
This item was submitted to [Loughborough's Research Repository](#) by the author.
Items in Figshare are protected by copyright, with all rights reserved, unless otherwise indicated.

Can multi-objective optimisation achieve more resilient outcomes in the UK's social housing sector?

PLEASE CITE THE PUBLISHED VERSION

<http://buildingsimulation2019.org/>

PUBLISHER

IBPSA

VERSION

AM (Accepted Manuscript)

LICENCE

CC BY-NC-ND 4.0

REPOSITORY RECORD

Forde, Joe, Christina J. Hopfe, Robert S. McLeod, and Ralph Evins. 2019. "Can Multi-objective Optimisation Achieve More Resilient Outcomes in the UK's Social Housing Sector?". figshare.
<https://hdl.handle.net/2134/38151>.

Can multi-objective optimisation achieve more resilient outcomes in the UK's social housing sector?

Joe Forde¹, Christina J Hopfe¹, Robert S. McLeod¹, Ralph Evins²

¹Building Energy Research Group, Loughborough University, Loughborough, UK

²University of Victoria, Victoria, Canada

Abstract

The housing crisis within the UK continues with growing private housing rental prices and increasing levels of homelessness. This situation has been driven by the homogeneous development of housing tenures under-supplying in-demand social and affordable homes. Previous work has seen the implementation of multi-objective optimisation within a broad range of building performance simulation software. The present work is novel in the implementation of a multi-objective decision support framework within software used for compliance with the low energy Passivhaus standard. This use of evidence-based decision support could enable local authorities to make better informed decision in relation to large development seeking Passivhaus compliance.

Results indicate that different optimal solutions are present depending on the criteria used to meet the standard. This means that it is important to select early in the design process either the heating load, or annual heating demand criteria if optimisation techniques are to be applied based on the Passivhaus certification criteria to the design.

Introduction

The domestic housing sector accounts for over a quarter of energy use and carbon dioxide emissions in the UK (Palmer & Cooper 2013). This represents one of the largest areas of consumption for the UK, and hence becomes one of the biggest sectoral areas when considering emission reductions required to meet the Climate Change Act (HM Government 2008), an act that binds the UK Government to nation-wide emission targets. As of March 31st 2016, there were 23.7 million dwellings in England, with 4 million of these being socially or affordably rented dwellings (DCLG 2017a). This represents a significant proportion despite seeing 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 housing crisis within the UK continues with growing private housing rental prices (HM Government 2018) and higher levels of homelessness (DCLG 2017c). These two issues create a complex problem: how to build more affordable homes without introducing significant carbon dioxide emissions or elevated

build costs. This problem is compounded when factors such as fuel poverty (BEIS 2017) indicate the requirement for high quality housing to reduce heating bills. With a suggested number of 75,000 social housing required to be built per year to match the estimated demand (Holmans 2014). This points to a severe issue as construction costs are required to be kept low in order to satisfy developer profit margins. Wherein the objective becomes the construction of the maximum number of dwelling units, whilst maintaining quality in order to combat energy efficiency and fuel poverty and meet the UK's decarbonisation strategy.

A potential solution to this problem is through the application of the voluntary Passivhaus standard (Hopfe & McLeod 2015). This energy performance standard introduces a much stricter set of performance criteria than are currently required for new build dwellings under the UK's Part L of the Building Regulations. Passivhaus has the same energy requirements across all climates (annual heating/cooling load below $10W/m^2a$ or an annual specific heating demand below $15kWh/m^2a$), but different design approaches may be required to meet the standard dependent on the climatic region (Schnieders et al. 2015). The standard has been adopted worldwide (e.g. Canada, Australia and the US). In the UK, multiple local authorities have pioneered the approach through authorities such as Exeter City Council's multiple Passivhaus compliant builds (Exeter City Council 2016). However, the construction of Passivhaus dwellings within social housing context is often cost prohibited, with a premium generally attached to the development of homes to this standard (Barnes et al. 2015).

This paper will explore an emerging approach to decision making in the built environment using multi-objective optimisation. Based on previous work (Evins 2013), and using evolutionary algorithms incorporating real-world design constraints, this paper determines optimal designs based on the heating demand or heating load (two distinct approaches which may be adopted to fulfill the Passivhaus criteria) and capital cost for a region in the UK for social housing using the Passivhaus certification criteria. This work represents, to the authors knowledge, the first im-

plementation of genetic algorithms to the Passivhaus Planning Package (PHPP) for the development of new build domestic dwellings.

Methodology

Selecting an appropriate region

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

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 data-set of fuel poverty levels at a sub-regional definition (BEIS 2017). This data-set has been used to identify the study region. From this data-set, in terms of proportion of households suffering from fuel poverty the Isle of Scilly was identified to be the most effected (19.4%). However, in real terms this represents only 203 (2017) households and a unique situation compared to the rest of England. Therefore the area with the second highest proportion of fuel poverty was selected. This area was Leicester with around 18.2% of homes suggested to be in LIHC fuel poverty, representing 126,348 (2017) households.

To establish 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 a range of data for a range of research applications (Remund et al. 2017). For this project, the weather data was interpolated for Leicester (52.6°N/-1.1°E, altitude 68m), with the nearest weather station with global radiation measurements being Sutton Bonington (approximately 25.5 kilometers away).

Specifying the building performance software and algorithm

The Passivhaus Planning Package (PHPP) is a steady state simulation engine 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. PHPP is also capable of calculating a range of other factors such as peak load, cooling demand and primary energy demand through a range of algorithms (McLeod et al. 2012) which are key performance indicators needed to demonstrate compliance with the Passivhaus standard. This is why it is used as the simulation software in the present work. One of the limitations of PHPP is its steady-state nature which limits the time-resolution of detail available. This is in contrast to dynamic thermal simulation which can provide information on a designed dwelling on hourly time scales and therefore offer a more refined analysis

than steady-state simulations (Hutton 2012).

Passivhaus demonstrates a robust low-energy standard applicable to any climate zone and has already seen application in the UK across both private and social housing projects (Ridley et al. 2014). However, capital cost is still a potential barrier as the Passivhaus costs are above that of low-cost social housing. However, interest has endured in the social sector due to the Passivhaus standard's potential to help alleviate fuel poverty (Exeter City Council 2016).

The Passivhaus standard will be used in this paper due to its applicability across any climate zone (Schnieders et al. 2015), compliance of in-use performance values with modeled values (Schnieders & Hermelink 2006), quality assurance (AECB 2012) and the standard also beginning to be used within the UK as a template for near Zero Energy Buildings (NZEB) (McLeod & Hopfe 2012) as well as within social housing (Ridley et al. 2014, Exeter City Council 2016). The standard has various requirements that must be met to attain certification. The factors required to attain Passivhaus certification at the design stage are shown through 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 condition, with only one of these conditions required for compliance. The heating load criteria differs from the annual heating demand criteria 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, or a moderately cold but overcast day with minimal solar radiation. 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 compliance (Ridley et al. 2014).

The optimisation system specifies (apart from the tool), the optimisation algorithms used to produce optimal results. For the purpose of this work the optimisation algorithm NSGA-II (Deb et al. 2002) was selected based on its well established use within building performance simulation (BPS) (Evins 2013), and the algorithms performance within BPS (Brownlee et al. 2011). The implementation of the NSGA-II algorithm is based on the VBA coded implementation developed by Evins (Evins et al. 2012). A population size of 200 was used for a total of 100 generations with a probability of crossover of 0.7 and probability of mutation at 0.5.

Table 1: Passivhaus certification criteria.

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

¹ The alternate criteria for heating demand is heating load and vice versa.

² The alternate criteria for cooling & dehumidity demand is cooling load and vice versa.

³ Dehumidity contribution (DC)

Choosing the construction and building typology

The area of Leicester is contained within the East Midlands where the most common building typology is semi-detached dwellings (Randall & Beaumont 2011). This is true when all tenancy types are accounted for, but it is unclear if this is also correct in the context of social housing. The 2008 English Housing Survey (DCLG 2017b) identifies across England that the most common house typology for social housing is terraced housing. This is however only marginally higher than the number of semi-detached households. 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 in England, which is masonry construction (DCLG 2017b). The building uses a cavity wall construction with a cavity of up to 300mm (similarly to the Denby Dale Passivhaus (Green Building Store 2011)) which is fully filled with insulation. The maximum total wall thickness is 500mm. The floor is insulated using slab insulation in line with design guidance to achieve an in-principle thermal bridge free junction with the wall system, and allowing for airtightness of the slab (Hopfe & McLeod 2015). A fixed construction was selected for the party wall which consists of 100mm block work, and 200mm 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 Figure 1. The ratio of dwelling length to width remains fixed, with the total floor area divided over the two stories being a variable. Therefore, wall area is calculated by the wall length at the given treated floor area (TFA) multiplied by the variable ceiling height for both stories for a single evaluation. Similarly, roof and floor area are calculated through the TFA variable.

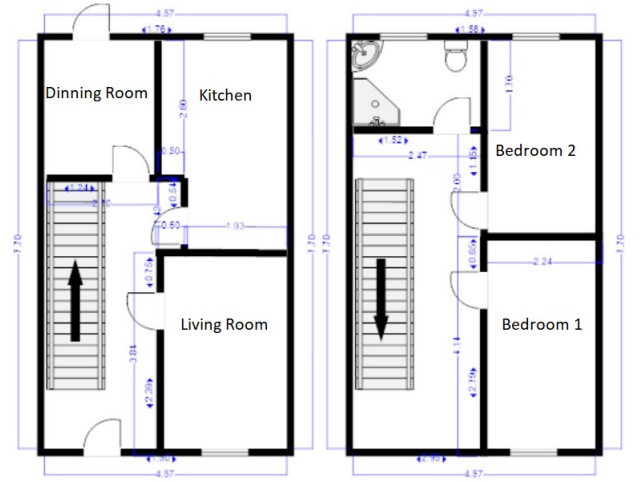


Figure 1: Floor plan illustrating the assumed room structure of the dwelling with ground floor (left) and 1st floor (right)

Objective functions, variables and constraints

Objective functions are functions in a system that are to be minimised or maximised such that. The objective functions selected here are construction cost per square meter and either annual heating demand or heating peak 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:

Table 2: Fixed cost estimates for all construction work and materials; these are not variables.

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

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

Where:

$$\begin{aligned}
A_{Roof} &= \text{Roof area [m}^2\text{]} \\
A_{EW} &= \text{External wall area [m}^2\text{]} \\
A_{PW} &= \text{Party wall area [m}^2\text{]} \\
A_{Floor} &= \text{Ground floor area [m}^2\text{]}
\end{aligned}$$

Variables and fixed construction costs are detailed within Table 2 and 3. Geometric factors such as wall and roof areas are dependent on the TFA and ceiling height variables. Factors such as wall construction costs are separated from insulation costs (which is defined by a variable) and are dependent purely on geometric variables for variation.

For the second objective there are two possible objective functions and both will be used to explore the relationship of optimal design solutions when using either annual heating demand or heating load as an objective function. The first of these two alternate functions is annual heating demand, and will be described through the following:

$$min(f_2) = (Q_T + Q_V) - (Q_S + Q_I) \quad (2)$$

Where:

$$\begin{aligned}
Q_T &= \text{Transmission heat loss [kWh/m}^2\text{a]} \\
Q_V &= \text{Ventilation heat loss [kWh/m}^2\text{a]} \\
Q_S &= \text{Available solar gains [kWh/m}^2\text{a]} \\
Q_I &= \text{Internal heat gain [kWh/m}^2\text{a]}
\end{aligned}$$

The alternate second objective function is heating load. This objective function can be defined similarly to the above but with peak powers instead of

heating demand. The mathematical description of the heating load objective function is the following:

$$min(f_2) = (P_T + P_V) - (P_S + P_I) \quad (3)$$

Where:

$$\begin{aligned}
P_T &= \text{Transmission peak load [W/m}^2\text{]} \\
P_V &= \text{Ventilation heat load [W/m}^2\text{]} \\
P_S &= \text{Solar heating power [W/m}^2\text{]} \\
P_I &= \text{Internal heating load [W/m}^2\text{]}
\end{aligned}$$

The peak load is tested under two different climate conditions (W1 and W2) (see McLeod et al. (2013)) representing two peak loads for heating in the selected climate zone, with the largest heating load selected to represent this criteria.

In order to ensure that only viable solutions are considered the optimisation system incorporated three constraints. These constraints are: overheating risk, minimum glazing area and primary energy demand. Two of these constraints, primary energy demand and overheating risk are required for Passivhaus certification (see Table 1). A further design constraint is applied to the building construction with a minimum of 10% of facade area to be glazing. This criteria is imposed for both the north and south facade to enable each room in the proposed room layout access to daylight.

Results

Overall comparison

Figure 2 demonstrates convergence over the 20,000 evaluations forming the optimisation for both the annual heating demand and heating load objectives. Early evaluations for both objectives demonstrate design solutions with far poorer performance in terms of both cost and heating load or annual heating demand. Comparing only valid Passivhaus designs the range in terms of construction cost is £363/m² for the annual heating demand objective and £292/m² for the heating load objective.

Figure 2 also compares the overall construction costs of the Pareto dominant solutions of the respective optimisation situations with objective functions of heating load and annual heating demand. As can be seen, from the final generation of solutions annual heating demand produces a wider range of results with many more failing the Passivhaus heating criteria. The heating load objective produces a lower but almost identical construction cost ideal solution with a difference of £3.39/m² (0.2% difference). Past the cost ideal solutions, marginal return is seen on further construction costs. By comparison to a baseline UK building regulation (Part L 2013 energy efficiency standard) compliant home with identical geometry and construction situation, the annual heating demand ideal cost solution will reduce demand by

Table 3: *U-value, geometric & cost estimate ranges of variables in the optimisation system.*

Variable	Description	Type ¹	U-val. range [W/m^2K]	Geometric Range [m^2]	Cost range [$£/m^2$]
Floor insulation	C_{FI}	Disc.	0.085 - 0.126	TFA/2	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	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.	$C_{Windows}$	10-100% facade area	Linked to glazing
East-window area	$A_{Windows}$	Disc.	$C_{Windows}$	0-100% facade area	Linked to glazing
North-window area	$A_{Windows}$	Disc.	$C_{Windows}$	10-100% facade area	Linked to glazing
Ceiling height	-	Cont.	-	2.3-2.6m	Linked to fabric
MVHR ²	C_{MVHR}	Disc.	85-95% efficiency	-	£6095 - 6633
Air change rate	-	Cont.	0.1-0.6 ACH	-	NA

¹Type selection between discrete (Disc.) and continuous (Cont.).

²Mechanical Ventilation with Heat Recovery (MVHR)

30.26 kWh/m^2a , but at a cost uplift of £388.85/ m^2 (BCIS 2015). The results for the Passivhaus design are explored in the following.

Comparison of variables

Figure 3 shows the percentage variable selection for both annual heating demand and heating load objectives for each evaluation in the final generation of solutions. As can be seen, most runs end up with a dominant variable being selected for all evaluations. However, there are some variables which remain non-dominated, these include south facing window area, roof U-value, MVHR efficiency and floor U-value. The two most varied are south facing window area and roof U-value, with south facing window area being very non-dominant in terms of selection for annual heating demand. As this factor has a large influence on both annual heating demand and construction cost, this drives a wide range of annual heating demand values along the Pareto front. The effect of south facing glazing is lesser for the heating load objective, but still important, with fabric factors such as roof, wall and floor U-values and floor area showing variation, although it is clear that south glazing area still drives the objective value differences along the Pareto front.

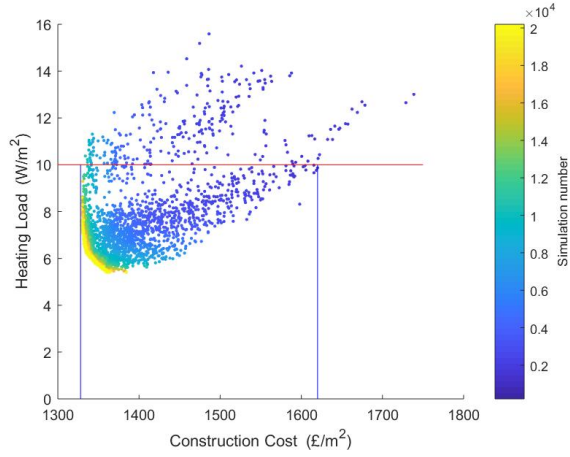
The relationship between south facing glazing and construction cost is significantly stronger for the annual heating demand objective, with evaluated design solutions demonstrating a wide range of south facing glazing areas. The relationship between south facing glazing and construction cost for the heating load objective is significant, albeit not as strong as that shown for annual heating demand. A smaller range of south facing glazing area is seen among viable design solutions for heating load. This difference in selection of glazing area drives a construction cost difference between the two criteria when used as objective functions. This is in agreement with findings from practical examples found during the Future Homes project (Ebbw Vale, Wales) where single objective optimisation was first applied to this problem

(McLeod 2010).

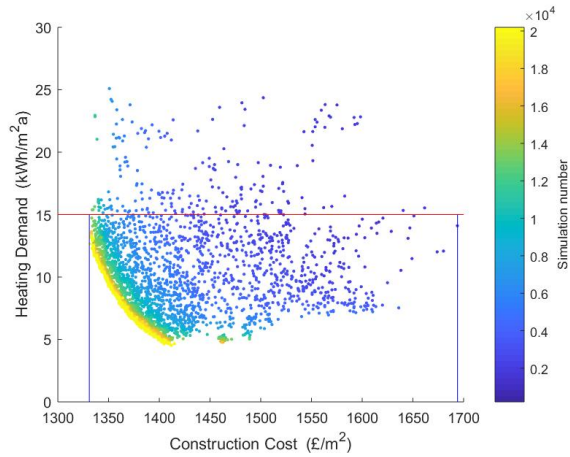
Across all generations multiple-regression analysis showed that for specific heating demand the strongest correlation with specific construction cost comes from south facing glazing ($r = 0.978$) as demonstrated by Figure 3, with the greatest correlations for reducing cost coming from decreased north facing glazing ($r = -0.827$), reduced floor insulation ($r = -0.840$) and reduced roof insulation ($r = -0.709$). In relation to the specific heating load the second strongest correlation with construction cost comes from south facing glazing ($r = 0.747$) whilst the strongest is ceiling height ($r = 0.792$). The strongest reduction in cost comes from the selection of uninsulated window frames ($r = -0.798$), whilst increased floor area ($r = -0.583$), decreased north facing glazing area ($r = -0.336$) and decreased floor insulation level ($r = -0.307$) show a strong to medium correlation.

Cost ideal solutions

Figure 4 shows the Pareto fronts for each of the heating objectives, highlighting the two cost ideal solutions. As can be seen, there is very little difference between these two cost ideal solutions. The difference between the heating load and annual heating demand solution is £3.48/ m^2 with the heating load solution being lower in cost. The lack of difference between these two solutions is due to the identical glazing area for both designs. Each design has 4.5 m^2 of glazing on both the north and south facades, the lowest allowable value for the selected wall area of each. This difference is driven by alternate fabric element selection, resulting in different specifications for wall, floor and roof insulation thickness. Examining this on an element by element basis the cost breakdown revealed that the wall, floor and roof insulation thickness the heating load solution used 30mm (£0.28/ m^2 cost difference), 50mm (£1.82/ m^2 cost difference) and 100mm (£1.38/ m^2 cost difference) less insulation in comparison to the best heating demand solution (AECOM 2017).



(a) Heating Load



(b) Heating Demand

Figure 2: All valid evaluations for the heating load and annual heating demand objective. Convergence is shown towards the Pareto optimal solutions demonstrated for both objectives. The horizontal, red line indicates the maximum allowable annual heating load or demand for a valid Passivhaus design. The vertical, blue lines indicate the minimum and maximum construction cost solutions that are compliant with the Passivhaus criteria.

Discussion

It was found that between the cost ideal solutions for annual heating demand and heating load a small cost difference is present due to differences in the fabric specification selected. The main saving from the fabric specification came from a reduction in floor insulation thickness. The floor insulation was more expensive than the roof and wall insulation which used mineral wool, as insulated slab was used to decrease thermal bridging (Hopfe & McLeod 2015). Both cost ideal solutions utilised the smallest possible glazing area arrangement. This meant zero east facing glazing and 10% of wall area for each of the north and south facades to be glazed. Across the entire dwelling this would offer an average daylight

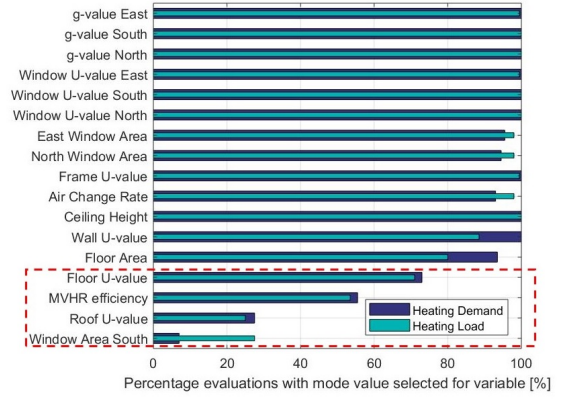


Figure 3: Most common, variables across the final generation of the optimisation. Most variables for both conditions demonstrate a dominant selection by this final generation. The red dashed box indicates variables that are yet to converge and create solution diversity across the final generation.

factor of 2.24%, marginally above the minimum of 2% recommended within British Standard BS 8206-2. This is a reasonable design pathway in the described design space for a cost ideal solution as glazing area offered the highest cost per meter squared of all variable components. When the system optimised without design constraints, glazing area for cost ideal solutions tended towards zero. Therefore, the trade-off between increased solar gains (minus transmission losses) and construction cost tended towards reducing solar gains, instead opting for increased fabric specification and also decreased infiltration. As infiltration did not have an associated cost this always tended towards the minimum value as highlighted by Figure 4. This assumption is unlikely to be true in a market where performance based contracts for factors such as airtightness is novel. However, in a mature market (where performance contracting is well-established) the uplift could be minimal or non-existent.

Across the entire Pareto front for each of annual heating demand and heating load there existed a mean construction cost difference of $\text{£}17.98/\text{m}^2$. The range of south facing glazing area used by heating load solutions is much less than that used by annual heating demand solutions. This is due to the calculation methods used for calculating these heating criteria. Annual heating demand calculation determines the energy balance for each month. Solar gains through the south facing facade glazing will outweigh transmission losses through the glazing on average across the heating season, creating a situation where more south facing glazing will decrease annual heating demand. For heating load the calculation method uses two test periods, one overcast but mild and another clear sky but cold, and selects the worse performing period. As south facing glazing area increases the

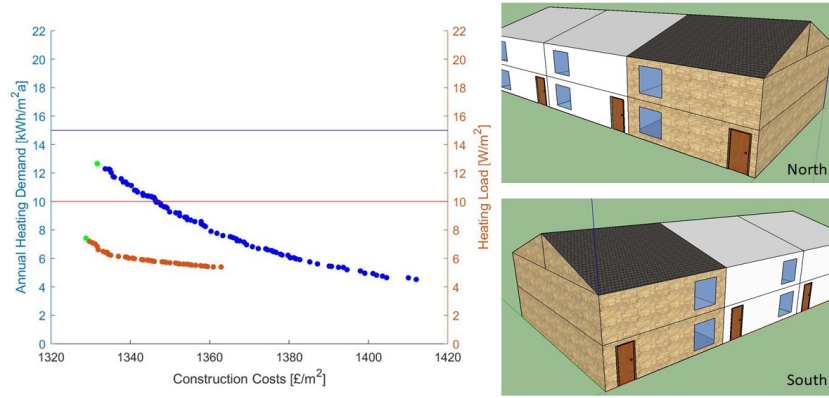


Figure 4: Pareto front highlighting the lowest construction cost solutions for dwellings complying with the annual heating demand (blue) and the peak heating load (red). The horizontal lines in red and blue represent the maximum allowable value for a solution to be Passivhaus compliant for the given objective. Visual representations (right) shows that the external appearance of these two dwellings are identical as they share the exact window-wall ratio for all facades (which represents the minimum allowable value possible).

clear sky test day will decrease heating load as a response to the solar gains causing the overcast day to become the period used for compliance testing. If south facing glazing area is decreased, the overcast day performs better and the clear sky test day is selected. This leaves only a small space for south facing glazing to dictate heating load value. Therefore, there exists less relation with south facing glazing compared to annual heating demand, and so a smaller cost range exists for the Pareto front generated for the heating load objective. The implications of this is that the use of the annual heating demand without the use of optimisation techniques in design has a higher risk of non-compliance.

The finding that heating load delivers a lower construction cost solution than annual heating demand correlates with similar findings by McLeod (2010) and is significant as heating load represents a less widely used heating compliance criteria for Passivhaus certification (Ridley et al. 2014). The use of the heating load objective also offers greater security to a designer as the constrained window of south facing glazing required will mitigate dependence on this expensive element to further improve energy performance, helping to highlight the building fabric, infiltration and HVAC efficiency as keys to Passivhaus compliance. However, the design space used for this work was limited, with options selected based on existing UK social housing construction and Passivhaus practice with masonry construction within the UK. Therefore it is unlikely to encapsulate the extent of options available to a designer at the early stage of a construction project. A different outcome could be achieved for example in a design space with considerably more expensive insulation than mineral wool used for roof

and wall insulation, and cheaper glazing options pursued. Such a situation would narrow the trade-off between fabric and glazing elements in terms of construction cost and performance and would alter the construction cost savings offered by the heating load objective across the Pareto front.

Conclusion

The importance of this work is drawn from the unique application of genetic algorithms to BPS, in this case PHPP, to support decision making in the context of social housing at a critical time within the UK housing market, to offer support for decision making. Further, this work expands knowledge through the unique application of genetic algorithms to the PHPP and to the social housing context within the UK. The findings present the economic case for the use of multi-objective optimisation utilising genetic algorithms to search large design spaces and the benefit of this against other Passivhaus designs in the considered design space which has been informed by the constraint of social housing for the specific case of a masonry end of terrace dwelling in Leicester.

The research presented within this paper also attempted to compare optimised results for the two space heating criteria of the Passivhaus standard to understand the variables selections required to meet each criteria. It was found that for the cost ideal solutions, the solutions meeting the heating load criteria achieve a lesser construction cost than the ideal cost heating demand solution (£3.48/m²), with a larger cost difference across the wider Pareto front on average (£17.98/m²). This is a key finding as it highlights the need for careful selection of space heating criteria to be used for compliance at the onset of a Passivhaus

project. A key driver to the construction costs across both objective functions for space heating is found to be glazing. With the proportion of south facing glazing having strong negative correlation to both space heating criteria and a positive correlation to construction cost.

References

- AECB (2012), 'Documentation Required for Passivhaus Certification'.
URL: <https://www.aecb.net/wp-content/plugins/aecb-publication-library/librarian.php?id=8130&file=8096>
- AECOM (2017), *Spon's Architects' and Builders' Price Book 2018*, 143 edn, CRC Press.
- Barnes, J., AECOM & Trust, P. (2015), Passivhaus Capital Cost Research Project.
URL: [http://www.passivhaustrust.org.uk/UserFiles/File/Technical Papers/150128 PH Capital Costs.pdf](http://www.passivhaustrust.org.uk/UserFiles/File/Technical%20Papers/150128%20PH%20Capital%20Costs.pdf)
- BCIS (2015), 'Housing development : the economics of small sites the effect of project size on the cost of housing construction Report for The Federation of Small Businesses'.
- BEIS (2017), Annual Fuel Poverty Statistics Report, 2017 (2015 data), Technical report, HM Government.
URL: <https://www.gov.uk/government/collections/fuel-poverty-statistics>
- Brownlee, A. E., Wright, J. A. & Mourshed, M. M. (2011), A multi-objective window optimisation problem, in '13th Annual Conference Companion on Genetic and Evolutionary Computation', Dublin, Ireland.
- DCLG (2017a), 'Dwelling Stock Estimates: 2016, England'.
- DCLG (2017b), 'English Housing Survey'.
URL: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/675942/2016-17-EHS-Headline-Report.pdf
- DCLG (2017c), 'Statutory homelessness and prevention and relief, July to September (Q3) 2017: England'.
- Deb, K., Pratap, A., Agarwal, S. & Meyarivan, T. (2002), 'A Fast and Elitist Multiobjective Genetic Algorithm: NSGA-II', *IEEE Transactions on Evolutionary Computation* **6**(2).
- Evins, R. (2013), 'A review of computational optimisation methods applied to sustainable building design', *Renewable and Sustainable Energy Reviews* **22**, 230–245.
- Evins, R., Pointer, P., Vaidyanathan, R. & Burgess, S. (2012), 'A case study exploring regulated energy use in domestic buildings using design-of-experiments and multi-objective optimisation', *Building and Environment* **54**, 126–136.
- Exeter City Council (2016), 'Exeter City Council: Low Energy development Information Pack'.
URL: <http://www.houseplanninghelp.com/wp-content/uploads/2016/09/Exeter-City-Council-Scheme-Information.pdf>
- Green Building Store (2011), 'Technical Summary: Denby Dale Passivhaus'.
URL: <https://www.greenbuildingstore.co.uk/wp-content/uploads/Technical-summary-Denby-Dale-Passivhaus.pdf>
- HM Government (2008), 'Climate Change Act'.
URL: http://www.legislation.gov.uk/ukpga/2008/27/pdfs/ukpga20080027_en.pdf
- HM Government (2018), 'Index of Private Housing Rental Prices, Great Britain'.
- Holmans, A. E. (2014), Housing need and effective demand in England A look at the big picture , Technical Report April, Cambridge Centre for Housing and Planning Research.
- Hopfe, C., J. & McLeod, R., S. (2015), *The Passivhaus Designer's Manual*, Routledge.
- Hutton, A. (2012), 'Dynamic Simulation Modelling'.
URL: <https://www.cibse.org/getmedia/321f4967-1455-4d0f-9199-d2cc399ae37f/cb10.pdf.aspx>
- McLeod, R. S. (2010), Passivhaus and PHPP implications for UK designers? Passivhaus seminar chair and speaker. , EcoBuild, Earles Court, London.
- McLeod, R. S. & Hopfe, C. J. (2012), 'A proposed method for generating high resolution current and future climate data for Passivhaus design', *Energy and Buildings* **55**, 481–493.
- McLeod, R. S., Hopfe, C. J. & Rezgui, Y. (2012), 'A proposed method for generating high resolution current and future climate data for Passivhaus design', *Energy & Buildings* **55**, 481–493.
- McLeod, R. S., Hopfe, C. J. & Rezgui, Y. (2013), 'Hygrothermal implications of low and zero energy standards for building envelope performance in the UK', *Journal of Building Performance Simulation* **6**, 367–384.
- Palmer, J. & Cooper, I. (2013), 'United Kingdom housing energy fact file'.
URL: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/345141/uk_housing_energy_fact_file_2013.pdf

Randall, C. & Beaumont, J. (2011), Housing, Technical Report Social Trends 41, Office for National Statistics.

Remund, J., Mueller, S., Kunz, S., Huguenin-Landl, B., Studer, C. & Cattin, R. (2017), *Meteonorm Handbook part 1: Software*, 7 edn.
URL: <http://www.meteonorm.com/images/uploads/downloads/mn72-software7.2.pdf>

Ridley, I., Bere, J., Clarke, A., Schwartz, Y. & Farr, A. (2014), ‘The side by side in use monitored performance of two passive and low carbon Welsh houses’, *Energy and Buildings* **82**, 13–26.

Schnieders, J., Feist, W. & Rongen, L. (2015), ‘Passive House for different climate zones’, *Energy and Buildings* **105**, 71–87.

Schnieders, J. & Hermelink, A. (2006), ‘CEPHEUS results: Measurements and occupants’ satisfaction provide evidence for Passive Houses being an option for sustainable building’, *Energy Policy* **34**(2 SPEC. ISS.), 151–171.