Chapter 7
A Dynamic-Based Methodology for Optimising Insulation Retrofit to Reduce Total Carbon

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Abstract Optimisation is frequently mentioned in frameworks and assessments of design for a circular economy. Adopting circular economy principles in building retrofit can reduce the use of materials and minimise emissions embedded in building materials alongside reduced operational emissions. This paper presents the optimisation of retrofitted insulation thickness, using Ireland as a case study. Detailed and robust dynamic finite element models were developed based on in-situ boundary conditions and combined with economic and environmental considerations. It was determined that optimising insulation based on cost was considerably different to optimising based on carbon. Cost-optimised insulation can reduce overall cost which could expand the reach of retrofit, allowing for more existing homes to be used more efficiently. However, this approach can lead to significant increases in operational carbon and therefore a balanced decision must be made. The methodology presented can be adopted for different regions by inputting local data, which will facilitate the adoption of circular economy principals in European retrofit plans. The approach can benefit developing circular insulation materials of low embodied carbon by building a case for their use.

Keywords Optimisation · Retrofit · Material-efficiency · Circular insulation

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7.1 Introduction

7.1.1 Motivation

Energy used in buildings is primarily for space heating and cooling in order to provide and maintain thermal comfort [1–3]. 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 [4]. Optimising costs is one way of increasing the affordability of retrofit [5]. As detailed in the new EU Circular Economy Action Plan [6], the 'Renovation Wave' initiated by the European Green Deal [7] will be implemented in line with circular economy principles, notably optimised lifecycle performance, and longer life expectancy of build assets. In the Renovation Wave Strategy [8], the Commission aims to at least double renovation rates in the next 10 years and make sure renovations lead to higher energy and resource efficiency. Furthermore, the Green Deal identifies the twin challenge of addressing both energy efficiency and affordability [9].

The thermal performance of insulation material can be improved by simply increasing its thickness, since thermal resistance and thickness are proportional [10]. However, this results in the negative effect of increasing the material use and overall 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, requires minimum upfront cost and results in maximum long-term heat energy savings throughout its service life [11–13] referred to as *optimisation of insulation thickness* (OIT).

The standard approach to retrofitting insulation is based on U-Value, which is a steady-state thermal parameter that is the inverse of the total thermal resistance of the building element. This means that the lower the U-value, the better the insulator. It is estimated that around 67% of the buildings in Europe were built prior to 1980; prior to the introduction of building energy codes for housing sector in Europe [14]. In Ireland, 50% of buildings were built before the introduction of building wall thermal requirements into building regulations [15, 16]. The majority of walls built before 1980 are of a U-value above 1.3 W/m^{2}K [17]. In Ireland, government agencies offer grants for wall retrofit, aiming to achieve U-values of 0.55 W/m^{2}K for cavity walls and 0.35 W/m^{2}K for solid [18]. This, together with the assumption that typical heat loss through uninsulated walls is 30% of the total [3], forms the initial baseline in predicting current and potential heat transfer behaviour when optimising designs in the present work.

Despite this reliance on U-value, studies have shown that steady-state coefficients do not reflect the actual performance [19]. Thermal analyses under steady state tend to overestimate or underestimate performance when compared to more realistic, or in-situ, dynamic conditions [20, 21]. This can result in oversized building elements,

increased upfront cost and associated carbon emissions. Therefore this study uses dynamic and in-situ environments for analysing the retrofit wall.
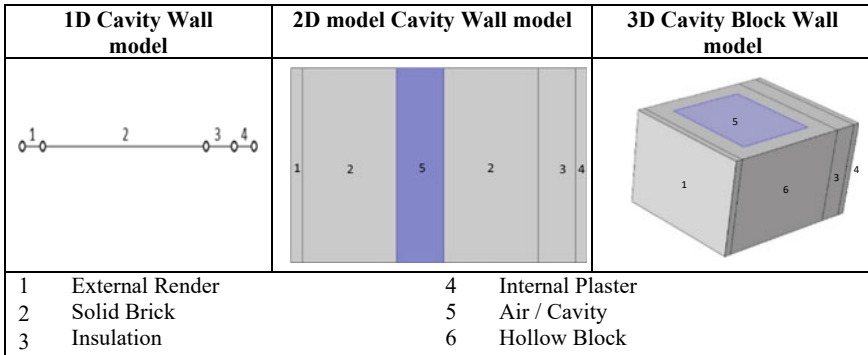
Ireland offers a unique testing ground for building energy analysis. Firstly, the Irish housing stock is recognised as amongst the least energy efficient in Northern Europe [22]. Second, Ireland is characterised as having a temperate oceanic climate, where the winter temperatures are mild and summer temperatures are moderate compared to the other European countries. This offers the opportunity to single-out home heating only, as air conditioning is rarely used or even installed in Irish homes.

7.2 Methodology

7.2.1 Finite Element Model (FEM) Development and Verification

Numerical Models were developed in Comsol® Multiphysics software of the three most common Irish wall types; Solid Wall (SW), Cavity Wall (CW) and Cavity Block Wall (CBW), the geometric domains are shown in Fig. 7.1 and Table 7.1 details thermal material properties. The inputs and assumptions were verified against experimental data under laboratory controlled conditions. The CW and SW type walls were verified against Hotbox data where one side of the wall air temperatures varied sinusoidally [23]. The CBW model was verified against published data [24]. The coefficient of variation (CV) and model efficiency factor (EF) were calculated to assess the capability of the models to reproduce real behavior. The coefficient of variation defines how well the model fits the experimental data by using offsetting errors between measured and simulated output. The EF compares the efficiency of the simulation model and the efficiency of describing the data as the mean of the experimental observations. The obtained simulation calibration index lies within the ASHRAE Guideline 14 [25] limits and therefore the models were considered calibrated. The following assumptions and simplifications were experimentally verified as acceptable for accurate models.

- Negligible thermal contact resistance between material layers.
- Isotropic thermal properties of the individual components, which are independent of temperature (Table 7.1).
- Mortar was not modelled since it has similar thermal properties to the solid component and represents a small percentage of the wall.
- One-dimensional conduction heat transfer model is used for a solid wall, a two-dimensional conjugate heat transfer model for cavity wall and a three-dimensional conjugate heat transfer model for the cavity block wall (Fig. 7.1).
- Workmanship, local variations, and thermal bridges were not considered.

1D Cavity Wall model	**2D model Cavity Wall model**	**3D Cavity Block Wall model**
1 External Render 4 Internal Plaster 2 Solid Brick 5 Air / Cavity 3 Insulation 6 Hollow Block		

Fig. 7.1 Comsol multiphysics models for three wall types

Table 7.1 Thermal properties sourced from manufacturers and standards [3]

Material	Thermal conductivity (W/mK)	Density (kg/m^3)	Specific heat capacity (J/kg K)
EPS	0.031	30	Negligible
Brick	0.63	1970	950
Block	1.33	2100	1000
Internal plaster	0.2	850	850
External render	1.2	1200	850

7.2.2 *Internal Boundary Condition Determination for FEM*

An online self-completion survey was used to determine common home-heating setpoint temperature and heating patterns as the internal boundary condition for the Finite Element Models. A slider scale for setpoint temperature and dropdown menus for heating usage at different times of the day were used. A pilot study was completed initially with 25 participants followed by a survey with 205 responses, 71.1% of which were from Dublin. The interpretation and analysis of data was carried out only for Dublin.

Microsoft Excel™ and Minitab packages were used to analyse the data. The response data was directly exported to Excel before being imported into Minitab. Student's *t*-test and Descriptive statics were used for testing the means of two groups and measuring of central tendency such as mean and median.

7.2.3   External Boundary Condition Determination for FEM

Due to the limited weather parameters available from the Irish Meteorological Service, the data from Meteonorm was used to define external boundary conditions for the finite element models. Sophisticated interpolation models are used within Meteonorm, which allow for reliable calculation of solar radiation, temperature and additional parameters at any location in the world [26]. The data was further analysed in an ASHRAE sky model [25] to determine the solar air temperature for different orientations of the walls.

The wind data (speed and direction) obtained from Meteonorm for Dublin airport was analysed and wind direction and wind speed was determined using windrose diagrams and probability density distribution methods. The results were then used to calculate the external heat transfer coefficient with a developed formula of $h = 1.53\,V + 1.43$. To clearly understand the predominant wind speed in the west direction, a statistical analysis was carried out based on probability density function (DPD) of the yearly wind speed distribution, for which the Weibull model was used [27]. The probability density function represents the fraction of time the wind speed prevails at the location under investigation.

7.2.4   Numerical Models and OIT Determination

The most commonly used insulation material in Ireland, which is EPS, and most commonly used heating fuel, which is heating oil, were used as the example to explain the methodology and analysis approach. The three common walls types were evaluated for the influence of (a) heating pattern, (b) insulation location and (c) wall orientation. If determined to be significantly influential, the realistic heating pattern, optimal insulation position and the orientation which resulted in the worst-case heat loss were taken forward for OIT determination.

Economic and environmental models (EEM) were developed utilising the same equations as for the Heating Degree Day (HDD) approach detailed in this publication [28], but substituting the HDD determined heat loss value for the robust and verified FEM-determined heat loss. The total heat loss determined by FEM was directly linked to the heat loss (Q_{dhl}) in the EEM model through a Comsol® Multiphysics-Excel™ live link interface. Figure 7.2 illustrates the framework for FEM-EEM integrated model. This paper mainly focuses on the FEM-Environmental Model results.
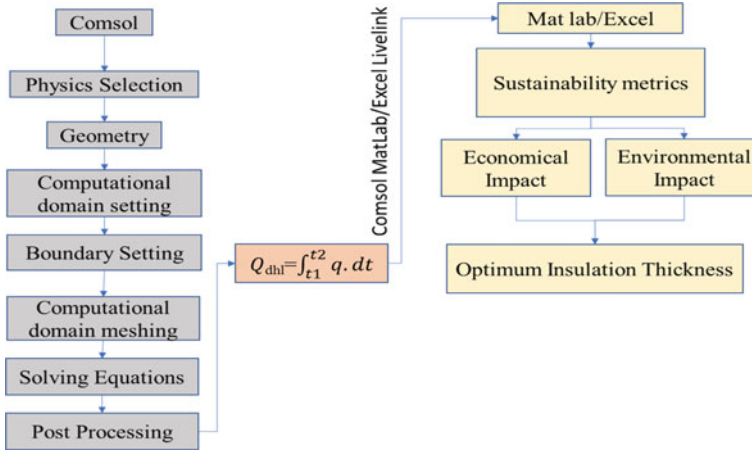
Fig. 7.2 Framework for integrated FEM-EEM model

7.3 Results

7.3.1 Internal Boundary Conditions

The mean set point temperature reported in the survey was 19.71 °C, which is 6.1% less than the comfortable indoor temperature recommended by World Health Organisation (WHO) [29]. The majority of the respondents came from working families and used the heaters only while they were at home resulting in a difference in heating pattern at weekends. The patterns were consistent with the literature [30–32]. Weekday and weekend heating patterns adopted for the numerical model input are shown in the below Fig. 7.3 for a single 24 h winter period.
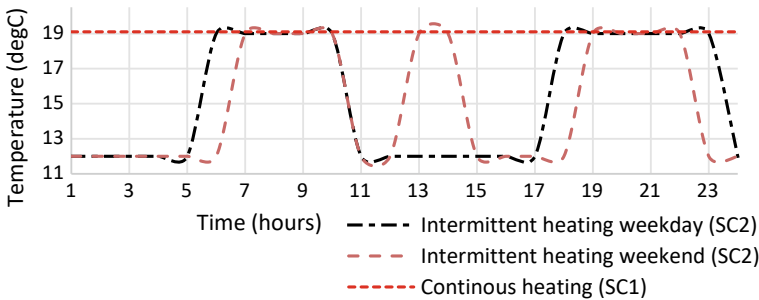

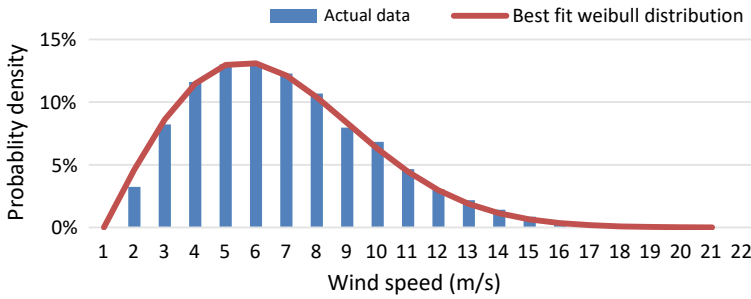**Fig. 7.3** Continuous and intermittent heating pattern for a 24 h period

**Fig. 7.4** Distribution of probability density (DPD) of annual wind speed for Dublin

7.3.2 External Boundary Conditions

For Dublin airport the wind blew from the west 14% of the time, from the north and south around 8% of the time and from the east 4–6% of the time. To clearly understand the predominant wind speed in the west direction, a statistical analysis was carried out based on DPD of the yearly wind speed distribution (Fig. 7.4), for which the Weibull model was used [27]. The probability density function represents the fraction of time the wind speed prevails at the location under investigation. The probability distribution curve for Dublin shows that the most frequently occurring wind speed is 6 m/s during winter, a value which corresponds to the peak of the probability density function.

7.3.3 Refined FEM Models

(a) Heating pattern: It was observed that, unlike continuously heated homes (SC1 in Fig. 7.5), under realistic heating patterns based on the survey responses (SC2) evidence of stored heat in thermal mass of the walls then returning to the internal space when the heating is turned off is identified by periods of positive internal heat flux (HFi) below (SC2). The overall impact on heat loss was very significant ranging from 20.9 to 27.5% higher (depending on wall type) in the continuous heating case compared to intermittent heating based on one week of weather data from January 2018.

(b) Insulation position: The above evidence of stored heat in thermal mass, re-released to the internal space is most evident in externally insulated walls. For externally insulated walls the living space takes longer to reach the target temperature, however, the heat stored in the wall during the heating period (brick/concrete layer) is prevented from fully dissipating into the outside environment. This stored heat is eventually released back into the indoor space during the non-heating period. Furthermore, in cavity walls and cavity block walls, the heat transfer coefficient
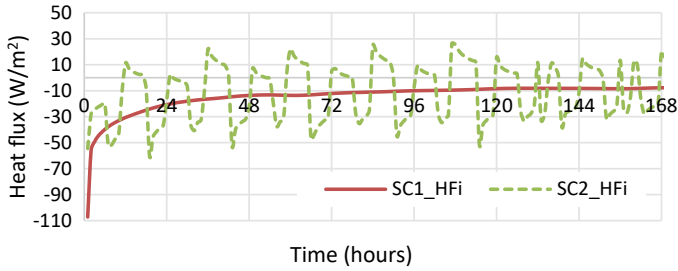
Fig. 7.5 Comparison of heatflux to solid walls for 1 week of constant internal heating (SC1), compared to common Irish heating pattern (SC2)

in the cavity is associated with the average temperature difference across it, which drives the buoyant flow of air. The higher the temperature difference, the greater the buoyancy force as will be the heat transfer coefficient. The heat transfer coefficient in the cavities of cavity block and cavity walls is lowest for internally insulated walls. These findings culminated in all wall typologies experiencing the lowest heat loss when internally insulated.

(c) Wall orientation: North facing walls in Ireland were found to experience significantly greater heat loss than other orientations and therefore should be used as the worst-case-scenario when designing for retrofit. For example north facing solid walls that are internally insulated experienced 29% greater heat loss than south facing. There is also greater conductivity and radiation across wall cavities due to the greater temperature difference across them during heating periods.

7.3.4 FEM-EM to Find OIT

Section 3.3 identified that the following should be included in the FEM portion of OIT determination; Intermittent heating pattern for internal boundary, defined solar air temperature and wind speed for six winter month heating period for external boundary, internally insulated walls as this results in lowest heat loss and north facing walls as they experience the worst-case heat loss in the building.

For determining economic and environmental impacts of changing insulation material thickness Table 7.2 values for calorific value, heating system efficiency and CO_2 emission factor and heating cost were used. For the economic analysis, costing for EPS insulation was taken as 78 €/m³ based on the methodology published in [28]. Local recent and future projection data should be used where possible.

A large number of combinations were produced comparing the multiple variables which influence OIT values. This study preliminarily examined OIT based on carbon emissions related to cradle-to-gate embodied carbon estimates of 2.55 kg CO_2/kg for EPS [35] alongside the operational emissions for heating oil over 10 years based on

Table 7.2 Parameters for heating fuel type: heating oil [33, 34]

Hv[a] (kWh/unit)	Efficiency[b] (η)	CO_2 emission factor[c] (kg/kWh)	Cost (€/kWh)
10.55 (l)	0.9	0.2736	0.0788

[a] Heating fuel value, or calorific value, is the amount of heat released during the complete combustion process
[b] Efficiency is the amount of useful heat produced per unit of input energy (fuel)
[c] CO_2 emission factor: is an estimate of greenhouse gas emissions per unit of human activity (space heating)
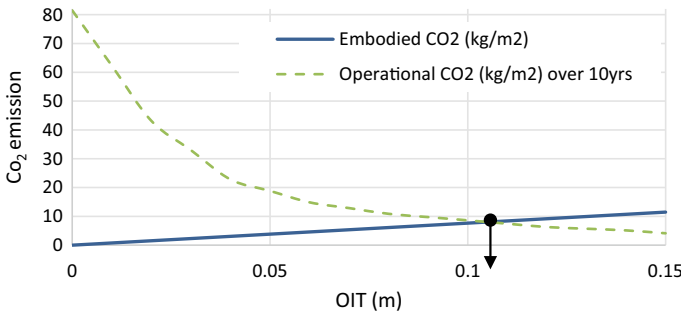
Fig. 7.6 OIT based on operational and embodied carbon for Internal EPS insulation on a Dublin Cavity Wall type using heating oil

the method outlined in [28]. To illustrate the findings, the example of EPS insulation, on cavity wall type, for Dublin, and heating oil as the heating fuel source is used in Fig. 7.6 below for environmental-OIT. OIT was determined to be 110 mm.

Conversely, when total cost is prioritised, 40 mm EPS was found to be optimal. The operational heating emissions at 40 mm EPS is considerably higher than for 110 mm. However, heating oil is associated with the greatest carbon emissions in Ireland when compared with the next most common alternatives of mains gas and electricity. As more efficient heating systems and renewable energy becomes more widespread resulting in lower operational-based CO_2, it is likely that reducing material production volumes will become more of a priority.

7.4 Conclusions and Recommendations

Using OIT insulation over a one-size-fits-all approach has the potential to save large quantities of carbon in a wholistic approach to circular design of buildings which includes both construction and operation. The method outlined here can be adopted for any region by substituting local data for: heating usage pattern, weather, wall typologies, insulation material and heating fuel. It is recommended that to ensure

efficiency of design, dynamic thermal analyses are carried out and real-time boundary data (or approximations of such) are used where possible over simplified or steady-state approaches.

It is understood that limited computational power and time result in the need to simplify models to some extent, therefore future research can adopt the assumptions used (Sect. 2.1) in the calibrated models in this paper with confidence. Internal insulation was always identified as the optimal design for reducing heat loss in all wall types for intermittently heated spaces. The coldest or most shaded orientation of the building should be used as heat loss is significantly more due to the low solar gains.

The limitations of this work includes that cooling loads were not analysed, the embodied carbon value was based on a relatively old determination from the UK and that this only includes cradle-to-gate carbon which omits end of life reuse or disposal. These areas must be further examined, in particular when applying the methodology to other, potentially warmer, countries. Material volumes, costs and emissions were based on the insulating material alone, and did not include other costs such as labour, render, or fixings. This was so that the change in insulation material thickness could be isolated for comparison between options.

As bio-based and recycled insulation becomes more commonplace alongside the growing marked in renewable energy, the presented methodology can be used to build a case for adopting the most emission and cost efficient circular design combinations. Furthermore, this tool can be used as part of the toolkit in aligning the Renovation Wave with the Circular Economy Action Plan.

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