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Optimisation of Retrofit Wall Insulation: An Irish case study

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Abstract

Ireland has one of the highest rates of emissions per capita in the world and its residential sector is responsible for approximately 10% of total national CO_2 emissions. Therefore, reducing the CO_2 emissions in this sector will play a decisive role in achieving EU targets of reducing emissions by 40% by 2030. To better inform decisions regarding retrofit of the existing building stock, this study proposes Optimum Insulation Thicknesses (OIT) for typical walls in 25 regions in Ireland. The calculation of OIT includes annual heat energy expenditure, CO_2 emissions, and material payback period. The approach taken is based on Heating Degree Day (HDD) and life cycle cost analysis methods for different combinations of insulation material, heat energy type, and Irish wall configuration. Results indicate that OIT increases with increased HDD and varies up to 30 % from lower to higher HDD regions in Ireland. The type of wall materials, configuration, insulation type, and heat energy type all have a significant impact on annual cost saving potential (up to 170 €/m^2) and carbon emission (up to 50 kg/m^2). The Analysis Of Variance (ANOVA) technique is used to compare the significant mean difference between combinations under OIT and cost savings.

Keywords: Optimum insulation thickness, heating degree day, retrofit, Ireland, CO_2 emissions

1 Introduction

Humanity's escalating production and use of energy have led to what is now being considered an environmental crisis. Inefficient use of unclean energy sources in the industrial, domestic, and transport sectors release immense volumes of greenhouse gases causing climate change, global warming, ozone depletion, and adverse effects on flora and fauna [1, 2]. It is now accepted that this threatens the quality of life of future generations and disruptive steps must be taken to mitigate this threat. To achieve this, several national, international, and global plans and targets have been agreed upon which aim at both moderating energy consumption and reducing greenhouse gas emissions [3]. At the time of writing, the European Commission (EC) is proposing a legally binding target of net zero greenhouse gas emissions by 2050 [4].

Globally, the building sector is the second largest consumer of energy. This sector accounts for approximately 40% of global energy consumption [5]. The preponderance of energy use in buildings is for space heating and cooling in order to provide and maintain thermal comfort [6-8].

Sustainability-focused energy efficient design and operation of buildings has the potential for significant and positive environmental impact. In particular, energy efficient retrofitting of existing buildings should be a primary focus since it is predicted that approximately 60% of the current building stock will still be in use in 2050 [9]. The main motivation for retrofit for Irish people was found to be the comfort rather than energy or CO_2 savings [10]. Thermal comfort in buildings is a complex and highly occupant and building-specific phenomenon. Although it falls outside the remit of this study, it is acknowledged that comfort take-back can be significant with research showing that it can result in actual energy savings falling short of predicted by between 10% and 36% or more [11-13]. However, it has also been identified that those choosing to retrofit, did so because they had the available savings and would not have availed of a loan or other financing mechanisms were they available [10, 14]. It has been proposed by similar Irish studies that making retrofit more affordable alongside the currently available grants [15, 16] could expand the market for retrofit [14, 17-19]. Reducing material costs is one way of increasing the affordability of retrofit. Furthermore, reducing the overall thickness of insulation required can have additional positive effects such as the lowered impact on room size for internal insulation and reduced workmanship, and therefore costs, in moving external elements such as guttering [20]. Energy efficiency retrofit in buildings (e.g. added insulation or boiler replacement) creates conditions that support improved occupant health and well-being [8]. In cold climates, energy efficiency improvements can lower rates of excess winter mortality while in hot climates; they can help reduce the risk of overheating and dehydration as well as several other health concerns [21]. Furthermore, the EC has identified the twin challenge of addressing both energy efficiency and affordability in achieving the Green Deal [22]. Optimising insulation for purpose can lower upfront costs without adversely affecting the potential post-retrofit savings on energy bills. The most significant contributor to indoor thermal comfort is the ambient air temperature, therefore, adequate levels of insulation are required to reduce heat loss through the building envelope and ensure a reasonable indoor ambient temperature is achieved [8]. However, the temperature of the room's walls, windows, floor, and ceiling, air circulation in the space, and the local relative humidity also have some influence. In recent years, several approaches have been used to evaluate the effect of different types of insulation material and type on thermal comfort and energy consumption [23-25]. On the other hand, thermal mass also contributes to improving thermal comfort both in winter and summer [8, 26].

A key factor that determines the energy performance of a building is the thermal behaviour of the building envelope. External wall insulation has been found to be one of the most cost-effective options for achieving low energy consumption and reduced greenhouse gas emissions both for newly built and refurbished walls [27-30]. However, the presence of thermal bridges in the building envelope which can be prevalent around balconies and junctions around doors and windows also influences the energy consumption and thermal comfort within a building [8, 31-33]. It is estimated that energy demand can be underestimated by 9% to 30% due to the presence of thermal bridges [34, 35]. However, the focus of this paper remains with optimising the external wall insulation thickness and excludes building-specific properties of thermal bridging, wall to window ratio, the orientation of the wall, and thermal mass.

A building's total energy consists of embodied energy and operational energy [36]. In recent years, the proportion of the embodied energy within this calculation is increasing due to advances in energy efficiency of the fuel and energy delivery system and the construction of more energy efficient buildings. There is additional energy and pollution associated with producing more insulation or highly insulating materials. Therefore, for low energy buildings considering the embodied energy in the analysis should be considered [37]. It is estimated that approximately 40% of the total energy of the building is associated with embodied energy [38]. Specific values for savings in embodied energy due to reduced insulation material has not been calculated for the research presented here, however future work will address this.

The selection of the type and thickness of insulation material is not trivial as there is a need for both low cost and high thermal resistance. For the latter, the performance of insulation material can be improved by simply increasing its thickness, since thermal resistance and thickness are proportional to one another [39]. However, this results in the negative effect of increasing the upfront cost. In an attempt to resolve this push-pull tension between cost and thermal performance, researchers have developed optimisation methods that, for given thermal conductivity and material price by volume, require minimum upfront cost and results in maximum long-term heat energy savings throughout its service life [30, 40, 41]. These methods have been referred to as *optimisation of insulation* or *optimisation of insulation thickness* (hereafter referred to as OIT) in the literature.

Many studies have been carried out to determine the optimal insulation thickness [42, 43]. Typically, the optimal insulation thickness is that which results in the most significant total energy savings for the shortest payback period [44-57]. Energy saving is calculated as the difference between the total cost of heating energy for the uninsulated wall compared to the insulated wall [58, 59]. The payback period is the time taken for the total investment of a product to be recovered by the total accumulated savings through heating/cooling energy pay-out [60]. Alternatively, a limited number of studies determine the optimal thickness based on CO_2 savings [61, 62].

Three key points of note become evident when considering the literature, as represented in Muddu et al. [42, 43] and Kaynakli's [20] studies. First, there are several demographic considerations that influence optimum insulation thickness. A significant factor is the external environment, and as references [42] and [43] indicate, much of the current knowledge is centred on climates which can be considered warm to hot. Another demographic influence is the energy mix based on fuel sources used in the given region. For example, hotter climates will have a heavier reliance on electrical energy for air conditioning purposes [63].

The second major influence on optimising insulation is the structural and material information. The insulation type under examination impacts greatly on what is found to be the optimal thickness [44-57]. Other considerations include the location of the insulation within the overall wall structure [40, 53], wall orientation [47, 53, 64-66], and the existing wall structure; with cavity walls [67], concrete walls [68], and brick walls [68] commonly examined. Although walls are most typically the focus of this type of examination, roof systems have also been optimised in a similar manner [46, 54].

Lastly, there does not appear to be a consensus with regard to the analysis methodology employed to determine the optimal insulation characteristics, with many different analytical, empirical, semi-empirical, and numerical methods used [42, 43]. Many studies in the literature employ the Heating Degree-Day (HDD)/ Cooling Degree-Day (CDD) concept to evaluate the heating and cooling loads [44, 45, 52, 59, 70, 71]. Others use Fourier formulations to calculate heating and cooling loads under dynamic thermal loading conditions [65-67, 72-75]. Within the different analysis techniques, there exist two viable cost functions; monetary and environmental selected based on the target stakeholder. The cost of retrofit insulation is of key relevance to stakeholders directly involved in payment, such as homeowners. Conversely, the environmental cost is of interest to policymakers. Considering the latter, a cross-section of the studies have considered the total environmental impact by including CO_2 emissions associated with the manufacture and installation of the insulation [59, 71, 76-78]. Another cost function identified is the impact of insulation on moisture and condensation risk [51, 79, 80].

Ireland offers a unique testing ground for building energy analysis in the context of retrofit insulation for two primary reasons. First, the Irish housing stock is recognised as amongst the least energy efficient in all of Northern Europe [81]. Clearly, if Ireland is going to achieve target emissions over the next few years and decades, efficient insulation retrofit must be considered. Second, Ireland is characterised as having a temperate oceanic climate [67, 68], where the winter temperatures are mild and summer temperatures are moderate compared to the other countries at similar latitudes. Compared with what has been considered in the literature, the Irish climate offers the opportunity to single-out home heating only, as air conditioning is rarely used or even installed in Irish residential buildings.

The overarching objective of this work is to contribute to knowledge in the field of building energy efficiency by considering the *optimisation of insulation* problems in the Irish context. Specifically, retrofit insulation for existing building stock is considered here in order to potentially inform decisions regarding energy upgrading in the Irish domestic sector. Beneficially, by selecting Ireland as the testing ground, the influence of wall and insulation materials, constituent combinations, and thicknesses can be analysed in a scenario which isolates heating as the only energy source for thermal comfort. It is hoped that this will support the insulation retrofit of the existing and pending building stock in Ireland and other countries and/or regions with similar climates, such as the United Kingdom. The following section presents a methodology which can be adapted for such countries with little modification.

2 Methodology

Heat losses in uninsulated residential buildings generally occur through external walls (30%), roofs (30%), floors (20%), air infiltration (10%), and doors and windows (10%) [8]. It should be noted that these percentages will vary greatly depending on the home design and construction. However, these figures are representative of the average house. Therefore, for the purposes of this study, the optimum insulation thickness has been calculated based on a 30% heat loss through external walls.

In moderate climates, the amount of energy required for heating is mostly determined using the Degree-Day method. Degree-day methods are considered as a straight forward, yet sufficiently accurate and reliable technique for quantifying the thermal energy demands in buildings [82, 83]. In this method, heating transmission loads are assumed to be proportional to the difference between the outdoor air temperature (T_o) and the threshold temperature (T_h). The threshold temperature for heating is the outdoor temperature at which heating is not required in order to maintain comfort within the building and this can be determined according to the desired indoor temperature, thermal properties of the entire wall, building information, and building use. For heating, the number, therefore, can vary, however the most commonly identified values in the literature are 15^{o}C [44] 16^{o}C [45],and 18^{o}C [45, 47, 52]. For this study, a threshold temperature of 15.5^{o}C is used which is commonly considered in Ireland [42, 84] and with regions with similar climates [85]~~.~~

2.1 Calculation of heating degree day for all regions in Ireland

This study considers the data published by The Irish National Meteorological Service [69] from 2003 to 2017 as recorded at weather stations located in all 25 counties in Ireland in order to provide an estimate of the climatic condition. Based on daily temperature data, annual HDD values across Ireland were calculated using Eq. 1 [86] and visually presented per county in

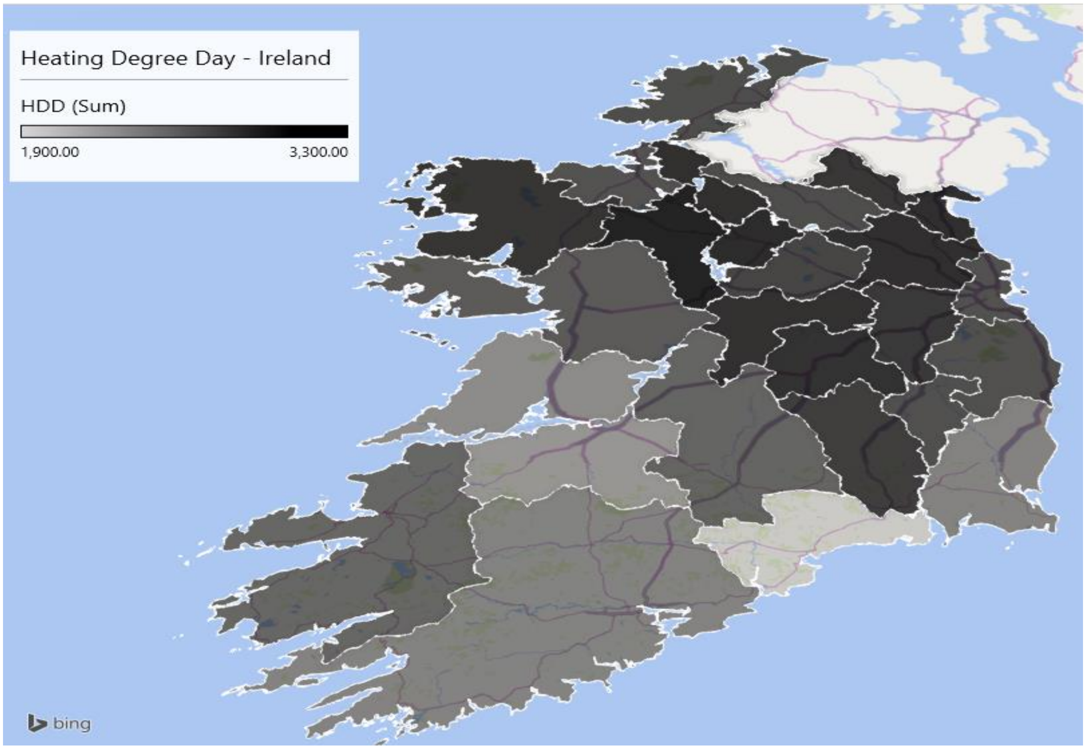


Figure 1.

$$\text{HDD} = \sum_{days} (T_h - T_o)^+ \quad (1)$$

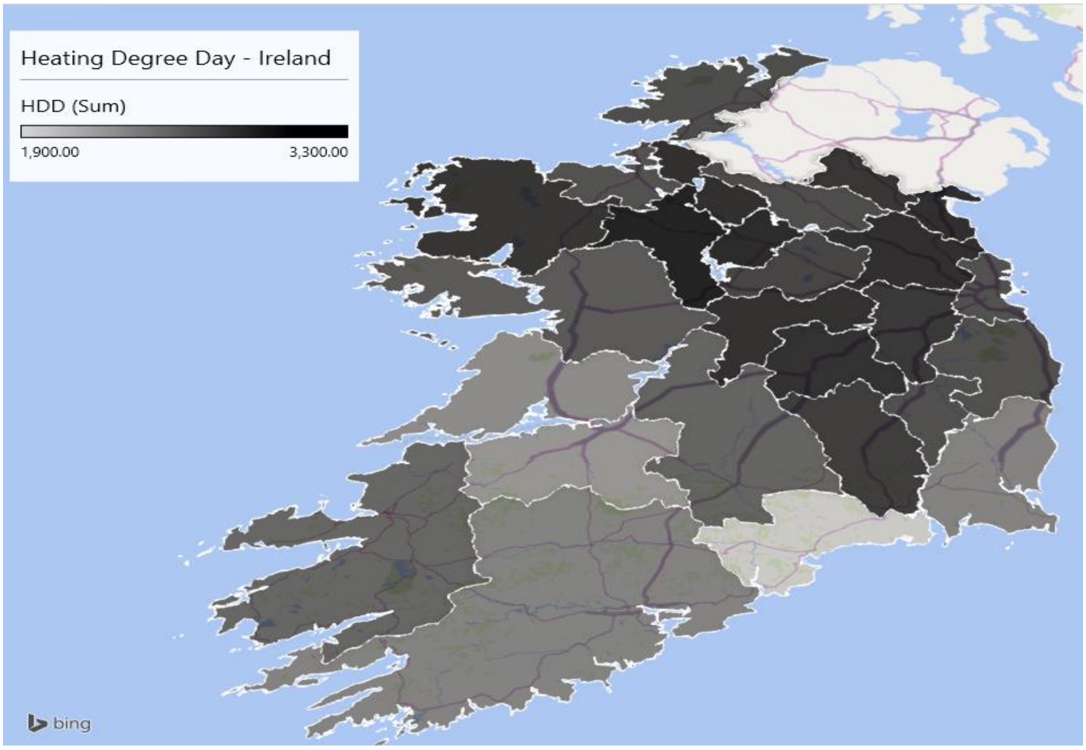


Figure 1: HDD of the different regions for Ireland made using Eq. 1

T_h is the threshold temperatures for heating. The positive sign above the parentheses indicates that only values greater than zero are considered since it represents the threshold after which energy is required for thermal comfort. The outdoor air temperature, T_o , is calculated using the average of the daily maximum and minimum values (Eq. 2).

$$T_o = \frac{T_{max} + T_{min}}{2} \qquad (2)$$

The HDD for all regions in Ireland calculated from Eq. 1 and 2 is plotted in

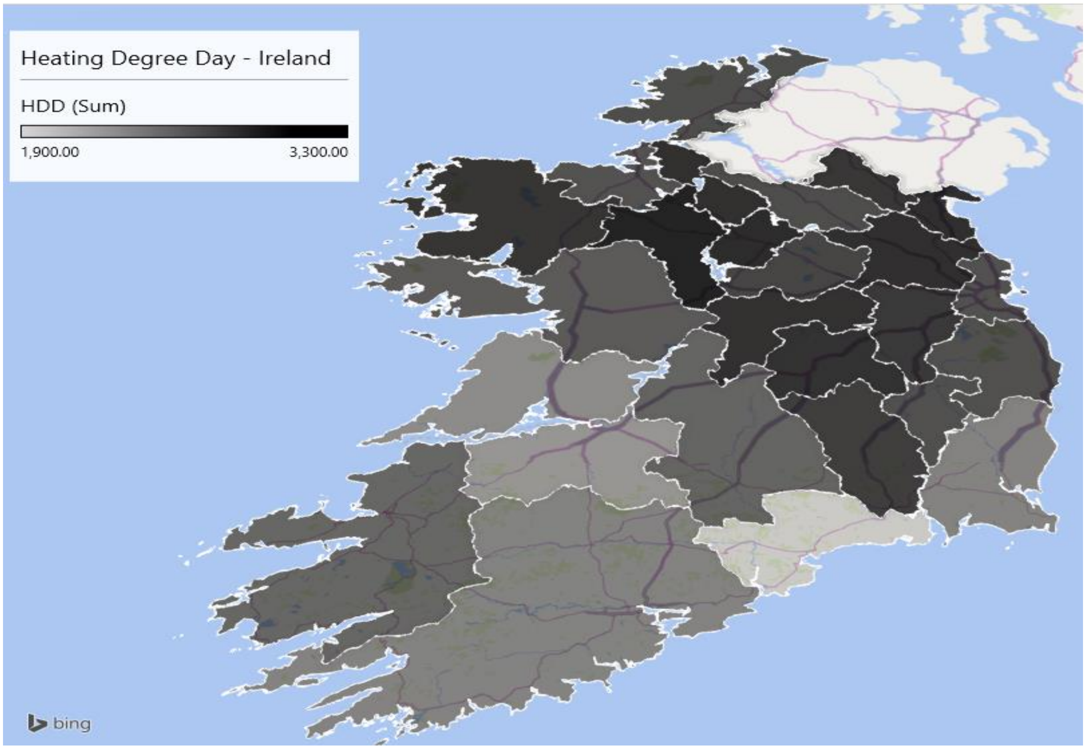


Figure 1. It shows that the variation of HDD across Ireland is relatively small, with a standard deviation of 357 about a mean of 2793.

2.2 Selection of the external wall structure and Fuel

The aim of this study is to investigate the optimum insulation thickness among the most commonly used Irish residential building wall types in order to inform decisions with regard to energy efficiency retrofits. Initially, the most common existing wall constructions were identified by combining publicly available Building Energy Rating (BER) [87] and Tabula [88, 89] databases in Figure 2. Similarly, the most used heat energy source in Ireland was determined from the same data sets. As Figure 2 shows, 300 mm cavity walls are the most common in Ireland, followed by a 300 mm filled cavity and partially filled cavity walls. The remaining wall construction type and material are dispersed across several lesser used scenarios such as stone and timber frame.

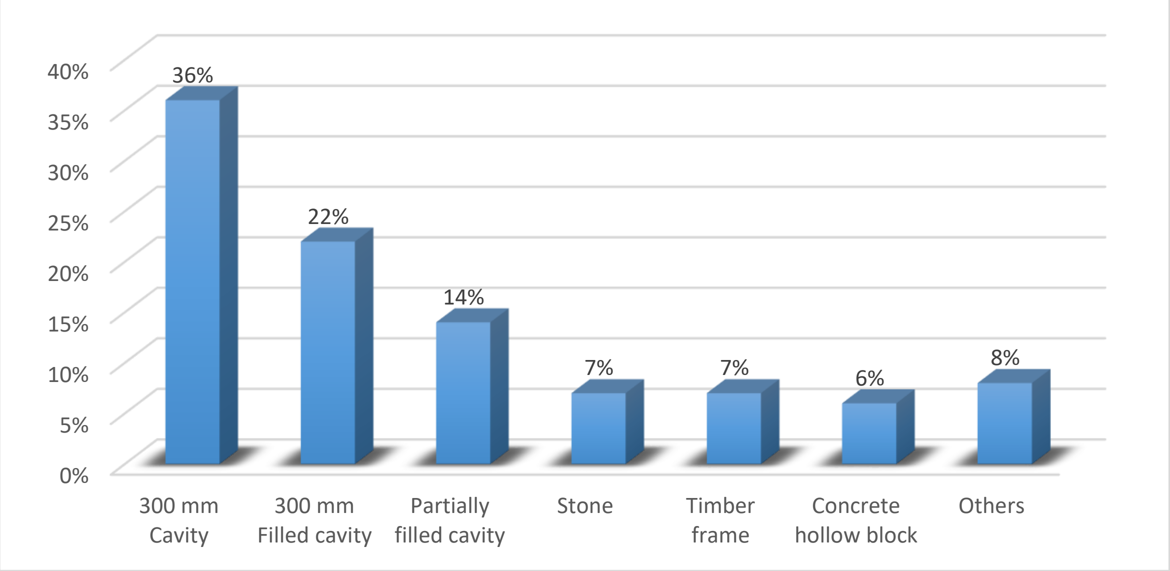


Figure 2: Classification of the wall types in Ireland

2.3 Wall configuration

The wall configurations for the most common wall types in Irish homes were decided in accordance with the NSAI Code of Practice for the Energy Efficient Retrofit of Dwellings (S.R.54) [8] and are listed in Table 1. In this study, only solid walls (W1, W2), hollow concrete block walls (W3), and cavity walls (W4) are considered, as they represent the majority of the residential building stock in Ireland. Typical layering for externally insulated walls consists of internal plaster, brick/concrete/cavity block, insulation, and external plaster.

Table 1: Structural configuration of walls considered in this study.

No.	Layer1 (Thickness)	Layer2 (Thickness)	Layer3 (Thickness)	Layer4 (Thickness)	Layer5 (Thickness)	$U_{(un)*}$ Value ($W/m^2 K$)

W1	Plaster (20 mm)	Brick (225 mm)	Insulation (varies)	Plaster (20 mm)		2.1
W2	Plaster (20 mm)	Concrete (225 mm)	Insulation (varies)	Plaster (20 mm)		3.8
W3	Plaster (20 mm)	Cavity block (225 mm)	Insulation (varies)	Plaster (20 mm)		2.9
W4	Plaster (20 mm)	Brick (100 mm)	Insulation (varies)	Brick (100 mm)	Plaster (2 mm)	2.5

* “un” means un-insulated wall

In this study, the optimum insulation thickness of external walls is calculated by using three types of energy sources for heating and three insulation types in buildings for each county of Ireland. Specification of fuel and insulation type used in this study is shown in Table 2 and Table 3 respectively. This study assumes that all old boiler systems will eventually be replaced to meet the minimum required efficiency of 90% as per Part L technical guidance document [90] and when electricity is used for heating the efficiency can be considered 100% [91].

Table 2: Thermal conductivities and cost of insulation [8]

Insulation materials (m)	Thermal conductivity (W/mK)	Cost (€/m^3)
Expanded Polystyrene (EPS)	0.031	78
Polyisocyanurate (Poly)	0.023	188.8
Rock wool (RW)	0.038	114.5

Table 3: Parameters of the fuels considered [89, 92]

Heating Fuel (hf)	Hv[1] (kWh/unit)	Efficiency[2] (η)	CO$_2$ emission factor[3] (kg/kWh)	Cost (€/kWh)
Electricity (E)	1(kWh)	1	0.4366	0.1992
Heating Oil (HO)	10.55 (litre)	0.9	0.2736	0.0788
Main gas (MG)	1(kWh)	0.9	0.2047	0.0922

1. Heating fuel value, or calorific value, is the amount of heat released during the complete combustion process
2. Efficiency is the amount of useful heat produced per unit of input energy (fuel)
3. CO$_2$ emission factor is an estimate of greenhouse gas emissions per unit of human activity (space heating)

2.4 Heat loss through the multi-layered wall

During the heating season, buildings experience heat loss from the warmer indoor to the colder outdoor environment. Heat loss occurring through a unit surface area of a multilayer wall, i.e. the heat flux, q_l, can be determined as,

$$q_l = U(T_i - T_o) \tag{3}$$

where U is the overall heat transfer coefficient or “U-value” (m^{2}K/W). For the uninsulated wall, the overall heat transfer coefficient is given by considering the series sum of the individual thermal resistances represented in the thermal network, depicted in Figure 3, such that U_{un}, (suffix un refers to uninsulated).

$$U_{un} = \left(\sum_{i=1}^{N} R_i\right)^{-1} = \left(\frac{1}{h_o} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \ \ldots\ldots \frac{x_n}{k_n} + \frac{1}{h_i}\right)^{-1} \tag{4}$$

Here, $k_{1,}k_2$ etc. are the thermal conductivities of the individual layers of wall, and $x_{1,}$ x_2 etc. are their respective thicknesses. At the exposed surfaces, h_o and h_i represent the outer and inner surface heat transfer coefficients. For the said wall, the net thermal resistance (R_{wall}), often referred to as the R-Value, is thus,

$$R_{wall} = \frac{1}{U_{un}} \tag{5}$$

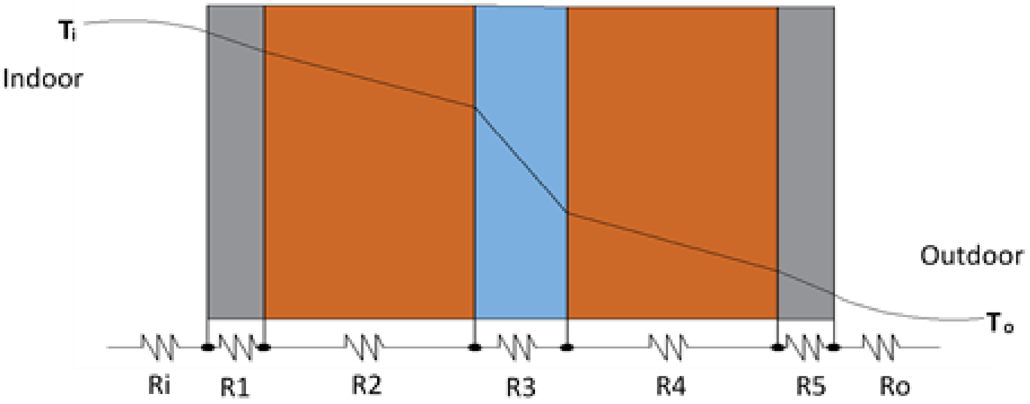


Figure 3: Thermal impedance network for a typical multi-layered wall

The purpose of retrofit insulation is to add additional thermal resistance to the wall structure, which for a given set of external thermal boundary conditions, reduces the magnitude of the heat transfer. Therefore, the overall thermal resistance of the wall with insulation can be expressed as,

$$R_{tot,ins} = R_{wall} + R_{ins} = R_{wall} + \frac{x_{ins}}{k_{ins}} \tag{6}$$

where x_{ins} is the insulation thickness and k_{ins} is the thermal conductivity of the insulation material. Thus, the overall heat transfer coefficient,$U_{tot,ins}$, for a wall with an added layer of insulation becomes,

$$U_{tot,ins} = \frac{1}{R_{wall} + R_{ins}} \tag{7}$$

The daily heat energy loss through the unit area of the wall can be expressed as the product of the heat flux and time. Here the time represents the number of seconds in one day i.e. the product of the number of seconds in one hour (3600 seconds) and the number of hours in one day (24 hours) which equals to 86400 seconds.

$$Q_l = 86400U(T_i - T_o) \tag{8}$$

Thus, theoretically, a calculation needs to be performed for every heating day of the 365-day calendar year. If the average outside temperature were to be represented by $T_{o,1}$ on day 1, $T_{o,2}$ on day 2, and so on up to $T_{o,365}$, the quantity of heat lost through the unit area of the wall for the whole year can be expressed as,

$$Q_{Ahl} = 86400U\left(T_i - T_{o,1}\right) + 86400\ U\left(T_i - T_{o,2}\right) + \cdots..+86400U\left(T_i - T_{o,365}\right) \tag{9}$$

or more succinctly as

$$Q_{Ahl} = 86400U \sum_{n=1}^{n=365} \left(T_i - T_{o,n}\right) \tag{10}$$

Combining this with Eq. 3, the annual heat lost from the multi-layered wall can be simplified to [85, 93]

$$Q_{Ahl} = 86400HDDU \tag{11}$$

Annual heat loss Q_{Ahl} can then be used, alongside the efficiency of the heating system, to determine the amount of energy supplied annually E_{Ah} by the heating unit as [85, 93],

$$E_{Ah} = \frac{Q_{Ahl}}{\eta} \tag{12}$$

2.5 Calculation of optimum insulation thickness and annual cost

Optimising insulation material, thickness, and position for given wall type and boundary conditions can lead to the reduction of energy used by the heating system. However, as the thickness of insulation increases, the cost of the insulation material increases, and a balance must be met between what is desired and what is economically practical. Considering this, cost analysis should be included in the calculation of suitable insulation thickness [42, 56].

In this study, the so-called ($P_1 - P_2$) method of Life Cycle cost analysis is used. This is widely used in energy technologies and related studies [94, 95] and it has previously been applied for evaluating the optimum insulation thickness [42, 46, 47, 56]. In this method, P_1 (Eq. 13) is the life cycle energy related to the market discount rate, which is calculated based on the present worth factor (PWF), which estimates the current worth of the sum of investments that is to be received at some future date. The determination of the present worth of one euro (for example) needed n periods (in years) in the future, with the market discount rate ‘d’ and inflation rate ‘i’ per period is given by Eq. 13 [96].

$$P_1 = (1 - \mathrm{C}\,i)\mathrm{PWF}(\mathrm{n}, i, \mathrm{d}) \tag{13}$$

The parameter ‘C’ in Eq. 13 refers to whether rental income is earned for the property. For owner occupied buildings C=0 and rented buildings C=1. This analysis considers buildings which are only owner occupied because in Ireland approximately 71% of the buildings are owner occupied [97]. Therefore, Eq. 13 becomes:

$$P_1 = PWF(d, i, n) = \sum_{j=1}^{n} \frac{(1+i)^{j-1}}{(1+d)^{j}} = \begin{cases} \dfrac{1}{d-1}\left[1 - \left(\dfrac{1+i}{1+d}\right)^{n}\right], & i \neq d \\ \dfrac{n}{1+i}, & i = d \end{cases} \tag{14}$$

In this analysis method, P_2 (Eq. 15) is the ratio of the life cycle expenditures incurred because of the additional capital investment to the initial investment, and can be defined as Eq. 15 [96]:

$$P_2 = \mathrm{D} + (1 - \mathrm{D})\frac{\mathrm{PWF}(0, \mathrm{d}, \mathrm{n_{min}})}{\mathrm{PWF}(0, \mathrm{m}, \mathrm{n_L})} + \mathrm{M_s}\ \mathrm{PWF}(0, \mathrm{d}, \mathrm{n_{min}}) - \frac{\mathrm{R_v}}{(1+\mathrm{d})^{\mathrm{n}}} \tag{15}$$

D is the ratio of down payment to the initial investment, M_s is the ratio of the first year miscellaneous costs to initial investment, R_v is the ratio of the resale value at the end of the analysis period to initial investment, n_L is the term of the loan and n_{min} is the year over which mortgage payments contribute to the analysis period [96, 98]. The parameters of P_2 are highly variable and differ depending on wall/house construction, ownership, year of purchase and resale, the economy etc. Furthermore, the availability of this data is very limited. For these reasons, additional capital investment is not considered for this study, as is common practice in the literature [43, 99]. Therefore, the value of P_2 is taken as unity here by assuming D is equal to one (no down payment is made during the purchase of the building), Ms equals to zero (by ignoring miscellaneous costs such as insurance and maintenance), and Rv equal to zero (means the building is considered to not be sold in the future). No previous Degree Day research was identified which includes values for D, Ms, and Rv resulting in a P_2 that is not equal to 1. A brief variational study was therefore conducted. By increasing the ratio of down payment value by 25% and miscellaneous cost by 1%, P_2 showed a positive variation of 2.3% and 9%. A negative variation of 5.6% was observed in P_2 when the resale value was increased by 10%. Any variation (positive/negative) experienced by P_2, is directly reflected in total cost, as P_2 is the linear function of the total cost. Therefore, the parameter values in Eq. 15 are highly sensitive in influencing the overall results in the analysis and require further research in order to enhance reliability when using this equation in HDD research.

Based on P_1 and P_2, the annual total cost expended on the energy consumed by the multilayered wall (C_t) can be calculated as:

$$C_t = P_1 C_F + P_2 C_{ins}.x_{ins} \tag{16}$$

where C_{ins} and x_{ins} are the cost of insulation per unit thickness and thickness of insulation respectively. C_F is the unit price of fuel (€/kg), which is calculated as the product of the cost of the fuel per unit (C_f) to the amount of fuel consumed annually (m_{Af});

$$C_F = C_f \; m_{Af} \tag{17}$$

$$m_{Af} = \frac{E_{Ah}}{H_v} \tag{18}$$

Therefore, the total cost depending on the heat loss of the building can be calculated as,

$$C_t = \frac{86400 \, PWF \; HDD \; C_F}{H_v \; \eta \, (R_{wall} + R_{ins})} + P_2.C_{ins}.x_{ins} \tag{19}$$

The net energy saving (S_{net}) obtained over the lifetime of the building (10 years) is the difference between the energy-saving cost for the insulated building and the insulation payout [5], such that,

$$S_{net} = S_{ins} - P_2.C_{ins}.x_{ins} \tag{20}$$

where S_{ins} is the energy savings due to the addition of insulation which can be calculated as the difference between the energy cost of the non-insulated and insulated building;

$$S_{ins} = \frac{86400 \, PWF \; HDD \; C_F}{H_v \; \eta} \left(\frac{1}{\mathrm{R_{wall}}} - \frac{1}{(R_{wall} + (R_{ins})} \right) \tag{21}$$

The payback period of the insulation cost, P_b is simply calculated by setting the net saving function to zero. For the case when $i \neq d$ the payback period can be estimated as,

$$\left[\frac{\frac{86400 HDD.C_F(T_i - T_o) - H_v.\eta.P_2.C_{ins}(k_{ins}R^2{}_{wall} + R_{wall}.x_{ins})(d-i)}{86400 HDD.C_F(T_i - T_o)}}{\ln[1+i] - \ln\,[1+d]} \right] \tag{22}$$

whereas for the case when $i = d$ this reduces to,

$$\frac{P_2.\,C_{ins}(k_{ins}R^2{}_{wall} + R_{wall}.\,x_{ins})(1+i)}{86400 HDD.\,C_F(T_i - T_o)} \tag{23}$$

The optimum insulation thickness of the multi-layered wall is then obtained by taking the first derivative of net saving, S_{net}, with respect to the insulation thickness, x, and setting the derivative function equal to zero. The optimum insulation thickness, x_{op}, is thus,

$$x_{op} = \sqrt{\frac{86400\ k_{ins} PWF\ HDD\ C_F (T_i - T_o)}{H_v\ \eta\ C_{ins} . P_2}} - k_{ins} R_{wall} \qquad (24)$$

An in-house computer code was developed to solve the relevant equations based on input parameters. The flow chart of the code is depicted in Figure 4. The input parameters wc, HDD, im and hf as obtained through literature search were defined in an input database file (excel file). The programme was coded in such a way that at every iteration it accesses the information from the input database file and runs the calculation. The number of iterations is dependent on the number of wall configurations (wc), HDD value, insulation materials (ins), and heating fuels (hf) used. The loop function (L1) is used to perform the series of iterations from the 1st combination of input parameters (j=1) to the nth input parameter (j=n) defined in the database. Once the code performs n iterations it saves all the data corresponding to insulation thickness (xi) and total cost (Ct). Each combination of the input parameter is solved for varying insulation thickness i.e. from i=0 to i=240mm at an interval of 20 mm. To perform the iteration for varying thicknesses another loop function L2 was used inside L1. For each combination of the input parameter and insulation thickness, yearly heat loss and the total cost were calculated using Eq. 11 and Eq. 19 respectively. Finally, the total cost (C_t) corresponding to all combinations of the input parameter and insulation thickness is saved into the output database file.

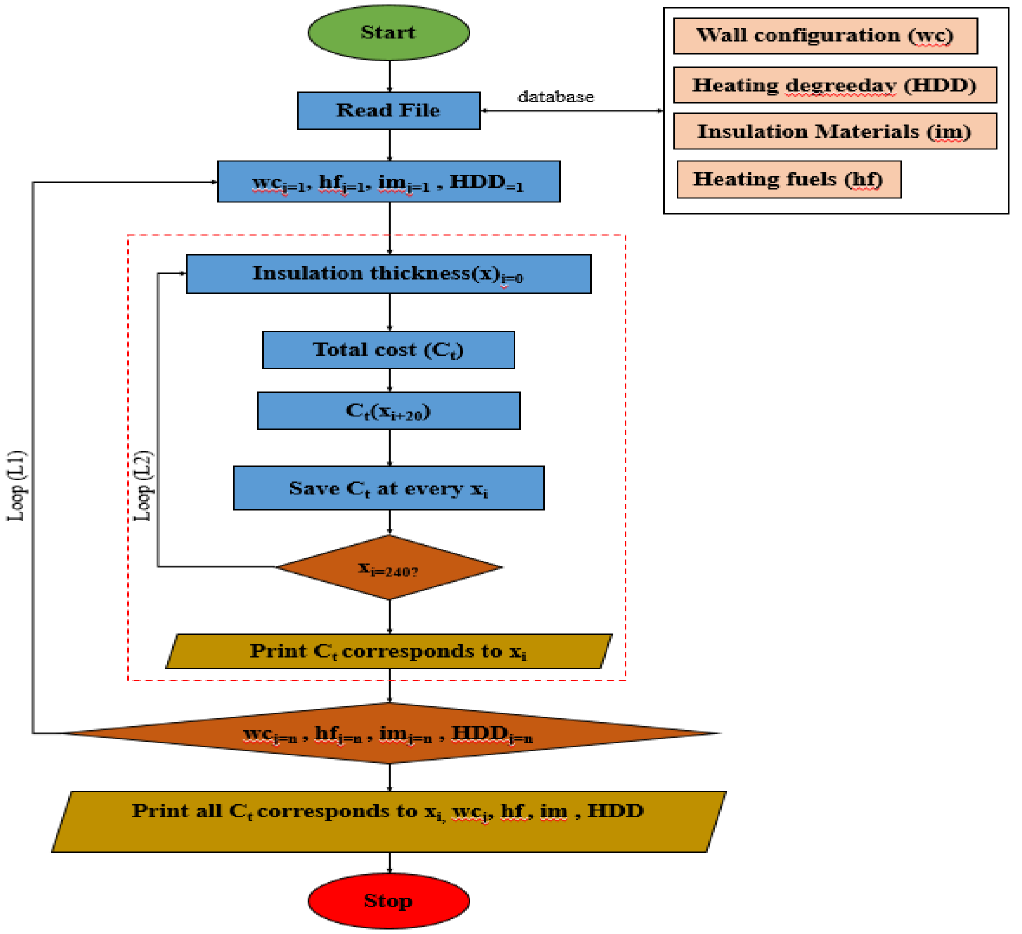


Figure 4: Flow chart of the computer code for optimisation of insulation thickness

2.6 Statistical Analysis

The results obtained for optimum insulation thickness and cost savings by solving Eq. 24 and Eq. 20 respectively are used to find the standard relationship between HDD and OIT. Further, the data was analysed to compare the performance of each combination of wall, fuel, and insulation. The regression model was used to find the standard relationship between HDD and OIT and Analysis of Variance (ANOVA) was used to compare the performance of the wall, fuel, and insulation combination

2.6.1 Linear regression model

A standard relationship is established between OIT and HDD under the considered thermal and cost parameters. The average OIT of all wall types with different combinations of heat source and insulation under different HDD regions across Ireland was considered. The data was analysed by using the regression model. The relationship between optimum insulation thickness and HDD shows a linear relationship [100]. This linear relationship with respect to different insulation materials and heating sources can be expressed in the form,

$$OIT = a + b\, t+e \qquad (25)$$

Where the independent variable t = $\sqrt{HDD}$, ‘a’ is the intercept and ‘b’ is the regression coefficient which measures the amount of change in OIT by a unit change in HDD. The intercept ‘a’ and the regression coefficient ‘b’ were estimated by the ordinary least square (OLS) method [101] by minimising the error sum of squares for each wall type under the assumption that error term ‘e’ follows a normal distribution with 0 mean and constant variance.

2.6.2 Analysis of Variance (ANOVA)

Analysis of Variance is carried out in order to compare the performance of each combination of wall type, fuel, and insulation (example of a combination being W1-E-EPS) based on their mean values of OIT and cost savings obtained for all HDD regions in Ireland. This is in order to determine what variable combinations are significantly different to the others. A statistical technique is used which compares the mean performance of the walls and depicts how differently these walls perform from one another. This technique, which compares the samples on the basis of their mean values is called Analysis Of Variance (ANOVA) [102].

In the analysis, each combination of wall configurations (example E-W1 in Appendix A

Table of Mendeley data attached to this article) is considered as a group. The ANOVA test was conducted between groups (Table 5-10 of Mendeley data) to compare the mean performance between them at a given level of significance. Typically in building energy research [103-105] this is assumed to be 5% (α=0.05). When the p-value is less than 5%, it indicates that the null hypothesis is rejected (the null hypothesis states that there is no statistically significant difference) and, therefore, there exists a significant difference between the groups.

A limitation of the ANOVA technique, as used here, is that it does not indicate which specific group differs significantly from which. In order to identify the difference between a specific group’s mean values, the least significant difference (LSD) test is conducted [101, 102]. This test can only be conducted when the results from ANOVA are significant. A non-significant difference can also exist if the difference between the specific group mean values is less than the LSD value calculated. Otherwise, it is considered significant [101].

3 Results and discussion

In this study, a thermal-economic analysis was conducted to determine the optimum insulation thickness of retrofit insulated walls in different regions in Ireland. For this purpose, the effect of HDD on optimum insulation thickness, heating demand, payback period, total cost savings, and quantity of carbon emission is presented first. This is followed by the impact of different insulation materials and heating sources used in Ireland. Finally, the influence of the most common wall construction types in Ireland is investigated. Thermal-economic parameters used in the calculations are given in Table 2. Regression analysis was carried out using Minitab (v19) to establish the standard relationship of optimum insulation thickness with HDD in Ireland. To do so, HDDs across 25 regions of Ireland were investigated for the most common wall construction types (Table 1) with different combinations of insulation materials (Table 2) and heat energy types (Table 3), all commonly used in Ireland. Although the results of the analysis such as optimum insulation thickness, payback period, cost savings, and carbon emission for all 25 regions in Ireland were calculated, for conciseness the results of four selected counties, which are representative of the range across the country, are discussed. The cost analysis in this study is based only on insulation material costs. The cost of labour, plaster, finishes, and other miscellaneous costs associated with installation and transportation are neglected.

3.1 Impact of different degree day regions in Ireland

The first illustrative example considers a solid wall construction type (W1), insulated with EPS insulation where natural gas is used as the heat energy source. The comparison of the four selected counties Waterford, Roscommon, Clare, and Donegal is considered as representative of a range of climate conditions in Ireland.

Figure 5 (a-d) shows the effect of insulation thickness on the total cost for different HDD regions considered. It is observed that once the incremental addition of insulation begins, the heating fuel cost starts to fall while insulation cost increases linearly. On the other hand, the total cost decreases and then begins to increase at a minimum point. This minimum point occurs at the optimum insulation thickness (OIT). Adding more insulation beyond this minimum point gives diminishing returns on the energy saved while insulation cost continues to increase linearly. For example, (a) shows the relationship between costs of the heat energy, insulation cost, and total cost for Waterford (HDD=1983). It is observed that the cost of heating decreases by diminishing increments with an increase in insulation thickness. The total fuel cost and the insulation cost intersects at a minimum point (optimum insulation thickness) of x_i=0.08 m when plotted versus insulation thickness. Similarly, Figure 5 (b-d) shows optimum insulation thickness values of 0.1 m, 0.12 m and 0.15 m obtained for Clare (HDD=2257) (b), Donegal (HDD=2844) (c) and Roscommon (HDD=3215) (d). A similar trend of results was observed for the walls investigated in the climatic region of Turkey [106], where it was found that the OIT for Erzurum (HDD=5293) was maximum (0.1 m) compared to the milder climate of Izmir (HDD=1781) with thickness 0.05. This illustrates that the optimal insulation thickness is sensitive to the local climatic conditions, with an expected trend towards thicker optimal insulation for colder climates. Dublin being the highest populated county represents the greatest number of houses compared to other counties [97], HDD for Dublin varies approximately 9.4% across Ireland. However, Waterford was chosen for comparison as it experiences the lowest HDD in Ireland. Waterford is in the southeast region in Ireland where HDD varies by approximately 20%. Roscommon was chosen as it experiences the highest HDD in Ireland, here Roscommon is considered as the representative county for west, Midwest, and midlands region in Ireland where HDD varies by approximately 5%. Clare and Donegal were chosen as they experience the lowest and highest HDD after Roscommon and Waterford, respectively. Clare being representative of the southwest and mid-west region of Ireland where HDD varies by approximately 8%. Donegal represents the northwest and northeast regions where HDD varies by 5%.

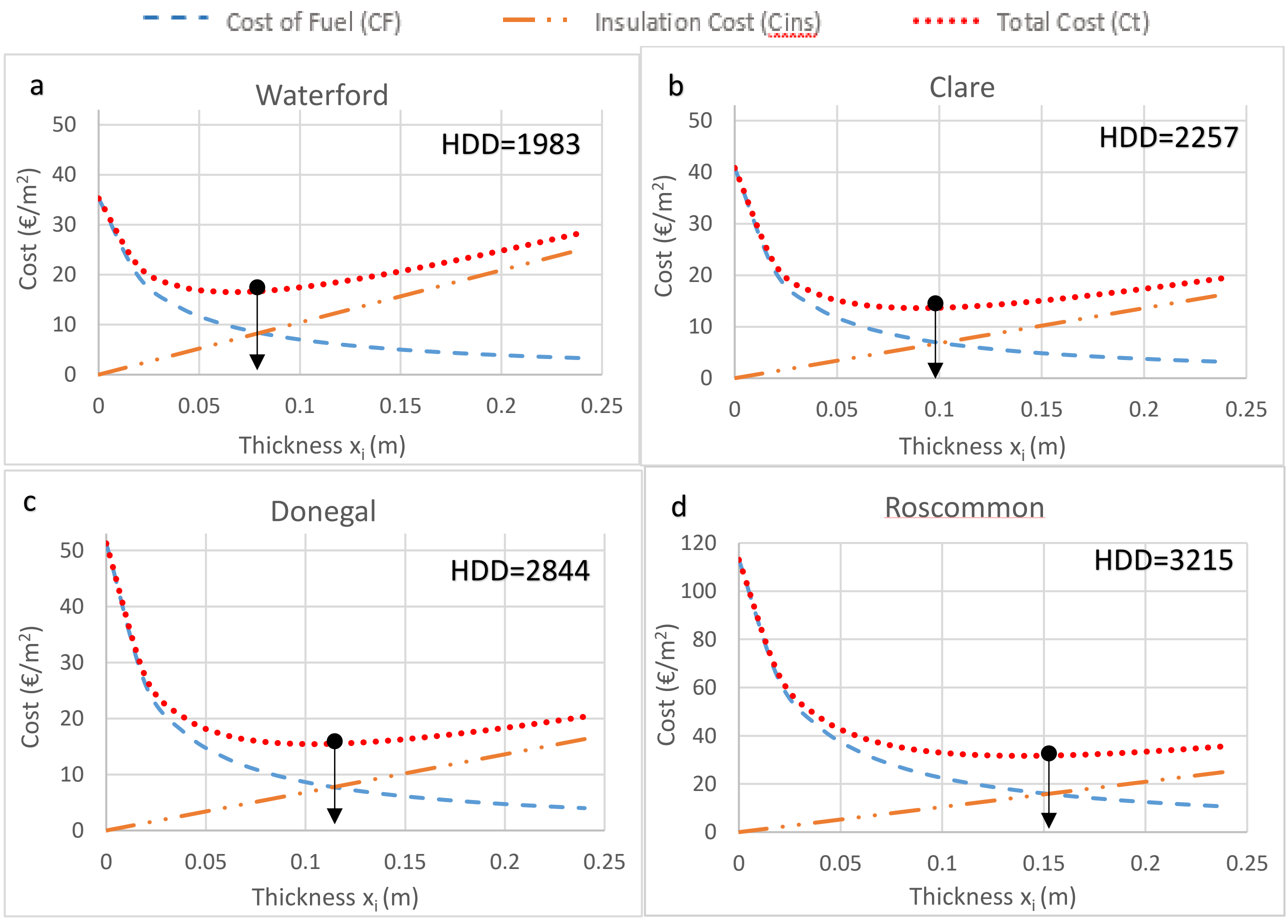


Figure 5(a-d): Variation of cost with insulation thickness for different HDD regions for electrical heating

Figure 6 shows that compared with Waterford, the colder regions (Clare, Donegal, Roscommon) have an increased optimum insulation thickness of 8.4%, 20.0%, 25.6% with electricity as the energy source and using the same insulation material for all. For heating oil as the energy source, this becomes an increase of 11.4%, 23.9%, 29.9% compared to Waterford or 9.2%, 21.5%, and 27.5% for gas. Thus, in terms of fixed insulation material, there is notable sensitivity of the optimal insulation thickness to both energy source and climate.

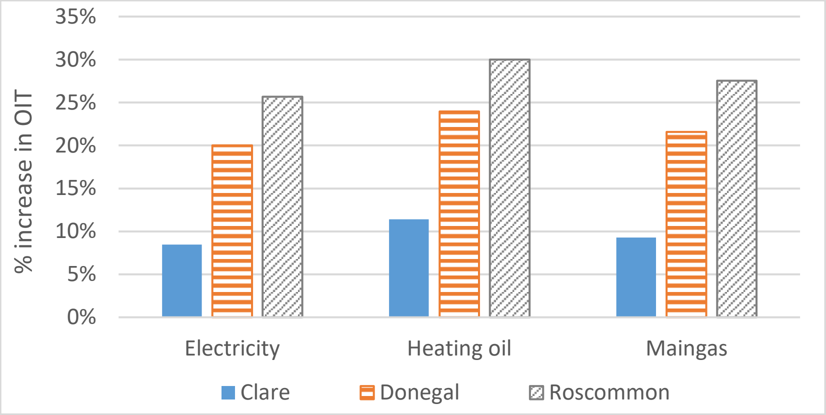


Figure 6: Comparison of increase of average OIT in Clare, Donegal, and Roscommon with Waterford

Total heating cost savings per unit area of the wall located in these selected counties are depicted in Figure 7. The total heating cost savings is the difference in the total heating cost of the wall between uninsulated and insulated conditions. Total heating cost is calculated by adding the cost of the insulation and the present value of the energy spent to supply heat over the life span of the building. The total cost savings increases up to a maximum value at which the optimum insulation thickness is determined. Increasing the thickness beyond the optimum value decreases the total cost savings. Figure 7 shows that cost savings increase with increased insulation thickness and tend to decrease after the OIT. Maximum savings of 41.5 €/m^2 at the optimum insulation thickness condition is observed in the Roscommon, where HDD is comparatively higher than the other regions considered. This is followed by Donegal, Clare, and Waterford with savings of 35.5 €/m^2, 27.2 €/m^{2,} and 18.5 €/m^2 respectively. This tendency of OIT with respect to HDD was also clearly illustrated in Bolatturk study [44], where results revealed that the wall at HDD= 5443 saw an increase in the annual savings in the range of 34% to 65% depending upon the heating source when compared to the wall at HDD=878. Thus, savings with OIT increases with an increase in HDD. Thus, both the OIT and level of annual savings increases with HDD.

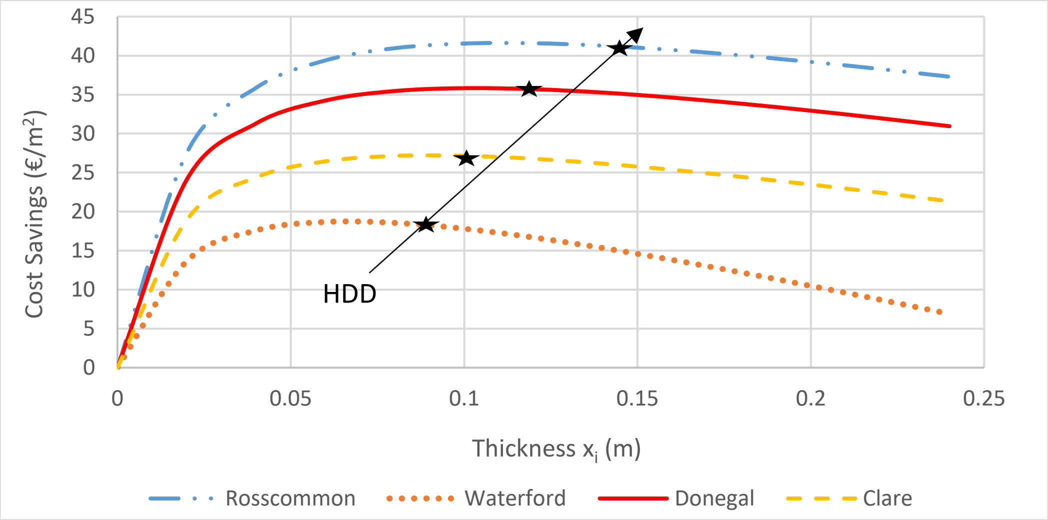


Figure 7: Variation of annual cost savings versus insulation thickness for different HDD regions

Figure 8 shows the variation of carbon emission versus insulation thickness for the different Irish HDD regions considered. Less efficient boilers and less insulated homes will have higher emissions of CO_2 [107]. As the figure shows, the CO_2 emissions decrease asymptotically with increased insulation thickness, which agrees with previous studies [71, 108, 109]. It follows that thicker insulation reduces annual heating demand and consequently the CO_2 emissions, though beyond approximately 0.1 m, CO_2 emission reductions are marginal in all cases. It is observed that CO_2 emissions increase with an increase in HDD as expected. At the optimum value of insulation thickness, minimum CO_2 emissions of 15.0.04 kg/m^2 are achieved by the wall located in Waterford which has comparatively low HDD=1983. For Clare (HDD=2257) this value is 17.4 kg/m^2, Donegal (HDD=2844) is 19.2 kg/m^2 and Roscommon (HDD=3215) is 22.3 kg/m^2. Thus, the geographical location of the wall across different HDD regions in Ireland has a significant effect (up to~20%) on the CO_2 emissions of the building for the cases considered here. This observation was also made for walls investigated across the climatic regions of Turkey [110] and China [111].

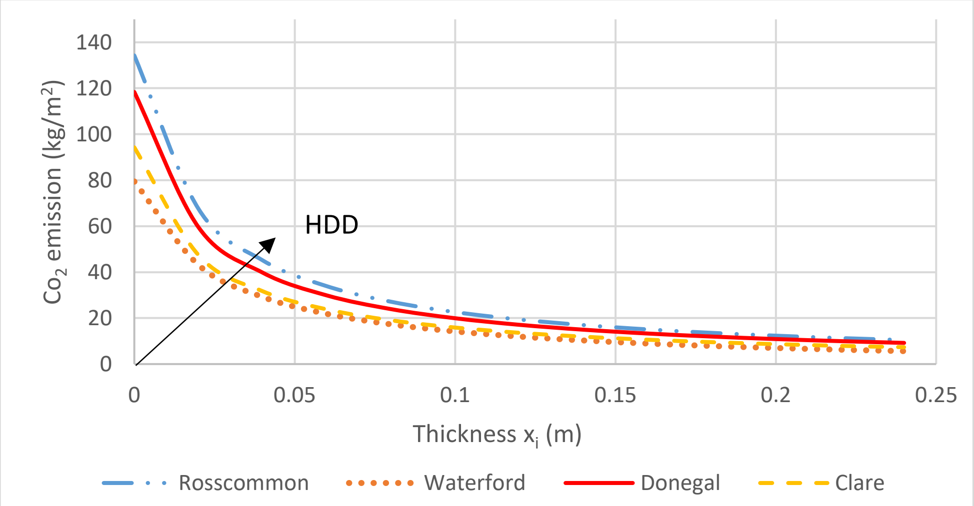


Figure 8: Variation of annual carbon emission versus insulation thickness for different HDD regions

Figure 9 presents the Variation of payback period with insulation thickness for the different regions in Ireland considered in this work in order to illustrate the sensitivity to climate. The payback period depends on the amount of heat energy used by the heating system in the household. Since the amount of energy needed for heating can be reduced by adding insulation, the money invested in the addition of insulation can be recovered or 'paid back' using the money saved resulting from the reduction in heat energy usage. As discussed at the start of Section 4, for this present study the invested money only refers to the material cost of the insulation. The time taken to recover the additional cost through savings is typically referred to as the 'payback period'. If all costs incurred when retrofitting insulation were considered, the payback periods would be considerably longer, though the conclusions would remain the same. From Figure 9 it is observed that the payback period for insulation material increases linearly with an increase in insulation thickness and is notably longer for colder climates. The same trend was observed in the previous literature [44-47]. At optimum insulation thickness identified in Figure 9, the payback period for material costs ranges from 0.7 years to 1.5 years for Roscommon, Donegal, Clare, and Waterford. It is noted that the application of thicker insulation for the higher HDD region is more costly while the material payback period is shorter, as is represented by the higher slopes for higher HDD regions. Therefore, the use of optimal thickness of insulation in higher HDD region is more advantageous.

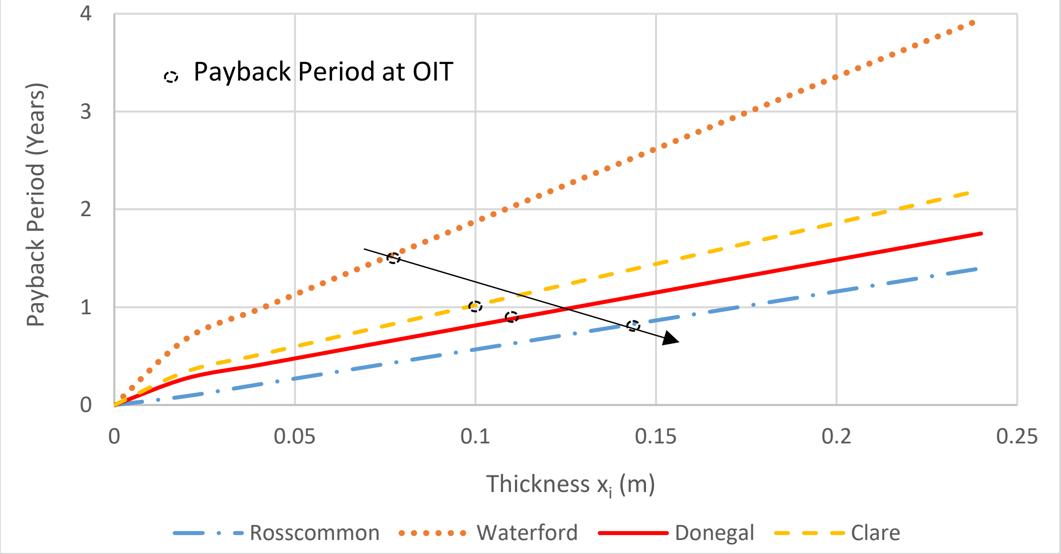


Figure 9: Variation of annual payback period versus insulation thickness for different HDD regions

3.2 Impact of insulation material and energy source on optimum insulation thickness

Currently, in Ireland, there are several insulation materials that can be used for external walls. These materials have different thermal characteristics that can result in different heat loss behaviour of the wall system and, therefore, impact building heat energy consumption differently. Similarly, changing the heating type impacts the overall heat energy and cost for the building. This section focuses on the impact of insulation materials (Table 2) and heat source (Table 3) on optimum insulation thickness for the wall (W1) located in the four selected provinces.

Figure 10 presents the variation of annual cost savings versus varying insulation thickness with respect to different types of insulation material using the selected baseline case, which is the wall (W1) located in Waterford with natural gas as heating fuel. It shows that annual cost saving increases non-linearly with an increase in insulation thickness up to optimum insulation thickness level for each material, though the trends are notably different. EPS has the largest cost savings of approximately 22.7 €/m^2 for an optimum thickness of 0.08 m followed by Rockwool (maximum savings of 19.2 €/m^2 for the optimum thickness of 0.06 m). Polyisocyanurate has the least savings of 18 €/m^2 for an optimum thickness of 0.039 m. It should be noted, however, that Polyisocyanurate achieves savings of only 20% less than EPS, though is half as thick. This is due to it being a higher cost product and it is notable here that the savings potential and OIT is sensitive to the per m^3 cost of the insulation material. The identification that lower cost insulation results in the greatest savings potential by OIT analysis was also found by Vincelas et al. [56].

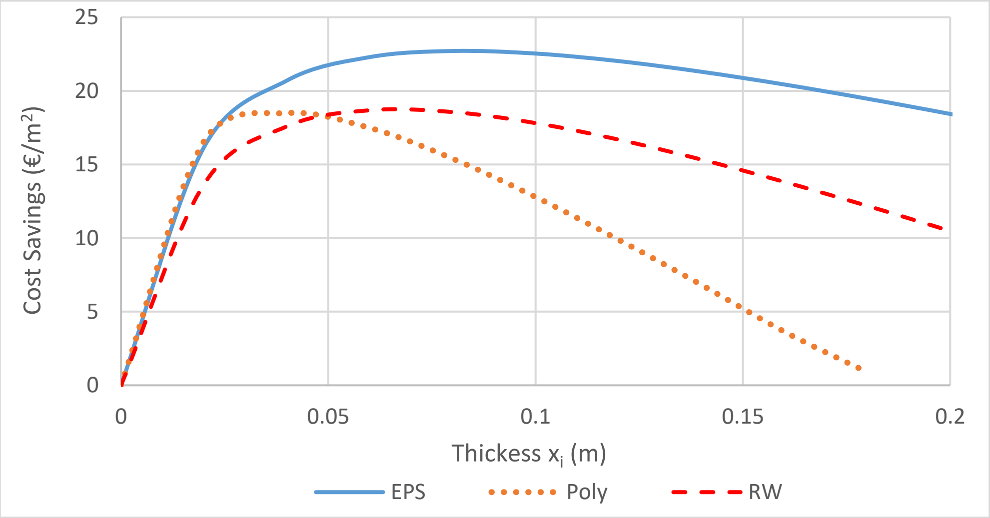


Figure 10: Variation of annual cost savings versus insulation thickness for different insulation materials

In addition to the insulation cost, maximum saving is also sensitive to the heating energy cost which is clearly illustrated in Figure 11. Here it is observed that maximum savings and higher OIT are shown when more costly heating energy sources are used, in this case, electricity. This was also concluded by Vincelas et al. [56]. Electricity as the heat energy source resulted in potential savings of approximately 44 €/m^2 for an optimum thickness of 0.1 m followed by mains gas with savings of about 18 €/m^2 for the optimum thickness of 0.067 m. The lowest savings potential of 14 €/m^2 for optimum insulation thickness of 0.05 m was observed for the heating oil scenario.

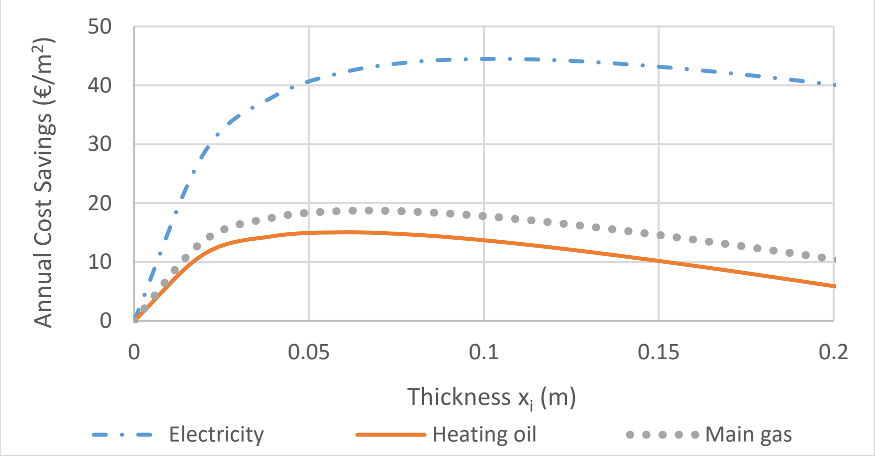
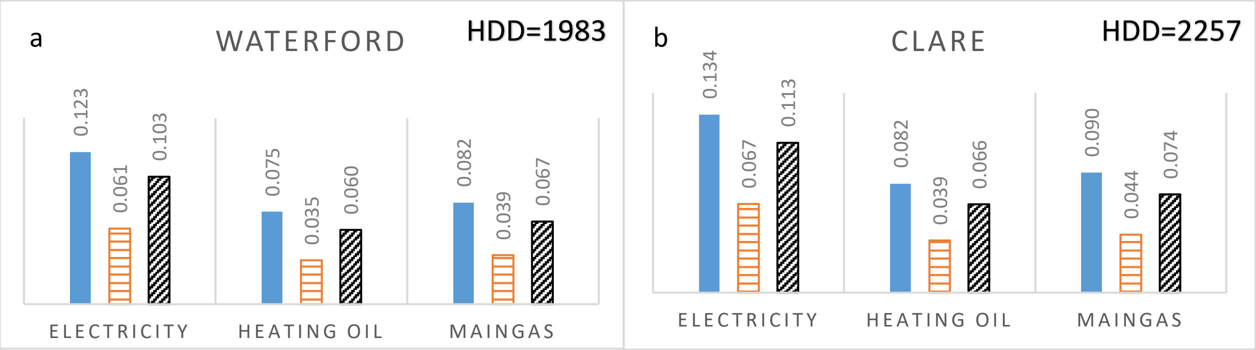


Figure 11: Variation of annual cost savings versus insulation thickness for different fuel sources for Waterford

Figure 12 (a-d) shows the optimum insulation thickness values with respect to insulation type and heating source for Waterford, Clare, Donegal, and Roscommon. Optimum insulation thickness is 50% greater for EPS than polyisocyanurate insulation. EPS is only 16% thicker OIT than Rockwool insulation with a payback period increasing approximately from 0.5 years to 1.2 years. These results agreed closely with all other counties considered. Using EPS as the insulation type, compared to electricity as the heat energy source, heating oil produces 40% lower OIT and main gas produces 46% lower OIT. Similar results were found using polyisocyanurate or Rockwool as the insulation type. This indicates that the heating source has a very significant impact on OIT, a finding which is consistent across all 25 counties in the Republic of Ireland (data not shown).



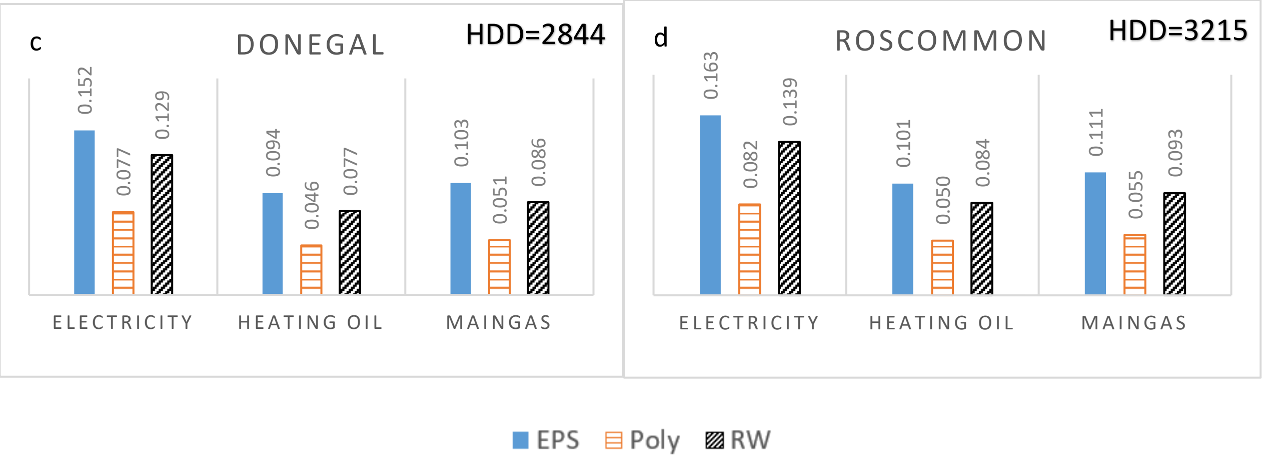


Figure 12(a-d): Optimum thickness of insulation to be used by different fuels (units in meters)

3.3 Impact of wall type on annual cost, payback period, and carbon emission

To illustrate variations resulting from wall type (Table 1), Rockwool insulation was chosen as it is commonly used in retrofitting. Mains gas was chosen as it is the most commonly used fuel source and the Dublin region was chosen as it represents the highest concentration of the Irish building stock. The total heating cost per square meter of the wall versus the insulation thickness of the external wall is depicted in Figure 13. The total heating cost is calculated by adding the cost of insulation material and the present value of the energy spent over the life span of the building.

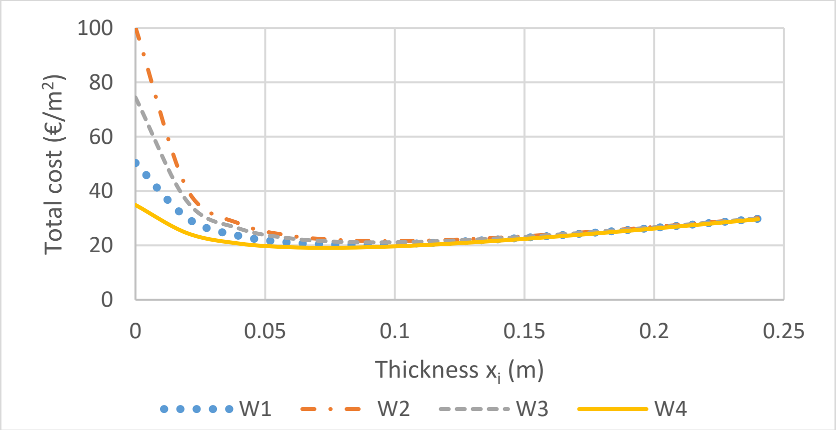


Figure 13: Variation of total cost versus insulation thickness for different wall types

From Figure 13 it is observed that heating cost decreases asymptotically with the increase in insulation thickness and thermal impedance for all wall types. For the no insulation scenario, the walls with lower thermal impedance showed the highest annual heating cost, for example, 90 €/m^2 for wall W2 (compared to 35 €/m^2 for W4). These low impedance walls also show a steeper initial descent as insulation thicknesses are increased. This is because the rate of increase in thermal impedance as insulation is thickened is very high initially for these walls, and therefore the reduction in total cost is more rapid. The graph indicates that after the optimum insulation thickness is achieved the total cost tends to increase marginally and is independent of wall type. This means that after OIT, wall type has no influence on annual heating cost. This is due to the fact that as the insulation layer becomes thicker, the contribution of the other layers (such as brick) to the overall thermal impedance of the wall becomes minimal which agrees closely with the literature [42, 56].

Similarly, Figure 14 shows that the CO_2 emission of the building has the same trend, at least initially, as that of the total cost in Figure 13. CO_2 emissions decrease considerably with an increase in insulation thickness up to the optimum point after which it continues to decline insignificantly. For the no insulation scenario, values of 116.36kg/m^2 (W1), 231.55kg/m^2 (W2), 171.92 kg/m^2 (W3) and 80 kg/m^2 (W4) were obtained. The type of wall has a significant effect on the CO_2 emission of buildings, of up to 65% reduction in the examined cases.

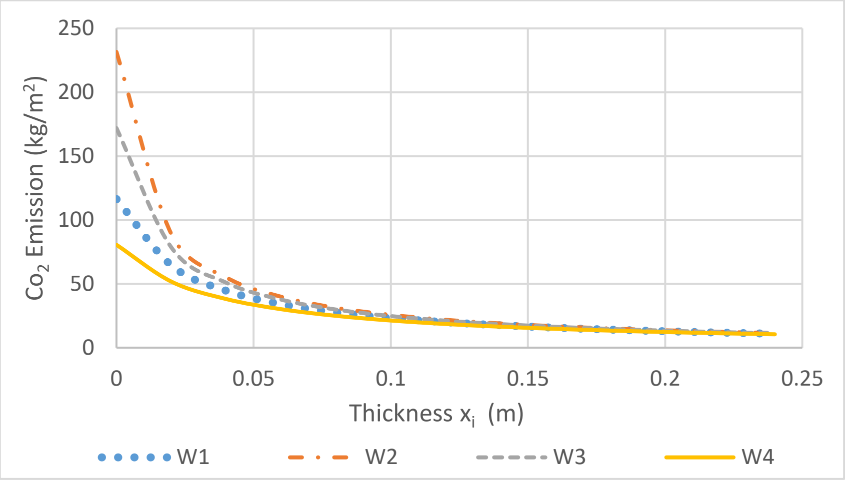


Figure 14: Variation of annual carbon emission versus insulation thickness for different wall

The variation of heating demand and payback period for different wall configurations at OIT, using the Dublin region as an example, is shown in Figure 15. It follows that the lower the thermal impedance of the wall, the higher the heating demand and the lower the payback period. From Figure 15 it is observed that amongst wall W1 to W4, wall W2 which has a lower thermal impedance, experiences maximum heating demand, and the minimum payback period. The minimum heating demand and the maximum payback period are obtained for wall W4 which has the highest thermal impedance of the walls studied (approximately 20% higher than W2). This agrees with data from all regions in Ireland (data not shown) with the average percentage of variation of 11% for heating demand and 7% for the payback period.

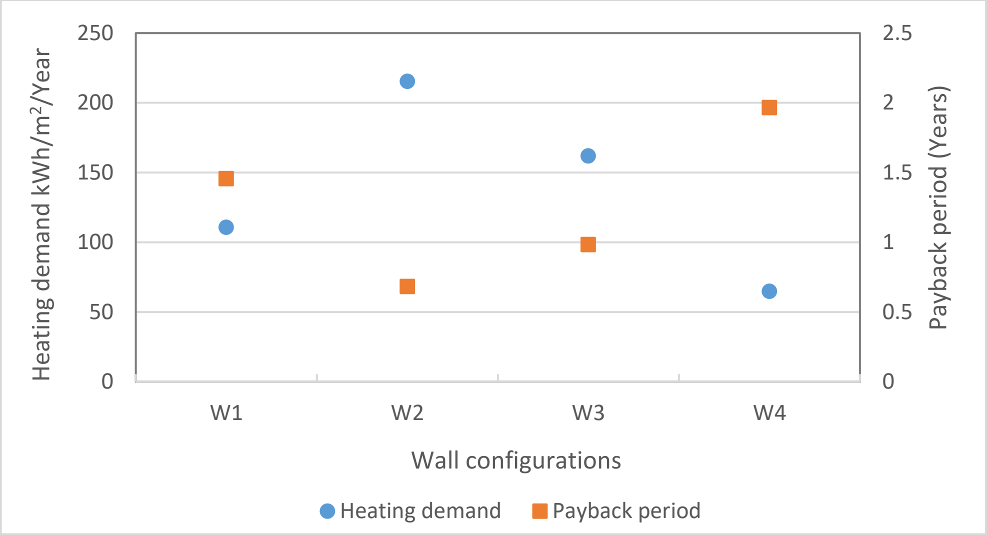


Figure 15: Variation of payback period versus insulation thickness for different wall types

3.4 Standard relationship between OIT and HDD

The results from the regression analysis carried out using Eq. 25 are tabulated in Table 4. The results indicate that P-value for all the considered cases equals zero which is less than five percent i.e. 0.05 indicating that each combination of the wall is significant at a 5 % level of significance. This means that there is a positive impact of HDD on OIT. For example, in the case of E-EPS, by a unit change in 't' (refer to section 2.6.1), there is a positive increase of 0.002984 units in OIT and it was found to be significant at 5 % level of significance.

Table 4 Standard relationship OIT based on HDD

WALL	**a**	**b**	**P-Value**
E-EPS	-0.0073	0.002984	0
E-POLY	-0.01473	0.001724	0
E-RW	-0.02435	0.002898	0
HO-EPS	-0.01981	0.002152	0
HO-POLY	-0.01458	0.001143	0
HO-RW	-0.0235	0.001949	0
MG-EPS	-0.04313	0.002757	0
MG-POLY	-0.01469	0.001236	0
MG-RW	-0.02413	0.002079	0

3.5 Analysis of Variance (ANOVA)

This section discusses the results of the ANOVA, carried out for the different combinations of wall, fuel, and Insulation materials, and the results are tabulated in table A1 to A6 in the appendix A section.

The results in Table A1 to Table A6, indicate that there exists a significant difference between the average performance of walls with different combinations of insulation materials and fuels, under both OIT and cost savings. Since the P-value was found to be less than a 5% level of significance. An example from Table A1 is used here to illustrate the methodology as follows. The average values of the insulation (EPS, POLY, and RW) under E-W1 were found to be significant since P-value is less than 0.05. It means that the average performance of the insulation with respect to OIT is significantly different when applied to wall W1 operated under electricity (E). Then, in order to determine which insulation performed most differently from which, a pair-wise comparison between the group means was conducted based on the LSD value calculated (for detailed calculations refer to [101, 102]). The difference between the average performance with respect to OIT of EPS and POLY was found to be 0.0737. Since this difference is greater than the LSD value (0.0053), it is concluded that there is a significant difference in the average performance between EPS and POLY. Similarly, this comparison holds true for all other possible combinations (EPS v/s RW, RW v/s POLY). Among the three insulation types, POLY performed well since it has the lowest mean value of OIT and cost savings. Among all other combinations considered the combination POLY-HO-W4 performed well with the lowest mean OIT of 0.038 m and mean cost savings of 12.106 €/m^2. Similarly, this above discussion holds true for all other groups in Table A1 to Table A6 with all differences between variables indicated being deemed significant.

4 Conclusions

The Irish housing stock is recognised as the least energy efficient in all of northern Europe. The average Irish home uses 7% more energy than the average EU home and CO_2 emissions from the sector are 58% higher [81, 112]. This study proposed the OIT of exterior building walls for 25 counties of Ireland using the most recent data via Degree Day and Life Cycle Cost Analysis methods. This study omitted the effects of any openings such as windows or vents as well as the influence of external gains (e.g. solar gains). The calculation considered three different types of insulation material, three heating sources, and four different types of wall configuration which are all common to Ireland. The impact of OIT on annual energy cost saving and CO_2 saving for the unit area of the walls were also implemented and the corresponding payback period was calculated. ANOVA was conducted to analyse the statistical significance between group means when changing the combination of wall, insulation, and heat source. The key findings obtained through this analysis are as follows:

- Optimum insulation thickness increases with HDD. The average percentage increase in OIT from lower heating degree day regions in Ireland to higher heating degree day region was in the range of from 26-30%, depending on heating fuel used.
- The impact of optimisation of insulation, in terms of both CO_2 savings and total cost, increases as HDD increases.
- Type of insulation material and heating source type has a significant impact on OIT. The average OIT across the HDD region of Ireland varies from 0.038 m to 0.160 m depending on the combination of insulation material, heat source, and wall type. The average minimum OIT (0.038 m) is achieved by cavity wall when POLY was used as an insulation material with heating oil as a heating source. The maximum OIT (0.160 m) was observed for the combination of concrete wall with EPS as the insulation material and electricity as a heat energy source.
- Optimum insulation thickness and cost savings increase as the cost of heating energy increases.
- Type of wall configuration also showed a significant influence on heating demand, annual cost, and CO_2 savings. The annual heating demand increases when the thermal impedance of the wall increases. The average savings achieved by walls at OIT in terms of both cost and CO_2 emission can be ranked (from highest to lowest) as concrete wall, cavity block wall, brick wall, and cavity filled wall.
- Analysis of variance indicated that each combination of wall, heating source, and insulation material showed a significant difference at $\alpha = 5\%$ level of significance.

The findings from this study indicate that, although thermal insulation is effective in oceanic temperate climatic regions, it is more effective in higher HDD regions. It is found that by retrofitting the external wall with OIT for all 28 regions in Ireland, an average cost saving of 75 - 180 €/m^2 can be achieved and reduction in the carbon emission in the range of 27 - 28 kg/m^3. Among the considered wall configurations in this study, cavity filled walls and cavity block walls together are the second most prolific in Ireland after unfilled cavity walls, therefore homes with these wall configurations should be targeted in national retrofit plans.

The methodology presented in this paper can be adapted for countries where air conditioning is rarely used, such as the UK, by inputting local climate, material, and wall data. It should be noted that for the results presented here, retrofitting costs only include insulation material and omit labour, transportation, and materials such as plaster finishes. Although the inclusion of these costs would give a truer reflection of the total payback period, they are relatively independent of insulation thickness and relatively constant between the combinations examined, particularly when comparing the same wall types. Although the inclusion of these costs would likely have little impact on the determined OIT, it would, however, provide a value for the total payback period and a truer reflection of costs. It is therefore suggested that future work building on the present research seek to include such costs. The results obtained in this study are solely for external wall insulation retrofit and the results may vary when the whole building is assessed as a system. In this study, the annual heat loss through the residential building walls is calculated using the HDD method. This is based on an outdoor and indoor threshold temperature. The applicability of the findings would be greatly improved in future HDD studies by using indoor set-point temperature data, if available, as this would allow for the variation between buildings. Another drawback of the method presented here is that the influence of thermal mass is neglected. It is evident that thermal mass plays a key role in the reduction of the total heat loss in the buildings and in regulating the thermal comfort in the buildings. However, the influence of thermal mass presents itself under dynamic boundary conditions [113]. Research is ongoing to develop an understanding and impact of thermal mass, intermittent heating conditions, external and internal gains, other insulation material, wall configuration, and heating sources on the optimisation of insulation under the Irish context.

Acknowledgements

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Appendix A

Table A1 Test of significance between insulations materials with respect to heating sources and walls under OIT

Groups	Mean Values of heating sources and wall configurations											
Insulation	E-W1	E-W2	E-W3	E-W4	HO-W1	HO-W2	HO-W3	HO-W4	MG-W1	MG-W2	MG-W3	MG-W4
EPS	0.1491	0.1593	0.1557	0.1400	0.0927	0.1027	0.0992	0.0837	0.1013	0.1114	0.1079	0.0922
POLY	0.0754	0.0829	0.0803	0.0688	0.0449	0.0524	0.0498	0.0383	0.0498	0.0573	0.0547	0.0432
RW	0.1273	0.1396	0.1353	0.1162	0.0780	0.0903	0.0860	0.0670	0.0843	0.0966	0.0923	0.0732
P VALUE	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
LCD	0.0053	0.0053	0.0053	0.0053	0.0046	0.0046	0.0046	0.0046	0.0042	0.0041	0.0042	0.0043

Table A2 Test of Significance between wall configurations with respect to heating source and insulation under OIT

Groups	Mean Values of heating sources and insulations								
Walls	E-EPS	E-POLY	E-RW	HO-EPS	HO-POLY	HO-RW	MG-EPS	MG-POLY	MG-RW
W1	0.1491	0.0754	0.1273	0.0927	0.0449	0.0780	0.1013	0.0498	0.0843
W2	0.1576	0.081686	0.13762	0.10107	0.051179	0.08732	0.10974	0.056081	0.09455
W3	0.1557	0.0803	0.1353	0.0992	0.0498	0.0860	0.1078	0.0547	0.0922
W4	0.1400	0.0688	0.1162	0.0837	0.0383	0.0670	0.0922	0.0432	0.0732
P VALUE	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
LSD value	0.0063	0.003372	0.005681	0.0042	0.0022	0.0063	0.0056	0.0024	0.0041

Table A3 Test of significance between heating sources with respect to walls and insulation materials under OIT

Groups	Mean values of wall configurations and insulation materials											
Heat sources	W1-EPS	W2-EPS	W3-EPS	W4-EPS	W1-POLY	W2-POLY	W3-POLY	W4-POLY	W1-RW	W2-RW	W3-RW	W4-RW
EPS	0.1491	0.1593	0.1557	0.1400	0.0754	0.0829	0.0803	0.0688	0.1273	0.1396	0.1353	0.1162
HO	0.0927	0.1027	0.0992	0.0837	0.0449	0.0524	0.0498	0.0383	0.0780	0.0903	0.0860	0.0670
MG	0.1013	0.1114	0.0860	0.0922	0.0498	0.0573	0.0547	0.0432	0.0843	0.0966	0.0923	0.0732
P VALUE	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
LCD	0.0055	0.0054	0.0057	0.0055	0.0027	0.0027	0.0027	0.0027	0.0054	0.0054	0.0054	0.0054

Table A4 Test of Significance between wall configurations with respect to heating source and insulation under cost savings

Groups / Walls	Mean Values of heating sources and insulations								
	E-EPS	E-Poly	E-RW	HO-EPS	HO-Poly	HO-RW	MG-EPS	MG-Poly	MG-RW
W1	75.63	68.02	68.52	28.958	24.016	25.78	34.85	29.495	30.002
W2	121.27	113.79	114.35	49.02	43.56	46.41	58.38	52.73	53.18
W3	179.42	113.43	114	48.87	43.41	46.24	58.2	52.54	53
W4	46.18	39.65	40.23	16.339	12.106	13.03	20.019	15.335	15.709
P value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LSD	8.9818	7.3252	7.3399	3.6533	2.9255	6.1881	4.0045	3.5639	3.5631

Table A5 Test of significance between insulations materials with respect to heating sources and walls under cost savings

Groups / Insulations	Mean Values of heating sources and wall configurations											
	E-W1	E-W2	E-W3	E-W4	HO-W1	HO-W2	HO-W3	HO-W4	MG-W1	MG-W2	MG-W3	MG-W4
EPS	75.63	171.66	122.02	46.18	28.958	70.8	49.02	16.339	34.85	83.91	58.38	20.019
POLY	68.02	163.12	113.79	39.02	24.016	65.18	43.56	12.106	29.495	78.09	52.73	15.335
RW	69.52	164.99	114.35	40.38	25.78	69.04	46.41	13.03	30.002	79.51	53.18	16.709
P	0.023	0.037	0.016	0.01	0.021	0.0352	0.0156	0	0.001	0.0157	0.036	0
LSD	5.913876	12.92055	9.279726	3.854379	3.418276	7.735423	5.480715	2.097841	2.902389	6.526535	4.673521	1.807456

Table A6 Test of significance between heating sources with respect to walls and insulation materials under cost savings

Groups / Heat sources	Mean values of wall configurations and insulation materials											
	W1-EPS	W2-EPS	W3-EPS	W4-EPS	W1-POLY	W2-POLY	W3-POLY	W4-POLY	W1-RW	W2-RW	W3-RW	W4-RW
E	75.63	171.66	122.02	46.18	68.02	164	113.79	39.02	68.52	163.99	114.35	39.38
HO	28.958	70.8	49.02	16.339	24.016	65.18	43.56	12.106	25.78	69.04	46.41	13.03
MG	28.958	83.91	58.38	20.019	29.495	78.09	52.73	15.335	30.002	78.51	53.18	15.709
P	0	0	0	0	0	0	0	0	0	0	0	0
LSD	4.05488	9.038129	6.587466	2.715856	3.931742	8.904528	6.281792	2.441125	4.671219	10.38023	7.425271	3.030847

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