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A Generalisable Bottom-up Methodology for Deriving a Residential Stock Model From Large Empirical Databases

Ciara Ahern
Technological University Dublin, ciara.ahern@tudublin.ie

Brian Norton
Technological University Dublin, brian.norton@tudublin.ie

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Keywords	Reference Dwelling; Stock Modelling; Energy Performance of Building Directive; Default values; Default Effect, Energy Performance Certification, Irish Housing Stock, Detached House, Detached Dwelling, Energy Performance Gap
Taxonomy	Engineering, Energy Systems, Emission Reduction, Energy Management, Energy Sustainability, Energy System Planning

Corresponding Author	Ciara Ahern
Order of Authors	Ciara Ahern, Brian Norton

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Dear Sir/Madam,

Thank you for taking the time to consider this submission.

A generalisable methodology is presented for the derivation of simplified default-free inputs to a bottom-up residential cost-optimality energy consumption model from an EPC dataset. 35 reference dwellings (RDs) are employed to appropriately characterise 406,918 dwellings. Use of these RDs enable quantification of (i) the energy saving potential of a predominant housing typology, (ii) the effect of default U-value use on the prebound effect in dwellings (iii) overall national building energy consumption.

The work is original and all evidence presented is unambiguous and cited.

Regards

Ciara Ahern

A generalisable bottom-up methodology for deriving a residential stock model from large empirical databases.

Ciara Ahern[a,b] **(***Corresponding Author)*

b Discipline of Building Engineering,
School of Mechanical and Design Engineering,
Technological University Dublin,
Bolton St.,
Dublin 1,
D01 K822,
Ireland.
Email: ciara.ahern@dit.ie

Brian Norton[a]

a Dublin Energy Lab,
Technological University Dublin,
Grangegorman,
Dublin 7,
D07 XT95,
Ireland.

Highlights

1. Establishes generalisable methodology to create a stock model from EPC datasets.
2. Renders transparent; process of characterising reference dwellings from an EPC dataset.
3. Data created can be used as inputs to determine cost-optimal energy refurbishments.
4. Presents data as required formerly by EU Commission Delegated Regulation No 244/2012.
5. Largely default-free characterisation based on large high quality empirical dataset.

Abstract

Average reference dwellings representing a predominant housing typology are defined in this work. Specifying such reference buildings is a prerequisite for (i) calculating cost-optimal energy performance requirements for buildings and building elements and (ii) ensuring valid calculations of national building energy consumption. In the EU, an Energy Performance Certificate (EPC) rating is an assessment of the energy consumption of a dwelling. The use of inappropriate default-values for the building envelope thermal transmittance coefficients (U-values) in the production of EPCs leads to an over-estimation of potential energy savings from interventions in the existing dwelling stock. A methodology is presented for the derivation of simplified default-free inputs to a bottom-up residential cost-optimality energy consumption model from an EPC dataset. 35 reference dwellings (RDs) are employed to appropriately characterise 406,918 dwellings. Use of these RDs enable quantification of (i) the energy saving potential of a predominant housing typology, (ii) the effect of default U-value use on the prebound effect in dwellings (iii) overall national building energy consumption.

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List of abbreviations

1S	Single Storey
2S	Two Storey
BER	Building Energy Rating
BREDEM	Building Research Establishment Domestic Energy Model
CISBE	Chartered Institute of Building Services Engineers
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
IWEC	International Weather for Energy Calculations
INSHQ	Irish National Survey of Housing Quality
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
U-value	Overall heat transfer coefficient (W/m^2K)
WMO	World Meteorological Organisation
Y-value	Thermal bridging transmittance coefficient (W/m^2K)
R-value	Thermal resistance of a building element (m^2K/W)

Nomenclature

ACH_{20}	Air exchange rate per hour (h^{-1}) from a pressure difference of 20 Pa between the inside and outside of a building, including the effects of air inlets
ACH_{50}	Air exchange rate per hour (h^{-1}) from a pressure difference of 50 Pa between the inside and outside of a 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)
α	Statistical confidence level (%) indicates the probability that the value of a parameter falls within a specified range of values
e	Maximum expected difference between the true population of a parameter and a sample estimate of that parameter.
g	Solar transmittance
H_{TB}	Heat loss due to thermal bridging (W/mK)
IH	Thermal inertia coefficient for intermittent heating
μ	Statistical mean
N_p	Population size
N_s	Sample size
P_f	Floor perimeter (m)
q_{50}	Air flow rate required to maintain an indoor dwelling pressure of 50 Pa above outdoor air pressure ($m^3/(h/m^2)$)
σ	Standard deviation
UH	Thermal inertia coefficient for solar and metabolic heat gains
U_m	maximum average U-value (W/m^2K)
V	Volume (m^3)
Ψ	Linear thermal transmittance coefficient (W/K)
z-score	Dimensionless quantity indicating how many standard deviations (σ) a random variable (x) is from the mean (μ)

1.0 Introduction

1.1 Policy Context

Households consume 27 % of end-use energy in the EU 28 [1]. The extent and duration of the dominance of the thermal characteristics of pre-existing houses depends on the construction rate, floor areas and specifications of new dwellings [2]. As average replacement rates for existing housing stocks in the EU are less than 0.1 % [3], the majority of Europe's existing dwellings will remain in place in 2050 [4]. In the United Kingdom, for example, around 75 % of dwellings that will exist in 2050 have already been constructed [5]. Accordingly, achieving less overall energy use requires energy refurbishment of existing dwellings [2, 6-9]; but as sub-optimal or partial refurbishments can render future energy performance improvements more difficult or expensive [10]. Understanding existing dwellings stocks is a prerequisite before making energy efficiency, policy or market interventions. However, there are few large-scale building monitoring projects [11-13], in the small samples of buildings studied [9, 11], evidence of patterns in energy demand in buildings by population and stock segmentations are limited [9, 11, 12, 14, 15], with little common [9, 16], transparent or prescribed data reported [9, 11, 12]. This absence of robust data inhibits the effectiveness of policy frameworks [11, 17, 18]. Evidence-based policies are a prerequisite to achieving targets for reduced building energy demand [11-14, 19-22].

The calculation of the total energy consumption of a dwelling stock combines stock and energy models [10]. A stock model describes the stock's size, composition and renovation status, whereas an energy model describes the average energy intensities of the various stock segments and assumed energy savings from renovation [10]. A paucity of observed data, together with a lack of documented transparency around energy performance model inputs have hindered agreement on the validity of building stock energy consumption models [11, 12, 14, 19].

The development and use of dwelling stocks energy consumption models [12, 23] is now driven by policies [24] to; a) reduce domestic energy use, b) lower greenhouse gas emissions, c) reduce dependence on imported fuels, d) reduce energy costs, and e) alleviate fuel poverty.

The 2010 EU Energy Performance of Buildings Directive (EPBD recast, 2010/31/EU) [25] thus requires EU Members States (MSs) to set minimum energy performance requirements [26] for; (a) new buildings, (b) major renovation of buildings and, (c) replacement of windows, roof, wall and/or heating and cooling systems. The 2012 EU Energy Efficiency Directive (2012/27/EU) [27] requires the inclusion of long-term national building renovation strategies in each National Energy Efficiency Action Plan (NEAPP).

1.2 Energy analysis of a building stock

The average change in energy intensity of a total dwelling stock changes [28] over time due to different construction techniques and materials [29], material and labour costs [30], architectural forms [29], heating systems [31], occupant comfort expectations [29], occupant behaviour [32], patterns of use of space within dwellings [33], appliance use [34], economic drivers [30], regulations [29], and the scope and prevalence of refurbishments [35]. Multi-collinearity between these factors complicate isolating each of the influences on dwelling energy consumption [36, 37] with one study finding half the variability in energy consumption to be unexplainable [36]. The interaction of thermophysics of a building with its local climate [32, 36, 38] and occupant behaviour [32] underlie energy consumption with heat energy consumption often dominated by building fabric characteristics [11, 39-43]. For similar buildings, heating system efficiencies, primary fuel types and heat sources cause large differences in energy consumption [44, 45] and carbon emissions [46]. Understanding residential energy consumption drivers thus requires disaggregated thermophysical characteristics [28, 36].

Modelling residential energy consumption can be;

a) Top-down; where historic cumulative energy assessments are regressed, as a function of national energy statistics, gross domestic product, population and climate, to determine dwelling stock energy consumption. As this approach cannot distinguish energy consumptions of individual end-uses it is unable to predict the effect of specific interventions. To do this, bottom-up models are required [43, 47-49].
b) Bottom-up models estimate energy consumption of a representative set of individual houses which are extrapolated to determine regional and national relationships between

dwelling characteristics and energy use [43, 50]. Bottom-up approaches are referred to as "statistical", "engineering" or a hybrid of both [51]. "Statistical" approaches use historical data to correlate relationships between energy end-uses and total energy demand. "Engineering" approaches, determine end-use energy based on building geometry and thermophysical relationships. As bottom-up engineering models address explicitly the effect of occupant behaviour and passive solar gains, they thus can assess the effect of thermal retrofit measures on residential housing stock energy consumption [15, 43, 48, 49, 51].

EPBD energy refurbishments are assessed against cost-optimal criterion to [2, 52];

i) ensure coherent and well-planned refurbishment standards that avoid low-cost but sub-optimal improvements, and
ii) invest in interventions that will recoup their life-cycle costs.

Rather than calculate the cost-optimal interventions for every single building [53], in EPBD guidelines [54] a set of reference buildings (RBs) are defined for each EU member state representative of national building stocks [35, 55, 56]. A common EU-wide reporting methodology (EU Regulation No 244/2012) for RBs; (i) provides more transparent reporting, (ii) enables comparison of building stocks across the EU, and (ii) enables cost-optimal building stock refurbishment interventions to be developed [15, 35, 55, 57].

Use of dynamic building energy simulation to model RBs can [17];

i) identify parameters important to overall performance,
ii) through changing those parameters, forecast the consequences of specific scenarios or policy-interventions,
iii) provide evidence for particular policy interventions.

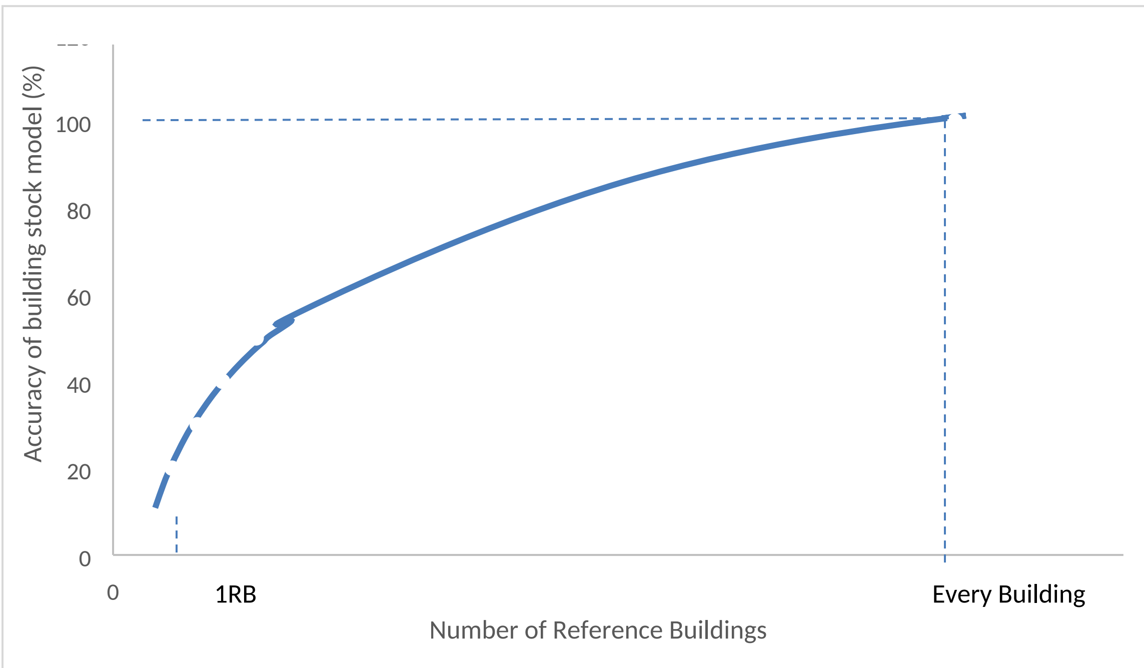
A RB that enables a national building energy consumption model to produce valid outcomes [53] should be;

a) based on high-quality empirical data [9, 11, 12, 34, 58, 59],
b) derived from statistically-significant samples [21],
c) as contemporaneous as possible [58],
d) a result of auditable processes [11, 34, 60, 61].

As shown in Figure 1, a building stock is more accurately reported by a larger number of RBs [54], so the effectiveness of RBs depends on the;

i) number of building subcategories employed [62],
ii) level of detail in defining each RB [56],
iii) validity of information used to characterise each RB [56, 60, 63],
iv) selection of default data [35, 53, 63, 64].

Figure 1 Illustrative indication of variation of energy consumption prediction accuracy of a stock model with the number of reference buildings considered



RBs are required for new and existing [25]; (i) single-family dwellings (including detached, semi-detached and terraced typologies), (ii) apartment blocks/multi-family buildings and (iii) office buildings. Directive 2002/91/EC of the EPBD requires "Energy Performance Certificates" (EPCs), be issued for buildings constructed, sold or leased in the EU [65, 66]. EPC's provide empirical national dwelling stock information that can inform characterisation of contemporaneous RBs [35, 67].

Single-family dwellings constitute 49.4 % of the total building floor area in the EU [68] while households consume 27 % of end-use energy in the EU 28 [1]. 34 % of the EU 28 population lived in detached single-family houses in 2013 [35]. More generally, energy efficiency retrofits remain important as 67 % of European housing was built prior to 1980 [69], before the introduction of thermal building regulations for the housing sector.

1.3 The Irish Housing Stock

The Irish housing stock was used as a case study. Rural detached, single-family dwellings are Ireland's predominant house typology, comprising 31 % of the pre-2006 stock as shown in Figure 2. This dwelling typology was chosen as a representative case study Reference Dwelling (RD) as:

i) 70 % of Irish detached dwellings were constructed before the mid 1970's when building thermal regulations required increased levels of thermal insulation [30, 35, 70-72].
ii) Ireland has the highest proportion, circa 90 %, of single-family dwellings in Europe. Though as shown in Figure 3, the UK, Greece, Norway and the Netherlands have similar profiles [35].
iii) Detached dwellings have relatively high surface area to volume ratios so generally exhibit larger heat losses than semi-detached or terraced houses of the same construction [53], with higher cost of heating to a given comfort level [73]. Detached dwellings are therefore targeted in energy-efficiency retrofit programmes [59, 74, 75]
iv) At 149m^2, the mean-weighted-average heated floor area[1] of an Irish detached dwelling is approximately twice the average European floor area [69].
v) 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 [73], b) being classified as 'hard to treat[2]'' [76] and, 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 Dublin (16 %) or other towns or cities (38 %) [75]. Older adults [75];
    - spend more time at home than younger adults,
    - are more likely to live in homes built before 1970 with lower thermal insulation standards[3],
    - have a higher likelihood of living alone, whilst

[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

- sedentary older adults prefer a minimum of a 2-3 ^{o}C higher internal temperature over the 18 ^{o}C minimum temperature recommended by the World Health Organisation [77].

Figure 2 Number of Irish dwellings by type[4] [71]

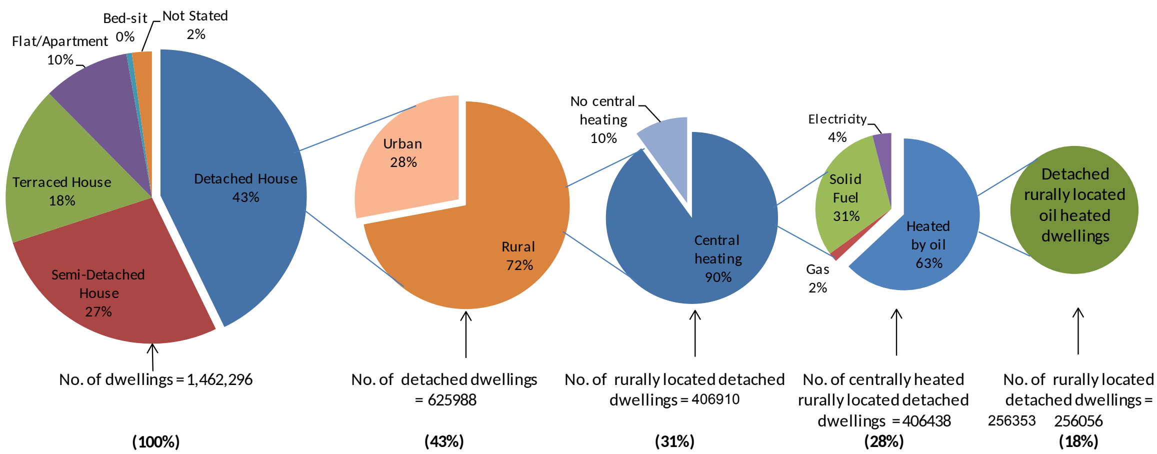
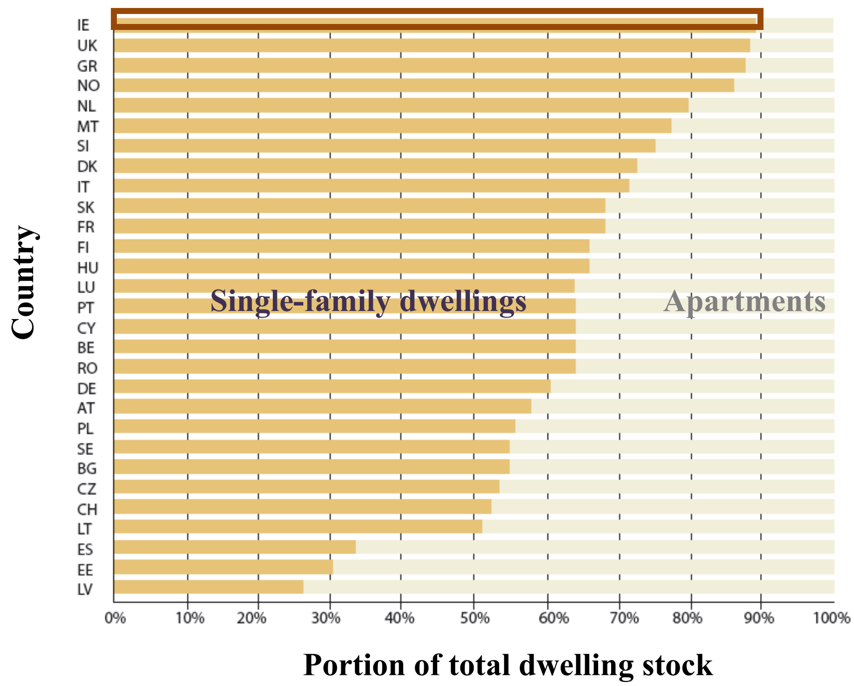


Figure 3 Distribution of single-family and apartment buildings in Europe [18]

[4] To allow quantification of default effect by comparison to previous study [70] C. Ahern, P. Griffiths, M. O'Flaherty, 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, Energy Policy, 55 (2013) 139-151., 2006 census data was used. Figures for 2016 census [78] 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 % .



2.0 Methodology

The methodology to describe a total building stock through RDs follows distinct stages [23, 79, 80]:

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

To ensure realistic RDs are created, data is assessed at each stage, for consistency before proceeding to the next stage [81].

There are three approaches [55] to defining reference buildings that are representative of climatic area, construction age and building size:

1. In the "Real Example Building" (*ReEx*) approach,a building type is selected by a panel of experts as the most representative of specific building size for period of construction and climate location. This approach is applied when statistical data is unavailable.

2. The "Real Average Building" (*ReAv*) approach identifies a representative building type through statistical analysis of a large building sample to find a real building mirroring the characteristics exemplifying mean geometrical and construction features of buildings in the statistical sample.
3. Based on the statistical analysis of a large building sample the "Synthetical Average Building" (*SyAv*) approach identifies an "archetype" defined as "a statistical composite of the features found within a category of buildings in the stock" [82]. The archetype is a notional building characterised by a set of properties detected statistically in a category of buildings [23, 29, 83-85].

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

2.1 Segmentation

EPCs are generated in Ireland through a methodology embodied in the national Dwelling Energy Assessment Procedure (DEAP) software administered by the Sustainable Energy Authority of Ireland (SEAI). SEAI made this detailed national empirical EPC dataset publicly available in 2014 [86]. 463,582 dwellings representing 31.7 % of the total dwelling stock constructed up to 2006 that had received an EPC by August 2014 were examined in this case study [87].

25 % (N=116,354) of the dwellings within the EPC database are detached dwellings, 28% of detached dwellings in Ireland were recorded as centrally heated in the national 2006 census – see Figure 2. 60 % of detached dwellings within the EPC database are rurally located while an average of 76 % of rural homes were oil-heated equating to 19 % nationally [87]. 18 % of detached homes were recorded as oil heated in the 2006 national census [71]. The relative sample sizes in the EPC dataset used are thus consistent with the national distribution of detached dwellings by construction period published by Ireland's national statistics office [71, 87]. 97 % of detached dwelling are either single or two-storey, 98 % are naturally ventilated [87].

As shown in Figure 2, rural, single and two-storey, oil centrally-heated and naturally-ventilated dwellings are the predominant dwelling type in Ireland accounting for 18 % of the national dwelling stock and 63 % of all detached dwellings. Dwellings with these characteristics were isolated from the larger dataset. To avoid inconsistencies, dwellings carrying a 'provisional' certificate were removed from the dataset. As shown in Table 1, this gave a sample of 50,236 dwellings, representing 12.35 % of the detached dwelling typology nationally. The margin of error of a sample dataset (N_s) of a given population (N_p) is given by Equation (1) [88];

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

"Acceptable" margins of error fall between 4 % and 8 % at a 95 % confidence interval [89]. 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) for each period of construction was calculated using Equation (1) with results shown in Table 1 for standard deviation (σ) of 0.5 (50 %). Because older dwellings change ownership less often there are fewer EPCs for older dwellings than newer dwellings. Older dwellings are thus somewhat less represented in Table 1 than newer dwellings. Notwithstanding. Notwithstanding, in all cases, Table 1 shows acceptable margins of error indicating a statistically representative sample while the sample number and proportion of detached dwellings in the empirical dataset is coherent with the actual number and proportion of detached dwellings nationally, so verifying intra-dataset consistency.

Table 1 Frequency of detached dwellings in representative empirical dataset compared with actual dwelling frequency by period of construction [71, 87]

			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%	

2.2 Analysis of microscopic data within EPC Dataset

Extracted from the Irish national EPC dataset [87], Figure 4 illustrates a typical U-value frequency distribution for dwelling walls and roofs by construction period revealing the thermal characteristics of Ireland's walls and roofs to be bi-modally distributed. Referring to Figure 4:

- 'Mode 2' building elements are walls and roofs as constructed with original with U-values[5] of 0.6 to 2.3 W/m^2K.
- 'Mode 1' dwellings are thermally-upgraded building elements with lower U-value ranging between 0.1 to 0.59 W/m^2K.

As more thermal retrofits are carried out more building elements U-values will fall within Mode 2 than Mode 1.The standard deviation[3] for Mode 2 is greater than that of Mode 1 demonstrating that retrofits harmonise levels of thermal insulation. Unlike walls and roofs, dwelling floor U-values have a normal distribution as there are fewer retrofits of floors due to the high replacement cost of floor coverings [90] together with the impracticality of retrofitting floor insulation, see Figures 6 and 7,

[5] Exact ranges determined in Section 3.0 using maximum likelihood estimation

Figure 4 highlights statistically anomalous spikes in the data split-across time-periods 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 and roofs. Analysis revealed that these result from default U-value selection [35, 80].

Where acquiring data would be prohibitively costly, nationally applicable default U-values for the building envelope are employed [72]. Use of such worst case default U-values ensure that a poor dwelling does not attain a better energy rating than is merited [35]. In the absence of empirical data in Ireland default U-values, as in many other EU member states, are determined by the type and date of construction and then prevailing building codes as shown in Table 2 [35, 91].

Table 2 Default U-values by period of thermal regulation in Ireland [92]

			Base-default U-values (W/m^2K)		
		Applicable Age Band	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

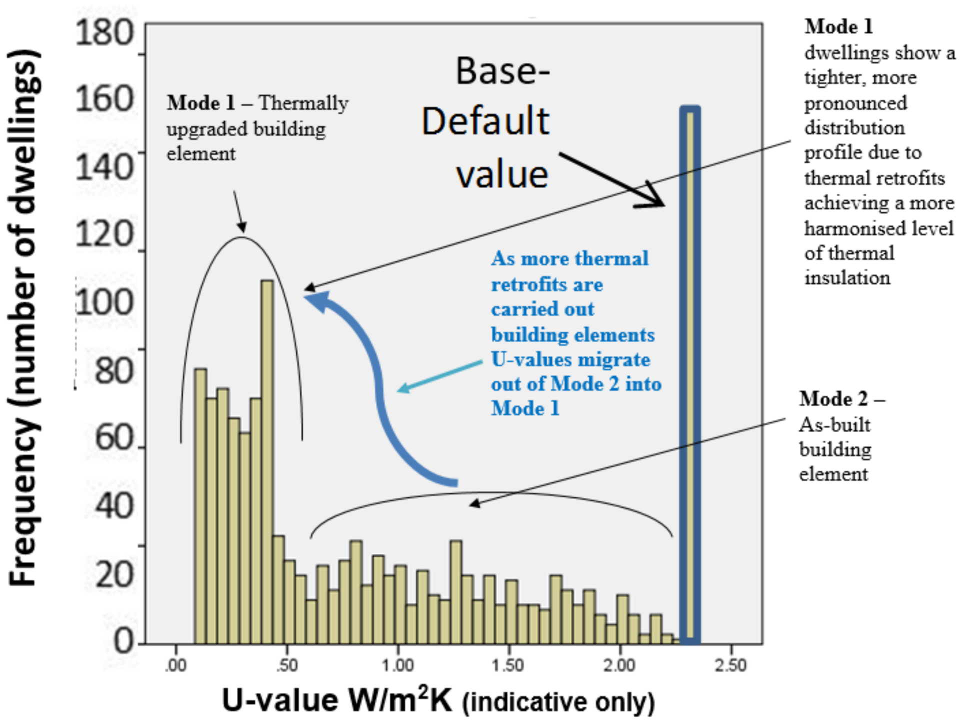
* 0.45 = ground floor and 0.6 = exposed/semi-exposed floor

The frequency of default U-value selection across construction period, together with the independence of default U-value selection to building element type, implies that building assessors often select thermal-default U-values by construction period in preference to calculating actual elemental U-values. Current default U-Values in Ireland under rank 100 % of walls and 82 % of roofs [35].

Procedures used in Ireland [70, 93] along those in Italy [29], Spain [94] and Austria [95] 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 construction period.

As more retrofit interventions are carried out in the housing sector, current base-default U-values become less relevant to the real statistical distribution over time especially with respect to Mode 1 dwellings [35, 80]. 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 the EPC database [35]. To eliminate the systemic error associated with outmoded base-thermal-default values [35] so data better meets accuracy, coherency, compatibly and clarity requirements; it is thus appropriate to remove default U-values from the database [96].

Figure 4 Illustrative typical frequency distribution of wall and roof U-values [87]



2.3 Validation of EPC Dataset

An analysis of dwelling element U-value distributions construction period is summarised in Figure 4. Thermally upgraded dwellings show a more pronounced distribution profile than dwellings yet to undergo significant thermal upgrades. Median U-values for upgraded dwellings are consistent with 2007 [97] and 2011 [98] Irish building regulations of 0.21 W/m^2K (2011) to 0.27 W/m^2K (2007) for walls, and 0.16 W/m^2K (2011) to 0.22 W/m^2K (2007) for roofs. Peaks observed consistently in distributions for upgraded dwellings relate to state-funded energy refurbishment grants to homeowners available through the SEAI [99] for insulated buildings elements as shown in Table 3.

Table 3 U-values required to meet state-funded thermal refurbishment grants in Ireland

<table>
<tr><td></td><td></td><td colspan="2">U-value (W/m²K)</td></tr>
<tr><td rowspan="3">Insulated Fabric Element</td><td>Wall</td><td colspan="2">0.27</td></tr>
<tr><td rowspan="2">Roof</td><td>Ceiling</td><td>0.16</td></tr>
<tr><td>Rafter</td><td>0.2</td></tr>
</table>

Data quality checks and measures taken to ensure final data quality corresponding to Eurostat validation levels ranging from 0 (lowest) to 5 (highest) summarised in Table 4 are shown in Figure 5 [96, 100]. The data was checked for internal consistency within the elements of the dataset to Eurostat validation level 1, intra-datasets time-series checks via differing periods of construction found data behaved consistently to validation level 2, while also confirming requirement to remove base-thermal default U-values [80]. Using other data together with intra-domain consistency checks confirmed the quality of the data in the refined EPC dataset to data validation level 5 [96, 100].

RDs characterised in this study best reflect the characteristics of the overall detached dwelling stock. All other reference dwelling characterisations published in Ireland [37, 67, 70, 101-105], as detailed in Table 4 are based on (i) outmoded base or as-built thermal default characteristics (see Table 2), (ii) smaller sample sizes, or (iii) indeterminate data.

Table 4 Summary of data quality checks and measures taken to validate EPC dataset [80]

		Description	Data provider	Action to check data was plausible

Valid-ation Level	1	File was compiled by an authorised authority	SEAI [106]	Review of SEAI audit and quality assurance mechanisms
	2	Intra-dataset time-series	Ahern [87]-Segmented dataset	Checks via differing time periods – data behaved consistently. Structural error in the data established. Base-thermal-default U-values (as described in Table 2) removed in the case of walls and roofs
		Defaults correlated with period of construction		
	5	Intra-domain consistency	Consistent with INSHQ dataset [107]	Check in respect of wall, roof and floor insulation levels
		Vernacular construction characteristics of dwelling thermal envelope established	INSHQ [107], TABULA [93, 103], CIBSE Guide A [108], literature [70, 109-114]	Base-thermal-defaults (as described in Table 2) removed as inconsistent with other data sources
				Data analysed in to established consistency with vernacular construction details and state-funded incentivised retrofit schemes

Figure 5 Methodological and validation process flowchart [80]

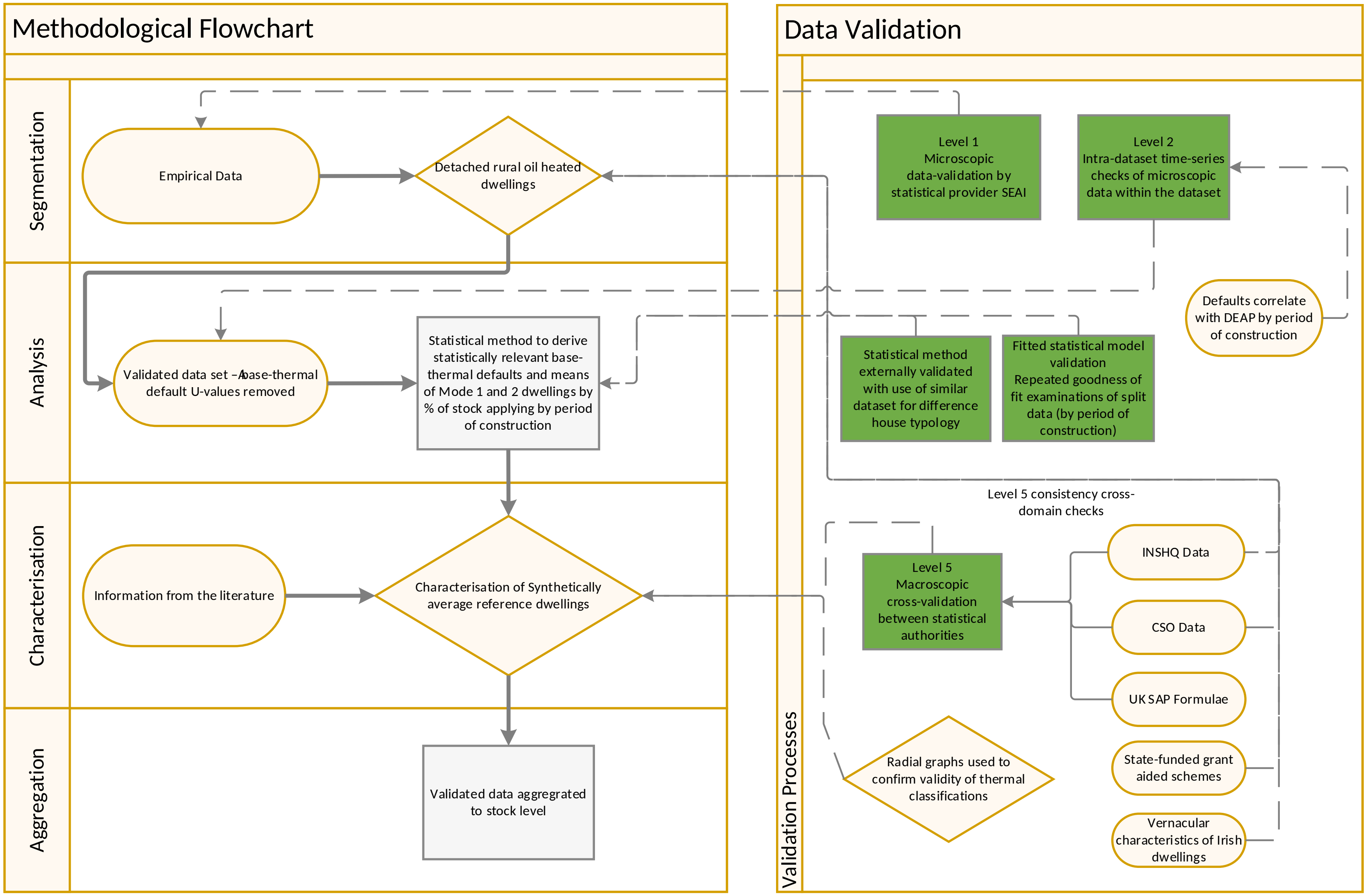


Table 5 Previous characterisations of the Irish housing stock

	Data sources for characterisation	Default Assumptions	Aggregated to Building Stock existing in…	No. of RDs created	Dwelling Type	Reference
Data sources for characterisation	EPC Database downloaded Aug. 2012/CSO 2011	EPC Database, default U-values not filtered. Default Y-value assumed	2011	175	All	Dineen *et al.* (2015) [101]
	EPC Database, Intelligent Energy Europe TABULA project	Default U-values derived from Building Regs, Default Y-value assumed	Not aggregated	10	All	Livingston and Ross (2013) [102]
	Multiple Datasources	Default U-values derived from Building Regs, Default Y-value assumed	2006	20	Detached, rural, oil heated dwellings only	Ahern *et al.* (2013) [70]
	EPC Database 2010, CSO 2006	Default U-values derived from Building Regs, Default Y-value assumed	2010	29	All	Badurek *et al.* (2012) [93]
	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 (2011) [67]
	As per Dinnen & Ó'Gallachóir (2011)	Default U-values derived from Building Regulations	Predicted from base year 2011, Modelling period 2012-2020	175	All	Dineen & Ó'Gallachóir (2017) [104]
	Homebound House Building Manual, 4th ed., 2004	Default Y-Values	Not aggregated	8	South orientated semi-detached two storey	Moran *et. al* (2017) [105]
	Unavailable [115, 116]	Unknown	Pre 1960 - 2002	13	All house-types	Famuyibo (2012) [37]
	EPC Database (2014) [87]	None	2006	35	Detached, rural, centrally heated dwellings	This research

2.4 Characterisation and Aggregation of Reference Dwellings to stock level

2.4.1 Overarching approach

Adapting the methodology established by Corgnati et al. [56] for office buildings in Italy to apply to existing RDs under the relevant EPBD directives [54, 57], SyAv reference dwellings where characterised as shown in Figure 6. Unreliable information within the database is replaced by other 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 7. The methodology ignores aggregated EPC data such as energy consumption in favour of establishing disaggregated thermophysical data by period of construction [29, 51, 55, 117, 118]. A study carried out in the UK using data for 12,500 gas centrally heated houses in 2009 [119], found approximately 75 % of the observed variance in the energy performance rating of the home was determined by heating system efficiency, external wall U-value and dwelling geometry. The RD are thus defined initially by these factors.

2.4.1.1 Heating and Hot Water Systems

As shown in Figure 1, for Irish dwellings 63 % use oil and 31% use solid-fuel. As Central Statistics Office (CSO) data on fuel-use in Ireland is more comprehensive than within the EPC database, CSO data relating to solid-fuel use was reclassified by DEAP construction period as shown in Table 6. Table 6 shows 1 in 3 dwellings constructed up until 1966 to be heated by solid fuel, reducing to 1 in 4 between 1967 and 1993 and 1 in 5 between 2000 and 2006. Where dwellings are heated by solid-fuel, the characteristics of solid-multi-fuel were employed. Characteristics of oil-fired and solid-multi-fuel systems are shown in Tables 7 and 8 respectively. Solid-fuel and oil boilers serve a radiator system [87]. 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].

Standardising heating and DHW system characteristics meant the dominant parameters determining dwelling energy consumption are dwelling envelope thermal characteristics, surface area, heating duration and set point temperature.

Figure 6 Categorisation of characteristic data required to define reference dwelling for existing dwellings [54, 56, 57, 120]

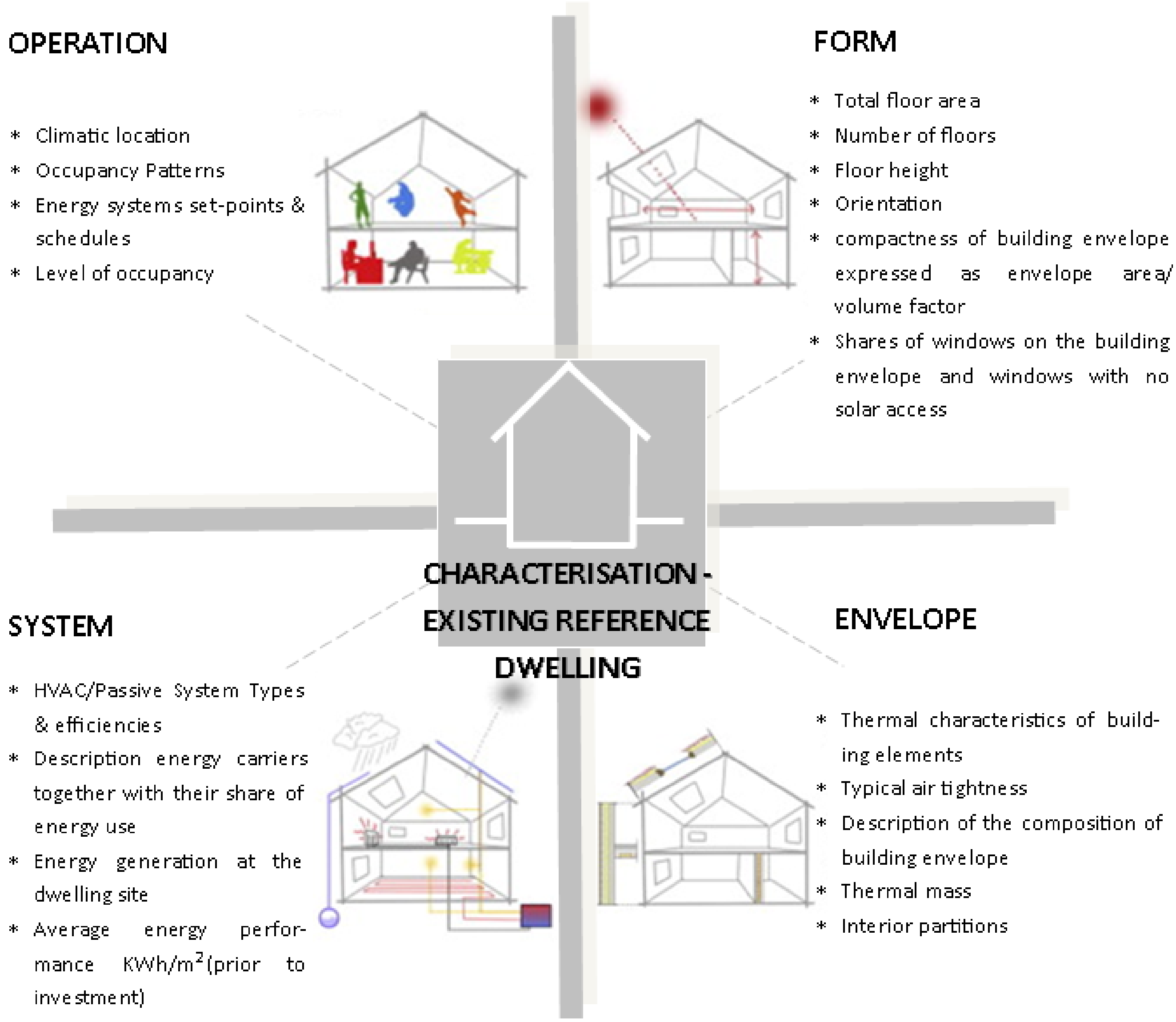


Table 6 Central heating fuel source by construction period [78]

		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%

Table 7 Synthetically Average (SyAv) space heating and DHW system characteristics for oil-heated RD [72, 87]

			Quantity	**Unit**	**Description and/or source**
Systems	Primary heating fuel		Oil		68 % RDs –see note with Figure 1 (2016 data)
	Secondary heating fuel		Coal		[87]
	Secondary heating proportion		10	%	[87]
	Efficiencies of space heating system	Primary heating generation η_b	81.2	%	[87]
		distribution	45.24	%	Boiler with uninsulated primary circuit (70.3% of the stock) [87].
		Primary system control and response category	1		71.2 % Control category 1¤ and 98 % Heating System response category 1¥ [87]
		Secondary heating efficiency	42	%	[87]
	Efficiencies of DHW system	Generation	81.56	%	56% Factory Insulated Tanks, 56% no electrical immersion used in summer [87].
		Distribution losses	45.24	%	[87]

¤ 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 8 Synthetically Average (SyAv) Heating and DHW system characteristics for solid-fuel heated RD [72, 87]

			Quantity	Unit	Description and/or source
Systems	Primary heating fuel		Solid-fuel Multi-fuel		24 % RDs – see note with Figure 1 (2016 data)
Systems	Secondary heating fuel		Solid-fuel Multi-fuel		[87]
Systems	Secondary heating proportion		10	%	[87]
Systems	Efficiencies of space heating system	Primary heating generation ɳ	54	%	[87]
Systems	Efficiencies of space heating system	distribution	48	%	Boiler with uninsulated primary circuit [87]
Systems	Efficiencies of space heating system	Primary system control and response category	1		69 % Control category 1[¤] and 78 % Heating System response category 3[¥] [87]
Systems	Efficiencies of space heating system	Secondary heating efficiency	42	%	[87]
Systems	Efficiencies of DHW system	Generation	61	%	31%/69 % Factory/ Loose jacket insulated tanks, 7% electrical immersion used in summer [87].
Systems	Efficiencies of DHW system	Distribution losses	6	%	[87]

[¤] 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]

2.4.1.2 Heat loss through the building fabric

The overall heat loss comprises heat transfer through the building envelope, linear thermal bridges and air infiltration. Using a sample of RDs 'BS EN 12831:2003 Heating Systems' was used to calculate relative percentage steady-state heat losses. 80 to 90% of the overall heat loss from dwellings is by planar heat losses through the building fabric; 8 to 16% is heat loss through air infiltration through the dwelling fabric and 4 to 16 % is heat loss through linear thermal bridges

[80]. The length of thermal bridges have increased as dwelling size and associated window ratios become larger with the progress of time [70]. The length of its linear thermal bridges in the RDs is captured initially via the classification of a dwelling by its construction period.

2.5 Categorisation

2.5.1 Operation

2.5.1.1 Climatic Location

The International Weather for Energy Calculations (IWEC) contains "typical" hourly weather parameters for building energy simulation [121]. The World Meteorological Organization (WMO) recommends use of 30-year climate averages to even out year-to-year variations. IWEC Weather Files are available for twelve locations in Ireland with data spanning from 1983 to 2008 [122]. When mean temperatures for twelve IWEC 2 locations in Ireland were mapped against population density [123], Mullingar weather station (Latitude 53.53^{o}N, Longitude -7.34 ^{o}W) was found to provide a SyAv weather data file representative of weighted geographic density of dwelling locations.

2.5.1.2 Operation & Occupancy Pattern, Set points and Schedules

Heating demand temperatures (i.e. thermostat setting where thermostats are used) and heating duration determine domestic space heating energy [36, 59, 60, 124, 125]. In Ireland, DEAP has 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 [126]. In both DEAP and the UK Building Research Establishment Domestic Energy Model (BREDEM) [125] the whole dwelling is assumed to be heated only for specific time periods with the living area heated to a 3 °C higher temperature than the rest of the home during these periods [125]. BREDEM differentiates weekdays and weekend heating schedules. Table 8 details the set-point temperatures and heating durations standardised in BREDEM and DEAP. As a wide variety of heating patterns exist [59, 125-127], neither BREDEM and DEAP reflect the heat consumption demand and duration characteristics of dwellings in the UK and Ireland accurately [45, 59, 125-127]. In England, an average dwelling is heated for 8.4 hours/day with that increasing to 8.7 hrs per day in the average detached dwelling

[59]. In Ireland, the average rest-of-home temperature is 17 °C [126]. The average temperatures and heating duration of dwellings are generally independent of year of construction and day of the week [127]. Living room temperatures are typically lower in the mornings than in the evenings [127] with temperatures of 21°C rarely reached [127].

Table 9 BREDEM, DEAP and assumed reference dwelling demand temperatures and schedules for space heating system [59, 72, 126, 127]

				Mean Temperature (°C)		Heating Duration (hrs)	
				Living Room	Rest of Dwelling		
Heating Period	BREDEM	Morning	07:00-09:00	21	18	2	9
		Evening	16:00 – 23:00	21	18	7	
		Weekends	07:00 – 23:00	21	18	16	16
	DEAP	Morning	07:00 – 09:00	21	18	2	9
		Evening	17:00 – 23:00	21	18	7	
	In this study	Morning	06:45 – 09:00	18.3 ¤	17 #	2 hrs 15 mins α	9 hrs 30 mins
		Evening	15:45 – 22:00	19.9 ¤	17 #	7 hrs 15 mins α	

¤ [127] # [126] α [127]

SyAv heating schedules and mean temperatures for an average year are required to produce a one-fits-all model of space heating energy consumption in detached dwellings. To include increased comfort temperatures, an energy consumption model should ideally reflect empirical mean housing stock temperatures [64]. To account for longer heating duration associated in detached houses [59], the assumed demand temperatures and heating schedules for the RD are based on available empirical evidence [126, 127] as detailed in Table 9.

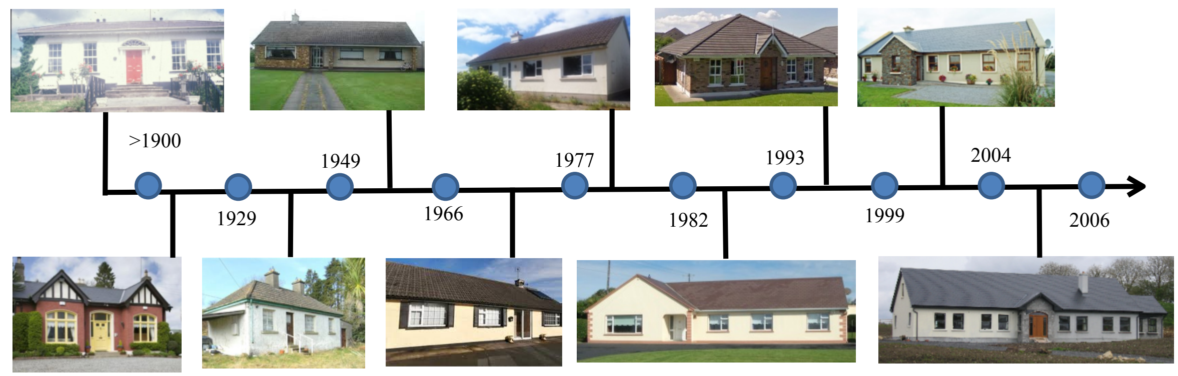
2.5.1.3 Level of occupancy

Typical levels of occupancy by DEAP construction period [30] are based on national census statistics [71] for Ireland corrected to apply to DEAP construction periods. SyAv occupancies established were subsequently weighted against the dominant dominant planar element U-value classifications established in Tables 12 and 13, Section 2.4.3.1 as shown in the summary results in Table 14, Section 3.2.

2.5.2 Form

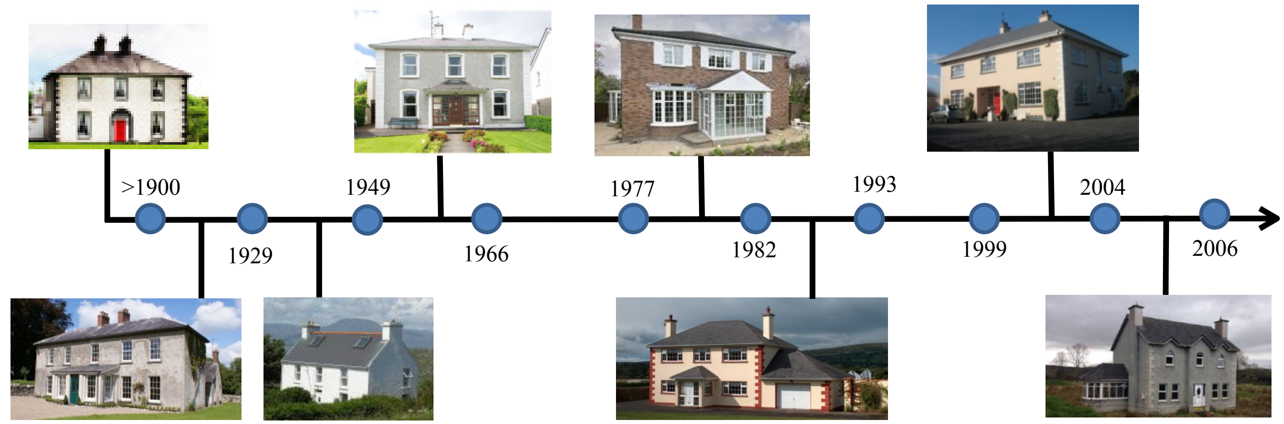
SyAv dwelling geometries were determined from the refined empirical database [87]. Dwellings geometries display a normal distribution. The thermal performance of single storey and two-storey dwellings with the same thermal fabric characteristics differ due to their different volume-to-surface-area ratios. Single and two-storey geometries were therefore established. Typical geometries by construction period depicted in Figure 7 are described in Table 10. From pre-1900 dwellings up and until 2006 the floor area of detached Irish dwellings grew by 1.6 % and 1.34 % per annum for single and two-storey respectively, relative geometries have grown proportional to the increase floor area but have remained have remained proportionally similar with time (see Figure 7). The geometries of the average single and two-storey models shown in Figure 8 imitate closely real-world dwelling forms as they are a statistical composite of the features of dwellings considered within the case study dwelling typology [80].

Figure 7 Timeline and average form of typical single and two-storey reference dwelling

a) Timeline of typical detached single-storey Irish dwelling	b) Average single-storey dwelling[6] (Ref: Average geometries listed in Table 9)
	 Average overall window ratio* = 20 % % share of windows long wall = 33.32 % % share of windows short wall = 16.66 % Floor to ceiling height 2.56m Long wall (m) = Short wall (m) x 2
c) Timeline of typical detached two-storey Irish dwellings	d) Average two-storey dwelling (Ref: Average geometries listed in Table 9)

[6] This geometry also pertains to a two-storey dwelling if attic converted to a habitable space applies when first floor height < 2.1 m

* Window area as a percentage of wall area; window area applyies to entire area of the window opening, including both frame and glass



Average overall window ratio = 19 %
% window long wall = 28 %
% window short wall = 22 %
Floor to ceiling height;
GF = 2.53 m; FF = 2.12 m
Roof Pitch circa 25^{o} in a square house

Table 10 Characteristic form of reference dwellings by period of construction [126]

		Single-storey dwelling									Two-storey dwelling									
		Area (m^2)					Height (m)	%	(m^3)	Area/Vol.	Area (m^2)					Height (m)		%	(m^3)	Area/Vol.
		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**
Period of Constr-uction	**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

2.5.2.1 Orientation and proportion of windows with no direct solar access

As they are used for aggregated thermal modelling, an RD has to be representative of the orientation of that dwelling type. EU commission delegated regulation 244/2012 [57] requires proportion of windows with no direct solar access to be reported. Houses in rural Ireland typically parallel the road [80]. A 2014 study [128] of 36 local authority urban housing schemes in Ireland, comprising 10,449 housing units, found 29 %, 27 %, 23 % and 21 % were north, south, west and east facing respectively. In this study SyAv dwelling geometries [as shown in Figures 7 (b) for single and Figure 7 (d)] for two-storey dwellings were oriented (distributed) in equal numbers through the cardinal axes (N-S), (NE-SW), (E-W), and (NW-SE). At each of the orientations the proportion of windows with no solar access was estimated as shown in Table 11 accounting for no solar access existing in Mullingar weather station (Latitude 53.53^{o}N, Longitude -7.34 ^{o}W), 50^{o} east and west of north.

Table 11 Proportion 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 9)	N-S	(Quantity of reference dwelling by category)/4	17 %	22 %
	NE-SW		50 %	50 %
	E-W		33 %	28 %
	SE-NW		50 %	50 %

2.4.3 Envelope

2.4.3.1 Typical thermal transmittance coefficients by construction period

A bimodal distribution was fitted to the empirical data to;

a) establish the proportion of Mode 1 and Mode 2 dwellings by period of construction (see Figure 8) to indicate refurbishments,

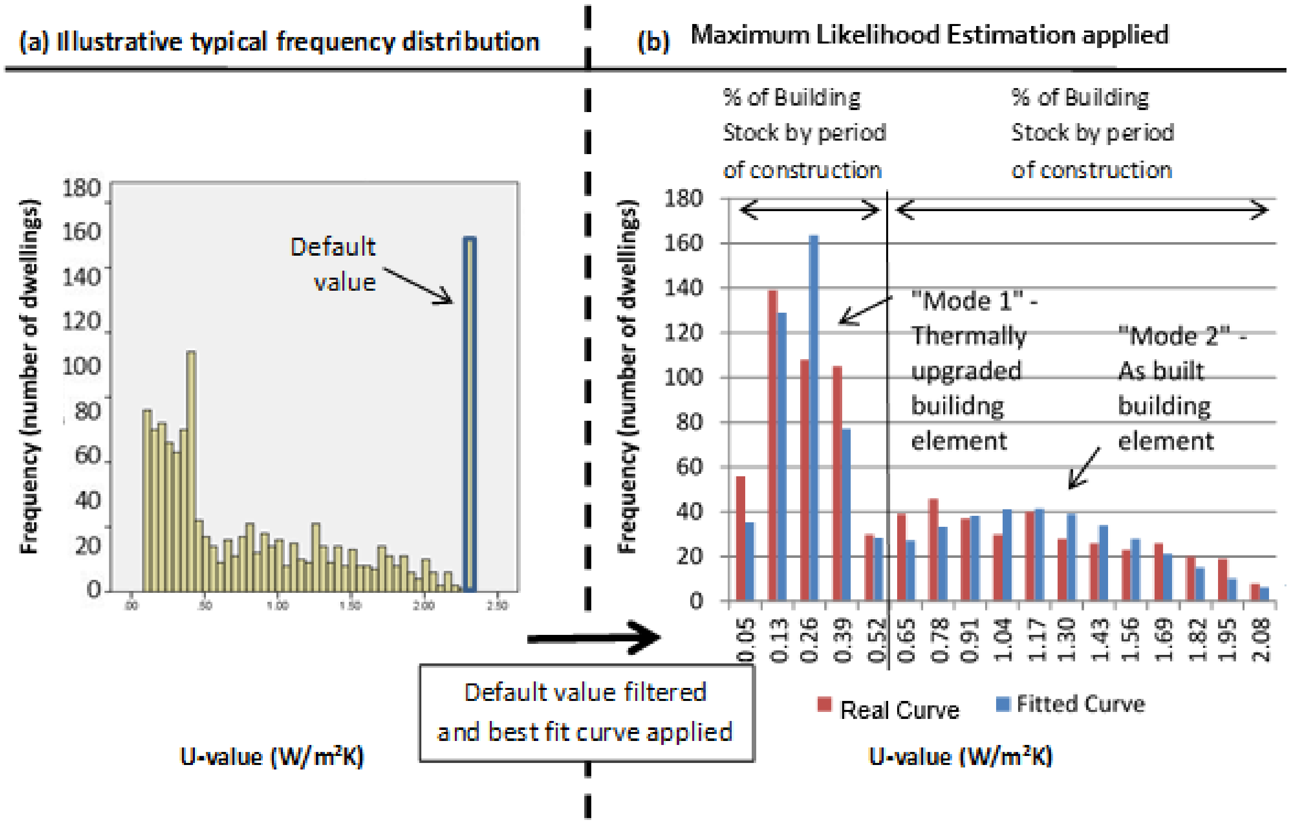
b) ascertain the means for Mode 1 and Mode 2 dwellings, (i.e. 'Mean 1' and 'Mean 2') by period of construction (see Figure 8).

Statistical means for Mode (1) 'Mean 1' and Mode (2) 'Mean 2' dwellings, for window, floor, roof and wall U-values were established by fitting a normal curve[7] to the empirical data using the Maximum Likelihood Estimation (MLE) method. The results of this analysis, collated with the percentage of the actual dwelling stock nationally [71, 107], is presented graphically in Figures 9 and 10 for single and two-storey dwellings respectively. Double-glazing air-filled with a 6 mm gap is assumed in DEAP to have an average U-value of 3.1 W/m^2K and single glazing an average U-value of 4.8 W/m^2K [70, 87]. 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 dwellings being 2.95 W/m^2K and 2.91 W/m^2K respectively. A solar g-value of 0.76 [72] is adopted for the RD as shown in summary results in Table 15, Section 3.2.

To establish thermal envelope characteristics for the RDs, each characterisation by construction period (shown on the horizontal axis in Figures 9 and 10) is subcategorised vertically by common thermal characteristics in Figure 11. A minimum of 4 to a maximum of 5 categorisations per age category, [(a) to (d) or (e)] was required to reflect accurately the reference sample dataset by construction period as shown in Figure 11. This resulted in a grouping of 45 single and 45 two-storey dwellings by construction period as shown in Tables 13 and 14 respectively. Due to thermal upgrades there was commonality in thermal characterisations across construction periods.

[7] The selection of the normal curve to fit the data is validated in [80] C. Ahern, Introducing the default effect: reducing the gap between theoretical prediction and actual Energy consumed by dwellings through characterising data more representative of national dwelling stocks, Building Engineering, Technological University Dublin, 2019.

Figure 8 (a & b) Illustrative typical frequency distribution and of wall and roof U-value's [87]



Commonalities are grouped under the column 'category' in Table 11 with the same colour and number; 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 validity of these classifications were confirmed via use of radial graphs shown in Tables 13 and 14. 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. Singular or unique classifications are not depicted in radial graphs as there is obviously no commonality.

The number of categories was reduced from 45 to 21 for single-storey dwellings and from 45 to 14 two-storey dwellings.

Figure 9 Mean (1) and (2) and default U-values for single-storey detached dwellings proportional to dwelling quantities by construction period (see Table 11 for base data)

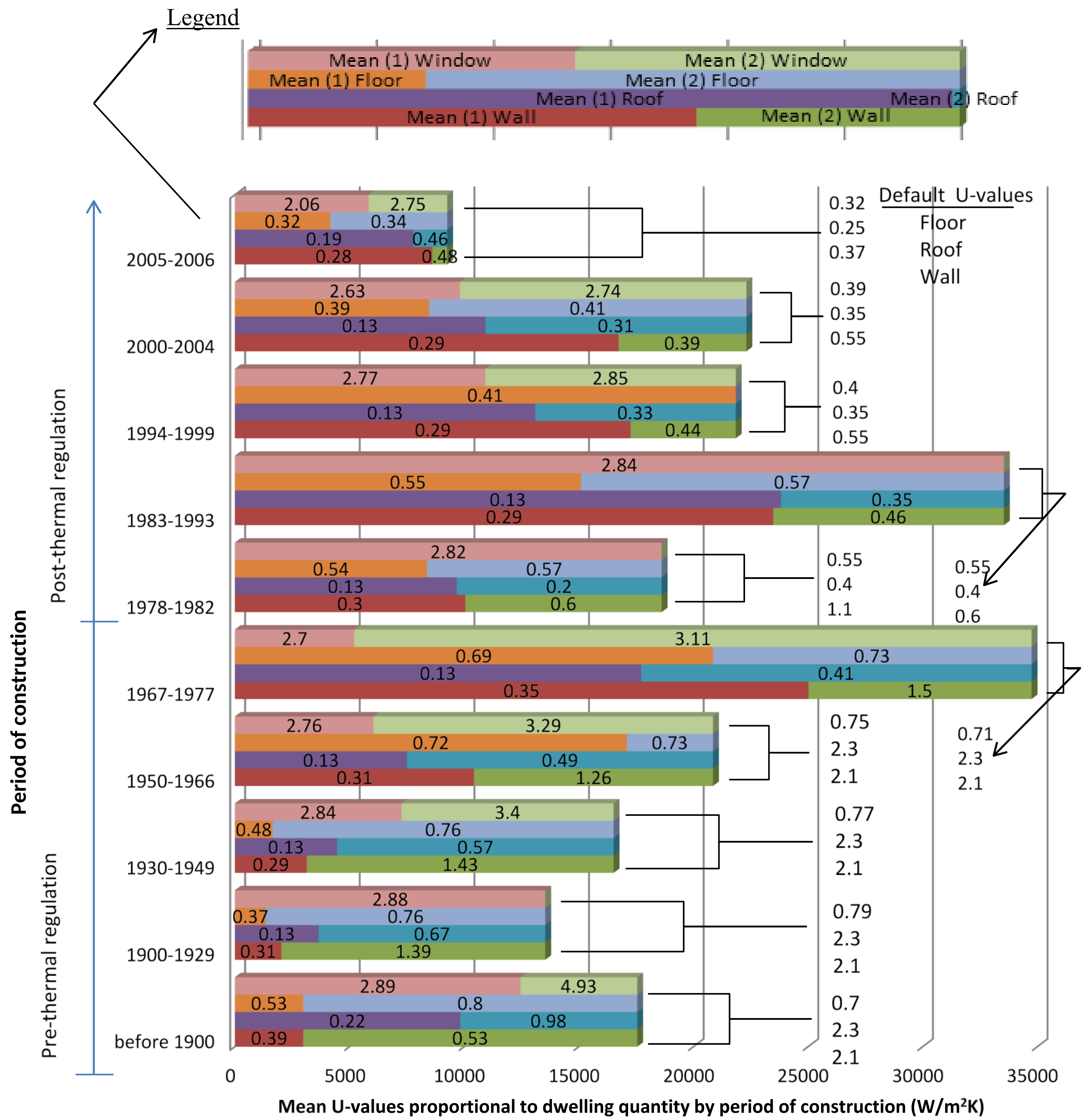


Figure 10 Mean (1) and (2) and default U-values for two-storey detached dwellings proportional to dwelling quantities by period of construction (see Table 11 for base data)

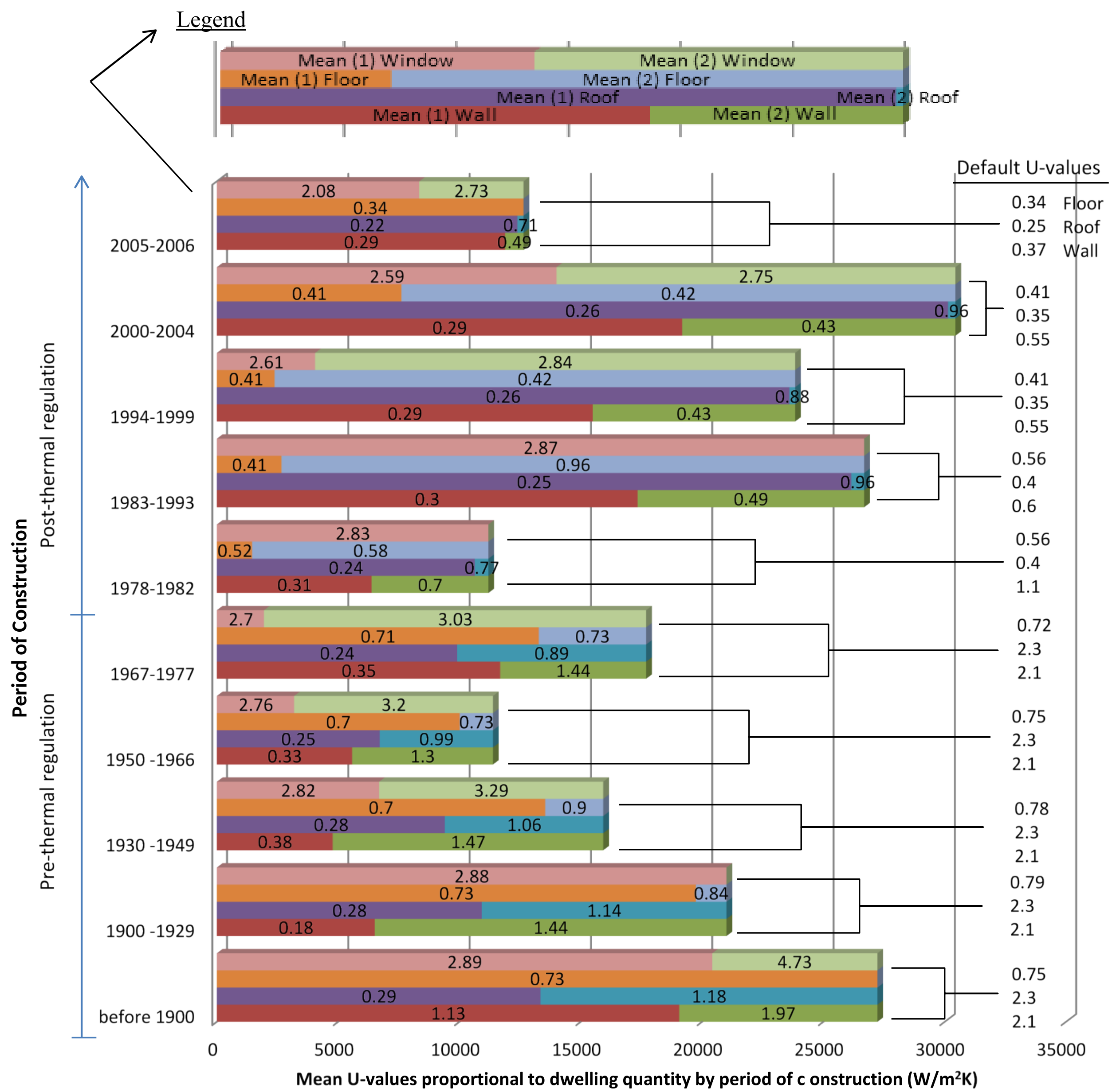


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Figure 11 Segmentation of synthetically averaged bi-modal exposed thermal characteristics for dwelling elements by period of construction

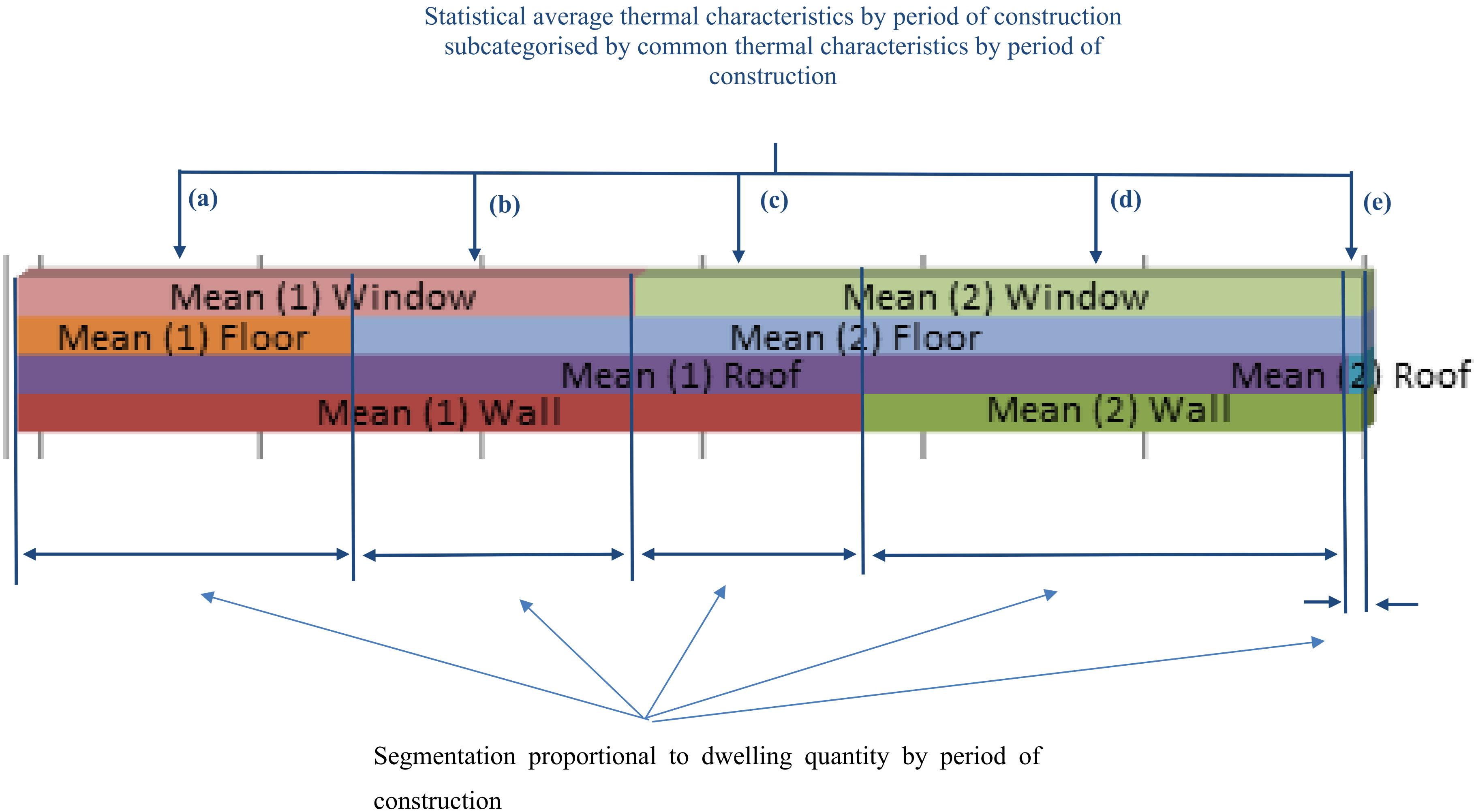
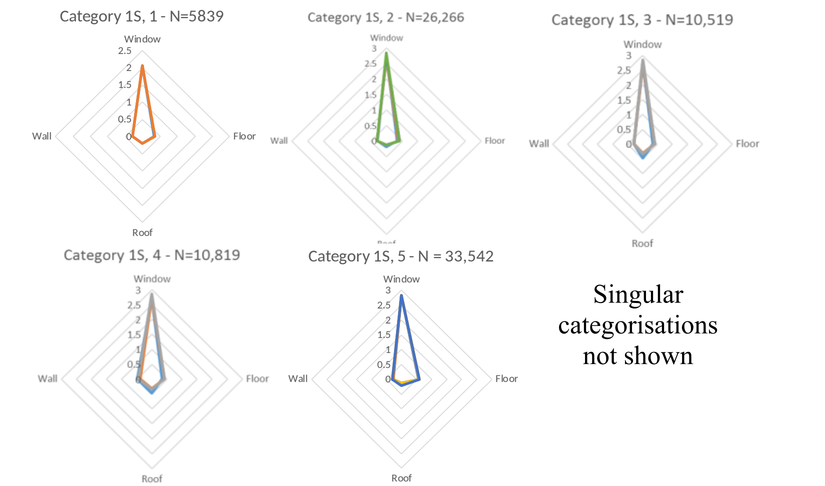


Table 12 Commonality analysis of statistical means across period of construction for single –storey (1S) dwellings – 45 No.

Period of Construction	Regulation	Years	Category 1S,x	Quantity		U-Value Window	U-Value Floor	U-Value Roof	U-Value 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



Singular categorisations not shown

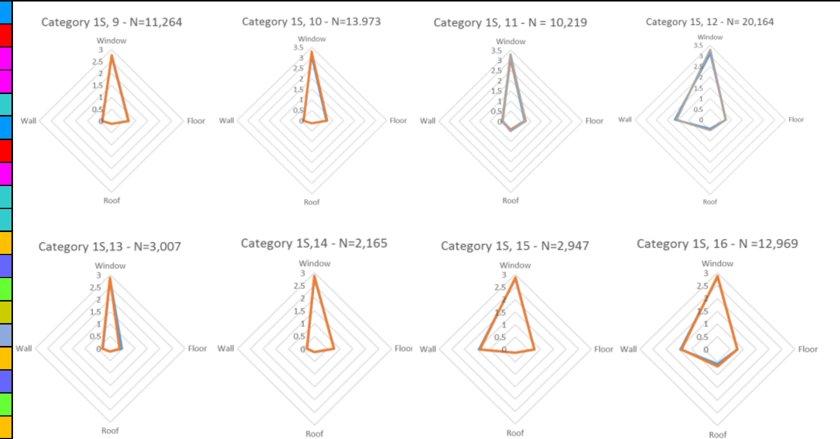
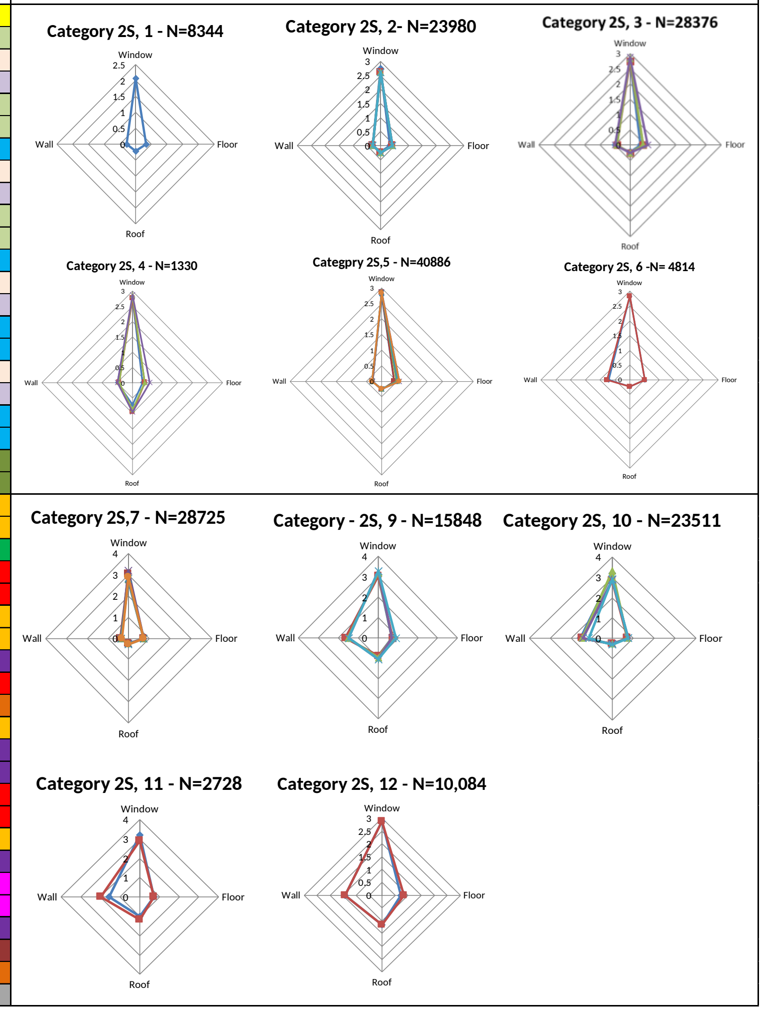


Table 13 Commonality analysis of statistical means across period of construction for two-storey (2S) dwellings – 45 No.

Singular categorisations not shown

		Category 2S,x	Quantity		U-Value Window	Floor	Roof	Wall	Radial Diagrams of Categorisations
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					



2.4.3.2 Air Tightness

The reasonable upper limit of dwelling air infiltration prescribed in the 2011 Irish building regulations is 7 m^3/hm^2. At 3.05 m^3/hm^2 at 50Pa or less, infiltration rates returned by the EPC dataset are much lower than expected. Dwellings in the dataset 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 [129]. The infiltration rates in the empirical dataset were thus unrepresentative of the overall dwelling typology. There are few published air-tightness charateristics of existing dwellings in UK and Ireland [130, 131]. A statistically small (28 dwellings) recent database for air tightness of Irish housing [130] focused on single-family residential semi-detached and terraced houses; 21 of which were pre-2006[8] dwellings. Two large scale (>200) databases for air infiltration rates in pre-2006 UK dwellings are available, covering 217 dwellings [132] and 471 dwellings [133]. Assuming little difference between Irish and UK housing construction, Ahern *et. al.* [70] reconfigured the results for the 471 UK dwellings [133] across DEAP age bands as shown in Figure 13.

GreenBuild Energy Rating and Building Information Services Ltd. have been conducting air-tightness tests in Ireland since mid-2007, amassing air-tightness test data [134] relating to 187 refurbished as well as as-built Irish dwellings. Using this database, 118 detached dwellings representing 63 % of sample set, were isolated from the larger dataset. Air-tightness results for similar dwellings constructed within the same period;

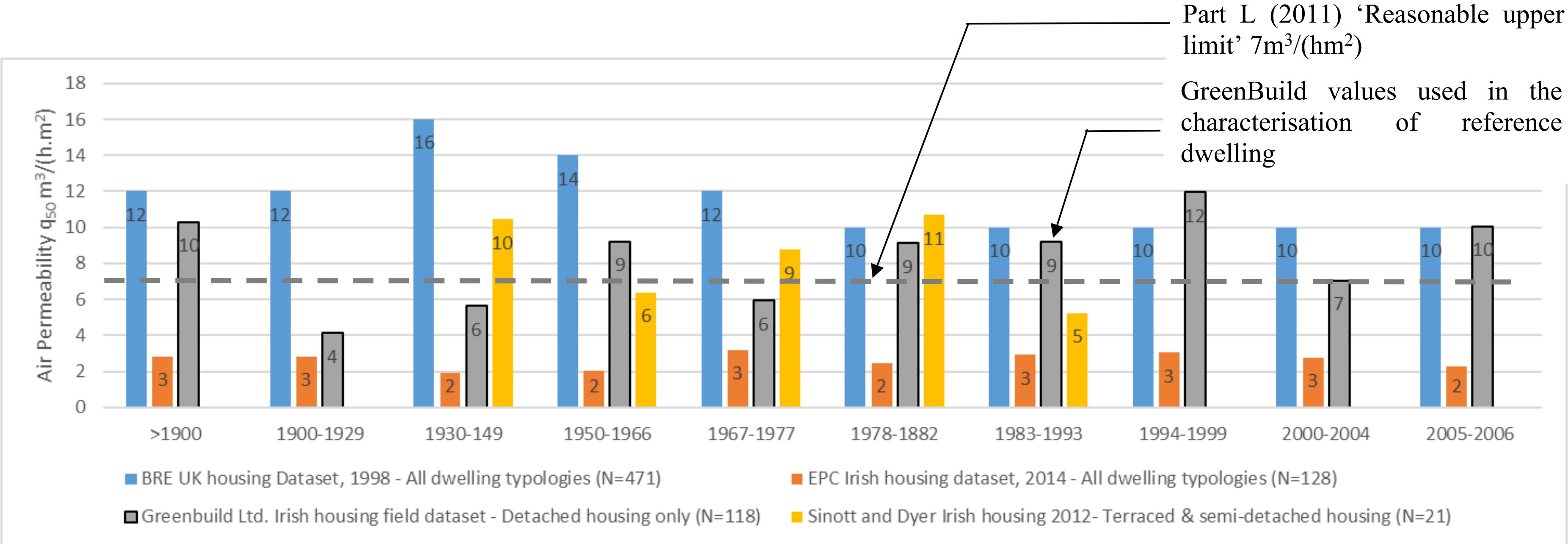
- varied widely, even for dwellings with similar construction characteristics,
- were not necessarily lower for refurbished dwellings than for as-built dwellings,
- did not relate to wall-construction type (solid concrete, cavity block etc.),
- were slightly better for post-thermal regulation dwelling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

The GreenBuild dataset is shown in Figure 12 to compare well with the 417 dwelling UK dataset. It was therefore employed in the characterisation of the case study RDs. Average air infiltration

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

rates were reconfigured against the thermal characterisations established in Section 2.4.3.1 then adopted for the characterisations of the SyAv RD as shown in summary result Tables 14 and 15, Section 3.2.

Figure 12 Comparison of air permeability datasets [70, 87, 130, 133, 134]



2.4.3.3 Thermal Bridging

The Y-value is the sum of all the non-repeating thermal bridging heat transfer coefficients divided by the total exposed area of the building envelope. The Y-value is added to the average U-value to account for thermal bridges [135, 136]. In DEAP a global default Y-value of 0.15 W/m^2K is applied for all existing dwellings [137], irrespective of dwelling type, that can either overestimate [138, 139] or underestimate [140] the heat loss due to thermal bridging. The linear thermal transmittance values in this study were sourced from UK SAP guidelines [141] as corresponding values in Irish regulations are linked to unrepresentative U-values [80].

The SyAv geometries by construction period listed in Table 10 were reclassified according to thermal classifications, established in Table 12 and Table 13. To calculate the Y-Values shown in Table 14. To determine the likely length of thermal bridges junctions it was assumed that;

(i) single-storey houses have a length twice the width while two-storey dwellings are square with a 25^o pitched roof, as shown in the average depiction of typical single and two-storey dwellings in Figure 8,
(ii) window heights and door widths are one metre, and
(iii) thermal bridges have a 200 mm extension on each junction end.

The adopted Y-values in Table 14, are 40 % to 47 % lower than those the DEAP [72] global default Y-value of 0.15 W/m^2K.

2.4.3.4 Internal heat capacity

The dynamic effects of solar and internal heat gains are taken into account by introducing coefficients that account for thermal mass [31, 72, 142]. The thermal mass of Ireland's predominant housing typology is categorised "medium" giving utilisation and intermittent heating factors of 0.2 and 0.11 MJ/m^2K respectively [87].

2.5 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 were established (as described in Section 2.4.1).
2) Synthetically average occupancies by DEAP period of construction were established (as described in Section 2.4.1).
3) Synthetically average dwelling forms, by DEAP construction period, were ascertained using maximum likelihood estimation of the microscopic data in the EPC dataset (as described in Section 2.4.2).
4) Lengths of thermal bridges were calculated based on synthetically average dwelling forms established in step 3 (as described in section 2.4.3.3)
5) 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 construction period (as described in Section 2.4.3.1).
6) The thermal data for planar elements (as established in step 5), categorised by DEAP construction period, was analysed for commonality.
7) Physical geometric characteristics, surface area of building envelope (m^2), window ratios (%) (as established in step 3), and length of thermal bridges (m) (as established in step 4), were classified to correlate with common thermal U-values classifications (as established in step 6).
8) Occupancy data and air-permeability characteristics established in sections 2.4.1.3 and 2.4.3.3 respectively were classified to correlate with dominant planar element U-value classifications (as established in step 6).
9) Proportion of heating fuel use in Table 5 (Section 2.3.1.1) were classified to correlate with dominant planar element U-value classifications (as established in step 6).
10) Orientations and proportion of windows with no solar access were estimated (as described in Section 2.4.2.1).
11) Clustered data formed SyAv reference dwellings; as detailed in summary results provided on Tables 14 and 15.

2.6.1 Statistical model validation and generalisability

For internal validation of the model's performance repeated data-splitting was used [143]. In the refined EPC dataset detached dwellings were isolated from the larger dataset, rural detached dwellings were then isolated. The dwellings were then classified by number of stories, then by construction period (10 No.) then by dwelling element (wall, roof, floor etc.). The MLE statistical model developed (as described in Section 2.4.3.1) was applied repeatedly to each split dataset. The robustness of the method was demonstrated by consistent goodness-of-fit of the cumulative distribution function to the real data [80].

To externally validate the methodology, an independent sample for a different housing typology from the same population was isolated from the original EPC dataset [87] used. The method has been shown to be valid by the goodness-of-fit of the fitted curve to the real curve for a different housing typology [80]. The recommended default U-values 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 single-family dwelling stock-at-large.

3.0 Results

Overall reference dwelling characterisations are summarised in Table 14. Results are reported as detailed in Commission Delegated Regulation (EU) No. 224/2012 [57] in Table 15.

Table 14 Characterisation of single (1S) and two-storey (2S) reference dwellings depicting Ireland's predominant housing typology

Regulation	Category	x	Quantity (N)		Heat loss through building fabric: Thermal transmittance; U-Value (W/mK): Window	Floor	Roof	Wall	Thermal bridging; Y-value (W/m^2K)	Air permeability ($m^3/(h.m^2)$)	Geometry: Area (m^2): Wall	Roof	Floor	Window	Door	Height (m): Ground floor height	First floor height	%: Window Ratio	(m^3): Volume	Surf. Area/Vol.: Compact-ness of Building Envelope	Occupancy	System: Heating fuel source: Oil	Solid Fuel
Post-thermal Regulation	1S,	1	105616	5839	2.06	0.33	0.19	0.28	0.08	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	0.09	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	0.09	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	0.09	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	0.09	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	0.09	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	0.09	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	0.10	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	0.09	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	0.09	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	0.09	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	0.09	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	0.09	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	0.09	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	0.09	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	0.09	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	0.09	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	0.09	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	0.09	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	0.09	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	0.09	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	0.08	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	0.09	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	0.09	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	0.09	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	0.09	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	0.09	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	0.09	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	0.09	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	0.09	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	0.08	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	0.08	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	0.08	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	0.08	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	0.08	12.00	179	110	103	25	3.82	2.56	2.37	14%	508	0.83	2.49	59%	31%

Table 15 Summary reference dwelling report complying with EU Commission Delegated Regulation 244/2012

		Quantity	Description and/or source
Primary energy conversion factors	electricity	2.19	[92, 144]
Carbon emission factors	electricity ($kgCO_2/kWh$)	0.473	[92, 144]
	oil (kerosene) ($kgCO_2/kWh$)	0.257	
	Coal ($kgCO_2/kWh$)	0.341	
Climatic conditions	location	Mullingar, Ireland	Section 2.4.1.1
	heating degree-days	2,389	Mullingar Weather Station - degree days below 15.5°C (occupied and unoccupied period) [123]
	wather file	IWEC2 file	See Section 2.4.1.1
	terrain	Rural	Nearby buildings not accounted for.
Geometry	length x width x height (m^3)	See Table 14	Related to the heated/conditioned air volume,
	number of floors	Varies	
	S/V (surface-to-volume) ratio (m^2/m^3)	See Table 14	
	ratio of window area over total building envelope area (%)	See Table 14	
Orientation		N, S, E, W, NE, NW, SE, SW	See Section 2.4.2.1
Internal gains	use	Single-family houses	According to the building categories proposed in Annex 1 to Directive 2010/31/EU
	average thermal gain per occupant (W/m^2/occupant)	93	CIBSE Guide A [108]
	delivered lighting energy($kWh/m^2/yr$)	1,149	BER database [87]

Table 15 Summary reference dwelling report (cont.) complying with EU Commission Delegated Regulation 244/2012

<table>
<tr><th colspan="3"></th><th>Quantity</th><th>Source and/or description</th></tr>
<tr><td rowspan="12">Building Elements</td><td rowspan="3">average U-value (W/m²K)</td><td>wall</td><td rowspan="3">See Table 14</td><td rowspan="3"></td></tr>
<tr><td>roof</td></tr>
<tr><td>window</td></tr>
<tr><td colspan="2">living area as a % of total floor area</td><td>16</td><td>[87]</td></tr>
<tr><td rowspan="2">thermal bridges</td><td>total length (m)</td><td>See Table 14</td><td></td></tr>
<tr><td>average linear thermal transmittance (W/mK)</td><td>See Table 14</td><td></td></tr>
<tr><td rowspan="2">thermal mass factors</td><td>Utilisation (J/m²K)</td><td>200</td><td rowspan="2">See Section 4.2.3.4</td></tr>
<tr><td>Intermittent heating (J/m²K)</td><td>111</td></tr>
<tr><td colspan="2">type of shading systems</td><td>Curtains</td><td></td></tr>
<tr><td colspan="2">average g-value of glazing</td><td>0.76</td><td>Wood/PVC Double 6mm air-filled glazing average U-value 3.1 W/m²K Table S9 DEAP [72]</td></tr>
<tr><td colspan="2">Windows Draught Stripped (%)</td><td>94</td><td>[87]</td></tr>
<tr><td colspan="2">infiltration rate [(m³/(hm²) at 50Pa]</td><td>See Table 14</td><td></td></tr>
</table>

4.0 Limitations of this Study

The EPC database employed [87] may present a favourable characterisation of the dwelling stock as homeowners must obtain an EPC to qualify for a state-led grant schemes. The estimated percentage of state-grant aided thermally refurbished dwellings in the database is 24 % [80]; reduced from 50 % in 2010 [93].

Where information within the database was found to be questionable or unreliable, the composition of the reference dwelling was informed instead through other available data and expert enquiries. Thus the quality of the characterisation relies on subjective expert judgment [118]. Due to lack of information on the composition of dwelling stocks, this has been a common approach [23, 56, 57, 70, 85, 118].

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 average range of temperature is modest [145] ranging from 7 to 11 ^{o}C [123, 146].

5.0 Conclusions

35 reference dwellings (RDs) have been derived to characterise appropriately, 406,918 dwellings, averaging one RD per 11,626 dwellings. The methodology describes produces reference dwellings that are;

i. founded in significant real-world dataset,
ii. 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. commonly and transparently reported in compliance with EU Commission Delegated Regulation No 244/2012.

Use of these RDs as inputs to national residential energy consumption enables models to better predict the energy saving potential of a predominant housing typology.

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Conflict of interest statement

There is no conflict of interest of the authors in relation to this work. Work is published to contribute to knowledge in this field.

Regards

Ciara Ahern