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# Temporal optimization for affordable and resilient Passivhaus dwellings in the social housing sector

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## HIGHLIGHTS

- Multi-objective optimisation applied to affordable Passivhaus delivery.
- Optimum Passivhaus compliance method depends on decision makers preferences.
- Peak load criterion is preferable for cost optimal and resilient design.
- Reduced south facing glazing improves future resilience to overheating.
- Multi-objective optimization facilitates evidence-based decision making.

## ARTICLE INFO

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## ABSTRACT

Scarcity of affordable energy efficient dwellings is a defining characteristic of the global housing crisis. In many countries this problem has been exacerbated by single objective cost-models which favour the homogeneous development of market tenures at the expense of delivering high-quality affordable homes. Despite the obvious environmental and fuel-poverty alleviation benefits of advanced energy performance standards, such as Passivhaus, they are often dismissed as an affordable housing solution due to elevated build-cost premiums. The present work attempts to reconcile this housing affordability – energy performance nexus by establishing a novel decision support framework for Passivhaus design using genetic multi-objective optimization. The use of constrained genetic algorithms coupled to the Passive House Planning Package software is shown to produce cost optimal designs which are fully compliant with the Passivhaus standard. The findings also reveal that the precise choice of Passivhaus certification criteria has significant impacts on overheating risks using future probabilistic climate data. This means that the design implications of using either the peak heating load or annual heating demand certification criteria must be temporally evaluated to ensure resilient whole-life design outcomes. In a typical UK context, the findings show that affordable Passivhaus dwelling construction costs can be reduced by up to £366/m$^2$ (or 22% of build cost). Use of this evidence-based decision support tool could thereby enable local authorities and developers to make better-informed decisions in relation to cost optimal trade-offs between achieving advanced energy performance standards and the viability of large affordable housing developments.

## 1. Introduction

The domestic housing sector accounts for over a quarter of energy use and carbon dioxide emissions in the UK [1] and a similar proportion of European final energy consumption [2]. As such it represents one of the largest sectoral areas to address when considering emission reductions required to meet the UK Climate Change Act [3] (an act binding the UK Government to nation-wide emission targets) and the Paris Agreement [4] (the first universal legally binding global climate protocol). As of April 2016, there were 23.7 million dwellings in England, with 4 million of these being socially or affordably rented dwellings [5]. This represents a significant proportion of the total housing stock despite a decrease in recent years as the number of privately rented properties increased. The issue of social housing is bound to become more relevant as the global housing crisis continues with growing private housing rental prices [6] and higher levels of homelessness

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reported both in the UK [7] and world-wide [8]. These two issues create a complex problem: how to supply more affordable homes without introducing significant carbon dioxide emissions or elevated build costs.

It is clear that the energy efficiency of new and existing homes will also need to increase if future energy demand is to be met without the use of fossil fuels [9]. Drivers for energy efficient housing in the social housing sector are further accentuated when conditions such as fuel poverty [10] indicate a requirement for high-quality housing and low fuel costs to mitigate unaffordable heating bills. With a suggested number of 75,000 social housing dwellings required to be built per year in the UK to match the estimated demand [11]. Collectively these challenges point to a wicked problem where construction costs are required to be kept low in order to satisfy developer profit margins, whilst complying with financial viability assessments and limiting impact on constrained local authority budgets. Reframed from a wider perspective the objective becomes the construction of the maximum number of dwelling units, whilst maintaining quality in order to address energy efficiency and fuel poverty targets whilst attempting to contribute meaningfully to sectoral, national and global decarbonisation strategies. Since these issues cannot be addressed in isolation, a shift in primary focus away from volume housebuilding towards providing better quality affordable housing (which minimises energy consumption) is urgently required.

A potential solution to this problem exists through the application of the voluntary Passivhaus standard [12] which has already been successfully applied, at scale, in the German housing market [13]. This energy performance standard introduces a much stricter set of performance criteria than are currently required for new build dwellings under most national building codes [14], including Part L (which addresses the conservation of fuel and power) within the UK Building Regulations. Passivhaus mandates the same energy requirements across all climates (either a peak heating/cooling load $\leq 10\ \mathrm{W/m^2}$ or an annual specific heating demand $\leq 15\ \mathrm{kWh/m^2a}$), and a limit on the total Primary Energy Demand to a maximum of $\leq 120\ \mathrm{kWh/m^2a}$ for all domestic applications [15]. This implies that different design approaches may be required to meet the standard dependent on the climatic region [16]. The standard has been adopted worldwide (e.g. Brazil, Canada, Europe, Australia and the US). In the UK, multiple local authorities have trialled the approach, and some (such as Exeter City Council) have achieved multiple Passivhaus compliant builds [17]. However, the construction of Passivhaus dwellings within a social housing context is widely viewed as cost prohibitive, with a premium generally attached to the development of homes to this standard [18]. This finding has been confirmed by a number of authors including Lynch [19] Márquez et al. [20] and Newman [12, pp 281–306]. In contrast a study of 12 Republic and Northern Irish Passivhaus dwellings by Colclough et al. shows that there is not always a significant cost premium present [21]. Furthermore, Colclough et al. point out that whilst Passivhaus compliant dwellings achieve greater performance in terms of indoor environmental quality (IEQ), they are also vulnerable to increased overheating risks, a finding that has been highlighted by McLeod et al. [22] and Sameni et al. [23].

A further potential limitation to the Passivhaus standard, in relation to climate impacts, is that it does not consider the complete lifecycle carbon emissions of a build through a lifecycle assessment (LCA) [24] which can identify a significantly larger climate impact than solely in-use energy modelling [25]. Noting this potential limitation, this work will focus on in-use energy consumption to support the dual challenge of reducing fuel poverty and decarbonisation. Whilst broader environmental issues in construction and homebuilding are covered by national and global sustainability standards such as BREEAM [26], LEED [27] and NABERS [28] these standards lack a detailed focus on the reduction of in-use energy demand to the extent provided by the Passivhaus standard. With its focus on in-use energy demand the Passivhaus standard is capable of a significant energy demand reductions against conventional building standards. Estimates of the reduction potential vary. For example a 55–83% reduction in energy demand is stated in the case of retrofit of historic buildings [29], a 63% reduction for a new-build housing proposal (compared to a conventional housing proposal) in a Mediterranean climate [20], whilst a 50% reduction was found in a study of more than 100 new-build dwellings (compared to conventional new build standards) in five northern and central European countries [30].

To investigate approaches to facilitate the delivery of cost optimal Passivhaus compliant designs this paper will explore an emerging approach to decision making in the built environment using multi-objective optimization [31]. Multi-objective optimization using genetic algorithms has been previously applied to a number of low-emission design problems in the built environment such as zero carbon buildings [32], sustainable building design [33], retrofit strategies [34], window and shading design [35], cost optimal low-energy buildings [36], residential building design [37] and office design [38]. Further, multi-objective optimization has been implemented within building performance software [39]. However, there has been little work on its application in the context of optimising the whole life performance of an entire energy performance standard [40]. To date the utilisation of genetic algorithms for Passivhaus building design has focused predominantly on their application in conjunction with dynamic thermal simulation models using tools such as EnergyPlus. Torres-Rivas et al. [41] used EnergyPlus and jEPlus to optimize Passivhaus dwellings for the avoidance of moisture risks and Figueiredo et al. [42] minimised overheating risks using EnergyPlus. Whilst Dalbem et al. [43] presented a methodology for the optimization of Passivhaus designs using an evolutionary algorithm, however, the EnergyPlus dynamic simulation engine was used in this study to create the numerical models which were then optimized. Such approaches present a significant issue for Passivhaus building designers seeking project compliance, wherein the Passive House Planning Package (PHPP), a quasi-steady state design tool, is the sole means authorised by the Passivhaus Institute to demonstrate compliance with the standard [44]. Therefore, results from optimization studies using dynamic thermal simulations would need to be translated to PHPP (and subsequently re-evaluated) adding time, potential errors and additional complexity to the optimization process. Previous work involving PHPP and computational optimization is limited [45], with the only other documented use of evolutionary algorithms within PHPP being by Forde et al. [46]. However, this work focused only on present day climatic conditions with no consideration of future performance and robustness. In an attempt to overcome these limitations this work builds on previous work conducted by Evins et al. [47] applying design optimization using the UK's steady-state Standardized Assessment Procedure (SAP). In setting out this approach it is acknowledged that the PHPP model contains inherent limitations such as only including overheating hours as a comfort criterion and therefore not providing information about the zonal temperature distribution between spaces in a building [12, p.105–124]. Therefore, in situations where greater spatio-temporal information is of interest a dynamic thermal simulation is required.

By using a multi-objective genetic algorithm coupled directly to the PHPP energy model and incorporating real-world design constraints, this paper determines optimal designs based on either the annual heating demand or peak heating load (two distinct approaches which may be adopted to fulfil the Passivhaus criteria). The optimization process is carried out against multiple design criteria in order to determine capital cost-optimal solutions for a specific region in the UK based on social housing design constraints and the Passivhaus certification criteria. This represents, to the authors' knowledge, the first implementation of multi-objective genetic algorithms within the PHPP design and certification framework across both present and future climate conditions.

This paper aims to bridge the gaps between research, development and the implementation of new decision-making techniques to address the complex problem of cost-optimal low energy housing provision. Although the work is based on the UK social housing context, the methodology is transferable to any national or regional context. Logically the application of the demonstrated approach will yield the greatest benefit in larger scale housing developments where the costs of inefficient early design stage decision making are amplified by the volume production of housing of a similar typology.

## 2. Methodology

### 2.1. Selecting an appropriate region and climatic data

To trial this approach to decision making, regional indices of fuel poverty were used to select an appropriate study region within the UK. This metric is used to identify the region where energy efficiency improvements could theoretically create the most benefit to occupants [48].

Since multiple definitions of fuel poverty exist, a specific framework must be adopted for consistency. For England, the Department of Business, Energy and Industrial Strategy (BEIS) has used the low income, high cost (LIHC) indicator to assemble a dataset of fuel poverty levels at a sub-regional definition. Whereas, Scotland use the 10% indicator [49] which proceeded the LIHC indicator in the UK [50]. For Northern Ireland and Wales only secondary fuel poverty data, based on energy modelling estimates, is available and is therefore not utilised. Since the LIHC definition and dataset has been used to identify the study region only England will be considered. From this dataset, in terms of the proportion of households suffering from fuel poverty, the Isles of Scilly (an archipelago off the Cornish coast, in southwest England) was identified to be the most affected (19.4%). However, in real terms, this represents a population of only 203 (2017) households and a unique situation compared to the rest of England [51]. Therefore, the area with the second highest proportion of fuel poverty was selected. This area was Leicester, in the UK Midlands, with around 18.2% of its homes suggested to be in LIHC fuel poverty, representing approximately 126,350 (2017) households [51] in real terms (see Fig. 1).

To generate suitable current day and future climate data for the selected study region the climate data interpolation software Meteonorm 7.2 was used. Meteonorm is a comprehensive climatological database that is designed to provide geographically interpolated climatic data for a range of research applications [52]. For this project, the present day (2020) weather data was interpolated for Leicester (52.6°N, −1.1°E, altitude 68 m), with the nearest weather station providing global radiation measurements being Sutton Bonington (approximately 25 km away). Future (2070) weather data was interpolated for the same coordinates using trajectories derived from the Intergovernmental Panel on Climate Change (IPCC) special report on emissions (SRES) A2 climate change scenario [53]. Although the A2 scenario is at the upper end of the SRES emission scenarios it is a widely used to investigate adaptation to plausible levels of climatic change, wherein adapting to the upper-end scenarios implies that lower-end scenarios are adapted for [54]. In contrast, the evaluation of a low emissions scenario would provide less information in terms of adaption, whilst potentially underestimating future overheating risks. Furthermore, the current global $CO_2$ emissions trajectory corresponds to a relatively high emissions scenario [54].

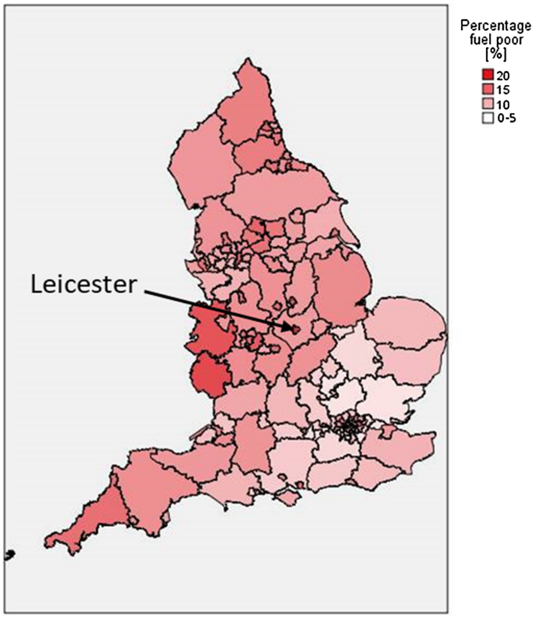


**Fig. 1.** Choropleth map of England showing percentages of the population from each sub-region suffering from fuel poverty.

### 2.2. Specifying the building performance software and algorithm

PHPP is a quasi-steady state building energy model which was developed to provide calculations in accordance with the international standard BS EN ISO 13790 (now EN52016-1) to determine monthly space heating demand. Through a range of algorithms PHPP is also capable of calculating a range of other performance metrics such as the peak heating and cooling loads, cooling energy demand, frequency of overheating and primary energy demand [55], which are the key performance indicators needed to demonstrate compliance with the Passivhaus standard. One of the limitations of PHPP, however, is its quasi steady-state nature which limits the time-resolution of detail available. This is in contrast to dynamic thermal simulation models which can provide information at hourly (and sub-hourly) time scales and therefore permit a more refined analysis than steady-state simulations [56].

The Passivhaus standard will be used in this paper due to its applicability across any climate zone [16], validation of in-use performance values with modelled values [57], quality assurance processes and the standard having gained acceptance within the UK as a template for near Zero Energy Buildings (NZEB) [22] particularly within social housing [58]. The standard includes various requirements that must be met to attain certification as mandated by the Passivhaus Institute, as shown in Table 1. When complying with the Passivhaus standard for space heating one of two criteria must be attained as highlighted by Table 1. The space heating condition can be met through the annual heating demand or the heating load criteria, with only one of these conditions required for compliance. The use of the alternate criteria and the requirement to meet only one or the other certification criteria is established within the Passivhaus standard [59]. The heating load

**Table 1**
Passivhaus certification criteria.

| Criteria | Maximum value | Alt. criteria? |
|---|---|---|
| Heating Demand [kWh/(m$^2$a)][1] | 15 | Yes |
| Heating Load [W/m$^2$][1] | 10 | Yes |
| Cooling & dehumidification demand [kWh/(m$^2$a)][2] | 15 + DC[3] | Yes |
| Cooling load [W/m$^2$][2] | 10 | Yes |
| Frequency of overheating [>25 °C] | 5% of the year[4] | No |
| Frequency of excessive humidity [>12 g/Kg] | 20% of the year | No |
| Airtightness test [1/h @$n_{50}$] | 0.6 | No |
| Primary Energy (PE) Demand [kWh/(m$^2$a)] | 120 | No |

[1] The alternate criteria for heating demand are heating load and vice versa.

[2] The alternate criteria for cooling compliance is either cooling load or cooling demand.

[3] Dehumidification contribution (DC) [12, pp 12].

[4] This is 10% with respect to the certification criteria, but typically 5% as a best practice design criterion.

criterion differs from the annual heating demand criterion as it seeks to establish the mean daily peak heating load during the winter season. This is done by considering two distinct weather conditions which have been found to cause maximum heating load. These two scenarios are a cold but sunny winter day with a cloudless sky (W1), or a moderately cold but overcast day with minimal solar radiation (W2) [55]. Annual heating demand uses the monthly method of EN 13790 (now EN52016-1) but performs energy balance calculations for each month of the year and is the more widely established method for demonstrating Passivhaus compliance [58].

The optimization system specifies the algorithms used to produce optimal results. For the purpose of this work the optimization algorithm NSGA-II [60] was selected based on its well-established use in building performance simulation (BPS) [33], and the performance outcomes of the algorithm in this context [35]. The implementation of the NSGA-II algorithm is based on VBA code developed by Evins [47]. A population (set of generated solutions) with a size of 200 was used for a total of 100 generations (iterations of the population) with a probability of crossover (method to create new solutions by using two existing solutions) of 0.7 and the probability of mutation (changes of variables within a new solution) at 0.5. The full optimization methodology in the context of this study is illustrated within Fig. 2.

### 2.3. Choosing the construction and building typology

The city of Leicester is located within the East Midlands region of England where the most common residential building typology is semi-detached dwellings [61]. This is true when all tenancy types are accounted for, but it is unclear whether this is also correct in the context of social housing. The 2008 English Housing Survey [62] identifies that the most common typology for social housing, across England, is terraced housing. This is however only marginally higher than the number of semi-detached dwellings. Therefore, it was decided to use an end-of-terrace house as a representative house type for Leicester. Further to this, the construction itself was chosen based on the most predominant construction method used in England, which is masonry construction [62]. The building uses a masonry cavity wall construction with an insulated cavity of up to 300 mm in depth (similar to the Denby Dale Passivhaus [63]) which is fully filled with mineral wool insulation (λ = 0.044 W/mK). The maximum total wall thickness is 500 mm (100 mm blockwork either side of insulated cavity). The loft insulation is also mineral wool with a maximum thickness of 500 mm, fitted within a cold roof. The floor is insulated using raft-slab insulation (λ = 0.033 W/mK) method in line with design guidance to achieve an, in-principle, thermal bridge-free junction with the wall system. This construction method has been widely used in Passivhaus dwellings and enhances the air-tightness of the slab [12]. A standard (i.e. non-varying) construction was selected for the party wall which consists of

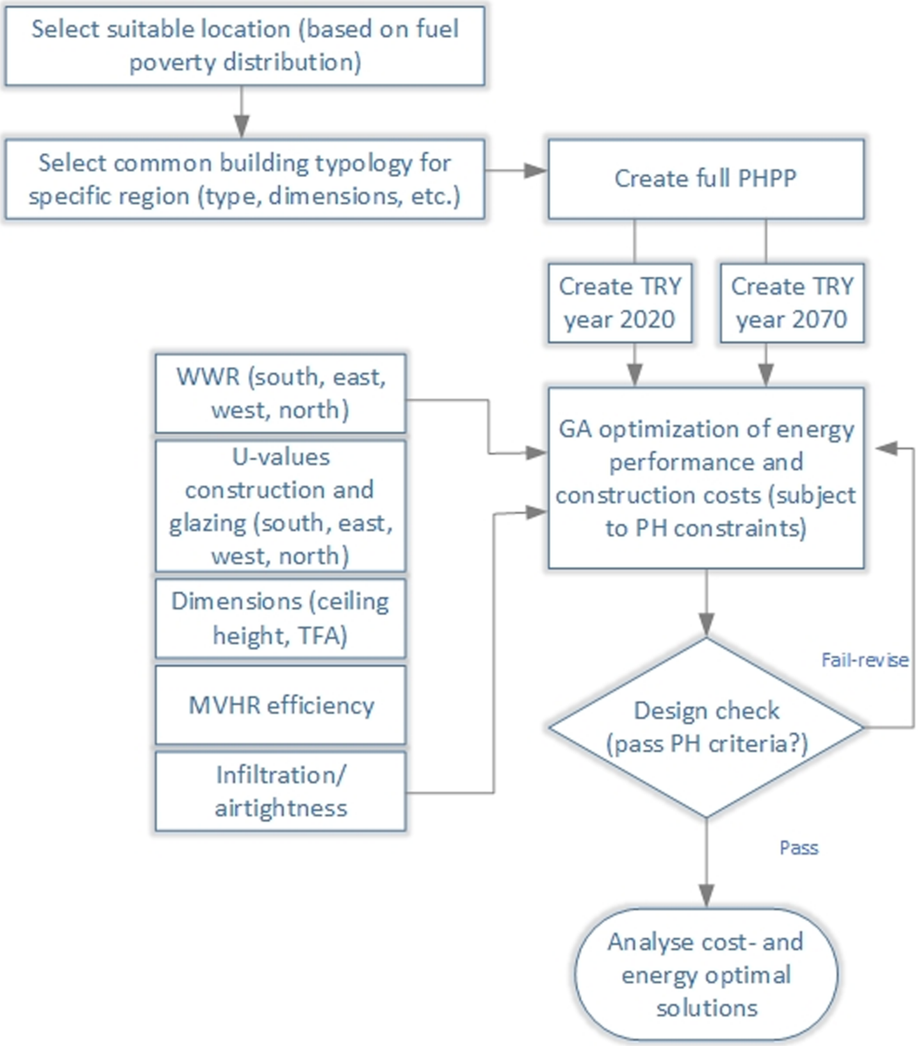


**Fig. 2.** Flow diagram of the Passivhaus design optimization methodology.

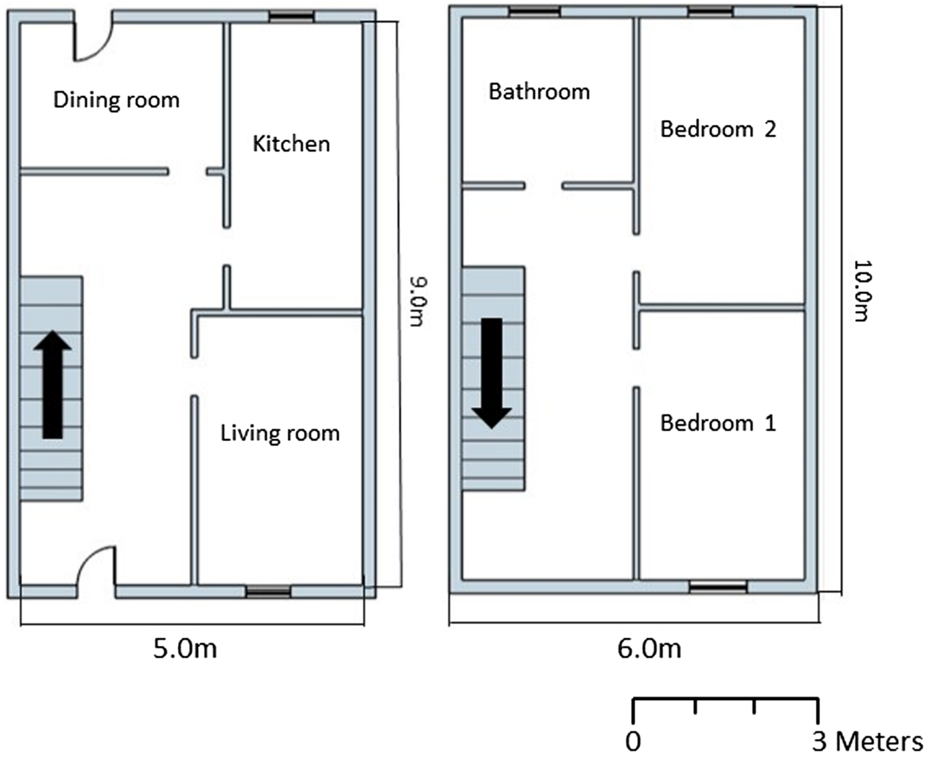


**Fig. 3.** Floor plan illustrating the assumed room structure of the dwelling with ground floor (left) and 1st floor (right). Approximate internal and external dimensions are shown.

100 mm block work, and 200 mm mineral wool insulation. Insulation is assumed for the party wall as the calculation method is only to be carried out for a single dwelling and not the entire terrace. The floor plan is displayed in Fig. 3. The ratio of dwelling length to width remains fixed, with the total floor area (divided over the two stories) being a variable. Therefore, the wall area is calculated by the wall length for a given treated floor area (TFA) multiplied by the variable ceiling height for both stories for a single evaluation. Similarly, the roof and floor area are calculated through the TFA variable. It is assumed that houses of the same geometry are located 16 m to the north, south and east of this property (to replicate a typical suburban context) with a party wall to the adjoined terrace housing to the west. All glazing units are triple glazed with four different window unit variations. These units are comprised of combinations of either a solid frame with high (g = 0.62) or low g-value (g = 0.52) glazing or a thermally insulated frame with high or low g-value glazing (see Table 3 for U-values of frames and glazing). The heating system used is an air-source heat pump supplying domestic hot water and space heating with radiators used for distribution.

### 2.4. Objective functions, variables and constraints

Objective functions are functions in a system that are to be minimised or maximised subject to constraints. The objective functions selected here are construction cost per square meter and either annual heating demand or peak heating load; to comply with one or the other Passivhaus certification criteria. All these functions are to be minimised. These objective functions are described mathematically below. $f_1$ represents capital construction cost and is described as:

$$\begin{aligned}\min(f_1)=&[(C_{RI} * A_{Roof}) + (C_{EWI} * A_{EW})\\ &+ C_{MVHR} + (C_{EWC} * A_{EW})\\ &+ (C_{PWCI} * A_{PW}) + (C_{Roof} * A_{Roof})+\\ &C_{Membrane}*(A_{EW} + A_{PW} + A_{Floor}+\\ &A_{Roof})+C_{HP} + (C_{Stairs+Upper} * TFA)+\\ &(C_{Substructure} * TFA) + C_{Ext.Doors} + C_{Other}\\ &+ (C_{Windows} * A_{Windows}) + (C_{FI} * A_{Floor})]\\ &/ TFA\end{aligned} \tag{1}$$

where

$A_{Roof}$ = Roof area [$m^2$]
$A_{EW}$ = External wall area [$m^2$]
$A_{PW}$ = Party wall area [$m^2$]
$A_{Floor}$ = Ground floor area [$m^2$]

Variables and fixed construction costs are detailed in Tables 1 and 2. Geometric factors such as the wall and roof areas are dependent on the

**Table 2**
Fixed cost estimates for all construction work and materials (note; these are not variables).

| Factor | Description | Cost [£][1] |
|---|---|---|
| External wall construction | $C_{EWC}$ | 130.48/$m^2$ |
| Party wall construction & insulation | $C_{PWCI}$ | 91.35/$m^2$ |
| Roof construction | $C_{Roof}$ | 78.24/$m^2$ |
| Airtightness membrane | $C_{Membrane}$ | 14.54/$m^2$ |
| Heat Pump | $C_{HP}$ | 8000 |
| Stairs & Upper Floor | $C_{Stairs+Upper}$ | 46.83/$m^2$ |
| Substructure | $C_{substructure}$ | 30.17$m^2$ |
| External door | $C_{Ext.Doors}$ | 950/unit |
| Other costs | $C_{Others}$ | 596.74/$m^2$ |

[1] All cost values obtained from SPONS 2018 [64] except membrane [65] and heat pump [66].

**Table 3**
U-values, geometric and cost ranges of variables used in the optimization system.

| Variable | Description | Type[2] | U-val. Range [W/m$^2$K] | Geometric Range [m$^2$] | Cost range[1] [£/m$^2$] |
|---|---|---|---|---|---|
| Floor insulation | $C_{FI}$ | Disc. | 0.085–0.126 | TFA/2[3] | 19.27–28.12 |
| External Wall ins. | $C_{EWI}$ | Disc. | 0.119–0.176 | – | 12.6–18.9 |
| Roof Insulation | $C_{RI}$ | Disc. | 0.087–0.147 | TFA/2[3] | 6.24–10.05 |
| Glazing | $C_{Windows}$ | Disc. | 0.52–0.61 | – | 380–600 |
| Window Sill | $C_{Windows}$ | Disc. | 0.81–1.57 | – | Linked to glazing |
| Window Jamb | $C_{Windows}$ | Disc. | 0.83–1.02 | – | Linked to glazing |
| Window head | $C_{Windows}$ | Disc. | 0.85–1.02 | – | Linked to glazing |
| Treated floor area | TFA | Cont. | – | 70–89 | Linked to fabric |
| South-window area | $A_{Windows}$ | Disc. | $C_{Windows}$[4] | 10–100% facade area | Linked to glazing |
| East-window area | $A_{Windows}$ | Disc. | $C_{Windows}$[4] | 0–100% facade area | Linked to glazing |
| North-window area | $A_{Windows}$ | Disc. | $C_{Windows}$[4] | 10–100% facade area | Linked to glazing |
| Ceiling height | – | Cont. | – | 2.3–2.6 m | Linked to fabric |
| MVHR[5] | $C_{MVHR}$ | Disc. | 85–95% efficiency | – | 6095–6633 |
| Air change rate | – | Cont. | 0.1–0.6 ACH[6] | – | NA |

[1] Cost information obtained from SPONS 2018 and Green Building Store [64,67,68].
[2] Type selection between discrete (Disc.) and continuous (Cont.).
[3] Geometric range of these elements is a function of TFA.
[4] U-value range of these elements is determined by the elements described as $C_{Windows}$.
[5] Mechanical Ventilation with Heat Recovery (MVHR).
[6] Values for ACH assuming the building is under or over pressurised to 50 Pa.

TFA and ceiling height variables. Factors such as wall construction costs are separated from their respective insulation costs (which are defined as independent variables, see Table 3) and are dependent purely on their geometric dimensions for variation.

For the second objective (space heating minimisation), there are two possible objective functions, and both will be used to explore the nature of optimal design solutions when using either the annual heating demand or the peak heating load as an objective function. The first of these two alternate functions ($\min(f_2)$) aims to minimise the annual heating demand, and is described as follows:

$$\min(f_2) = (Q_T + Q_V) - (Q_S + Q_I) \tag{2}$$

where

$Q_T$ = Transmission heat loss [kWh/m$^2$a]
$Q_V$ = Ventilation heat loss [kWh/m$^2$a]
$Q_S$ = Useful solar gains [kWh/m$^2$a]
$Q_I$ = Internal heat gain [kWh/m$^2$a]

The second of the alternate objective functions aims to minimise the peak heating load. This objective function can be defined similarly to the above but using peak power terms instead of heating demand. The mathematical description of the heating load objective function ($\min(f_3)$) is as follows:

$$\min(f_3) = (P_T + P_V) - (P_S + P_I) \tag{3}$$

where

$P_T$ = Transmission peak load [W/m$^2$]
$P_V$ = Ventilation heat load [W/m$^2$]
$P_S$ = Solar heating power [W/m$^2$]
$P_I$ = Internal heating load [W/m$^2$]

The peak heating load is evaluated under two different weather conditions (W1 and W2) in the PHPP climate file (see Section 2.2 [55]) which creates two corresponding peak load conditions (P1 and P2) for heating in the selected climate zone. Wherein the largest of the two heating loads is selected to represent the peak load criterion.

To ensure that only viable design solutions are considered the optimization system incorporated three constraints. These constraints are, the: maximum overheating risk, maximum primary energy demand and minimum glazing area. The first two of these constraints, primary energy demand and overheating risk are mandatory requirements for Passivhaus certification (see Table 1). The last design constraint (minimum glazing area) is applied to the building construction to ensure that a minimum of 10% of the facade area is glazed. This criterion is imposed for both the north and south facades of the terraced dwelling to ensure that each room in the proposed room layout receives adequate access to daylight.

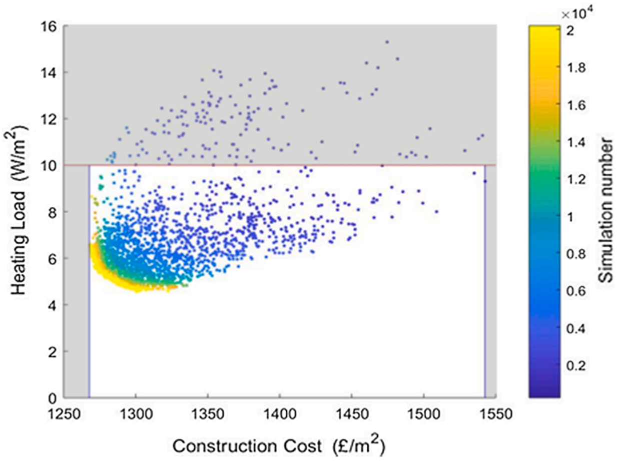
## 3. Results

### 3.1. Overall comparison

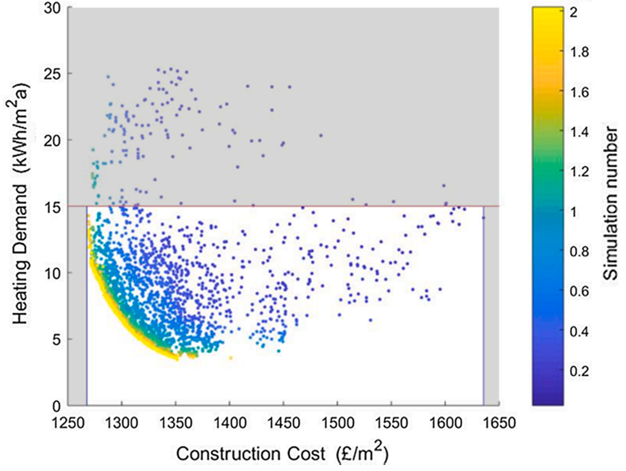
This section shows the results for the optimization of the construction cost objective with either the annual heating demand or peak heating load used as a secondary objective. These simulations make use of the present-day (2020 TRY) climate data for Leicester. Comparison will be made between the two heating criteria to determine whether one approach leads to better outcomes in terms of capital construction costs.

Fig. 4(a) and (b) demonstrates that convergence is achieved over the 20,000 evaluations forming the optimization for both the peak heating load and annual heating demand objectives respectively. Early evaluations (shown as dark blue dots in Fig. 4(a) and (b)) for both objectives demonstrate design solutions with far poorer cost and energy performance for the respective heating criteria. Comparing only valid Passivhaus designs (i.e. those beneath the red line in Fig. 4(a) and (b)) the variance, in terms of construction cost, is approximately £366/m$^2$ (22.4% of build cost) for the annual heating demand criterion and £275/m$^2$(17.8% of build costs) for the heating load criterion.

Convergence is shown to occur in the Pareto zone of optimal solutions for both objectives. Fig. 4(a) and (b) also contrast the range of capital construction costs of Pareto dominant solutions (shown as yellow dots in Fig. 4(a) and (b)) for the respective approaches to Passivhaus compliance. The horizontal, red line indicate the maximum allowable heating load or space heating demand for a valid Passivhaus design, according to the respective criteria. The vertical, blue lines indicate the minimum and maximum construction costs for solutions that are compliant with the Passivhaus criteria. As can be seen, from the final generation of solutions the annual heating demand criteria produces a wider range of results with many more failing to meet the Passivhaus standard. Whilst, the heating load objective produces a marginally lower construction cost ideal solution with a difference of approximately £2/m$^2$ (0.12% difference). In comparison to a baseline UK building regulation (Part L 2013 energy efficiency standard)



(a): Peak Heating Load



(b): Specific Heating Demand

**Fig. 4.** Showing the Pareto fronts and all valid solutions (within the white rectangle) for the peak heating load and annual heating demand objectives.

compliant home with identical geometry (in the same context), the annual heating demand ideal cost solution shown here (Fig. 4(b)) would reduce the heating demand by 33.2 kWh/m$^2$a, but with a capital construction cost uplift of £326/m$^2$ [69]. Assuming an electricity price of £0.15 kWh [70] the notional payback period of the annual heating demand solution is around 66 years. The implications for the various Passivhaus designs within the final generation are explored further in the following sections.

### 3.2. Driving variables

This section looks to compare the selection of variables chosen for all solutions across the final generation of the optimization for both heating criteria. This enables a better understanding of which variables are driving optimal solutions and which variables are dominant within good compromise solutions. Across the final generation there are 200 evaluations, with each representing a potentially valid solution. Each solution is composed of a selection of values for 17 different variables. Fig. 5 shows the percentage of times in which a variable is selected for both the annual heating demand and heating load objectives in their respective final generations. As can be seen, many runs end with a dominant variable being selected for all evaluations. However, there are some variables (red dashed box within Fig. 5) which remain non-dominated (i.e. where different variable values are selected across the final generation). These include south-facing window area, roof U-value, MVHR efficiency and floor U-value. The two most non-dominated variables for both compliance criteria are south-facing window area and roof U-value. As these factors exert a large influence on both annual heating demand and construction costs, this drives a wide range of annual heating demand values along the Pareto front creating solution diversity. The influence of south-facing glazing area is lower for the heating load criterion, with fabric factors such as MVHR efficiency, roof and floor U-values showing greater variation, although the south facing glazing area still effects the objective value diversity along the Pareto front.

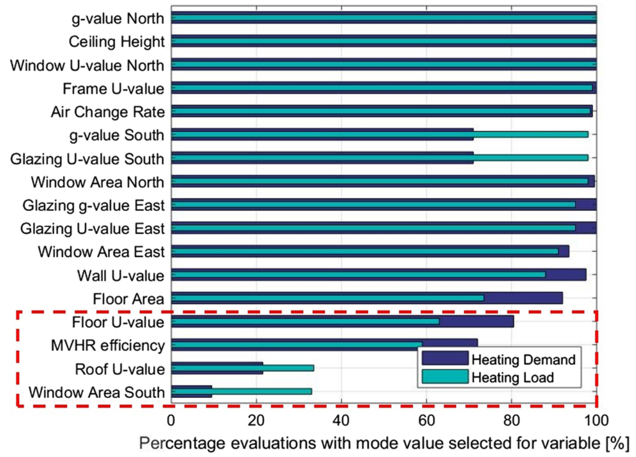


**Fig. 5.** Most common variables (by modal %) across the final generation of the optimization.

The relationship between south-facing glazing and construction cost is significantly stronger for the annual heating demand objective, with evaluated design solutions demonstrating a wide range of south-facing glazing areas. Whilst the relationship between south-facing glazing and construction cost for the heating load objective remains significant, it is not as strong as that shown for annual heating demand and consequently a smaller range of south-facing glazing area is seen among viable design solutions. This difference in the selection of glazing area drives the construction cost difference between the two criteria, since triple glazed window units are expensive relative to the cost of an equivalent area of external wall. This finding is in agreement with the build cost analysis studies of the Future Homes project (Ebbw Vale, Wales) where single objective optimization was first applied to this problem [15]. For annual heating demand solutions, the U and g-values of the south facing glazing also have an impact on driving solution diversity. However, this does not drive a wider range of geometrical solutions, rather it creates more diversity between solutions with similar glazing areas. For the heating load criterion, the U and g-values of the glazing have only a limited impact on driving solution diversity due to the direct trade-off between useful solar heat gains and increased transmission losses under peak load conditions.

### 3.3. Cost ideal solutions

A common design outcome for many homebuilding projects is the cost ideal solution. This is a solution that can deliver the minimum relevant design criteria (such as regulatory compliance) at the least cost. For the present-day climatic conditions, this solution can be found at the extreme left of the Pareto front of the Passivhaus heating demand and load compliance criteria optimizations. This section will explore the differences between cost ideal solutions for each heating criteria and determine the drivers underpinning the resultant capital construction cost differences in each case.

Fig. 6 shows the Pareto fronts for each of the heating criteria, highlighting the two cost ideal solutions (shown as green dots in Fig. 6). The horizontal lines in red and blue represent the maximum limit for a

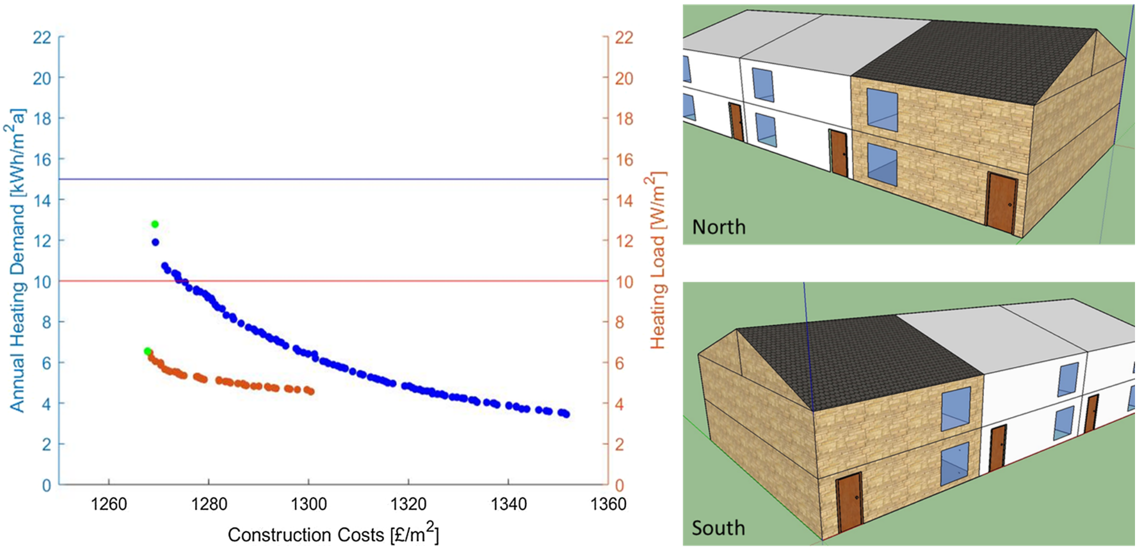


**Fig. 6.** Pareto front highlighting the lowest construction cost solutions (green) for dwellings complying with the annual heating demand (blue) and the peak heating load (red) criteria.

solution to be Passivhaus compliant for the given objective. Visual representations (right) shows the external appearance of the heating load design, however, the annual heating design differs very little with only 0.5 $m^2$ additional south facing glazing. In real terms the difference between the heating load and annual heating demand cost ideal solutions, in this context, is very small at approximately£2/$m^2$ with the heating load solution being slightly lower in cost. The variables driving this difference are shown within Table 4.

As can be seen, the relatively small difference in cost ideal solutions is driven by the annual heating demand solution using 0.5 $m^2$ more glazing on the south façade and with a lower U-value. Both solutions share common features, notably very low south and north facing glazing (around 10–15% window-wall ratio (WWR)). For each heating criteria the insulation is also reduced to the minimum allowed within the optimization, however, very good air tightness is maintained and the U-value of north facing glazing is kept low (0.51 $W/m^2K$) to minimise transmission losses from the already minimised glazing areas. Determining cost-ideal solutions is essentially a single objective optimization problem to minimise cost within the constrained design space. Therefore, both heating solution approaches use very similar constructions. Noticeably, the solution for the cost-ideal heating load objective does not come close to exceeding the compliance criteria of 10 $W/m^2$ due to the relaxation of the permissible thermal values being constrained by the limiting backstop U-values. It is therefore possible that lower cost materials, with a worse thermal specification could (in this specific context) produce more cost optimal heating load compliant designs.

### 3.4. Present-day versus future optimization

In order to assess the temporal resilience of the present-day solutions over time further optimization runs were carried out using a location specific future climate file. The IPCC SRES A2 emissions scenario for the year 2070 was chosen (see Section 2.1) in order to represent a plausible future climate. The outcomes were then compared to optimization runs using the present-day climate data for the same location. To highlight the differences between the two Pareto fronts, three aspects are interrogated in greater detail: (i) optimal solutions with respect to the lowest heating requirement (either demand or peak load), (ii) optimal solutions with respect to the lowest costs, and (iii) good compromise solutions (i.e. those that offer a balanced solution between both objectives). This is demonstrated by clustering the solutions as shown in Fig. 7.

In Fig. 7, the peak heating load solutions are shown within dotted ovals, whilst annual heating demand solutions are shown within solid lines. Both present and future solutions are shown and grouped according to their position along the Pareto front. All the solutions were selected from the final generation for each of the heating objectives. In terms of optimal solutions with regards to heating demand or peak load solutions (green ovals), it can be noticed that decreasing the energy consumption with the same parameter space is easier when choosing the heating demand criteria. Annual heating demand's lowest heating solution is around 4 $kWh/m^2a$ which is less than a third of the level required for certification according to the Passivhaus standard. Similarly, the peak heating load solutions are around 6 $W/m^2$, a level which is almost half of the 10 $W/m^2$ required for certification under the Passivhaus standard. As such the annual heating demand offers a more robust solution if there is a strong preference for annual heating demand minimisation over capital construction cost (i.e. this might be a preferred approach where long term fuel poverty alleviation is a primary concern). Solutions with optimal future heating demand or peak load show a dominance in the following factors: very good floor and roof insulation (U value = 0.08 $W/m^2K$), 0% east façade WWR, 10–15% north façade WWR, a very low north façade glazing U-value (0.52 $W/m^2K$) in all instances (as opposed to variations in the south facing glazing), and an MVHR efficiency of 95%.

If the lowest construction cost is prioritised (red ovals) both the heating demand and peak load will increase using future climate data due to the increased U-values in all fabric elements. However, the present value of future capital construction costs required to achieve optimal and compliant solutions will correspondingly decrease in both future cases. Further, the future cost-optimal annual heating demand solutions are approaching the thresholds of non-compliance. In comparison heating load solutions, show a more uniform compliance overtime, implying less sensitivity to climatic changes, a finding that was previously identified by McLeod et al. [55]. This suggests that there is an increased risk of future non-compliance with the use of the annual heating demand criterion relative to the peak heating load criterion when the lowest possible construction cost is prioritised over performance. As might be expected U-values typically increase for cost-ideal solutions compared to solutions that are optimal for the heating criteria. This is most apparent in the roof U-value in the cost optimal solutions which at 0.15 $W/m^2K$ represents the upper limit recommended by Passivhaus design requirements [59]. The percentage of north facing

**Table 4**
Variable selection for construction cost ideal solutions for both heating objectives.

| Heating Objective | Wall U-value (W/m$^2$K) | Floor U-value (W/m$^2$K) | Roof U-value (W/m$^2$K) | Glazing area east (m$^2$) | Glazing area north (m$^2$) | Glazing area south (m$^2$) | Glazing north U-value (W/m$^2$K) | Glazing south U-value (W/m$^2$K) | Air change rate (ACH) | MVHR efficiency (%) | Construction cost (£/m$^2$) | Annual heating demand (kWh/m$^2$a) | Heating Load (W/m$^2$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Annual heating demand | 0.126 | 0.126 | 0.147 | 0 | 3.5 | 4 | 0.52 | 0.52 | 0.1 | 85 | 1269 | 12.8 | 6.5 |
| Heating load | 0.126 | 0.126 | 0.147 | 0 | 3.5 | 3.5 | 0.52 | 0.61 | 0.1 | 85 | 1267 | 13.1 | 6.5 |

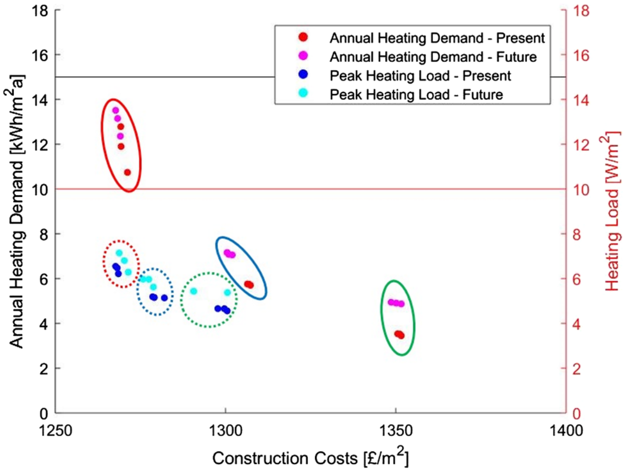


**Fig. 7.** Showing the lowest cost (red ovals), compromise (blue ovals) and lowest heating requirement (green ovals) for both the annual heating demand and peak heating load solutions optimized under current and future climate conditions.

glazing in cost-optimal solutions is identical to solutions focusing on heating criteria. In both cases the south facing WWR remains close to the lower threshold of around 10% for all solutions. The MVHR efficiency is reduced in cost optimal solutions compared to optimal heating solutions with an efficiency of 85% for both the present-day climate and the future climate scenario. Consequential cost uplifts are found to be associated with specific design constraints. For example, when an overheating frequency criterion of 5% is used, the MVHR efficiency increases to 90% for the future climate scenario in all cases. This increased efficiency requirement (and associated cost-uplift) is needed to compensate for the reduction in useful solar gains during the heating season imposed by the reduced south facing WWR required to mitigate summertime overheating. Such findings highlight the need to consider the optimization of low energy buildings on a whole-life temporal basis.

In practice, where a trade-off between cost and energy performance is desirable, mid-Pareto compromised solutions are often selected. Predictably the compromise solutions (Fig. 7, blue ovals) show that both heating demand and peak load increase whilst construction costs decrease for all cases. As for the cost optimized solutions, the peak load criterion appears to offer safer compromise solutions, with less variance over time. Compromise solutions show the importance of using more efficient MVHR units under future climate scenarios, with both heating criteria using more efficient units under future conditions (circa 2% average efficiency increase for heating demand and 3% increase for heating load condition compared to present climate solutions). Optimal compromise solutions show wall U-values to be the worst performing fabric element at 0.13 W/m$^2$K in comparison to roof and floor U-values of 0.09 W/m$^2$K and 0.085–0.1 W/m$^2$K respectively. More stringent glazing U-values are observed for north facing glazing as opposed to south, apart from for heating demand solutions under current climate conditions where all window U-values are the same. The south facing glazing percentage is around 30–40% for specific heating demand solution and 10–15% for solutions focusing on peak load. For heating load solutions, any potential uplift in performance derived from the improved MVHR unit efficiency would be negated through future (cost-optimised) solutions which require less roof insulation (decreased by 40 mm on average across all solution) and less floor insulation (100 mm average decrease across all solutions).

When looking at the differences in parameters for present day to future climate simulation for all cases, the south-facing glazing area changes significantly as demonstrated by Fig. 8. This reduced future glazing requirement explains the above-mentioned increases in heating demand and load despite the warmer external winter design

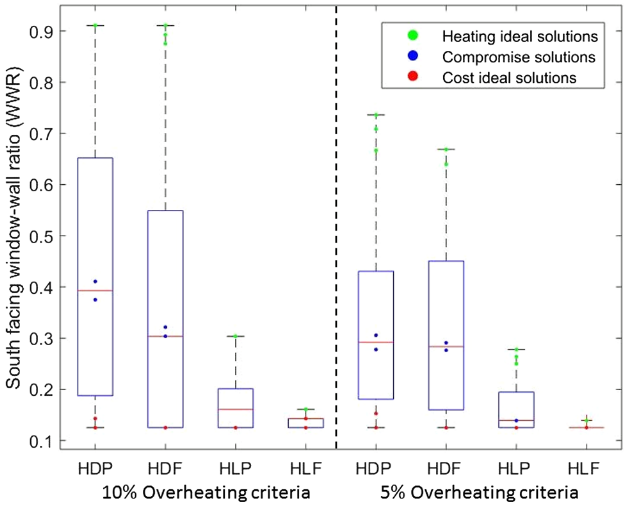


**Fig. 8.** Boxplot showing the distribution of south facing window-wall ratios for Pareto optimal solutions for annual heating demand under present climate (HDP), and under future climate conditions (HDF); and, peak heating load under present climate (HLP) and for future climate conditions (HLF).

temperatures in the future climate scenario. This is a consequence of the overheating criterion (required for Passivhaus certification) which acts as a constraint by limiting the number of overheating hours to less than 10%. The reason for the average cost decrease for future compliance is largely due to the reduced south facing glazing area.

Analysis of the implications of imposing a 10% overheating criteria versus a 5% overheating criteria provides further insight into the design implications of this constraint. Fig. 8 illustrates the difference in south facing WWRs when designs are optimized with either a 10% overheating constraint or a 5% overheating constraint. For peak heating load very similar WWRs are seen in both instances. However, for the annual heating demand a significantly lower south facing WWR is required for optimizations fulfilling the 5% overheating criteria. Comparing the annual heating demand solutions for both overheating constraints, the fabric specification of the heating ideal and compromise solutions remain identical apart from the south facing WWR. For cost ideal solutions, the south facing WWR for the 5% and 10% overheating constraint are identical. The much-reduced south facing WWR for the annual heating demand ideal solutions using the 5% overheating criteria leads to reduced energy performance compared to the heating ideal solution optimized with 10% overheating criteria. This results in a 25% increase in the space heating demand (of 0.89 kWh/m$^2$a). This finding highlights the need to consider the trade-off between occupant comfort/wellbeing in summertime and energy performance during the heating season.

Finally, the temporal resilience of solutions optimized under present climate conditions were tested under 2070 climate conditions (assuming the A2 climate pathway as described in Section 2.1) to examine overheating risk. The heating load solutions were first examined. Due to the reduced south-facing glazing generally required for peak heating load solutions, the overheating risk is typically reduced under future climate conditions. The present-day heating load ideal solution did not exceed the Passivhaus overheating criteria (of exceeding 25 °C for more than 10% of the year) under the 2070 climate conditions. In respect to construction cost-ideal solutions, the designs remained similar for both the present-day and 2070 climate.

For annual heating demand, a larger difference is visible in terms of the optimized solutions since the annual heating demand optimal solutions under the present-day climate fail the Passivhaus overheating criteria of 2070. Due to the annual heating demands greater dependence on south-facing glazing, heating ideal solutions optimized under present-day climate conditions are prone to future overheating. This finding is further amplified if a 5% overheating criterion is imposed rather than the Passivhaus standards compliance requirement of 10%. Since the cost ideal solutions for the annual heating demand objective are very similar to the cost ideal heating load solutions, they are similarly unaffected by overheating in 2070 and vary little when optimized to future conditions due to their reduced south facing glazing area.

## 4. Discussion

This research has found that relatively small cost difference exists between the cost ideal solutions for annual heating demand and heating load certification of a terraced Passivhaus dwelling located in the UK Midlands. This is due to the relatively small differences needed in the fabric specification required to achieve either criteria. Slightly reduced glazing is used in the cost ideal heating load solution leading to the marginal difference in construction costs. Both cost ideal solutions utilised close to the smallest possible glazing area arrangement to achieve compliance. This meant zero east facing glazing (on the gable end wall) and around 10% of WWA for each of the north and south were glazed. Across the entire dwelling, this minimal glazing ratio would achieve an average daylight factor of 2.24%, marginally above the minimum of 2% recommended within British Standard BS 8206-2 [71]. This is a reasonable design pathway for affordable housing in the described design space for a cost ideal solution as the glazing area presents the highest cost per meter squared of all variable components. When the system was optimized without design constraints, the glazing area for cost ideal solutions tended towards zero, however this can be considered a non-viable solution in respect of daylighting. Therefore, the trade-off between increased solar gains (minus increased transmission losses) and construction cost tended towards reducing solar gains, which were compensated for by increased fabric specification and decreased infiltration. As reduced infiltration did not have a nominal associated cost this always tended towards the minimum value (0.1 ACH). This assumption is unlikely to be true in an emerging market (such as the UK) where performance-based contracts for factors such as airtightness remain novel. However, in a mature market (where performance contracting is well-established, such as in Germany and Austria) the uplift could be minimal or non-existent.

Across the entire Pareto front for both compliance criteria, (i.e. the annual heating demand and heating load) there existed a mean construction cost difference of approximately £26/m$^2$ with around a £56/m$^2$ building cost difference between the two heating objective ideal solutions. This is largely driven by the range of south facing glazing areas deployed, with heating load solutions typically requiring much less glazing than is needed by annual heating demand solutions. This is due to the calculation methods used to derive these distinct criteria. The annual heating demand calculation determines the net energy balance for each month. Since solar gains through the south facing glazing outweigh transmission losses through the glazing on average across the heating season, increased south facing glazing will decrease the annual heating demand. For the heating load, the calculation method uses two test weather periods, one with a clear sky but cold temperatures (W1) and the other an overcast sky but milder temperatures (W2). The weather condition which causes the poorest performance in terms of peak heating load for the given location is then selected. Under W1 conditions there is a trade-off between the amount of useful solar gains which can be harvested during the sunlit hours and the increased rate of transmission losses occurring as a function of the glazed area's higher U-values outside this period. Conversely under W2 conditions there are less solar gains but also lower transmission losses as cloudy conditions tend to be milder, and consequently the benefits of large south facing glazed areas are reduced. Therefore, in optimising designs based on peak load there is a weaker relationship with south facing glazing compared to annual heating demand, and consequently a smaller cost range exists for the Pareto front generated for the heating load objective. The implications of this are that the use of the annual heating demand criteria without the use of design optimization techniques engenders a higher risk of non-compliance and associated build-cost uplifts.

The finding that heating load delivers a lower construction cost solution than annual heating demand confirms similar findings by McLeod [15] and Newman [12, pp 281–306] and is significant as the heating load represents a less widely used heating compliance criteria for Passivhaus certification [58]. The use of the heating load certification criterion mitigates dependence on south facing glazing as an expensive means of further improving energy performance, thereby helping to highlight the importance of building fabric, form, air-tightness and MVHR efficiency as key aspects of affordable Passivhaus design.

Comparison of optimal designs under future climate conditions with present day optimal solutions provides insight into the long-term robustness of each design criteria. Notably for both the heating demand and peak load criteria, future optimal solutions require (on average) less south-facing glazing. This is largely dictated by the requirement to meet the overheating constraint within PHPP (without introducing additional external shading devices). The application of reduced south facing glazing in the present, will however lead to sub-optimal designs with respect to increasing the annual heating demand. Therefore, it is possible that to avoid an increase in present-day energy use to mitigate future overheating risks moveable shading systems could be implemented. External or integral shading systems would however introduce an additional cost consideration and did not form part of the optimization system process used in this research since they are uncommon in standard UK social housing designs at present.

Across future climate scenarios, the use of the annual heating demand criterion proved a more secure criteria for attaining the Passivhaus standard in cases where the lowest absolute heating solution and compromise solutions are preferred. However, for the lowest cost solutions certification based on heating demand increases the risk of non-compliance under future climate conditions. Therefore, the intended project outcomes and acceptability of future risks (such as overheating) should drive the selection of the most appropriate heating certification criteria. This is to say if a local authority or developer wishes to maximise construction output at minimal cost a peak heating load criterion is preferable since it minimises the risk of future underperformance whilst maximising potential housing delivery. Conversely, if attaining maximum energy efficiency and future robustness to fuel poverty is a priority then an annual heating demand solution may be preferable, but only if future overheating risks are carefully considered (since mitigating future overheating risks will entail capital and operational cost implications). Regardless of the compliance criteria chosen, when designs are cost-optimized for a future climate scenario the annual heating demand or peak load increases. This finding appears counter-intuitive but is a direct consequence of the need to mitigate overheating risks by reducing the south facing glazing area to limit solar gains and due to the slackening of fabric U-values as a result of optimising designs for a milder future climate.

## 5. Conclusion

The importance of this study is drawn from the novel application of a genetic algorithm to the Passive House Planning Package assessment criteria and its incorporation in a multi-criteria decision framework. It has been shown through this implementation that the choice of Passivhaus compliance criteria affects the overheating risk and that the future robustness of each compliance criteria depends largely on key stakeholder preferences.

It was found that for heating objective ideal solutions, the Passivhaus peak heating load criteria could be achieved at a significantly reduced construction cost ($\approx$£56/m$^2$) compared to the ideal heating demand solution. This is a key finding as it highlights the need for careful evaluation of the space heating criteria to be used for compliance at the outset of a Passivhaus project. The cost savings implicated by this simple choice of certification criterion could be shown to produce significant savings for social housing providers if scaled across the UK (assuming the finding is true for other climatic zones).

A key driver of the construction costs across both objective functions for space heating was found to be the glazing. With the proportion of south facing glazing having a positive correlation to both space heating criteria and construction cost. Total glazing area to floor area ratio for both criteria shows a weak correlation to heating demand and load, however. This was found to be due to the directional nature of useful solar gains, and the construction cost of north glazing being less than south due to the south facing glazing using higher g-value panes to increase the transmitted component of incident solar gains.

Use of future climate data under the Intergovernmental Panel on Climate Change A2 scenario for Leicester highlighted overheating risks with certain solutions. The most at-risk solutions were identified to be low-heating demand ideal solutions with a high proportion of south facing glazing. However, trade-off solutions that were lower cost with higher heating demands proved resilient through to 2070. This was due to the lower proportion of south-facing glazing and lower fabric specification. This information is important for social housing providers seeking to avoid future overheating risks in low energy buildings which may otherwise entail dwellings requiring expensive remediation measures. Such remedial costs could potentially be avoided by following the methodology set out here in order to evaluate these issues temporally at the design stage through multi-objective design, and resilience testing.

It should be noted that the design space used for this work was limited, with options selected based on existing UK social housing construction typologies using masonry wall construction typical within the UK. Therefore, it is unlikely to encapsulate the full extent of options available to a designer at the early stage of a construction project. A different outcome could be anticipated for example in a design space with considerably more expensive insulation than mineral wool used for roof and wall insulation, and if cheaper glazing options were pursued. Such a situation would narrow the trade-off between fabric and glazing elements in terms of construction cost and performance and would thereby alter the construction cost savings offered by the heating load objective across the Pareto front. Further work could advance this methodology by using a more sophisticated daylight quality metric (such as spatial daylight autonomy) to ensure designs have adequate access to light throughout the year. This could form an additional objective function or design constraint.

Although this study is focused on the UK context, the methodology presented is applicable in different international contexts by using localised construction information, climatic and cost data. The international application of this methodology is complimented by the Passivhaus standard's global applicability. The approach can also be extended beyond the scope of social housing by applying appropriate variable constraints and construction information relevant to the type of building being considered.

The present work shows the potential importance of multi-objective optimization as an aid to decision making and whole life cost optimization in low-carbon building design. The extensive design space exploration inherent to this approach enables a wider range of design options to be explored compared to manual parametric approaches, thereby increasing the information available to the designer and helping to achieve better informed decision making. The ability to facilitate evidence based decision making makes multi-objective optimization a powerful tool for enabling the proliferation of low and zero energy domestic housing construction through the identification of resilient, low-cost, low-energy solutions within the design space. As such, decision support has a vital role to play both in improving the quality of affordable housing provision and in facilitating the demand side reductions necessary to help mitigate the climate crisis.

## CRediT authorship contribution statement

**Joe Forde:** Methodology, Software, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Data curation, Project administration. **Christina J. Hopfe:** Conceptualization, Writing - original draft, Writing - review & editing, Supervision, Project administration. **Robert S. McLeod:** Conceptualization, Writing - original draft, Writing - review & editing, Supervision, Project administration. **Ralph Evins:** Software, Resources.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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