2)	0.33
Std Dev (2)	0.23
Proportion (1)	60%

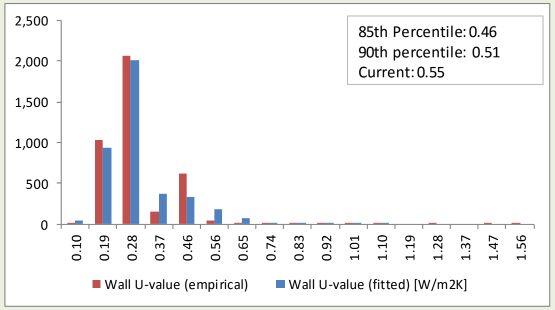
Floor



Mean (1)	0.41
Std Dev (1)	0.02
Mean (2)	0.41
Std Dev (2)	0.13
Proportion (1)	92%

Figure C9 Statistical analysis of dwelling envelope thermal frequency distributions for dwellings constructed between 2000 and 2004

<table>
<tr><th>U-Value</th><th>Wall</th><th>Roof</th><th>Floor</th></tr>
<tr>
<td>Two-storey</td>
<td>



<table>
<tr><td>Mean (1)</td><td>0.29</td></tr>
<tr><td>Std Dev (1)</td><td>0.02</td></tr>
<tr><td>Mean (2)</td><td>0.43</td></tr>
<tr><td>Std Dev (2)</td><td>0.14</td></tr>
<tr><td>Proportion (1)</td><td>63%</td></tr>
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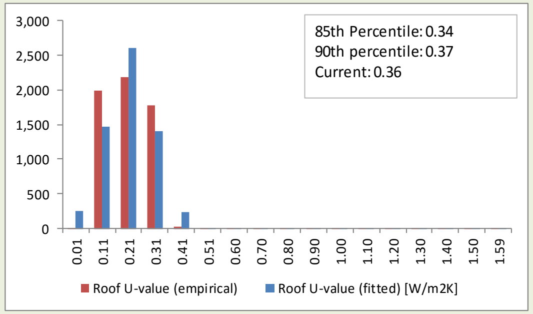

<table>
<tr><td>Mean (1)</td><td>0.26</td></tr>
<tr><td>Std Dev (1)</td><td>0.09</td></tr>
<tr><td>Mean (2)</td><td>0.96</td></tr>
<tr><td>Std Dev (2)</td><td>0.50</td></tr>
<tr><td>Proportion (1)</td><td>99%</td></tr>
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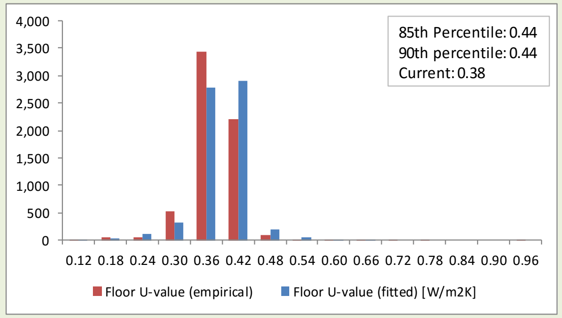

<table>
<tr><td>Mean (1)</td><td>0.40</td></tr>
<tr><td>Std Dev (1)</td><td>0.08</td></tr>
<tr><td>Mean (2)</td><td>0.42</td></tr>
<tr><td>Std Dev (2)</td><td>0.02</td></tr>
<tr><td>Proportion (1)</td><td>25%</td></tr>
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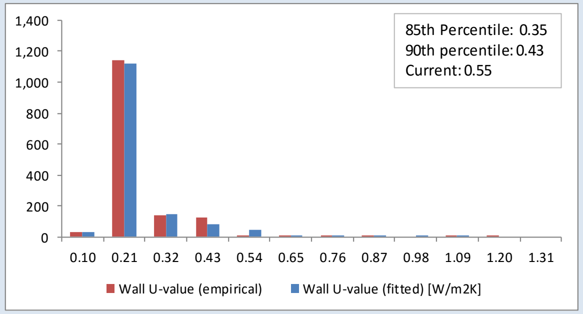
<tr>
<td>Single-storey</td>
<td>



<table>
<tr><td>Mean (1)</td><td>0.29</td></tr>
<tr><td>Std Dev (1)</td><td>0.02</td></tr>
<tr><td>Mean (2)</td><td>0.39</td></tr>
<tr><td>Std Dev (2)</td><td>0.16</td></tr>
<tr><td>Proportion (1)</td><td>75%</td></tr>
</table>
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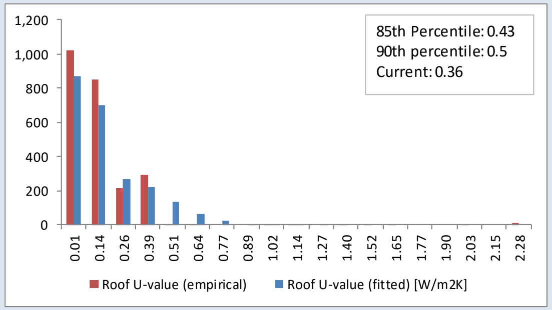
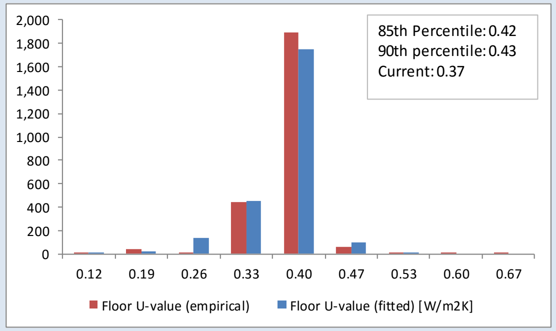
<td>



<table>
<tr><td>Mean (1)</td><td>0.13</td></tr>
<tr><td>Std Dev (1)</td><td>0.01</td></tr>
<tr><td>Mean (2)</td><td>0.31</td></tr>
<tr><td>Std Dev (2)</td><td>0.23</td></tr>
<tr><td>Proportion (1)</td><td>49%</td></tr>
</table>
</td>
<td>



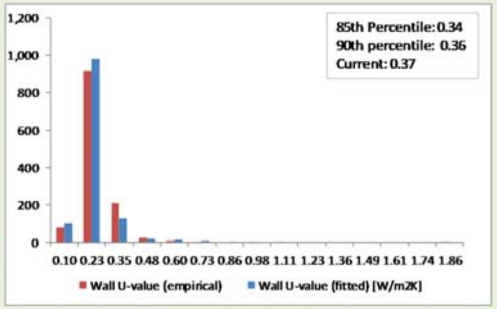
<table>
<tr><td>Mean (1)</td><td>0.39</td></tr>
<tr><td>Std Dev (1)</td><td>0.06</td></tr>
<tr><td>Mean (2)</td><td>0.41</td></tr>
<tr><td>Std Dev (2)</td><td>0.01</td></tr>
<tr><td>Proportion (1)</td><td>38%</td></tr>
</table>
</td>
</tr>
</table>

Figure C10 Statistical analysis of dwelling envelope thermal frequency distributions for dwellings constructed between 2004 and 2005

U-Value	Wall	Roof	Floor

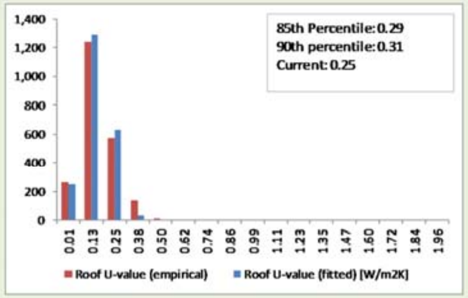
Two-storey

Wall



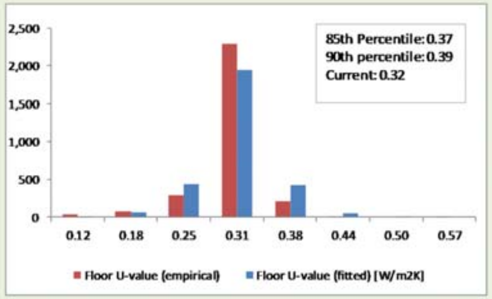
Mean (1)	0.29
Std Dev (1)	0.05
Mean (2)	0.49
Std Dev (2)	0.20
Proportion (1)	94%

Roof



Mean (1)	0.22
Std Dev (1)	0.07
Mean (2)	0.71
Std Dev (2)	0.47
Proportion (1)	98%

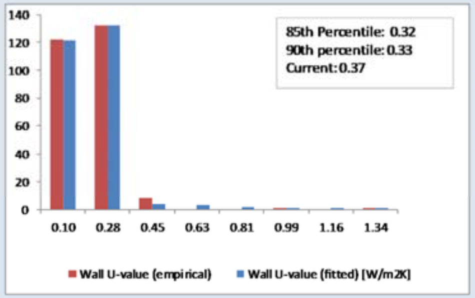
Floor



Mean (1)	0.34
Std Dev (1)	0.01
Mean (2)	0.34
Std Dev (2)	0.05
Proportion (1)	39%

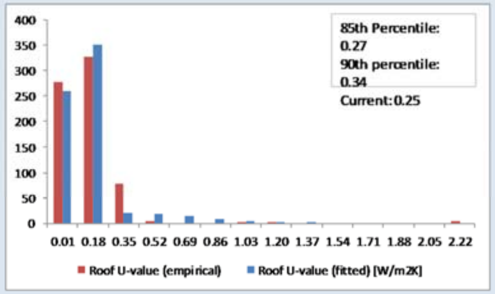
Single-storey

Wall



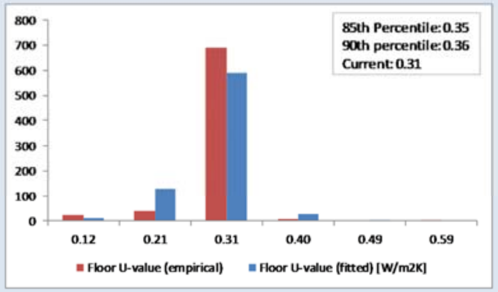
Mean (1)	0.28
Std Dev (1)	0.03
Mean (2)	0.48
Std Dev (2)	0.33
Proportion (1)	93%

Roof



Mean (1)	0.19
Std Dev (1)	0.05
Mean (2)	0.46
Std Dev (2)	0.39
Proportion (1)	84%

Floor



Mean (1)	0.32
Std Dev (1)	0.06
Mean (2)	0.34
Std Dev (2)	0.01
Proportion (1)	45%

C.3 Assessment of goodness of fit of the normal distribution function to the empirical data

Cross-reference Section 3.2.3.1 for analysis of tables C2 to C7 – Highlighted cells indicate any variance between the empirical and fitted data points of the cumulative distribution function greater than 0.1 W/m²K.

Table C2 Comparison of Empirical (E) and Fitted (F) data points for two-storey walls by period of construction

		Two-storey Wall																													
Period of Construction		<1900			1900 - 1929			1930 - 1949			1950 - 1966			1967 - 1977			1978 - 1982			1983 - 1993			1994 - 1999			2000 - 2004			2005 - 2006		
Empirical / Fitted Distribution		E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-
Percentile	50%	1.43	1.43	0.00	1.33	1.31	-0.02	1.17	1.20	0.03	0.59	0.73	0.14	0.56	0.51	-0.05	0.34	0.34	0.00	0.30	0.30	0.00	0.30	0.30	0.00	0.30	0.30	0.00	0.29	0.29	0.00
	75%	1.90	1.91	0.01	1.72	1.67	-0.05	1.68	1.64	-0.04	1.34	1.39	0.05	1.13	1.43	0.30	0.56	0.65	0.09	0.35	0.35	0.00	0.35	0.35	0.00	0.36	0.37	0.01	0.34	0.32	-0.02
	80%	1.97	1.96	-0.01	1.81	1.75	-0.06	1.78	1.73	-0.05	1.52	1.50	-0.02	1.45	1.58	0.13	0.59	0.72	0.13	0.38	0.40	0.02	0.38	0.40	0.02	0.40	0.42	0.02	0.35	0.33	-0.02
	85%	2.02	2.01	-0.01	1.92	1.85	-0.07	1.92	1.84	-0.08	1.64	1.63	-0.01	1.66	1.71	0.05	0.59	0.80	0.21	0.47	0.45	-0.02	0.47	0.45	-0.02	0.51	0.46	-0.05	0.36	0.34	-0.02
	90%	2.05	2.06	0.01	2.01	1.97	-0.04	2.02	1.97	-0.05	1.72	1.79	0.07	1.67	1.84	0.17	0.77	0.89	0.12	0.53	0.50	-0.03	0.53	0.50	-0.03	0.53	0.51	-0.02	0.36	0.36	0.00
	95%	2.11	2.14	0.03	2.08	2.15	0.07	2.16	2.15	-0.01	1.77	2.01	0.24	1.70	2.02	0.32	0.95	1.02	0.07	0.54	0.57	0.03	0.54	0.57	0.03	0.54	0.58	0.04	0.40	0.39	-0.01
Current Default		**2.10**			**2.10**			**2.10**			**2.10**			**2.10**			**1.10**			**0.55**			**0.55**			**0.55**			**0.37**		

Table C3 Comparison of Empirical (E) and Fitted (F) data points for two-storey roofs by period of construction

		Two-storey Roof																													
Period of Construction		<1900			1900 - 1929			1930 - 1949			1950 - 1966			1967 - 1977			1978 - 1982			1983 - 1993			1994 - 1999			2000 - 2004			2005 - 2006		
Empirical / Fitted Distribution		E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-
Percentile	50%	0.48	0.46	-0.02	0.42	0.42	0.00	0.40	0.37	-0.03	0.37	0.33	-0.04	0.37	0.33	-0.04	0.23	0.25	0.02	0.25	0.25	0.00	0.26	0.25	-0.01	0.26	0.25	-0.01	0.20	0.21	0.01
	75%	1.16	1.19	0.03	1.08	1.11	0.03	0.81	0.91	0.10	0.76	0.85	0.09	0.74	0.81	0.07	0.33	0.33	0.00	0.36	0.32	-0.04	0.33	0.31	-0.02	0.33	0.31	-0.02	0.26	0.26	0.00
	80%	1.29	1.31	0.02	1.22	1.24	0.02	1.03	1.07	0.04	0.92	1.00	0.08	0.86	0.94	0.08	0.37	0.35	-0.02	0.39	0.34	-0.05	0.36	0.33	-0.03	0.36	0.33	-0.03	0.26	0.27	0.01
	85%	1.48	1.44	-0.04	1.37	1.38	0.01	1.19	1.22	0.03	1.12	1.15	0.03	1.01	1.07	0.06	0.42	0.37	-0.05	0.40	0.36	-0.04	0.36	0.34	-0.02	0.36	0.34	-0.02	0.28	0.29	0.01
	90%	1.69	1.60	-0.09	1.58	1.53	-0.05	1.43	1.40	-0.03	1.32	1.32	0.00	1.21	1.22	0.01	0.46	0.41	-0.05	0.40	0.38	-0.02	0.38	0.37	-0.01	0.38	0.37	-0.01	0.34	0.31	-0.03
	95%	1.88	1.81	-0.07	1.83	1.75	-0.08	1.76	1.63	-0.13	1.62	1.55	-0.07	1.52	1.43	-0.09	0.49	0.46	-0.03	0.40	0.42	0.02	0.40	0.40	0.00	0.40	0.40	0.00	0.40	0.34	-0.06
Current Default		**2.30**			**2.30**			**2.30**			**2.30**			**2.30**			**0.40**			**0.35**			**0.35**			**0.35**			**0.25**		

Table C4 Comparison of Empirical (E) and Fitted (F) data points for two-storey floors by period of construction

		Two-storey Floor																													
Period of Construction		<1900			1900 - 1929			1930 - 1949			1950 - 1966			1967 - 1977			1978 - 1982			1983 - 1993			1994 - 1999			2000 - 2004			2005 - 2006		
Empirical / Fitted Distribution		E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-
Percentile	50%	0.73	0.73	**0.00**	0.74	0.74	**0.00**	0.73	0.73	**0.00**	0.73	0.72	**-0.01**	0.73	0.72	**-0.01**	0.57	0.57	**0.00**	0.41	0.41	**0.00**	0.41	0.41	**0.00**	0.41	0.41	**0.00**	0.34	0.34	**0.00**
	75%	0.85	0.85	**0.00**	0.86	0.84	**-0.02**	0.84	0.86	0.02	0.83	0.80	**-0.03**	0.81	0.77	**-0.04**	0.64	0.62	**-0.02**	0.44	0.43	**-0.01**	0.44	0.43	**-0.01**	0.44	0.43	**-0.01**	0.37	0.35	**-0.02**
	80%	0.89	0.88	**-0.01**	0.90	0.87	**-0.03**	0.89	0.88	**-0.01**	0.84	0.83	**-0.01**	0.84	0.80	**-0.04**	0.64	0.63	**-0.01**	0.44	0.44	**0.00**	0.44	0.43	**-0.01**	0.44	0.43	**-0.01**	0.37	0.36	**-0.01**
	85%	0.94	0.92	**-0.02**	0.94	0.91	**-0.03**	0.94	0.91	**-0.03**	0.84	0.86	0.02	0.84	0.84	**0.00**	0.64	0.64	**0.00**	0.44	0.44	**0.00**	0.44	0.44	**0.00**	0.44	0.44	**0.00**	0.37	0.37	**0.00**
	90%	0.94	0.96	0.02	0.94	0.96	0.02	0.94	0.94	**0.00**	0.94	0.91	**-0.03**	0.85	0.88	0.03	0.64	0.66	0.02	0.44	0.45	0.01	0.44	0.44	**0.00**	0.44	0.44	**0.00**	0.37	0.39	0.02
	95%	1.02	1.03	0.01	1.02	1.03	0.01	1.02	0.99	**-0.03**	0.94	0.97	0.03	0.94	0.95	0.01	0.70	0.69	**-0.01**	0.47	0.46	**-0.01**	0.47	0.46	**-0.01**	0.47	0.46	**-0.01**	0.39	0.41	0.02
Current Default		**0.76**			**0.79**			**0.77**			**0.83**			**0.72**			**0.72**			**0.38**			**0.38**			**0.38**			**0.32**		

Table C5 Comparison of Empirical (E) and Fitted (F) data points for single-storey walls by period of construction

		Single-storey Wall																													
Period of Construction		<1900			1900 - 1929			1930 - 1949			1950 - 1966			1967 - 1977			1978 - 1982			1983 - 1993			1994 - 1999			2000 - 2004			2005 - 2006		
Empirical / Fitted Distribution		E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-
Percentile	50%	1.42	1.41	**-0.01**	1.31	1.28	**-0.03**	1.30	1.27	**-0.03**	0.55	0.69	0.14	0.47	0.43	**-0.04**	0.33	0.32	**-0.01**	0.30	0.29	**-0.01**	0.30	0.30	**0.00**	0.29	0.29	**0.00**	0.28	0.28	**0.00**
	75%	1.83	1.75	**-0.08**	1.67	1.65	**-0.02**	1.75	1.69	**-0.06**	1.45	1.37	**-0.08**	0.60	0.59	**-0.01**	0.58	0.56	**-0.02**	0.32	0.31	**-0.01**	0.36	0.37	0.01	0.31	0.31	**0.00**	0.30	0.30	**0.00**
	80%	1.92	1.83	**-0.09**	1.79	1.74	**-0.05**	1.81	1.78	**-0.03**	1.57	1.49	**-0.08**	0.67	0.71	0.04	0.59	0.63	0.04	0.33	0.32	**-0.01**	0.40	0.42	0.02	0.32	0.32	**0.00**	0.31	0.31	**0.00**
	85%	1.97	1.92	**-0.05**	1.92	1.84	**-0.08**	1.96	1.89	**-0.07**	1.68	1.63	**-0.05**	1.10	1.20	0.10	0.59	0.71	0.12	0.37	0.33	**-0.04**	0.51	0.46	**-0.05**	0.35	0.35	**0.00**	0.32	0.32	**0.00**
	90%	2.03	2.03	**0.00**	2.00	1.96	**-0.04**	2.08	2.03	**-0.05**	1.82	1.80	**-0.02**	1.53	1.43	**-0.10**	0.60	0.79	0.19	0.45	0.45	**0.00**	0.53	0.51	**-0.02**	0.42	0.43	0.01	0.34	0.33	**-0.01**
	95%	2.16	2.20	0.04	2.14	2.15	0.01	2.20	2.23	0.03	2.03	2.03	**0.00**	1.74	1.65	**-0.09**	0.60	0.91	0.31	0.53	0.59	0.06	0.54	0.58	0.04	0.52	0.52	**0.00**	0.36	0.36	**0.00**
Current Default		**2.10**			**2.10**			**2.10**			**2.10**			**2.10**			**1.10**			**0.55**			**0.55**			**0.55**			**0.37**		

Table C6 Comparison of Empirical (E) and Fitted (F) data points for single-storey roofs by period of construction

		Single-storey Roof																													
Period of		<1900			1900 - 1929			1930 - 1949			1950 - 1966			1967 - 1977			1978 - 1982			1983 - 1993			1994 - 1999			2000 - 2004			2005 - 2006		
Empirical / Fitted Distribution		E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-
Percentile	50%	0.35	0.30	-0.05	0.33	0.42	0.09	0.28	0.35	0.07	0.23	0.18	-0.05	0.16	0.14	-0.02	0.13	0.13	0.00	0.13	0.13	0.00	0.16	0.14	-0.02	0.16	0.14	-0.02	0.20	0.19	-0.01
	75%	0.78	0.88	0.10	0.74	0.87	0.13	0.52	0.74	0.22	0.40	0.59	0.19	0.37	0.40	0.03	0.18	0.18	0.00	0.26	0.25	-0.01	0.26	0.31	0.05	0.26	0.31	0.05	0.26	0.24	-0.02
	80%	0.91	1.03	0.12	0.90	0.97	0.07	0.68	0.83	0.15	0.47	0.68	0.21	0.40	0.47	0.07	0.21	0.27	0.06	0.27	0.32	0.05	0.28	0.37	0.09	0.28	0.37	0.09	0.26	0.25	-0.01
	85%	1.15	1.19	0.04	1.10	1.09	-0.01	0.86	0.92	0.06	0.61	0.77	0.16	0.40	0.55	0.15	0.26	0.36	0.10	0.40	0.39	-0.01	0.36	0.43	0.07	0.36	0.43	0.07	0.28	0.27	-0.01
	90%	1.40	1.37	-0.03	1.35	1.22	-0.13	1.05	1.04	-0.01	0.77	0.88	0.11	0.50	0.65	0.15	0.36	0.47	0.11	0.40	0.48	0.08	0.40	0.50	0.10	0.40	0.50	0.10	0.40	0.34	-0.06
	95%	1.66	1.62	-0.04	1.62	1.42	-0.20	1.40	1.22	-0.18	1.15	1.05	-0.10	0.68	0.77	0.09	0.50	0.62	0.12	0.40	0.58	0.18	0.40	0.60	0.20	0.40	0.60	0.20	0.40	0.64	0.24
Current Default		**2.30**			**2.30**			**2.30**			**2.30**			**2.30**			**0.40**			**0.35**			**0.35**			**0.35**			**0.25**		

Table C7 Comparison of Empirical (E) and Fitted (F) data points for single-storey roofs by period of construction

		Single-storey Floor																													
Period of		<1900			1900 - 1929			1930 - 1949			1950 - 1966			1967 - 1977			1978 - 1982			1983 - 1993			1994 - 1999			2000 - 2004			2005 - 2006		
Empirical / Fitted Distribution		E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-	E	F	+/-
Percentile	50%	0.77	0.77	0.00	0.73	0.74	0.01	0.73	0.74	0.01	0.73	0.72	-0.01	0.73	0.72	-0.01	0.57	0.56	-0.01	0.41	0.40	-0.01	0.41	0.40	-0.01	0.41	0.40	-0.01	0.34	0.33	-0.01
	75%	0.86	0.86	0.00	0.84	0.84	0.00	0.84	0.83	-0.01	0.83	0.79	-0.04	0.73	0.74	0.01	0.64	0.57	-0.07	0.41	0.42	0.01	0.41	0.41	0.00	0.41	0.41	0.00	0.34	0.34	0.00
	80%	0.88	0.88	0.00	0.87	0.86	-0.01	0.84	0.85	0.01	0.84	0.82	-0.02	0.78	0.75	-0.03	0.64	0.58	-0.06	0.42	0.42	0.00	0.41	0.42	0.01	0.41	0.42	0.01	0.34	0.35	0.01
	85%	0.91	0.90	-0.01	0.91	0.89	-0.02	0.87	0.87	0.00	0.84	0.86	0.02	0.84	0.79	-0.05	0.55	0.59	0.04	0.44	0.43	-0.01	0.42	0.42	0.00	0.42	0.42	0.00	0.36	0.35	-0.01
	90%	0.94	0.93	-0.01	0.94	0.93	-0.01	0.94	0.90	-0.04	0.85	0.90	0.05	0.84	0.83	-0.01	0.57	0.62	0.05	0.44	0.44	0.00	0.44	0.43	-0.01	0.44	0.43	-0.01	0.37	0.36	-0.01
	95%	0.99	0.98	-0.01	0.98	0.98	0.00	0.94	0.95	0.01	0.94	0.96	0.02	0.84	0.89	0.05	0.57	0.67	0.10	0.44	0.45	0.01	0.44	0.46	0.02	0.44	0.46	0.02	0.37	0.39	0.02
Current Default		**0.77**			**0.77**			**0.76**			**0.76**			**0.67**			**0.51**			**0.37**			**0.37**			**0.37**			**0.31**		

Appendix D – Validation of macroscopic characterisation

Table D1 Typical window ratios by EPC period of construction [178]

Age band of main dwelling	House or Bungalow	Flat or Maisonette
A, B ,C	WA = 0.1220 TFA + 6.875	WA = 0.0801 TFA + 5.580
D	WA = 0.1294 TFA + 5.515	WA = 0.0341 TFA + 8.562
E	WA = 0.1239 TFA + 7.332	WA = 0.0717 TFA + 6.560
F	WA = 0.1252 TFA + 5.520	WA = 0.1199 TFA + 1.975
G	WA = 0.1356 TFA + 5.242	WA = 0.0510 TFA + 4.554
H	WA = 0.0948 TFA + 6.534	WA = 0.0813 TFA + 3.744
I	WA = 0.1382 TFA – 0.027	WA = 0.1148 TFA + 0.392
J, K	WA = 0.1435 TFA – 0.403	WA = 0.1148 TFA + 0.392
WA = window area TFA = total floor area of main part plus any extension		

Source: SAP

Appendix E – Papers published

E.1 Published paper arising from Chapter 3 of this work

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The statistical relevance and effect of assuming pessimistic default overall thermal transmittance coefficients on dwelling energy performance certification quality in Ireland

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ABSTRACT

In the EU, Energy Performance Certificates (EPCs) are issued for dwellings whenever they are constructed, sold or leased. Where requiring data would be prohibitively costly, nationally applicable default-values for the thermal transmittance coefficients of the building envelope are employed. Use of such worst case default U-values ensure that a poor dwelling does not attain a better energy rating than is merited. In the absence of empirical data in Ireland thermal-default U-values, as in many other EU member states, are determined by the type and date of construction and then prevailing building codes. Using 463,582 dwellings representing 32% of the total Irish dwelling stock, this work assesses the relevance of current default U-values. Significant levels of retrofits have been found to lead to the default U-values used now being higher that is typical in reality, thus decreasing the accuracy, and hence credibility, of an EPC. Lack of certification accuracy also inhibits investment in energy efficiency.

1. Introduction

Building energy classification allows inter-comparison of building energy use [1,2]. The EU Directive on Energy Performance of Buildings (EPBD) [Directive 2002/91/EC] mandates comparable energy performance classifications, in the form of Energy Performance Certificates (EPCs), be issued for buildings constructed, sold or leased across the European Union [3,4]. Different approaches to calculating the energy classification of dwellings have been adopted across EU Member States [2,5]. In Ireland and in the UK the energy classification of a building compares energy consumption and CO_2 emissions theoretically calculated for an actual building, with a standardised benchmark building of the same typology and floor area as shown in Eqs. (1) and (2) below [6];

$$\frac{\text{Primary Energy Use}_{actual}}{\text{Primary Energy Use}_{benchmark}} = \text{Energy Performance Coefficient}\left[\frac{KWh}{m^2.annum}\right] \quad (1)$$

$$\frac{CO_2\ \text{Emissions}_{actual}}{CO_2\ \text{Emissions}_{benchmark}} = CO_2\ \text{EmissionsIndicator}\left[\frac{kgCO_2}{m^2.annum}\right] \quad (2)$$

An EPC:

- Presents the calculated energy performance coefficient of the building on a scale of A (which should have the lowest fuel bills) to G [2].
- Uses the same scale to define the impact a home has on the environment through greenhouse gas emissions.

In Ireland [7] and in the UK [8] publically-available EPC methodologies are used to calculate the energy classification of dwellings. EPC methodologies at the national level need to have;

- credibility and accuracy so that buildings with better labels should use less energy [2,9],
- applicability to a wide variety of buildings balancing some loss of accuracy with remaining representative [5],
- clarity so that users should be able to understand (a) the overall result and (b) the effect of choices (input) on the calculation result [5,9],
- reproducibility so that for a specific building the underlying method used leads to the same result; irrespective of subjective or arbitrary choices and independent of the user [2,5],
- transparency and encourage improvement to ensure the energy label of a given building is relevant and useful [2,5,9].
- cost-effectivenes

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- obtaining the building data needed for an energy performance certificate must not be too labour intensive to avoid significantly adding to the cost of the label particularly compared to the impact of the certificate on the energy performance [5].
- complexity and user skills – avoiding poorly user-interfaced complex simulation programmes that require a high training level for the programme user [10].

The results outputted by EPC methodologies can only offer an estimation of the actual building energy consumption since input data is often based on default operating conditions for *inter alia* external temperatures, internal loads, system efficiencies, prices and occupancy patterns [2,9,11–16]. There can thus be a major gap between the theoretical prediction and actual energy consumed in homes when occupied by real people [2,11,17]. In general, and as shown in Fig. 1 theoretical predicted energy consumption tends to be [11];

- Overestimated for average and less energy-efficient dwellings. This is explained partly by the 'prebound effect' [14] wherein occupants consume 30% less heating energy on average than the theoretical predicted rating, and
- underestimated when observing new or retrofitted dwellings. This is explained partly by the 'rebound effect' [18] wherein thermally retrofitted dwellings enable higher internal comfort temperatures more affordable leading to increased energy consumption rather than reduced energy bills [11,19–22].

Eqs. (1) and (2) show that the benchmarking process is a comparative analysis [2] that also informs an associated advisory report recommending feasible energy efficiency measures from both technical and economical perspectives [2,9,15]. The underlying premise being that a householder decisions are predicated on financial savings. Informing the household about cost-effective energy-saving measures is anticipated therefore to result in marked behavioural change to reduce their energy costs [23,24]. However even when the majority of recommendations are economically advantageous, consumers are not generally persuaded to act rationally to adopt these measures [23–25]. A barrier perceived by homeowners is inaccuracy wherein the financial savings in reality smaller that the label estimates [17]. To overcome this barrier energy consumption associated with improving an EPC label after a specific energy saving intervention in a particular dwelling should reflect closely the actual decrease in energy consumption [3,11]. The effectiveness of the rating therefore depends on the proper selection of default data [2,13]. Where accurately obtaining all of the required building envelope data would be excessively labour-intensive and/or invasive, national default values are sometimes employed. Default values are normally pessimistic so as to [5];

- avoid offering a better than merited energy rating,
- allow the homeowner to know the energy advantage of carrying out retrofits,
- encourage the homeowner to maintain records of energy upgrades that inform EPCs, and
- encourage assessors to seek out information to improve the energy rating.

An illustrative case of two identical buildings is examined in Table 1 [5]. Where for one building the data item is not observable on site or via documentary evidence so a default is used, while for the other building the actual data available was used.

Information on the thermal characteristics of older dwellings is often more difficult to obtain than for recently constructed dwellings. If an improvement in the energy performance certification is the basis for renovation, use of pessimistic default values may lead to higher improvement expectations in the EPC rating [5,11]. Arkestijn and van Dijk [5] raised the policy-related question of whether it is fair to give a worse energy rating simply because less information is available. Furthermore, if the lack of information associated with the building is to be penalised – how tough should the penalty be? In other words how pessimistic should the default value be?

A thermal transmittance coefficient or U-value of a building element is the rate of heat transfer (in watts) through one square meter of the building element divided by the difference in temperature across the element structure expressed in W/m^2K. The U-value is used to inform the heat energy consumption characteristic of a dwelling. The optimum choice of a default U-value characteristics should be based on empirical evidence. In the absence of such empirical data and as shown in Table 2, Irish thermal default U-values (similar to many other EU member states) were determined from [26,27];

- building element type,
- the date of construction for pre-thermal regulation dwellings (pre-1978).
- prevailing draft or finalised building codes by period of construction for post-thermal regulation dwellings (1978–2006) – allowing a grace period of generally two to three years after a proposed change in draft or finalised regulations for a dwelling to be completed [27].

Ireland [28,29] along with Italy [30], Spain [31] and Austria [32] use methodologies to calculate residential stock energy consumption using default U-values applied to equally default dwelling typologies classified by period of construction. The objectives of this work are to use the recently published Irish national empirical energy performance certification database [33] and SPSS® software, to:

- Assess the relationship of current default U-values relative to the empirical statistical distribution.
- Make recommendations for updated default U-value's relative to the empirical statistical distribution.
- Discuss the potential impact of default U-Value selection on the validity of,
- Energy performance certification,
- Use of default U-values as key inputs to national building energy consumption models.
- Highlight the potential contribution of their use to prebound effect in existing dwellings

2. Case study—the housing stock of Ireland

2.1. Context

As can be seen in Fig. 2, rural detached, oil-heated dwellings, Ireland's predominant house typology, comprises 18% of the total dwelling stock. This dwelling typology makes a good case study dwelling as;

- it qualifies as a reference dwelling under the European Commission delegated regulation no. 244/2012 [34],
- shown in Fig. 3, whilst Ireland has the highest proportion of single family dwellings in Europe [35] it is not extraordinary in this regard. Countries such as The UK, Greece, Norway and The Netherlands have similar profiles.
- 34% of the EU 28 population lived in detached houses in 2013 [36].

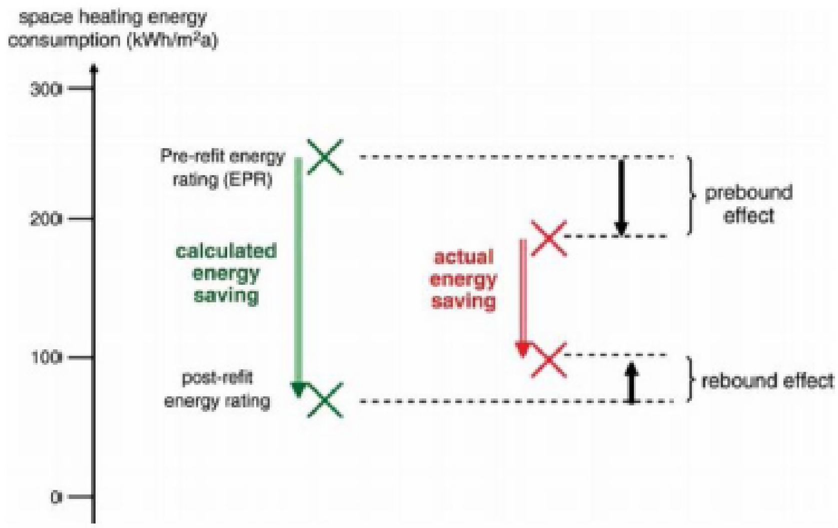

Fig. 1. How the prebound and rebound effects may limit energy saving to be less than envisaged [14].

Table 1
Building energy rating and payback periods for two identical buildings with and without information [5].

		Default U-value employed?	Building Energy Rating	Payback period for thermal upgrade measures
Information available?	Yes	No	High	Realistic
	No	Yes	Low	Unrealistically short

Table 2
Irish building regulation summary[27].

		Applicable Age Band	Default U-values (W/m² K)		
			Roof	Wall	Floor
Year of Regulation	N/A	<1978	2.3	2.1	1.2
	1976 (Draft)	1978–1982	0.4	1.1	0.6
	1981 (Draft)	1983–1993	0.4	0.6	0.6
	1991	1994–1999	0.35	0.55	0.45/0.6
	1997	2000–2004	0.35	0.55	0.45/0.6
	2002	2005–2006	0.25	0.37	0.37

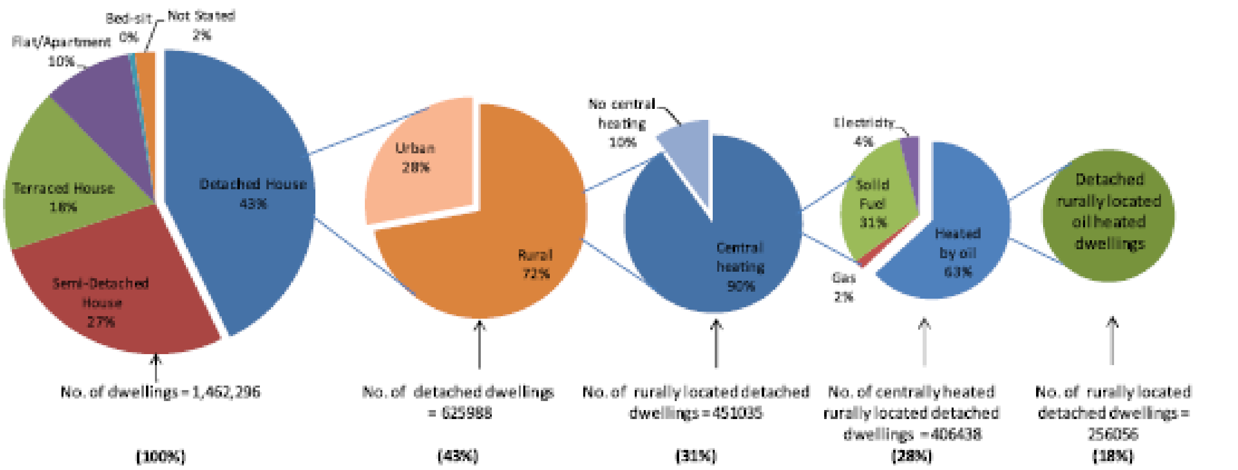

Fig. 2. Number of Irish dwellings by type [38].

- 67% of European housing was built prior to 1980 [37] and the introduction of meaningful thermal regulation of the housing sector. Mirroring this, 70% of Irish detached dwellings were constructed before the mid 1970s when constructional changes caused primarily by amendments to draft or actual thermal regulations led to increased levels of thermal insulation in Irish dwellings [27,28,38].

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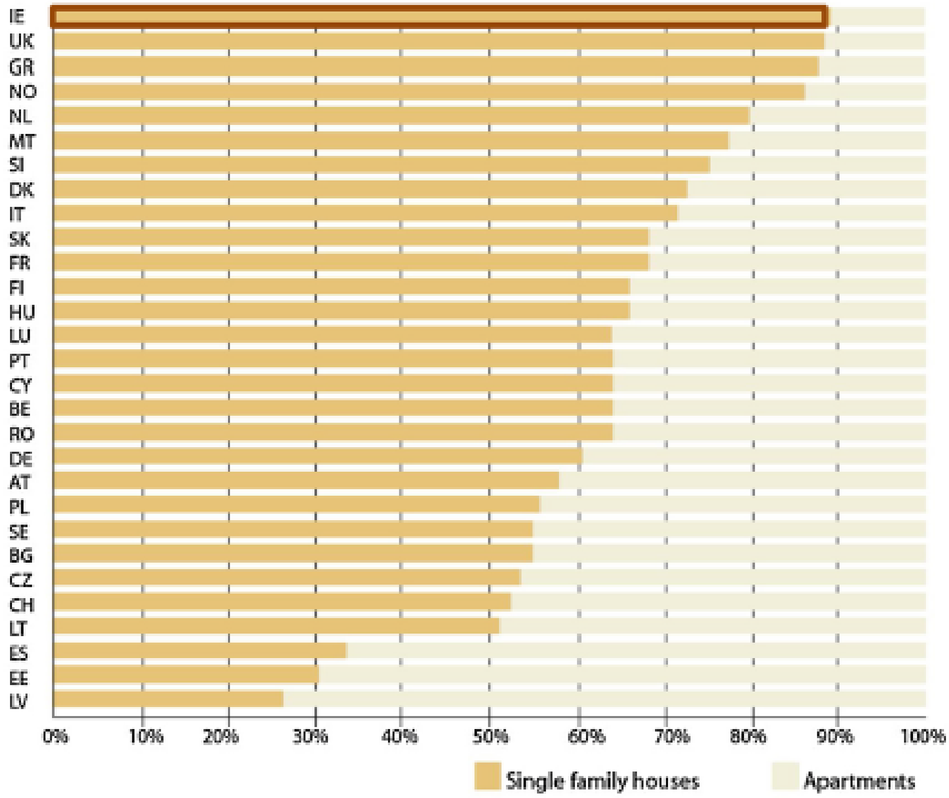

Fig. 3. Single family and apartment buildings in Europe [35].

2.2. Methodology

EPCs in Ireland are generated through a methodology embodied in the national Dwelling Energy Assessment Procedure (DEAP) software programme administered on behalf of the state by the Sustainable Energy Authority of Ireland (SEAI). SEAI made this detailed national empirical dataset publicly available in 2014 [39]. 463,582 dwellings representing 31.7% of the total dwelling stock constructed up to 2006 received an EPC by August 2014 [33]. Rural, detached, single and two-storey, oil centrally-heated and naturally-ventilated dwellings were isolated from the larger dataset. Dwellings carrying a 'provisional' certificate were also filtered. As shown in Table 3, this resulted in a sample of 50,236 dwellings representing 11% of the available database. Table 2 shows that the refined dataset compares well with the national distribution of detached dwellings by date of construction [27]. Due to older dwellings changing ownership less often, EPCs have been carried out on older dwellings less frequently than newer housing. Newly-constructed detached dwellings are thus more represented in the empirical dataset [33].

Fig. 4(a) shows an illustrative typical U-value frequency distribution for a real thermal building element extracted from the Irish national empirical dataset using SPSS® software [33]. The frequency distribution reveals the thermal characteristics of Ireland's reference dwelling envelope to be normally bi-modally distributed with "Mode 2" reducing relative to "Mode 1" likely due to retrofit interventions. The position of current default value relative to the statistical distribution was examined. Statistical probability tests performed found the default value to often have no statistical significance to the empirical distribution. Moreover, as more retrofit interventions are carried in the housing sector current defaults become less relevant to the real statistical distribution over time especially with respect to "Mean 1". The default U-value was thus filtered from the database and hence the solver tool in EXCEL® was used to employ the method of maximum log likelihood as the best method [40] for estimating the best fit curve for probability distribution of large datasets. Fig. 4(b) shows how a curve was fitted to the real data. Thermally upgraded or Mode 1 dwellings show a tighter and more pronounced distribution profile than Mode 2 dwellings which have yet to undergo significant thermal upgrades. In general and as illustrated in Fig. 4 (b), the standard deviation for Mode 2 tends to be greater than that of Mode 1; this is attributed to thermal retrofits achieving a more harmonised level of thermal insulation.

2.2.1. How pessimistic should the default U-value be?

If it is accepted that pessimistic default U-values should be employed when producing EPC's to (i) keep the cost of certification at an affordable level and, (ii) aid the reproducibility and robustness of the method for situations where information is lacking. When selecting how pessimistic default U-values should be, the key issue, is the potential impact of that selection point on the EPCs accuracy. Table 4 discusses the implications whilst Fig. 5 outlines the scale of default selection options relative to a normalised statistical distribution of a dwelling elements thermal characteristic.

Table 4 outlines how the selection of;

a) '*moderately optimistic*' to '*very optimistic*' default U-values are not desirable as it may act as a disincentive to carrying out thermal energy efficiency upgrades in the housing sector,
b) '*Very pessimistic*' default U-values are likewise not desirable due to the significant risk of

Table 3
Frequency of detached dwellings in representative empirical dataset compared with actual dwelling frequency by period of construction [33,38].

Period of Construction		Frequency detached building typology nationally		Frequency empirical dataset	
		N	%	N	%
Pre-thermal regulation	< 1900	44784	11%	1294	3%
	1900–1929	34552	8%	2901	8%
	1930–1949	32453	8%	2110	7%
	1950–1966	32245	8%	3662	11%
	1967–1977	52457	13%	6559	13%
Post-thermal regulation	1978–1982	29817	7%	5695	19%
	1983–1993	60233	15%	8375	14%
	1994–1999	45694	11%	7080	15%
	2000–2004	52764	13%	8867	17%
	2005–2006	21910	5%	3693	17%
Total		**406909**	**100%**	**50236**	**11%**

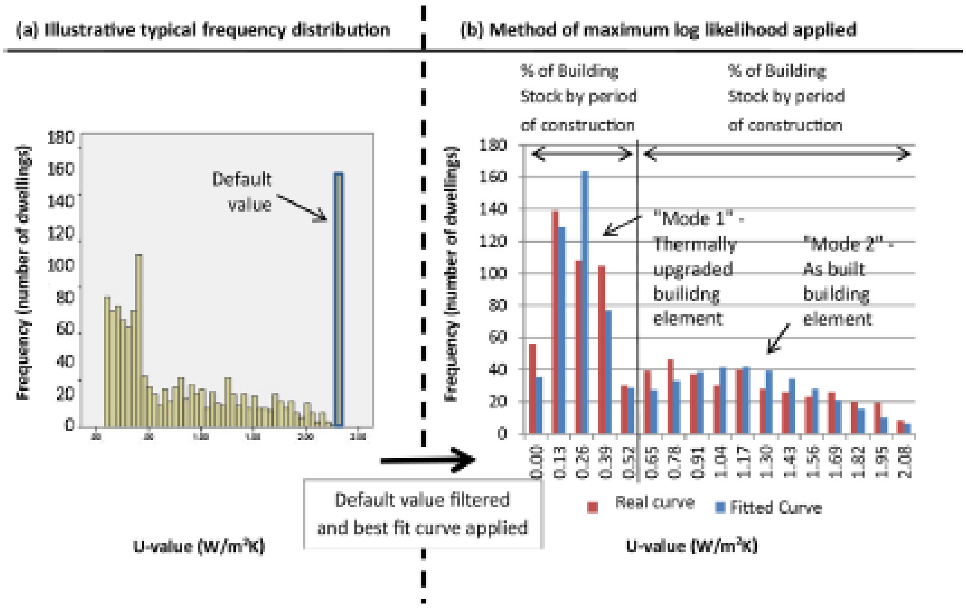

Fig. 4. a & b Illustrative typical frequency distribution and analysis of wall and roof U-values [33].

(i) greatly overestimating the potential saving from retrofit intervention and
(ii) the creation of a very punitive system for existing dwellings where information is often difficult to obtain.

c) '*Realistic*' statistically derived means will often lead to an underestimation of the potential to improve the energy performance rating.

'*Moderately pessimistic*' and '*pessimistic*' thus remain. Fig. 5 shows how the use of;

d) '*moderately pessimistic*' default U-values (50th to 84.1st percentile point), results in a slight loss of validity and a better comparative energy performance rating of the two identical buildings examined in Table 1, however there is significant risk of overestimating the potential savings from a retrofit intervention for dwellings occupying the 84.1st to 100th percentile point (15.9% of the dwelling stock assuming a normal distribution).
e) '*pessimistic*' default U-values (84.1st to 97.7th percentile point) will lead to a greater loss in validity than that of *moderately pessimistic* U-values, but only a slight risk of overestimating the potential savings from a retrofit intervention for dwellings occupying the tail of the distribution (15.9–6.7% of the dwelling stock).

Assuming the empirical data to distribute normally, it is relatively straightforward to pick a '*reasonably pessimistic*' default U-value between the 85th or 90th percentiles as shown in Fig. 5. Selection of a default U-Value in this zone will ensure a reasonable level of accuracy for the certificate but also allow the home-owner to perceive the energy advantage of carrying out thermal retrofits. As Mode 2 dwellings are yet to engage in upgrade measures, Mode 2 is the relevant mode for analysis to recommend empirically derived defaults U-values. The dataset [33] was thus analysed to recommend default U-values based on the 90th percentile point of the Mode 2 distribution – assuming it accounted for a meaningful proportion of the dwelling stock.

2.3. *Results*

2.3.1. *Position of current defaults relative to average empirically derived (real) U-values*

Pre-thermal regulation building elements are generally assumed to be have been originally constructed without insulation [27]. Fig. 6 demonstrates that building energy assessors were often

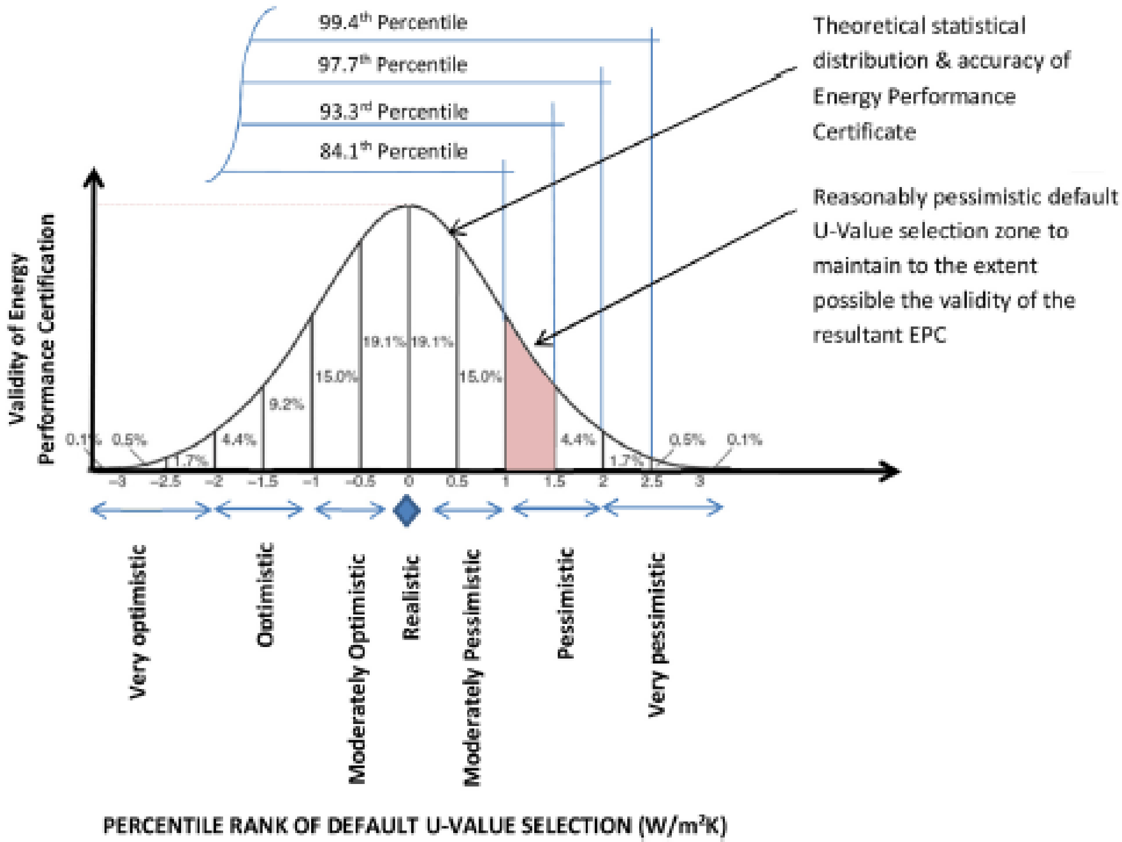

Fig. 5. Relationship of default U-value selection to quality aspects of energy performance certification relative to normal statistical distribution.

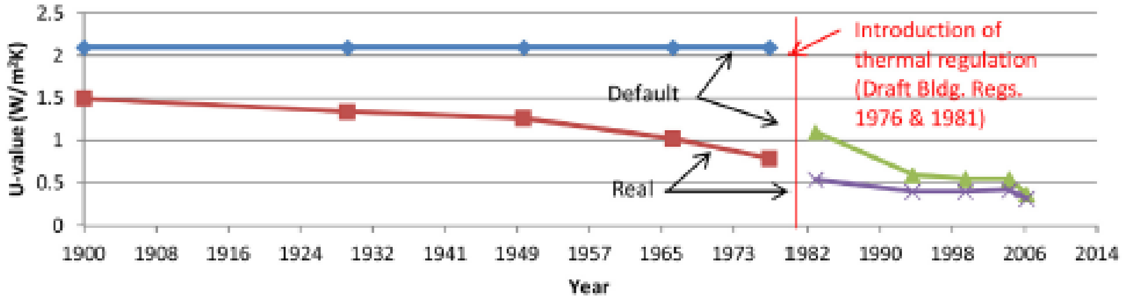

Fig. 6. Average wall U-value in the default and empirical dataset over time [28,33].

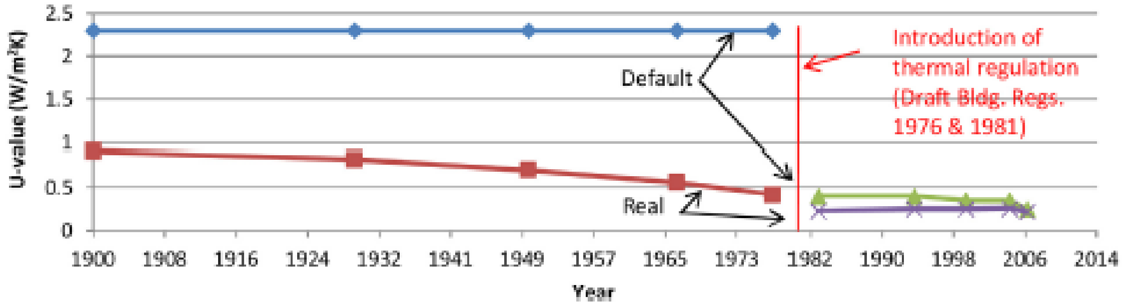

Fig. 7. Roof U-value in the default and empirical dataset over time [28,33].

Table 4
Implication of default U-value selection on Energy Performance Certification.

Thermal Default	Very Optimistic	Optimistic	Moderately Optimistic	Realistic	Moderately Pessimistic	Pessimistic	Very Pessimistic
	Loss of Validity			Loss of Validity			
Loss of Validity Scale Implication for Energy Performance Certification	**Significant** Increasing loss of accuracy leading to an increasingly significant risk that, • improvement measures could actually worsen the energy rating rather than make it better and, • assessors and end-users might be less motivated to gather detailed information about the building where it is not readily available.	**Slight**		**Slight** Using statistical means determined empirically shall significantly increase the statistical accuracy of the performance certificate however if the realistic value is too optimistic for the particular building being examined without information, it may lead to an underestimation of the potential to improve the energy performance rating	**Significant** Increasing loss of accuracy leading to an increasingly significant risk of, • the results returned by the process greatly overestimating the potential savings from the retrofit intervention and • a punitive system, especially for existing buildings.		

able to identify the presence of insulation in pre-thermal regulation dwellings, demonstrated by the gap between the maximum regulation default wall U-value and the real mean U-values by period of construction. The data indicates that end-users either;

(i) constructed to better specifications than required by thermal regulation prevailing at the time or
(ii) have carried out autonomous energy-efficiency improvements

Greater deviation from the current default wall U-values is observed in pre-thermal regulation dwellings constructed pre-1900 and up and until circa 1978. A high degree of autonomous energy-efficiency improvements is noted in dwellings constructed between 1950 and 1977. These dwellings were found to have the worst heat loss characteristics within this typology, which may have provided greater motivation for the end-user to invest in upgrade measures [28]. In post-regulation dwellings constructed between 1978 and 2006; and as time progresses the disparity between the default and real U-value lessens. Notably however, in the period between 2005 to 2006, 6 to 7% of dwelling walls surveyed were not compliant with the prevailing thermal regulations. This may be attributable to a lax adherence to building control measures during Ireland's recent housing construction boom [41].

In 2014, 58% of walls and 64% of roofs were found to have significant levels of insulation; an increase from 3% and 7% in 2001–2002 [42]. Roof U-values range from 0.13 to 0.29 W/m^2K and, as shown in Fig. 7, do not significantly vary by period of construction. Roof U-values are generally lower than wall U-values; wall U-values range from 0.15 to 0.41 W/m^2K for pre-thermal regulation dwellings (with the exception of pre-1900 two-storey walls at 1.13 W/m^2K) and 0.28–0.31 W/m^2K for post-thermal regulation dwellings. The improved thermal characteristic of roofs is attributable to the relative ease and lower cost of retrofitting attic insulation compared to wall insulation.

Figs. 6 and 7 demonstrate that;

(i) the strong association of a dwellings age with its energy efficiency is diminishing as retrofits in the sector are carried out, and
(ii) the use of pessimistic default thermal characteristics as inputs to national energy consumption models considerably overestimates the energy saving potential of the existing housing stock.

2.3.2. *Assessment of level of thermal retrofits for Ireland's predominant housing typology*

The percentage of significantly retrofitted or Mode 1 dwellings by period of construction and building type is presented in Table 5. Table 5 indicates that 44% of walls and 47% of roofs in pre-thermal regulation dwellings have undergone significant thermal retrofits, whilst 71% of walls and 80% of roofs in post-thermal regulation dwellings have either undergone autonomous energy efficiency upgrades or were constructed to better the maximum allowable U-value of the time.

2.3.3. *Recommendation to revise default U-values*

Due to the difficulty of (i) retrofitting floor insulation in an occupied dwelling [28], and (ii) identifying the presence of floor insulation retrospectively, the empirical database did not reveal any thermal upgrades of floors. Table 6 thus presents recommendations for walls and roofs only. The thermal performance of single storey and two-storey dwellings – with the same thermal characteristics – will differ owing to a different volume to surface area ratio. One and two-storey dwellings are thus distinguished.

Irish thermal default U-values, similar to many other EU member states, were determined;

Table 5
Percentage of walls and roofs which have been significantly thermally retrofitted and/or upgraded by period of construction [33].

Period of Construction		Walls: % significantly retrofitted or autonomously upgraded, single-storey	Walls: % significantly retrofitted or autonomously upgraded, two-storey	Walls: Weighted average		Roofs: % significantly retrofitted or autonomously upgraded, single-storey	Roofs: % significantly retrofitted or autonomously upgraded, two-storey	Roofs: Weighted average	
Pre-thermal regulation	<1900	17%	70%	49%	44%	56%	49%	52%	47%
	1900–1929	15%	31%	25%		27%	52%	42%	
	1930–1949	19%	30%	24%		27%	59%	43%	
	1950–1966	50%	49%	50%		36%	59%	44%	
	1967–1977	72%	66%	70%		51%	56%	53%	
Post-thermal regulation	1978–1982	54%	57%	55%	71%	52%	95%	68%	80%
	1983–1993	70%	65%	68%		71%	98%	83%	
	1994–1999	79%	65%	72%		60%	99%	80%	
	2000–2004	75%	63%	68%		49%	99%	78%	
	2005–2006	93%	94%	94%		84%	98%	92%	

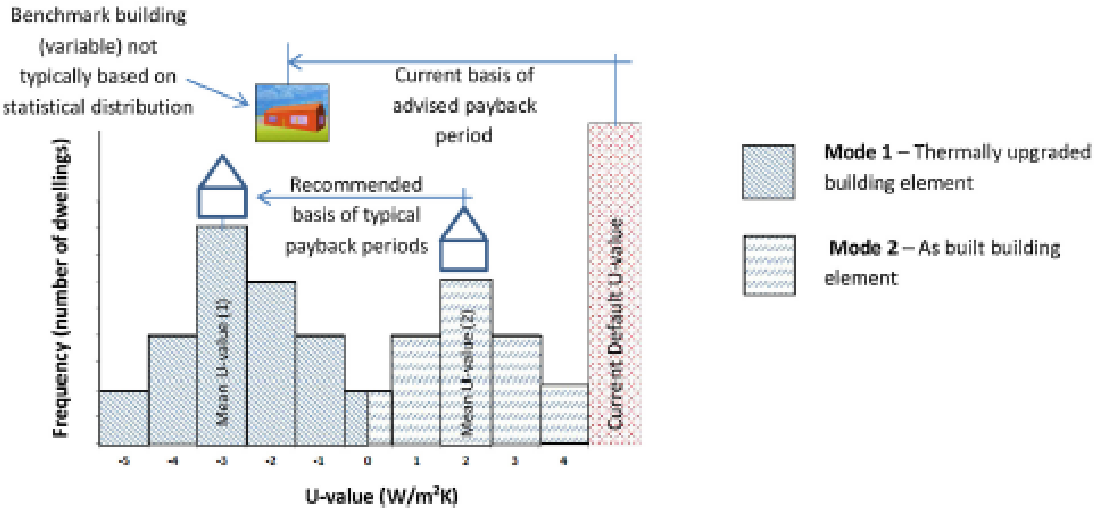

Fig. 8. Basis of typical pay-back period calculation arising from thermal retrofits.

(i) from the type and date of construction for pre-thermal regulation elements and;

- Walls – Recommendations for updated default U-values in Table 6 reasonably approximate current default U-value of 2.1 W/m^2 K. A small average reduction of – 10% of the ratio of standard deviation over the mean or Relative Standard Deviation (RSD) for single-storey walls and – 8% RSD for two-storey walls is thus recommended.
- Roofs – Recommendations for updated default U-values in Table 6 deviate significantly from the current default U-value of 2.3 W/m^2 K. An average reduction – 60% RSD for single-storey roofs and – 38% for two-storey roofs is thus recommended. The difference between single and two-storey dwellings might be attributed to the fact roof surface area on single storey dwellings impacts the dwelling heat loss characteristic to a much greater extent than in the equivalent two storey-dwelling. This may have provided more motivation to the home- owner to carry out thermal upgrades to this element.

(ii) by the maximum allowable U-value at time of construction for post-thermal regulation elements;

- Walls – Pre-thermal regulation single and two-storey walls behave similarly; however post-thermal regulation, single-storey dwelling walls tend to perform better thermally than their two-storey counterpart. Therefore an average reduction of – 19% RSD to the current thermal default is recommended for single-storey detached dwellings while an average – 7% RSD reduction is recommended for two-storey walls. Dwellings constructed between 1978 and 1982 see the largest deviation of 30 and 14% for one and two-storey dwellings respectively, this may be attributable to the 1979 oil crisis making people more aware of the value of insulation and the positive effect of the draft thermal building regulations published in the mid 1970s.
- Roofs – post-regulation, roofs show a better approximation to the current default with an average RSD of ±11 and 10% for single and two-storey dwellings respectively. Oddly between 2000 and 2006 the recommended defaults are greater than the current defaults, this is also attributed to a lax adherence to building control measures during Ireland's recent housing construction boom [41].

3. Discussion & recommendations

The building sector, and especially pre-existing housing, is often identified as providing 'enormous' [43,44] potential for CO_2 reduction. Monitoring of the energy performance of the building stock has generally provided knowledge, analysis and evidence insufficient to [11,35]:

Table 6
Recommendation of empirically derived default U-values for detached Irish dwellings [33].

Period of Construction		Wall: Current Default	Wall: Recommended single-storey default U-value ($W/m^2 K$)	RSD (%)[a]	Wall: Recommended two-storey default U-value ($W/m^2 K$)	RSD (%)[a]	Roof: Current Default	Roof: Recommended single-storey default U-value ($W/m^2 K$)	RSD (%)[a]	Roof: Recommended two-storey default U-value ($W/m^2 K$)	RSD (%)[a]
Pre-thermal regulation	>1900	2.10	1.92	−9% −10%	2.09	0% −8%	2.30	1.40	−38% −60%	1.62	−30% −38%
	1900–1929	2.10	1.83	−13%	1.86	−11%	2.30	1.13	−51%	1.58	−31%
	1930–1949	2.10	1.08	−1%	2.02	−4%	2.30	1.00	−57%	1.43	−38%
	1950–1966	2.10	1.89	−10%	1.89	−10%	2.30	0.61	−73%	1.32	−43%
	1967–1977	2.10	1.78	−15%	1.78	−15%	2.30	0.50	−78%	1.21	−47%
Post-thermal regulation	1978–1982	1.10	0.77	−30% −19%	0.94	−14% −7%	0.40	0.36	−10% ±11%	0.34	−15% ±10%
	1983–1993	0.60	0.57	−5%	0.58	−3%	0.40	0.30	−25%	0.36	−11%
	1994–1999	0.55	0.45	−18%	0.53	−4%	0.35	0.35	0%	0.35	−0%
	2000–2004	0.55	0.42	−24%	0.53	−4%	0.35	0.40	14%	0.38	−9%
	2005–2006	0.37	0.31	−16%	0.34	−9%	0.25	0.24	−6%	0.28	−13%

This table was created from an analysis of the data of the 90th percentile point of Mode (2) if it accounted for significant proportional of stock; Mean 2 + [std.dev × 0.9].
[a] Ratio of standard deviation over the mean or Relative Standard Deviation (RSD).

- track the progress and impact of policy implementation,
- make comparisons between different policy and market regulatory environments,
- recommend best practice to achieve energy efficient buildings.

This results work highlights how use of pessimistic default thermal characteristics as inputs to national energy consumption models will cause the model to considerably overestimate the energy saving potential of the existing housing stock for pre-regulation dwellings (prebound effect). The practice of employing default characteristics in energy consumption models questions whether [14,17,22];

- the energy saving potential of the building sector is as large as previously thought and
- the burden for CO_2 reductions on this sector is realisable.

Ambitious CO_2 reduction targets exist for the existing housing stock [2,14,35]. EPC databases are rich in information that represents a significant opportunity to contemporaneously inform empirically derived residential energy consumption models. Gathering the information necessary to populate an EPC database is also expensive and labour intensive. The inclusion of pessimistic defaults in resultant EPC databases means that these rich databases cannot act as an accurate tool for monitoring the energy consumption of the dwelling stocks in line with the original intention of the EPBD directive. It is strongly recommended that intelligent databases should continually analyse EPC data to produce empirically derived housing typologies, by period of construction and by percentage of the dwelling stock applying – Mode 1 and Mode 2 as shown in Fig. 4(b). These databases then more accurately inform national residential energy consumption models and policies thus narrowing the energy performance gap.

To further highlight the impact of use of default model inputs and virtual dwelling typologies on the prebound effect; a sensitivity analysis to the use of statistically derived mean U-values to residential energy consumption models is recommended. Ireland's national EPC empirical dataset could be exploited to create a *real* validated reference dwelling typology by period of construction for Ireland's predominant housing typology. The resulting data can hence be used as simplified and validated inputs to a bottom-up residential energy consumption models.

In order to produce (i) a building energy label, (ii) recommend energy efficiency measures and (iii) calculate payback periods; a typical EPC calculation engine for dwellings compares the predicted energy consumption of the actual dwelling with that of a standardised benchmark building of the same typology as shown in Eqs. (1) and (2) and Fig. 8.

As discussed in Section 1, where defaults are employed the programme will return unrealistically short payback periods for refurbishment works. To,

i remove this known barrier to the uptake of energy efficiency upgrades in the residential sector and,
ii allow the end user to make a more informed decision on retrofitting strategies,

reports of the assessor should highlight how building element U-Values were determined, how accurate they believe those values to be and carry out a sensitivity analysis highlighting the impact their assumptions may have on the energy label and/or potential energy savings resulting from thermal retrofits. To produce a range of results in this analysis, it is recommended that a typical Mode 2 dwelling by period of construction be characterised to replace the actual dwelling of Eqs. (1) and (2) as shown in Fig. 8 and as described by Eqs. (3) and (4) below:

$$\frac{\text{Primary Energy Use}_{\text{Mode2 Typical}}}{\text{Primary Energy Use}_{\text{Benchmark}}} = \text{Energy Performance Coefficient } (EPC)\left[\frac{KWh}{m^2.annum}\right] \qquad (3)$$

Typical paybacks achieved through refurbishment measures by period of construction could also be indicated as shown below;

$$\frac{\text{Primary Energy Use}_{\text{Mode2 Typical}}}{\text{Primary Energy Use}_{\text{Mode1 Typical}}} = \text{Energy Performance Coefficient } (EPC)\left[\frac{KWh}{m^2.annum}\right] \qquad (4)$$

The consequent realistic payback periods, increase the credibility of the advisory report associated with the EPC.

4. Conclusions

Analysis of Ireland's predominant housing typology in 2014 finds 58% of walls and 64% of roofs to have significant levels of insulation; an increase from 3% and 7% in 2001–2002. The results indicate that 44% of walls and 47% of roofs in pre-thermal regulation dwellings have undergone significant thermal retrofits, whilst 71% of walls and 80% of roofs in post-thermal regulation dwellings have either undergone autonomous energy efficiency upgrades or were constructed to better the maximum allowable U-value of the time. These significant levels of thermal retrofits in Irish housing sector are leading to;

- a diminishing association between a dwellings age and its energy efficiency,
- a positively shifting bi-modal distribution of thermal characteristics,
- default U-values chosen as described in Section 1, have become increasing outmoded.

The use of outmoded default U-values to necessarily maintain the cost-effectiveness of EPC decreases the accuracy and hence credibility of both the EPC and its associated advisory report. A perceived lack of certification accuracy by the homeowner inhibits investment in energy efficiency.

Adoption of "*reasonably pessimistic*" statistically relevant default U-values shall underrank the performance of circa 90% of dwellings and, where used, is assumed to be a significant contributing factor to the prebound effect in dwellings.

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E.2 'Default' Reference Dwelling paper

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State of the Irish housing stock—Modelling the heat losses of Ireland's existing detached rural housing stock & estimating the benefit of thermal retrofit measures on this stock

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HIGHLIGHTS

- ► Model constructs base geometry of detached rural Irish dwellings by age band.
- ► Model quantifies savings to this stock via The National Insulation Scheme.
- ► Results offer significant contribution to Ireland's carbon abatement projections.
- ► Greatest savings result from retrofitting the pre 1979 stock.
- ► Government needs to introduce PAYS scheme or similar to engage public at large.

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ABSTRACT

Ireland's housing stock has been identified as being amongst the least energy efficient in Northern Europe. Consequently, atmospheric emissions are greater than necessary. Government funded schemes have been introduced to incentivise the uptake of thermal retrofit measures in the domestic Irish market. A study of Ireland's housing highlights the dominance of detached houses (43%), 72% of which are rurally located and are predominantly heated with fuel oil. This paper investigates the economic and carbon case for thermal retrofit measures to the existing detached, oil centrally heated, rural housing stock. The study found the case for energy efficiency measures to be categorical and supports the Irish Government's focus on energy efficiency policy measures. Thermal retrofit measures in the detached housing stock have the potential to realise an averaged 65% theoretical reduction in heating costs and CO_2 emissions for houses constructed prior to 1979 (coinciding with the introduction of building regulations) and around 26% for newer homes, thus offering a significant contribution (44%) to Ireland's residential carbon abatement projections and hence in meeting the EU's directives on energy and carbon. The greatest savings (36%) of Ireland's carbon abatement projections result from improving the energy efficiency of the pre 1979 stock.

1. Introduction

Ireland's housing stock has been identified as being amongst the least energy efficient in Northern Europe (Brophy et al., 1999; Lapillonne et al., 2012); therefore energy consumption in the domestic sector is greater than necessary (Clinch and Healy, 2004, 2000). Examining CO_2 emissions per dwelling, the average Irish dwelling in 2005 emitted 47% more CO_2 than the average dwelling in the UK. Emissions were 92% higher than the average for the EU-15 and 104% more than the EU-27 (SEAI, 2008).

Regulations governing the energy efficiency of new dwellings were not introduced in the Republic of Ireland until 1979. 50% of the current housing stock was constructed prior to 1979 and it was not until 2006 that significant thermal retrofits were introduced. Hence most houses in Ireland are considered to be thermally sub-standard (Brophy et al., 1999, Clinch and Healy, 2000).

Ireland's recently published (2009) *National Energy Efficiency Action Plan 2009–2020* (NEEAP) identifies the following major energy efficiency challenges in the Irish Residential Sector:

1. To create a generation of buildings that meet expectations of comfort and functionality while significantly reducing energy usage and CO_2 emissions; and

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Nomenclature

1S	Single storey
2S	Two storey
ACH_{50}	Air exchange rate per hour resulting from a pressure difference of 50 Pa between the inside and outside of the building, including the effects of air inlets
ACH	Air exchange rate per hour induced by wind of a normally exposed site between the inside and outside of the building, including the effects of air inlets
A_f	Floor area (m^2)
A_{ope}	Maximum combined area of doors windows and rooflights (m^2)
BER	Building energy rating
BRE	Building research establishment
CIBSE	Chartered institute of building services engineers
CSO	Central statistics office of Ireland
DCENR	Department of communications, energy and natural resources
DEAP	Dwelling energy assessment procedure
DG	Double glazed
EDRT	Energy demand reduction target
e_k	Default correction factor for exposure
EPBD	Energy performance of buildings directive
EPC	Energy performance coefficient
ESB	Electricity supply board
ESRI	Economic and social research institute of Ireland
EU-15	The 15 countries that were members of the EU before the enlargement on 1st May 2004
EU-27	Total EU member countries as of time of publication
fg_1	Default correction factor taking into account the influence from annual variation of the external temperature
fg_2	Temperature reduction factor taking into account the difference between annual mean external temperature and external temperature
G_w	Correction factor taking into account the influence from ground water.
$H_{T,ig}$	Heat loss coefficient through the ground (W/K)
IEA	International Energy Agency
IES	Integrated environmental solutions
INSHQ	Irish National Survey of Housing Quality
k	Soil thermal conductivity (W/m K)
koe/m^2	Kilogramme of oil equivalent per metre squared
MPEPC	Maximum permitted energy performance coefficient
NEEAP	National energy efficiency action plan
PAYS	Pay As You Save
R_{si}	Internal wall surface thermal resistance (m^2 K/W)
R_{se}	External wall surface thermal resistance (m^2 K/W)
RSD	Ratio of Standard Deviation over the mean
SAP	UK Standard Assessment Procedure
SEAI	Sustainable Energy Authority of Ireland (formerly Sustainable Energy Ireland—SEI)
SG	Single glazed
toe/dw	Tonnes of oil equivalent per dwelling
UCD	University College Dublin
Uope	Average U-Value of windows, doors and rooflights (W/m^2 K)
U_m	Maximum average U-Value (W/m^2 K)
V	Volume (m^3)

2. To address the legacy of older housing with poor energy and CO_2 performance.

The recent downturn in the Irish economy combined with the oversupply of new dwellings has resulted in an average vacancy rate of 15% (over 260 K homes) and a collapse in new house building (Fitzgerald, 2005; Kitchen et al., 2010; CSO, 2011). Given that in some locations it could well be over a decade or more before excess housing stock becomes occupied, depending on an economic recovery, liquidity amongst lenders, and demographic demand (Kitchen et al., 2010), if a significant reduction in energy consumption of the domestic housing sector is to occur, then it will be necessary to undertake extensive thermal refurbishment (retrofitting) of the current housing stock. (Beddington, 2008; Gupta, 2009, 2010; Bernier et al., 2010; Curtain, 2009; Bell and Lowe, 2000). The Irish government has thus introduced *The National Insulation Scheme* designed to encourage home owners to increase the efficiency of the existing housing stock.

A large contributing factor to the high energy consumption of the typical Irish home is that the nation's housing stock has larger than average floor areas; the average (useful floor area) size of an Irish dwelling being 104 m^2 in 2003 representing the fourth largest figure in Europe behind Luxembourg, Denmark, and Malta. Also Ireland has on average the greatest number of rooms in Europe at 5.6 rooms per person in 2002 (Federcasa, 2006).

Another key variable impacting on energy consumption in the residential sector is the type of dwelling. Detached dwellings normally have a greater floor area than other dwelling types; they also have high surface area to volume ratios and thus have a greater heat loss in W/K, than other house types of the same construction period. A seminal study by Shipworth et al. (2010) found that detached homes have a tendency to be heated for longer than other house types and Scott et al. (2008) found they have a stronger association with fuel poverty than semi-detached houses, apartments or bedsits; indeed, based on an expenditure index, inhabitants of flats and apartments are two-thirds less likely to be fuel poor than those in detached houses, all other things being equal. Detached dwellings should therefore be particularly targeted in energy-efficiency retrofit programmes (Lomas, 2010; Shipworth et al., 2010).

The higher running costs associated with detached dwellings and the pervasiveness of this dwelling type in the Irish landscape is an indicator of why Ireland is said to have such a high degree of fuel poverty; approximately 150,000 homes were estimated to be experiencing fuel poverty in 2005 (Curtain, 2009). This trend is exacerbated by the residents of the older housing being elderly, retired and often widowed occupants who are asset rich and cash poor. Furthermore, Ireland has an ageing population, currently 11% of the population are aged 65 and over and this is set to increase to 25% by 2060 (Begley, 2011).

An analysis of Ireland's housing stock shows that 43% are detached properties and of this 43%, 72% are rurally located. Furthermore 70% of this house type was constructed prior to the introduction of the building regulations (CSO 2006). Due to the prevalence and relative inefficiency of detached housing in Ireland; this study will analyse these dwellings, seeking to quantify the effectiveness of thermal retrofits.

2. Methodology

A full physical description for Irish dwellings does not exist from any one source. Creating a base geometry and set of thermal characteristics for detached dwellings was therefore a major piece of the work undertaken in this study.

A base geometry based on a sampling of rural detached dwellings was created. A set of thermal characteristics were then applied to this base geometry according to age bands; assuming similar characteristics of construction. The age bands were based on Ireland's national Dwelling Energy Assessment Procedure, (DEAP). DEAP is Ireland's implementation of the EU directive on the Energy Performance of Buildings (Directive 2002/91/EC, EPBD). See Tables 1 and 2 for the summary base geometry and thermal characteristics established for Irish detached dwellings by DEAP age band.

Tables 1 and 2 were compiled using datasets which were provided by University College Dublin's Energy Research Institute, these included the 2006 national census (CSO 2006) and the Irish National Survey of Housing Quality 2001–2002 (INSHQ). Other data sources were the DEAP manual, and the UK's Building Research Establishment (BRE) publications. Table 3 summarises the data used.

The central statistics office (CSO) census data relates the total number of detached rural centrally heated dwellings in Ireland (totalling 406,910 dwellings) by age and floor area. The age bands used by DEAP differ from the age bands quoted in the CSO dataset, therefore an adjustment had to be made so that U-values as ascribed in DEAP could be attributed to actual census housing quantities; the average number of houses built in a CSO construction period was found and then the number of houses was redistributed in line with DEAP age groups, see Table 4.

The INSHQ (sample set of over 40,000) asked much more detailed questions pertaining to the heating, hot water and comfort systems than the CSO, the results from this dataset were extrapolated and applied to housing quantities outlined in Table 4 by DEAP age band. The statistics package SPSS® was used to manipulate information contained in the datasets.

The BRE was used to establish infiltration rates (sample set of 471 dwellings) and glazing ratios were established from the UK Standard Assessment Procedure (SAP) database; again applied by DEAP age band.

Table 1
The base geometry a standard Irish domestic detached dwelling.

DEAP age band	DEAP year of construction	Area (m^2)							
		Single storey			Two storey			Common	
		Wall	Roof	Floor	Wall	Roof	Floor	Window	Door
A	Before 1900	97	149	142	147	75	71	24	5.7
B	1900–1929	97	149	142	147	75	71	24	5.7
C	1930–1949	97	149	142	147	75	71	24	5.9
D	1950–1966	98	151	143	148	75	72	24	5.9
E	1967–1977	99	155	147	151	77	74	24	6.1
F	1978–1982	105	160	152	157	80	76	21	6.1
G	1983–1993	105	164	156	158	82	78	22	5.9
H	1994–1999	109	183	174	165	91	87	25	6.3
I	2000–2004	115	204	194	174	102	97	27	6.8
J	2005–2006	120	230	219	182	115	110	31	6.8

Data from various sources, refer to Table 3.

Table 2
Thermal characteristics of a standard Irish domestic detached dwelling.

DEAP age band	DEAP year of construction	U-Values ($W/m^2 K$)							Infiltration rate ACH_{50}
		Wall	Roof	Door	Floor[a]		Window		
					Single storey	Two storey	Single glazed	Double glazed	
A	Before 1900	2.10	2.30	3.0	0.68	0.84	4.80	3.10	12
B	1900–1929	2.10	2.30	3.0	0.68	0.84	4.80	3.10	12
C	1930–1949	2.10	2.30	3.0	0.68	0.84	4.80	3.10	16
D	1950–1966	2.10	2.30	3.0	0.67	0.84	4.80	3.10	14
E	1967–1977	2.10	2.30	3.0	0.67	0.83	4.80	3.10	14
F	1978–1982	1.10	0.40	3.0	0.52	0.63	4.80	3.10	12
G	1983–1993	0.60	0.40	3.0	0.52	0.63	4.80	3.10	10
H	1994–1999	0.55	0.35	3.0	0.37	0.43	4.80	3.10	10
I	2000–2004	0.55	0.35	3.0	0.36	0.42	4.80	3.10	10
J	2005–2006	0.37	0.25	3.0	0.31	0.34	4.80	3.10	10

Data from various sources, refer to Table 3.

[a] Wall thickness taken as 300 mm; soil type taken as DEAP default—thermal conductivity 2.0 W/m K; R_{si}—0.17 m^2 K/W and R_{se}—0.04 m^2 K/W; presence of floor insulation and thickness as per Table S6 in DEAP.

Table 3
Data Sources used in heat loss model.

Central Statistics Office	**Irish National Survey of Housing Quality (INSHQ) 2001–2002**	**DEAP Manual**	**Building Research Establishment**	**EN 12831:2003 Heating Systems in buildings—method for calculation of design heat load**
Number of centrally heated detached rural housing in Ireland	Single or two storey (established from presence of a stairs)	U-values for the different age bands of the existing housing stock	Infiltration rates (ACH_{50})	Correction factor for annual variation of external temperature (fg_1)
Dwelling age	Floor areas predating 1980	Internal temperature	Glazing ratios	
Planning permission office—floor areas post dating 1980	Window typeType of heating system			
	Number of external doors present			

Table 4
CSO detached housing quantities corrected by DEAP age band.
Source: CSO 2006.

CSO year of construction (Inclusive of 'not stated')	Total no. of detached houses built in that period	DEAP age band	DEAP year of construction	Total no of detached houses built in that period
before 1919	61,802	A	before 1900	44,784
1919 to 1940	35,068	B	1900–1929	34,552
1941–1960	33,154	C	1930–1949	32,453
1961–1970	23,350	D	1950–1966	32,245
1971–1980	61,596	E	1967–1977	52,457
1981–1990	56,693	F	1978–1982	29,817
1991–1995	24,798	G	1983–1993	60,233
1996–2000	44,719	H	1994–1999	45,694
2001 or later	65,730	I	2000–2004	52,764
		J	2005–2006	21,910
	406,910			406,910

Using default thermal characteristics thus established, combined with an International Weather for Energy Calculation (IWEC) file for Dublin, the heat load for a statistical occupancy and year was established by DEAP age band.

On the basis that improvements to energy efficiency are found to offer the cheapest and most readily available carbon abatement opportunities (SEAI, 2009) and in line with Ireland's National Energy Efficiency Action Plan, the same dwellings were then remodelled assuming that the occupant had availed of the government grant aided National Insulation Scheme.

Concurrently with the fabric improvement measures it was also assumed that the occupant reduced the infiltration rate of the dwelling. More detailed information regarding the thermal retrofit measures is outlined in Section 2.5.

To calculate the heat load of the dwellings a modified version of The European Design Standard was used – BS-EN 12831:2003 Heating Systems in buildings – Method for calculation of design heat load which is referenced in BS EN 15450:2007.

The main parameters of this calculation are outlined below

- Areas of fabric elements
- *U*-values of fabric elements
- Infiltration rates
- Thermal bridging factors
- Internal temperature
- External temperature

The prescribed calculation was modified in the following manner;

- Exact details of dwelling construction are unknown so a default *U*-Value prescribed in DEAP was used to calculate thermal bridging. The default value of $y=0.15\,W/m^2\,K$ was applied to all dwellings. The total surface area in this case excludes the ground floor.
- T to allow translation between air permeability ($m^3/h\cdot m^2$) and air change rates at 50 Pa pressure difference (ACH50) Ventilation heat loss was calculated using the formula $Q=1/3(ACH)V\Delta t$.

Default correction factors were as follows; $fg_1=1.45$, $fg_2=0.48$ and $G_w=1.00$ Therefore $fg_1fg_2G_W=0.7$.

2.1. Dwelling envelope characteristics and areas

The CSO Planning Permission office holds data on floor areas from 1980 to the present day. For floor areas predating 1980 it was necessary to refer to the INSHQ. Positive responses to the existence of a staircase in the INSHQ were used to establish the number of storeys. On average 42% of the detached dwelling stock are single storey and 58% have two storeys. The results show that the trend of increasing floor area with time is followed within this housing category (SEAI, 2008).

The dwellings were assumed to be rectangular in construction with a length twice the width; this assumption was confirmed by an analysis of rural large scale ordinance survey maps. The average ground floor area for a one storey dwelling was found to be 161 m^2 and the average for a two storey was found to be 81 m^2. The floor is assumed to be a solid ground floor. Default *U*-values by date of construction were interpolated from DEAP Table S8 using exposed perimeter to area ratio (*P*/*A* ratio).

DEAP states that if the wall type cannot be identified or does not fit into any particular category to assume wall type is 'stone'. Referencing Table S3 in DEAP, insulated stone and cavity wall behave similarly; there is a significant thermal improvement only where insulation is present; it was therefore necessary to quantify the presence of cavity insulation by DEAP age band. The INSHQ was used to correlate year of construction with presence of a cavity wall and cavity insulation. The presence of cavity walls steadily increases over time; the presence of infill cavity insulation however is slow to catch up. The effect of the draft and actual Building Regulations in the mid 1970's is notable with the presence of cavity walls jumping to over 70%, with the presence of insulation at approx 90% (see Fig. 1). An analysis of cavity wall (without insulation) corresponds with that of stone type wall, which supports DEAP's assumption that unidentified/unknown wall types can use the default values of 'stone'.

In the absence of an Irish dataset, glazing ratios were extracted from Table S4 of the UK Standard Assessment Procedure (SAP, 2005) on the assumption that the UK and Irish Housing Stock are similar. Irish Building regulations quote a typical storey height of 2.4 m, thus wall area net of glazing was calculated.

Default window *U*-values for various window construction types were taken from the DEAP Manual. The default values for timber frame and PVC are the same. The predominant window types across all age bands are timber and PVC (INSHQ). The *U*-value for all single glazing was taken as 4.8 $W/m^2\,K$. The *U*-value for double glazing was taken as follows;

- House Bands A–I (Pre 2004 double glazing) assumed to be timber frame/PVC at a *U*-value of 3.1 $W/m^2\,K$.
- House Band J (Post 2004 double glazing) was assumed to be low E, hard coat, air filled glazing with an associated *U*-value of 2.2 $W/m^2\,K$ (DEAP).
- Retrofit glazing was assumed to be 4 mm low E, argon filled with an associated *U*-value of 2.2 $W/m^2\,K$.

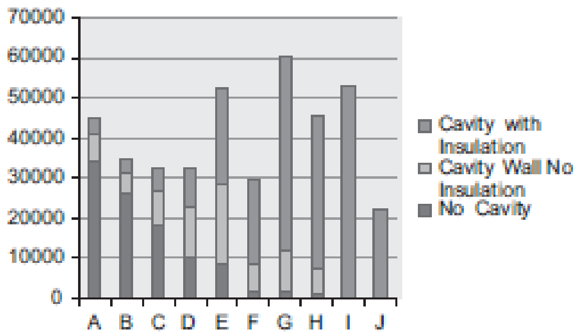

Fig. 1. Corrected quantity of detached dwellings by wall type and DEAP age band.
Source: INSHQ 2001–2002.

Using the INSHQ dataset an analysis was undertaken to establish the pervasiveness of double glazing. Notably, the prevalence of double glazing increases with time; however there is evidence of a large degree of retrofitting in pre-1940 houses which would have been originally constructed with single glazing. INSHQ data is available up to the year 2001; it is assumed that all houses built after 2001 are double glazed and compliant with the building regulations at time of construction. The percentages established from the smaller INSHQ dataset were applied to the larger CSO (2006) dataset to obtain the quantities of rural detached houses by glazing type and hence the data was correlated to DEAP age bands. A large percentage (36%) of all detached housing remained single glazed in 2002, of this 36%, 72% are in the DEAP age bands A–E (1900–1977). Table 5 depicts quantities of housing with single and double glazing by category.

All roofs were assumed to have an 18° typical pitch (based upon current Irish building regulations) this resulted in the roof area being typically 5% larger than the floor area. In 2001, 82% of detached housing in Ireland had roof insulation (Clinch and Healy, 2004), consequently all roofs are assumed to be insulated, moreover DEAP does not quote *U*-values for uninsulated roofs, therefore default roof *U*-values for insulated roofs were taken from Table S5 of DEAP with insulation thickness unknown.

The INSHQ was used to establish the typical number of doors present by dwelling type and dwelling age. DEAP states that single doors can be assumed to have an area of 1.85 m^2 with double doors being twice that. For this study, doors are assumed to be solid wooden doors with a *U*-value of 3 W/m^2 °C. In order to conservatively account for the presence of a double patio door (not quantified in the INSHQ study) one door is assumed to be double with the remainder being single. Referencing Table 2; average door area of detached housing was found to be approximately 6 m^2.

Table 1 shows the increasing floor, window and door area over time.

2.2. *Infiltration rates and Irish dwellings*

No Irish or UK database which specifically focuses on infiltration rates of detached dwellings exists (Pan, 2010). There is one, recently published, statistically small (28 dwellings) database for air tightness on Irish housing available (Sinnott and Dyer, 2012) which was focused on single family residential semi-detached and terraced houses. Only two large scale (> 200) databases for air infiltration rates in pre-2006 UK dwellings are known: one held by British Gas plc covering some 217 dwellings (Etheridge et al., 1987) and the other held by BRE covering 471 dwellings. The published data from the British Gas database compares well with the BRE data but is somewhat limited in detail (Stephen, 1998). The BRE database grouped the tested dwellings by age band. The majority of the dwellings in the BRE air leakage database, as in the UK generally, are of semi-detached, terraced and apartment type construction. It was not possible to isolate typical infiltration rates for detached housing from the databases.

In general the test infiltration rates recorded on the Irish database are lower than that of the BRE database; however the Irish database, with only 28 dwellings recorded, is not considered statistically significant. Therefore, on the assumption that Irish and UK housing construction methods differ little, the results from the cumulative distributions of 50 Pascal air change rates (ACH_{50}) for the 471 dwellings on the BRE database were extrapolated and reconfigured over the DEAP age bands; see Table 2 for summary results.

The infiltration rate of BRE tested homes generally lies between 10 and 16 air changes per hour at 50 Pa pressure difference (ACH_{50}), the average of the BRE sample of dwellings was 14.8 ACH_{50} (Uglow, 1989) this indicates that the degree of air tightness of UK, and by assumption Irish Dwellings is low (EN 12831:2003 E).

Air Permeability, measured in $m^3/(h \cdot m^2)$ at 50 Pa pressure difference, is the physical property used to measure air-tightness of the building fabric and is the term used within the current building regulations. It is defined as 'air leakage rate per envelope area at the test pressure differential across the building envelope of 50Pa' (Note: Envelope area is inclusive of ground floor area). Using ACR_{50} divisors for 1 and 2 storey dwellings of 20.6 and 17 (Table 4.21 of CIBSE Guide A) the air permeability of the existing detached Irish housing stock was calculated, see Fig. 2.

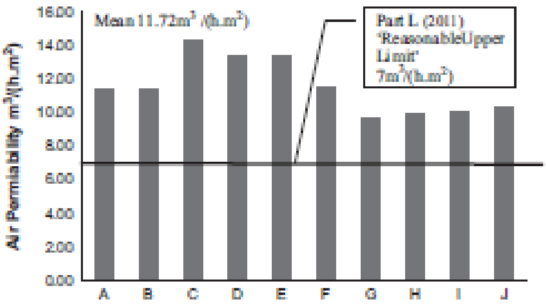

Fig. 2. Estimated air permeability of detached housing categories $m^3/(h \cdot m^2)$ by DEAP age band.

Table 5
Dwelling age by window type by DEAP age band.
Source: INSHQ 2001–2001/CSO 2006.

INSHQ year of construction	(%) Single glazed	(%) double glazed	DEAP age band (Double glazed)[a]	Corrected no. of double glazed houses	DEAP age band (Single glazed)[a]	Corrected no. of sinlge glazed Houses
Pre 1940	52	48	A_{DG}	23,109	A_{SG}	21,675
	52	48	B_{DG}	17,829	B_{SG}	16,723
	52	48	C_{DG}	18,775	C_{SG}	13,678
1941–1970	65	35	D_{DG}	21,024	D_{SG}	11,221
	65	35	E_{DG}	34,116	E_{SG}	18,341
1971–1980	65	35	F_{DG}	20,300	F_{SG}	9,518
1980–1996	73	27	G_{DG}	44,030	G_{SG}	16,203
	73	27	H_{DG}	39,923	H_{SG}	5,772
			I_{DG}	52,246	I_{SG}	517
			J_{DG}	21,910	J_{SG}	0
				293,262		113,648

[a] SG and DG denotes single glazing and double glazing, respectively. The age bands used by DEAP differ from the age bands quoted in the CSO and INSHQ datasets. The average number of houses built in that period was found and then the number of houses was redistributed in line with DEAP age groups.

All of the dwellings exceed the 'reasonable upper limit' for air permeability referred to the Technical Guidance Document Part L (2011) of 7 $m^3/(h \cdot m^2)$ at 50 Pa (DECLG, 2011). The mean between dwelling types used in this study is 11.72 $m^3/(h \cdot m^2)$, this figure correlates well with the UK mean air permeability if 11.5 $m^3/(h \cdot m^2)$ (Johnston et al., 2011).

2.3. Occupancy Profile

The typical occupancy profile was established from a study carried out in 2009 by Shipworth et al. (2010). The study found that the average dwelling has the heating system operating from 06:45 to 09:45 in the mornings and from 15:45 to 19:30 in the afternoons totalling 6.75 h; however it found that detached houses have the heating system operating longer with an average of 8.7 h per day. The study found that heating duration was generally independent of year of construction. To account for the longer running hours associated with detached housing it was assumed that heating came on earlier and switched off later. The assumed hours of operation of the heating system in the model were 06:00 h to 10:00 h and 15:00 h to 20:00 h totalling 9 h.

2.4. Design temperatures

An outdoor design condition of −3 °C was selected. In a statistical Irish weather year for Dublin, between the hours of 7 am and 10 pm the outdoor temperature only falls below −3 °C for 4 h annually. Default internal design temperatures are given in Annex D (Table D.2) of EN 12831:2003; a default value of 20 °C was used. This allows some capacity in the system if the outdoor temperature drops to −4 °C the internal temperature will fall to 19 °C, which is acceptable considering houses are generally only currently achieving a maximum indoor temperature of 18.8 °C (SEAI, 2008). The Shipworth et al. (2010) study confirmed the selection of the internal temperature set point of 20 °C finding that UK homes are generally heated to 19.7 °C.

In accordance with The Chartered Institution of Building Services Engineering (CIBSE) guidelines (CIBSE Guide F), it was also assumed that the heating system is not required when the outdoor temperature is greater than 15 °C.

2.5. Thermal retrofit measures

2.5.1. Fabric improvement measures

Fabric improvement measures that were considered were as follows;

- Wall insulation
- Roof insulation
- Floor insulation
- Replacing single glazing with double glazing

A practical approach was taken with improvement measures—for instance due to the high cost and relative inconvenience to the occupier of replacement floor coverings and in line with the findings of Clinch and Healy (2004) who found there was a low penetration of floor insulation retrofits in Irish homes (with just a quarter of Irish homes so equipped). It was assumed that floor *U*-values remain static.

The Fabric *U*-Values for the roof and walls were brought in line with, The Irish National Insulation Programme—Better Energy Homes, grant aided scheme administered by SEAI (SEAI 2011) which policy makers hope will encourage refurbishment of existing homes. *U*-values for rafter and flat roof fitted insulation differ (0.2 and 0.16 W/m^2 K, respectively). A 50/50 split on rafter and flat roof distribution was assumed therefore roof *U*-values were globally reduced to 0.18 W/m^2 K. All wall *U*-values were brought to 0.27 W/m^2 K, it is assumed that cavity wall infill insulation or external insulation cladding is employed to achieve this reduced wall *U*-value.

It is assumed that due to the high cost of replacing glazing that if the dwelling is already fitted with double glazing at the time of the INSHQ (2001-2002), then no adjustment to the *U*-value was made (even if the *U*-value is relatively poor compared to the modern double glazing available on the market today). If the house is single glazed, the glazing was replaced with double glazing achieving a *U*-value of 2.2 W/m^2 K.

2.5.2. Infiltration rate measures

An SEAI pilot study carried out by Energy Action (2010) found that there was no correlation between retrofitting external wall insulation and improving infiltration rates. It is assumed that as part of the thermal upgrade on the property that the air tightness of the building envelope is increased by the following means (Johnston et al., 2011):

- Sealing the junction between the skirting board and the floors with an appropriate sealant.
- Fitting a compressible seal complete with an appropriate locking mechanism to the loft hatch (where present) and sealing service penetrations using an appropriate sealant.

No account is taken of improved air tightness with replacement glazing and assumed weatherstripping. Even though weatherstripped dwellings have lower infiltration rates than those without weatherstripping, the effect is nowhere near as pronounced as the effect of construction type. This is because weatherstripping is usually only applied to components (windows and doors) and it is known the majority of leakage occurs through background (adventitious) openings (Stephen, 1998).

There exists a wide range of air tightness standards in Ireland and other countries. They range from the current (2011) Irish building regulations which suggest a 'reasonable upper limit' of 7 $m^3/h \cdot m^2$, to less than 1 $m^3/h \cdot m^2$ @ 50 Pa representing the PassivHaus Standard amongst others (Pan, 2010; DECLG, 2011). The air tightness standards in Ireland and the UK are less stringent compared with other European countries such as Belgium and Finland (Sinnott and Dyer, 2012; Cornish, 1989; Pan, 2010).

An air permeability of 7 $m^3/h \cdot m^2$ shall be applied to refurbished dwellings in this study. This is in line with The Energy Savings Trust good practice guidelines and Part L1a Indicative Standard for SAP, 2005 but is lower than the L1a 2010 target and the Energy Savings Trust target for new dwellings of 5 $m^3/h \cdot m^2$ (EST, 2005;, DCLG, 2010). This figure results in a mean ACH_{50} of 7.35 which Bell and Lowe (2000) have shown to be very achievable and even conservative. This is considered reasonable as air tightness is more difficult to achieve in a refurbishment scenario than for new build as sometimes pipes etc are not accessible.

3. Model results and analysis

3.1. Before thermal retrofit measures

Table 6 shows the heat loss characteristic of the dwelling in W/K and kWh/m^2; as expected, a single storey house has a greater heat loss than a two storey dwelling of the same internal volume due to a greater amount of exposed surface area. There is a high degree of variation with a ratio of standard deviation over the mean (RSD) of 35% between the dwelling category with the worst

Table 6
Ranked summary heat loss rate and annual heat energy consumption pre-thermal retrofit measures by DEAP age band in W/K and kWh/m².

House type[a]	1SDG	1SSG	2SDG	2SSG
	W/K	W/K	W/K	W/K
E	834	875	751	792
C	822	862	745	786
D	818	859	736	777
A	800	840	719	760
B	800	840	719	760
F	425	460	439	474
I	410	456	396	442
J	377	N/A	360	N/A
H	376	419	365	394
G	371	409	356	394
House type	kWh/m²	kWh/m²	kWh/m²	kWh/m²
C	221	232	200	211
D	218	229	197	208
E	217	227	195	206
A	215	226	193	204
B	215	226	193	204
F	107	116	110	119
G	91	100	87	96
H	83	92	80	89
I	81	90	78	66
J	66	N/A	63	N/A

[a] 1S and 2S denote single storey or two storey dwellings, respectively; SG and DG denotes single glazing and double glazing, respectively i.e. A1SDG—house type A, single storey, double glazed, J2SSG—house type J, two storey, single glazed.

heat loss characteristic (*E*) in W/K and the dwelling category with the best heat loss characteristic (*G*).

The positive effect that the Building Regulations have had on the heat loss characteristics, which came into effect in 1979 (in time for DEAP age band *F*) is evident from Fig. 3.

The relationship between increasing house size and heat loss is clearly shown with heat loss steadily increasing with time from Age Band *A* to *E*. It is evident from Table 6 that, for detached dwellings, improvement in *U*-values brought about via the updating of the national Building Regulations over time failed to outweigh the effect of the trend towards increasing floor, window and door areas over time.

Pre-thermal retrofit measures the presence of single glazing, on average, results in a 7% increase in the heat loss (W/K) for both one and two storey dwellings. A larger percentage return in respect of replacement glazing was expected, however analysis of the results (Table 7) showed that pre thermal improvement measures, the large, thermally poor exposed wall and roof areas account for approximately 63% of heat loss, thus the heat loss of the glazing is relatively low.

House type G shows a relatively good heat loss characteristic due, in the main, to smaller floor areas with resulting smaller roof and wall areas. It also has a relatively good infiltration rate. Smaller floor areas also have the effect of reducing the thermal bridging coefficient (a function of exposed surface areas).

House types H, I and J have larger window and door areas than house type G which contribute to their relatively high heat loss characteristic, however the model took no account of the requirement for a reduced average *U*-value (U_{ope}) relating to larger than average window, door and roof light areas (A_{ope}), which is prescribed in the building regulations to account for this phenomenon.

Within housing categories A–E (196,492 houses) the model resulted in an averaged Building Energy Rating (BER) of E2. Heating energy consumption averaged at 212 kW h/m² with a total average dwelling energy consumption of 344 kW h/m², corresponding to a heating energy proportion of 62%.

With the newer housing category F–J (210,418 houses) the model resulted in an averaged C2 BER rating. Heating energy consumption for detached housing averaged at 91 kW h/m² with a total average dwelling energy consumption of 193 kW h/m², corresponding to a heating energy proportion of 47%.

The average heating energy proportion for all dwelling types is 53% (SEAI, 2008). Pre thermal retrofit measures the heating energy proportion for house types A–E is significantly higher than the national average which is another indicator of why this housing category has such a high correlation with fuel poverty (Clinch and Healy, 1999).

3.2. Post thermal retrofit measures

Fig. 3 shows the scale of energy that can be saved for detached housing in Ireland via the National Insulation programme based on the standard heat loss model. House types A–E (1900–1077) can potentially realise the greatest savings due to their poor base point.

Referencing Table 8 post thermal retrofit measures, the RSD between the dwelling category with the worst heat loss characteristic in W/K (J) and the dwelling category with the best heat loss characteristic (F) is much reduced at 6% (versus 35% before measures). House types I and J now exhibit the greatest heat loss in W/K; the difference is attributed, in the main, to the relatively larger window areas and then to the larger floor and roof areas which have a relatively poor *U*-value.

Referencing Table 8 it can be concluded that, based on the standard heat loss calculation, which ignores solar gains, that as thermal retrofit measures are employed in detached dwellings, the floor *U*-value assumes a much greater relative influence on the overall heat loss characteristic of that dwelling. The thermal bridging and ventilation heat loss coefficients also become more significant. The results indicate that a policy measure designed to reduce *U*-values as areas increase, as in the case of U_{ope}, is necessary. This measure would be especially significant in single storey detached dwellings due to the relatively large associated envelope areas; envelope areas being a direct function of floor area.

The presence of a high degree of glazing and doors with their relatively poor thermal properties adversely affects the heat loss characteristics of newer housing.

Within housing categories A–E, thermal retrofit measures improve the average dwelling BER from an E2 to a C2/C3. It was not possible to achieve the desired C1 category outlined in the reference abatement case of the SEAI 2009 report 'Irelands Low-Carbon Opportunity' (SEAI, 2009) without reducing the *U*-value of the floor and further reducing that of the roof. Heat energy consumption averaged at 73 kWh/m² with a total average dwelling energy consumption of 186 kW h/m², corresponding to a heating energy proportion of 39%.

Within the newer housing categories F–J thermal retrofit measures improve the average dwelling from a building energy rating from a C2 to a C1, heat energy consumption for detached housing averaged at 62 kWh/m² with a total average dwelling energy consumption of 157 kWh/m². This corresponds to a heating energy proportion of 40%.

Again, referencing Table 8 post thermal improvement measures; despite house types I and J being the most recently constructed (post 2000) dwellings; they consume the greatest amount of energy in kWh/annum than all the older dwellings in this category. However; due to the fact that their relative floor area is so large in respect to the older dwellings in this category, house types I and J are attributed the best heat energy rating in kWh/m² with a BER of C1 and B3, respectively.

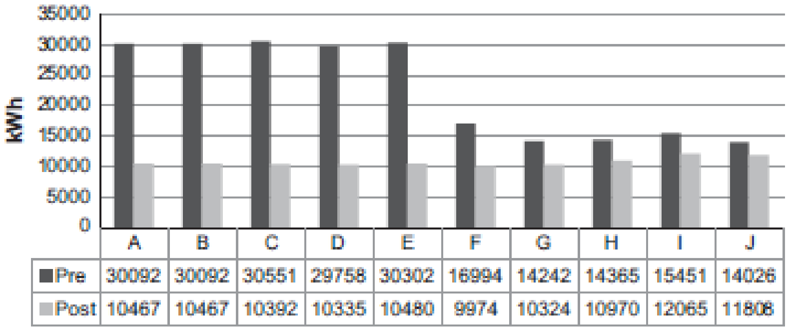

Fig. 3. Average design heat load by DEAP age band—pre and post thermal retrofit measures (kW h).

Table 7
Heat loss coefficient (W/K) by element and housing category pre and post thermal retrofit measures.

Element	House types A-E (1900 -1977; Pre Bldg. Regs.)				House types F–J (1978–2006; Post Bldg. Regs.)			
	Pre		Post		Pre		Post	
	Mean	(%)	Mean	(%)	Mean	(%)	Mean	(%)
Thermal bridging coefficient	39	5	39	14	45	11	45	16
Roof	260	32	20	7	49	12	25	9
Doors	18	2	18	7	19	5	19	7
Walls	246	31	32	12	86	21	35	12
Glazing	95	12	74	23	91	22	64	23
Floor	55	7	55	20	41	10	41	14
Ventilation heat loss coefficient	83	11	45	17	77	19	53	19
Total heat loss coeefficient	796	100	283	100	408	100	282	100

Table 8
Ranked summary heat loss rate post thermal retrofit measures by DEAP age band in W/K and kWh/m².

House type[a]	1SDG	1SSG- > 1SDG	2SDG	2SSG- > 2SDG
	W/K	W/K	W/K	W/K
J	333	N/A	292	N/A
I	331	307	296	272
H	305	282	274	251
E	304	282	271	249
D	299	277	267	245
C	298	276	265	244
A	297	276	265	243
B	297	276	265	243
G	293	273	262	242
F	286	267	256	237
House type	kWh/m²	kWh/m²	kWh/m²	kWh/m²
C	80	74	71	66
B	80	74	71	65
A	80	74	71	65
D	80	74	71	65
E	79	73	70	65
F	72	67	64	60
G	72	67	64	59
H	67	62	60	55
I	65	60	58	54
J	58	N/A	51	N/A

[a] 1S and 2S denote single storey or two storey dwellings, respectively; SG and DG denotes single glazing and double glazing, respectively i.e. A1SDG—house type A, single storey, double glazed, J2SSG—house type J, two storey, single glazed.

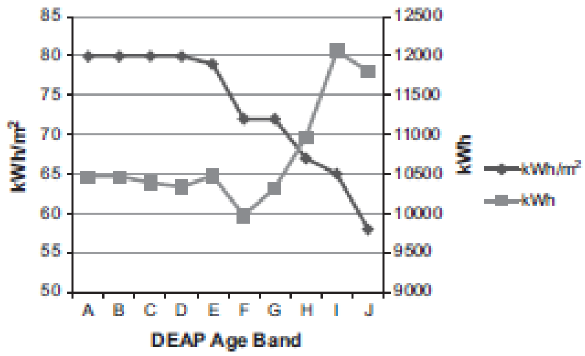

Fig. 4. The trend in heat energy consumption by DEAP age band post thermal improvement measures, expressed in terms of kW h/m² and kW h.

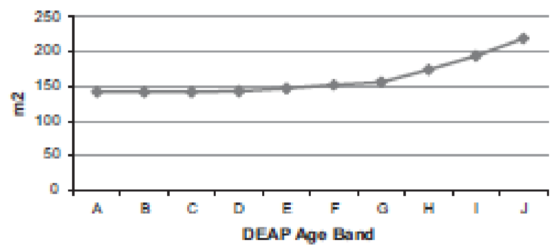

Fig. 5. The trend in floor area for detached dwellings by DEAP age band.

Referencing Fig. 4; Over the period 1900–2006, when kWh/m² is plotted by DEAP age band the trend shows a significant overall decrease with time (RSD—8%) suggesting a pattern of reduction in energy consumption with time; however the same graph shows the total energy consumption in kWh showing an overall increase (RSD—5%) over the same period. The apparent contradiction is explained by the steady and more rapid growth in the floor area of dwellings over time (RSD—16%); see Fig. 5.

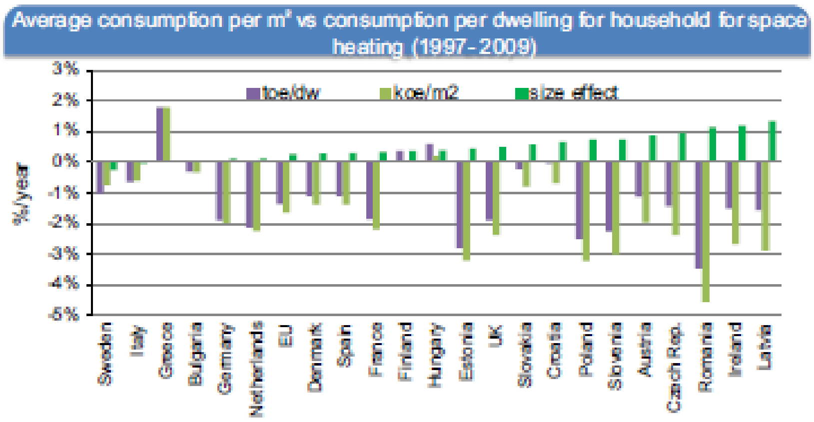

Fig. 6. Heating energy use per dwelling, per m^2 and size effect (1997–2009)*.
*1997–2008 for Spain, Slovenia and Romania, floor area of Irish dwellings increases by 1.2%/annum from 1997 to 2009.
Source: Odyssee.

Table 9
Model results: potential cost and carbon savings and payback by DEAP age band.

DEAP age band	Amt. of houses in category	Cost[b] (m€)			CO_2[a] ($MtCO_2$)			Average (%) Reduction		(%) Saving by category		Average payback period[c]	
		Pre	Post	Saving	Pre	Post	Saving						
A	44785	79.6	29.1	50.5	0.352	0.127	0.225	64	65%	19	82%	12	12 yrs
B	34552	61.4	21.4	40.0	0.267	0.094	0.173	65		14		12	
C	32454	58.5	19.9	38.6	0.255	0.087	0.168	66		14		11	
D	32244	56.6	19.7	37.0	0.247	0.086	0.161	65		13		12	
E	52457	93.8	32.5	61.3	0.409	0.141	0.268	66		22		11	
F	29817	29.9	17.6	12.3	0.13	0.076	0.054	42	26%	4	18%	24	33 yrs
G	60233	50.6	36.7	13.9	0.22	0.16	0.06	27		5		30	
H	45694	38.7	29.6	9.1	0.169	0.129	0.04	24		3		35	
I	52764	48.1	37.6	10.5	0.21	0.164	0.046	22		4		33	
J	21910	18.1	15.3	2.8	0.079	0.067	0.012	15		1		45	
	406910	**535**	**259**	**276**	**2.34**	**1.13**	**1.21**	**45**		**100**	**100%**	**23**	

[a] Oil boiler fired on kerosene with a calorific value of 37,201 kJ/l and an efficiency of 80% CO_2; emissions for kerosene—0.257004 $kgCO_2$/kW h Oil (EPA 2008).
[b] Cost of oil €0.61/1000 litre oil fill.
[c] Price of oil inflated 4.52% annually.

This phenomenon also applies at EU level where between 1997 and 2009 "20% of energy efficiency progress for thermal uses has been offset, all things being equal, by the fact that dwellings are becoming larger" (Lapillonne et al., 2012). Lapillonne et al. (2012) refer to this phenomenon as the 'size effect'. The size effect for Irish dwellings is particularly pronounced with a growth in dwelling floor area of 1.3% per annum between 1997 and 2007 (total 13%) (Dennehy et al., 2009) versus 0.25% per annum (total 3%) for the same period at EU level (Lapillonne et al., 2012). Referencing Fig. 6, if 1.2% growth in floor areas between 1997 and 2009 (total 14.4%) is assumed for Irish dwellings in general around 75% of the overall reduction in energy consumption gained in tonnes of oil equivalent per dwelling (toe/dw) through energy efficiency measures has been offset by the so called size effect. The size effect is therefore analogous to increasing indoor design temperatures which shall have a similar effect on overall energy use by eroding energy efficiency gains. The size effect for detached dwellings in Ireland is especially pronounced with a growth in floor area of 2.9% per annum between 1997 and 2006 (26% in total) offsetting all energy efficiency gains achieved within this housing category.

In this regard the authors are critical of the energy performance assessment methods adopted in the Irish Building Regulations for dwellings. The regulations require designers to calculate compliance using DEAP; the primary energy consumption figure in kWh/m^2/yr of the proposed dwelling is calculated and this figure is divided by that of the primary energy consumption of a reference dwelling, resulting in the energy performance coefficient (EPC). In order to demonstrate that an acceptable primary energy consumption rate has been achieved, the calculated EPC of the dwelling being assessed should be no greater that the maximum permitted energy performance coefficient (MPEPC), the MPEPC is currently 0.6 (DECLG, 2011). Whilst the reduction in the MPEPC from 1 in the 2007 regulations to 0.6 in the 2011 regulations is welcome, the calculation uses the same floor area for the reference dwelling as that of the actual dwelling; therefore this method of calculating energy efficiency does not militate against the size effect phenomenon and effect an actual reduction in the annual energy use of the dwelling. Therefore, using the same rationale adopted in the building regulations of reducing U_{ope} in line with increasing A_{ope}, this study recommends that the Building Regulations look to area-weighting the maximum average U-value (U_m) by reducing this value in line with increasing building floor area (A_f).

Table 10
Cost of thermal retrofit measures by element.

	1SDC		1SSC		2SDC		2SSC	
	Mean	(%)	Mean	(%)	Mean	(%)	Mean	(%)
House types A–E (1900 -1977; Pre Bldg. Regs.)								
Glazing	0	0	3600	22	0	0	3600	18
Walls	9760	78	9760	61	14800	90	14800	74
Roof	2259	18	2259	14	1131	7	1131	6
Air tightness	500	4	500	3	500	3	500	2
	€12,519	**100**	**€16,119**	**100**	**€16,431**	**100**	**€20,031**	**100**
House types F–J (1978 -2006; Post Bldg. Regs.)								
Glazing	0	0	3563	20	0	0	3563	18
Walls	11080	77	10850	62	16720	90	16350	74
Roof	2823	20	2666	15	1410	7	1331	6
Air tightness	500	3	500	3	500	3	500	2
	€14,403	**100**	**€17,579**	**100**	**€18,630**	**100**	**€21,744**	**100**

3.3. *Economic and carbon analysis*

Table 9 outlines the running costs and potential savings resulting from the model by DEAP Age Band.

The total spend on energy in the residential sector in 2006 was €2.5 billion and the average spend on energy per permanently occupied dwelling in 2006 was €1767[3]. If we apply the average heat energy proportion of 53% to this figure the average spend on heating Irish homes is €937 (SEAI, 2008).

The model results in an average heating running cost of approximately €1792 for house types A–E (1900–1977) which is an increase of 92% on the national average and €919 for house types F–J (1978–2006) which approximates the national average.

The values produced by the model are high as it is assumed that the dwelling is heated to a constant temperature of 20 °C, in all weather conditions up to a balance temperature of 15 °C; and solar gains are ignored. However the percentage reduction achievable through the energy efficiency upgrades in line with NEAPP policies is representative.

Table 9 shows that at current oil prices and emission rates, for every euro saved in running costs arising from the thermal retrofit measures a saving of 4.35 $kgCO_2$/€ results.

The model predicts a reduction of 65% in running costs and CO_2 emissions for house types A–E and a reduction of 26% in running costs and CO_2 emissions for house types F–J from retrofit measures, and forecasts a total saving of 276 million euro and a CO_2 abatement of 1.21 $MtCO_2$. By applying the base vacancy rate of 15% annual savings of €235 million and 1.03 $MtCO_2$ result.

There is evidence of savings take-back when houses are thermally retrofitted (Lomas, 2010, SEAI, 2008, Clinch and Healy, 2003, 1999). In 2004 it was found that 12.7% of Irish households have some difficulties (intermittent) in heating their homes, 4.7% were chronically fuel poor with 17.4% being totally fuel poor (Clinch and Healy, 2004, Clinch et al., 2001). If we assume that all the savings, for chronically and totally fuel poor houses, go towards alleviating fuel poverty and there is no reduction in fuel consumption from the thermal retrofit measures, then potential savings can be discounted by 22.1 % (4.7%+ 17.4%). This will result in estimated cost savings of €183 million and a corresponding reduction of 0.80 $MtCO_2$.

The SEAI (2009) report 'Irelands Low-Carbon Opportunity' estimates a total national residential carbon abatement potential of 1.84 $MtCO_2$ by 2030 through incrementally upgrading dwellings to a C1 BER. This study suggests that thermally retrofitting the detached housing stock alone can contribute 44% of this target abatement figure; with the vast majority (82% corresponding to 36% of the national total) of this from housing categories A–E. Policy measures should therefore concentrate on detached housing constructed prior to the implementation of the building regulations.

3.4. *Payback analysis*

The cost of retrofitting external insulation varies widely depending on a number of variables. The most important being the surface area of the house, depth of insulation and maturity of the market. Assuming a depth of 150 mm, the installed cost in Ireland in 2009 was approximately €100/m^2. This figure compares unfavourably with countries such as Germany where the market has been given the opportunity to mature and where competition between contractors has emerged. The average price of external wall insulation in Germany, where labour costs would be comparable to Ireland is in the region of €60/m^2. Prices therefore would be expected to fall significantly as the market matures, scale is achieved and increased competition emerges. The model budgets for a price of €100/m^2 for retrofitting external wall insulation thus ensuring conservative estimates on the payback (Curtain, 2009).

To establish the cost, of replacing single with double glazing, open market prices were sought. In 2010, the approximate installed price of white PVC was €133/m^2 and colour PVC was €150/m^2. Timber and aluminium windows were more expensive at €245/m^2 and €299/m^2, respectively. Colour PVC at an installed cost of €150/m^2 was assumed in the calculation (BMQS, 2011).

Retrofitting additional roof insulation was budgeted at €15/m^2. This figure is relatively low due to the economy of scale gained from the larger than average roof areas associated with detached housing. Achieving a greater level of air tightness was assumed to cost €500 (Montague, 2011).

Table 9 details calculated payback periods achieved for the retrofit measures. For house types A–E the average payback period is approximately 12 years and for house types F–J the average payback is approximately 33 years. Table 10 details retrofit costs by element for the various house types, the average estimated refurbishment costs are €16,379/dwelling. Table 10 shows that retrofitting wall insulation is by far the most costly measure due to relatively large wall areas. For this reason two storey dwellings are more costly to retrofit than single storey dwellings. Air tightness is a low cost retrofit measure that has a high impact. The estimated total cost of refurbishment cost for house types A–E and F–J is €3.2 billion and €3.6 billion, respectively.

[3] Provisional data from 2008 indicated an average non-inflation adjusted bill of approximately €2, 200 (Curtain, 2009).

4. Government Policy Measures

Research has shown that the majority of abatement opportunities are cost negative (SEAI, 2009). However if the cost and CO_2 measures are to be realised it is important that the public at large, which includes landlords, engage with the policy measures the government has implemented, but the hard truth is that in recessionary times, money is an issue (Cillo and Lachman, 1999; Bernier et al., 2010).

> "*Lack of money (or competing demands for available funds), lack of technical expertise, and uncertainty about one's continued occupancy at a particular location all combine to prevent customers from choosing to invest in energy efficiency in their homes and businesses*" (Cillo and Lachman, 1999).

The findings of Cillo and Lachman in their 1999 paper are supported by research carried out in Ireland in 2009 by Amárach Research wherein it was found that 58% of homeowners responsible for energy bills said they did not have enough money saved to upgrade their home, whilst 29% said they did not know which upgrade measures their homes needed. The research also stated that 43% had made energy efficiency improvements and were keen to do more, 28% had considered, but had not carried out, improvements, whilst 16 % had not considered an energy upgrade before (Colley, 2010).

> "*The results indicate that Irish people are ready to invest in energy efficiency if the requirement for upfront finance is removed,*" (Colley, 2010)

If society is to realise the benefits of energy efficiency upgrades, financial obstacles of this nature must be overcome if any significant volume of energy efficiency work is to be realised.

The market based Pay-As-You-Save (PAYS) approach to energy efficiency investment offers people the opportunity to upgrade the energy efficiency of the building they occupy without requiring them to provide upfront finance and without placing debt obligation on them. A PAYS tariff is instead assigned to the building through a utility bill. Customers who sign up for the PAYS tariff see an immediate financial benefit, as the repayment tariff is set up to amount to less than the energy savings that the customer makes. Such a system, known as the 'Green Deal', which contains the Golden Rule that "*The expected financial savings must be equal to or greater than the costs attached to the energy bill*" was expected to commence in the UK in Autumn 2012 (DECC, 2010). Customers could even use such a tariff to make incremental improvements over time. PAYS therefore promises the prospect of creating a continuous demand for innovative technologies to meet customers' needs in a changing energy landscape (Cillo and Lachman, 2001; Colley, 2010; Curtain, 2009; Bernier et al., 2010).

In 2006, the International Energy Agency (IEA) recommended a range of policy instruments to encourage greater energy efficiency in the residential and services sectors including;

> "*The creation of incentives for energy utilities to implement or promote certified energy-saving measures among their client base, or the imposition of obligations on them to do so*"

(IEA, 2006).

There is precedent in Ireland for this type of scheme. In the aftermath of the 1979 oil crisis, ESB and Moy Insulation teamed up to offer attic insulation to customers, requiring no upfront capital investment, but instead adding the cost to the energy bills of the participating customers. This scheme was deemed to be a commercial success and by 2004, 80% of Irish homes were so equipped (Colley, 2010; Clinch and Healy, 2004).

The Irish Government's Department of Communications, Energy and Natural Resources has recently gone out to consultation on a programme that could encourage the energy supply sector to adapt their business models to incorporate PAYS. The department is proposing that the programme, to be called the Energy Demand Reduction Target (EDRT) (DCENR, 2010) shall have a particular focus on stimulating end-use efficiency and may involve passing a law forcing the energy supply sector to substantially reduce the amount of energy consumed in Ireland.

There is a considerable role for the government in such a scheme as longer term PAYS investments (such as external wall insulation retrofit) could arguably place a disproportionate risk (debt) on utility companies that the government would need to underwrite, possibly through the establishment of a green bank or through the issue of green bonds. Furthermore, the government and state agencies would have a key role in marketing, monitoring and regulating such a scheme and perhaps designing appropriate financing arrangements. Curtain in a 2009 study found that the overall cost to the state of administering a PAYS scheme would be recouped many times over in terms of carbon credits alone and states that "this is before ancillary employment, energy savings, health, morbidity and political benefits are considered", Curtain (2009) goes on to state that the state's fuel poverty mitigation bill comes to approximately €400 million per annum.

5. Limitations of this study

- The heat loss calculation outlined in BS EN 12831:2003 Heating Systems in buildings is a steady state heat loss calculation meaning heat gains are not included. This will lead to an overestimation of the energy saving potential of the thermal retrofit measures because heat gains as a result of solar penetration into the dwelling will reduce the heating energy requirement. Notwithstanding the above, the results of this study were compared with a sample set of base geometries modelled in DEAP (which accounts for solar gain) and results correlated well. The general trends resulting from this study give an insight into the scale of cost savings achievable.
- The calculation does not account for the significant effect of user habits in the operation of a heating system (Firth et al., 2009; Shipworth et al., 2010; Guerra-Santin and Itard, 2010; Gram-Hanssen, 2010). For example, it is considered unlikely that a household will turn on the heating for an hour in June for a 1 degree temperature difference; however, it is necessary to allow this to ensure the model was working within defined parameters.
- It is assumed that the entire dwelling, meaning all rooms, is heated for the duration of defined occupancy period to a fixed internal temperature. This is unlikely due to operating costs. However it is known that after insulation is installed dwelling occupants may heat more of their house, and to a higher temperature (Lomas, 2010).
- Type of Tenure is ignored, 21% of dwellings in Ireland are occupied by tenants. Landlords who, by and large, do not pay the energy costs of heating are not motivated to invest in the energy efficiency of the property, while tenants who pay the bill are not motivated to invest in the fabric of a building they do not own (Curtain, 2009; Scott et al., 2008). However detached housing suffers less from this phenomenon, than other dwelling types, as they have the highest degree of owner occupation.
- This study has not taken into account the quality of retrofit work.
- The model took no account of the requirement for a reduced average *U*-value (U_{ope}) relating to a larger than average

window, door and roof light areas (A_{ope}) described in the building regulations.

- Referencing Section 2.2; the model used average figures for infiltration rates from the BRE database (ACH_{50}) for both single and two storey dwellings. CIBSE ACH_{50} divisors were used to convert these figures to ACH the result is a higher permeability for two storey dwellings over one storey which is misrepresentative, future air permeability studies should quantify whether the tested dwelling is single storey or two storeys.

6. Areas for future study

- Another national survey on housing quality should be carried out as the information currently available is outdated. In addition to the survey questions originally asked, the study should establish typical occupancy profiles for domestic units along with habits of heating use. Thus allowing for energy efficiency measures to be accurately quantified with respect to prevailing outdoor weather conditions. The study should also quantify the amount of glazing and its orientation to allow for dynamic simulation of the building conditions. DEAP age bands should be used to categorise the results.
- Pre-refurbishment monitoring and feedback for case study dwellings is necessary. This ensures there is a robust learning process in place for the design team, owners (landlords) and occupants, which is carried out through post-implementation evaluation. This approach establishes feedback loops for comparing expectations with outcomes, enabling assessment of the effectiveness of the low-carbon interventions (Gupta and Chandiwala, 2010).
- More statistical weather files need to be established for rural Ireland.
- With regard to energy efficiency upgrades

  "Energy demand targets and utility targets perhaps provide the most promise particularly in the context of budget constraints. A comprehensive solution would require elements of regulation and grant aid. Further analysis of costs and benefits associated with these options and detailed research into how they might be financed is urgently required if the opportunities are to be effectively captured"

  (Curtain, 2009).
- A database of air tightness of Irish Housing by DEAP age band, house type and number of storeys is required.
- Further study is required to establish a thermal policy measure which looks to area weighting the maximum average U-value (Um) by reducing Um in line with increasing building floor area (Af).

7. Conclusions

The case for energy efficiency measures is categorical; the potential exists to reduce running costs and CO_2 emissions by an average of 63% for housing constructed prior to the 1979 building regulations (house types A–E) and by 26% for newer housing.

The ratio of amounts of CO_2 which can be potentially saved to the amount of money saved was calculated as 4.35 $kgCO_2$/€. Nationally an annual saving of €183 million euro is theoretically achievable with a resultant saving of 0.80 $MtCO_2$ arising from insulation retrofits, the replacement of single glazed windows and increasing air tightness.

The greatest savings (82%) or €150 m and 0.66 $MtCO_2$ are achieved by addressing the pre building regulation housing stock. Pre 1940 dwellings are normally without a cavity or an existing filled cavity will require either internal or external insulation. Dwellings constructed between 1940 and 1970, constructed with cavity walls, will provide the shortest payback as they are more easily retrofitted with insulation blown into the cavity. This is positive as houses built between 1941 and 1979 demonstrate the highest level of persistent fuel poverty and would benefit most from fitting cavity wall insulation (Clinch and Healy, 2004).

As thermal retrofit measures are employed within the existing stock and the thermal properties of the dwellings become more uniform, the floor area is ultimately the most influential factor on the heat loss characteristic of a dwelling as large floor areas result in increased building envelope surface areas which correlate with an increased level of glazing, increased levels of thermal bridging, increased ventilation loss due to larger volumes and presumably more bathrooms and thus penetrations to the exterior.

While the thermal characteristics of the buildings improve with time and energy use per m^2 is decreasing, the majority of energy efficiency progress for thermal use in Irish dwellings is being offset, all things being equal, by the fact that dwellings have become larger. In order to militate against the size effect, this study recommends a policy measure which looks to area-weighting the maximum average *U*-value (U_m) by reducing U_m in line with increasing building floor area (A_f).

Under the thermal retrofit measures employed in the model it was not possible for house types A–E to achieve the desired C1 category outlined in the reference abatement case of the SEAI, 2009 report 'Irelands Low-Carbon Opportunity' (SEAI, 2009) without reducing the *U*-values of the floors and further reducing that of the roofs. Irish homes have a low penetration of floor insulation. Homeowners would need to be incentivised to insulate floors possibly by introducing a greater grant allocation for this measure.

As insulation levels improve, the significance of ventilation heat loss is greater. There is significant scope for improvement in the air tightness of Irish dwellings, old and new. Irish dwellings are on average much more leaky that dwellings in many other countries, notably in Canada and Scandinavia. Cavity masonry construction exhibits the worst air tightness characteristics (Stephen, 1998). As part of retrofit measures, air tightness needs to be considered.

External wall insulation is the most costly thermal retrofit measure but shall become more cost effective as the market matures.

Research has shown that, at state level, the majority of carbon abatement opportunities are cost negative. However the costs of energy efficiency retrofit measures are significant and possibly prohibitive for the end-user. The Irish state needs to adopt an active role in alleviating the financial obstacles faced by society at large if meaningful energy efficiency measures are to be realised in the Irish housing stock.

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