Taylor & Francis
Taylor & Francis Group

Intelligent Buildings International

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tibi20

Carbon-optimised refurbishment measures for a simulated house in Edinburgh

Seyed Masoud Sajjadian

To cite this article: Seyed Masoud Sajjadian (20 Mar 2025): Carbon-optimised refurbishment measures for a simulated house in Edinburgh, Intelligent Buildings International, DOI: 10.1080/17508975.2025.2480114

To link to this article: https://doi.org/10.1080/17508975.2025.2480114

Published online: 20 Mar 2025.

INTELLIGENT BUILDINGS INTERNATIONAL
https://doi.org/10.1080/17508975.2025.2480114

Carbon-optimised refurbishment measures for a simulated house in Edinburgh

Seyed Masoud Sajjadian

School of Computing, Engineering and the Built Environment, Edinburgh Napier University, Edinburgh, UK

ABSTRACT

This research is conducted in the context of current efforts for net zero delivery in Scotland. Such a target is widely acknowledged as challenging by the industry necessitating some aspects of building design to change for higher performance. This study looks at 'what is optimal' in terms of carbon, both in operation and embodied in materials for dwellings by using the Pareto Optimal solution in a simulated case study in Edinburgh. At first, the potential of available glazing systems to find an optimum in operational and embodied carbon is investigated. The study then calculated the embodied carbon and operational carbon for added insulation and compared them against each other to find the most energy and environmentally-efficient option. An analysis to investigate the LCA of the 52 HVAC systems for the second phase of the building's life span is then conducted and finally a parametric analysis of using shading devices to observe if they can offer operational savings for the case study concludes the paper. This study demonstrates some recommended design solutions by globally used standards e.g. Passivhaus and common practices may not lead to carbon emissions minimisation in the refurbishment process.

ARTICLE HISTORY
Received 6 August 2024
Accepted 7 March 2025

KEYWORDS
Multi-objective optimisation; pareto-optimal front; sustainable refurbishment; net zero; building performance simulation

1. Introduction

In the UK, refurbishment of existing dwellings is key to achieving net zero by 2050 as they account for about 30% of energy use and around 20% of greenhouse gas emissions in the UK (House of Commons Environmental Audit Committee 2021). In England and Wales, achieving EPC C by 2030 and by 2033 in Scotland has been a target since 2020 (Department for Business, Energy and Industrial Strategy 2020; Scottish Government n.d.). To support the low carbon refurbishment of homes, building regulations, PAS 2035, PAS 2030, Enerphit, Energiesprong and Trust Mark are developed and widely used in the UK. The standard Assessment Procedure (SAP) and Reduced Data SAP (RdSAP), the Passive House Planning Package (PHPP) and dynamic thermal simulations have been the main tools for assessing and planning for the upgrades. The barriers have also been well documented by (UKGBC et al. 2021) including cost and finance, supply chain, householder offering, tenure issues, national policies and technical issues. One of the primary technical barriers is the complex process of selecting the appropriate refurbishment solution. This challenge can be effectively tackled by harnessing the optimisation capabilities integral to simulation tools. Such tools offer the means to thoroughly analyse various refurbishment options, considering environmental impact during the life span of the building.

There are 29 million homes in the UK and only 15% of them have been built since 1990. Such data indicates the UK has one of the oldest stocks in Europe (Department of Business, Energy and Industrial Strategy Committee 2022). UK Energy Research Centre (2020) estimated that at least one million homes need to be

CONTACT Seyed Masoud Sajjadian m.sajjadian@napier.ac.uk

refurbished every year for 30 years to meet the net zero target by 2050. On the other hand, before Covid pandemic over 3.2 million households in England (13% of all households) were suffering from fuel poverty. The percentage was significantly higher in Scotland and Northern Ireland (25% and 18% respectively) and slightly lower in Wales (12%) (Whitehead, Taylor-Robinson, and Barr 2022). Furthermore, the UK public has also experienced significant growth in living costs which has escalated the situation even further. Public Health England states strong relationship between poverty and different kinds of illness including heart diseases, cancer, respiratory illnesses and even suicide (Public Health England 2018; ASHRAE 2020; McCormack et al. 2016). Sustainable refurbishment plays a crucial role in the UK's efforts to create healthier communities, environmental conservation and combating climate change.

The UK government has introduced various incentives and regulations to encourage sustainable refurbishment, including grants, tax incentives, and building standards. In literature, two prevalent modes of classification are described as shallow and deep even though some studies have proposed more detailed and less conventional classifications for refurbishment (Shah 2012; Fahlstedt et al. 2022). The net-zero target for the UK arguably requires deep refurbishment where more than two to three minor modifications should be made to a building. Deep refurbishment generally covers the heating system and is hence crucial for lowering emissions to zero (Semprini, Gulli, and Ferrante 2017).

Furthermore, discussions about overall carbon emissions from refurbishment or replacement of existing buildings are analysed in several studies and various governments and agencies with no firm consensus of which would save more carbon emissions (Schwartz, Raslan, and Mumovic 2022; Erlandsson and Levin 2004). The studies highlight the extent of the challenge in relation to existing buildings, on one hand, there is no one-size-fits-all decision-making framework for the refurbishment process and on the other hand, the decision to refurbish or replace is debatable. (Power 2008; Carpino, Bruno, and Arcuri 2020) added more intricacy to the debate and underlined the social importance of refurbishment and neighbourhood renewal in the context of energy efficiency, cost and carbon measures.

Refurbishment with the primary objective of achieving carbon neutrality or carbon reduction as much as possible has been the target of various studies since the publication of the UK Net Zero Strategy. The concept generally aligns with the global commitment to address climate change by reducing CO2 emissions and promoting sustainable practices within the built environment sector. Table 1 summaries all those studies in the UK residential building context since 2020 using the Google Scholar database, the methodology they used and their findings:

Considering the aforementioned studies, the need for developing methods and frameworks for refurbishment in the context of net zero policies in the UK is evident. This paper aims to use a case study and apply the optimisation methods to find the most favourable option (optimal) in a detached house in Edinburgh.

Table 1. Summary of sustainable refurbishment studies for UK dwellings since 2020.

Authors	Focus	Methods	Findings
Li et al. (2022)	Retrofit interventions to the English residential stock	National Household Model (NHM)	Rapid development of Heat Pump and wind turbines in the country and attention to materials with low embodied carbon
Bennadji et al. (2022)	Energy and Carbon reduction potential of the existing UK residential buildings	Applying the building typology approach to predict energy savings targeting the EnerPHit standard	The energy-saving potential of refurbishment to PH standard in the UK is 87% and carbon reductions are about 76%.
Anthony Higney and Kenneth Gibb Higney and Gibb (2022)	Tenements net zero retrofit in Glasgow	Economic appraisal and cost-benefit analysis	Higher values and higher benefit-cost ratios for the refurbishment of tenements compared to demolition
Royapoor et al. (2023)	UK domestic heating	Review paper	The hydrogen cost for home heating could be 1.7 times the cost of natural gas cost at the end of the decade even though challenges remain in user acceptability
Lingard (2020)	Optimum energy-efficient retrofit required to minimise energy use and electrical demand for an average semi-detached dwelling using a heat pump	Dynamic Thermal Simulation with IES VE	Solid wall insulation and low U-value glazing are the cost-optimal solution

2. Methods

The house model was created in DesignBuilder V 7.0.2.006 which uses Energyplus in its calculation engine. The software models energy load, comfort, airflow, ventilation, etc. The origins of EnergyPlus are Building Loads Analysis and System Thermodynamics (BLAST) and the Department of Energy 2 (DOE2) developed by the United States Department of Energy. EnergyPlus uses Conduction Transfer Function (CTF) calculations (The Board of Trustees of the University of Illinois and the Regents of the University of California through the Ernest Orlando Lawrence Berkeley National Laboratory 2010). The optimisation capability of the software based on the principles of the Genetic Algorithm is conducted. This provides a trade-off between embodied carbon and operational carbon. In any refurbishment project, there is an opportunity to enhance building performance measures including the following items:

- Layouts and zoning for effective HVAC operation
- Solar gain control with glazing types, sizes and shadings
- Minimisation of heat loss with insulations
- Upgrading heating system

In this study, the refurbishment choices in passive domain were common and low-tech, as they are most cost-effective, affordable, and most likely to be practical as per the general policy of the UK government for refurbishment (RICS, n.d.) and without alteration to the building aesthetics and general architecture as shown in Figure 1:

When embodied carbon is reliably quantifiable and the total number of designs (C^v), Where C is the number of Choices, V is the number of Variables, is over 3, the optimisation process is performed to create a spread set of solutions and a Pareto-optimal front. The Pareto-optimal front, also known as the Pareto frontier or Pareto set, is a concept in multi-objective optimisation and decision-making named after the Italian economist and sociologist Vilfredo Pareto (Pareto 2014). It represents the set of all feasible solutions in a multi-objective optimisation problem for which no other feasible solution improves one objective without degrading at least one other objective. In simpler terms, in a scenario where multiple conflicting objectives exist to optimise simultaneously, e.g. maximising profit while minimising cost, the objectives are often in conflict, meaning improving one might worsen another. The Pareto-optimal front covers all the solutions where one objective cannot be improved without sacrificing performance in another.

Visualising the Pareto-optimal front includes plotting the trade-offs between the objectives. Each point on the Pareto-optimal front represents a solution where it is not possible to make any objective improved without making another one inferior. Solutions that sit outside of the Pareto front are considered dominant because there exists at least one other solution that is better in at least one objective and not worse in any others.

The Pareto-optimal front is necessary for decision-making as it helps decision-makers understand the trade-offs inherent in their choices. It provides a set of options that represent the best compromises between conflicting objectives, allowing decision-makers to choose the most suitable solution based on their

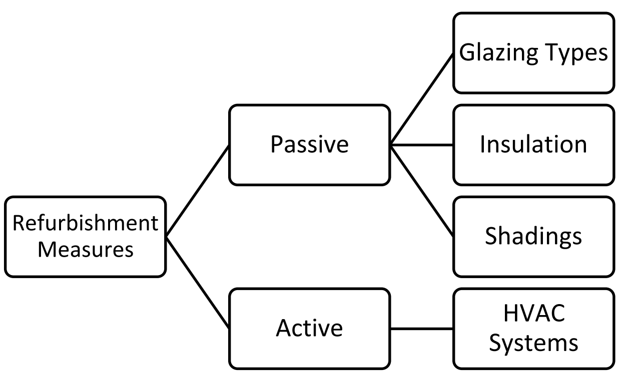

Figure 1. Refurbishment measures for simulations.

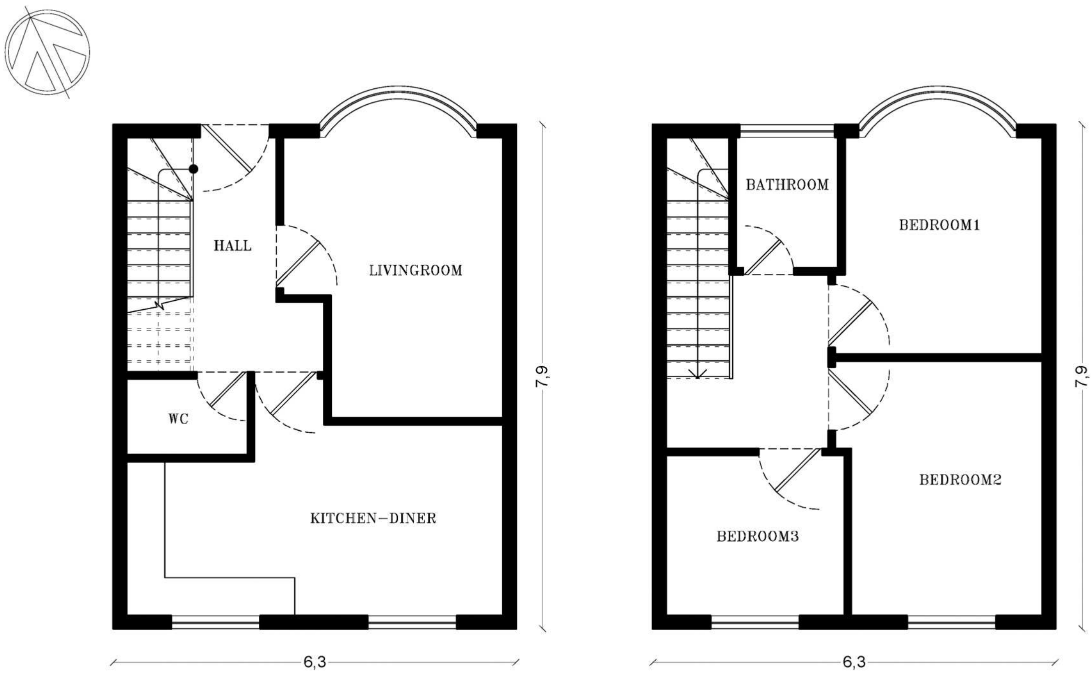

Figure 2. Floor plans of the simulated house in metres.

preferences and priorities. This method allows the most effective design solutions to be selected among a huge number of choices in refurbishment and minimising carbon emissions. The model where the process is implemented is a 3-bed house, with a floor area of 99.54 m^2 as shown in Figures 2 and 3. The existing condition of the house is provided in Table 2:

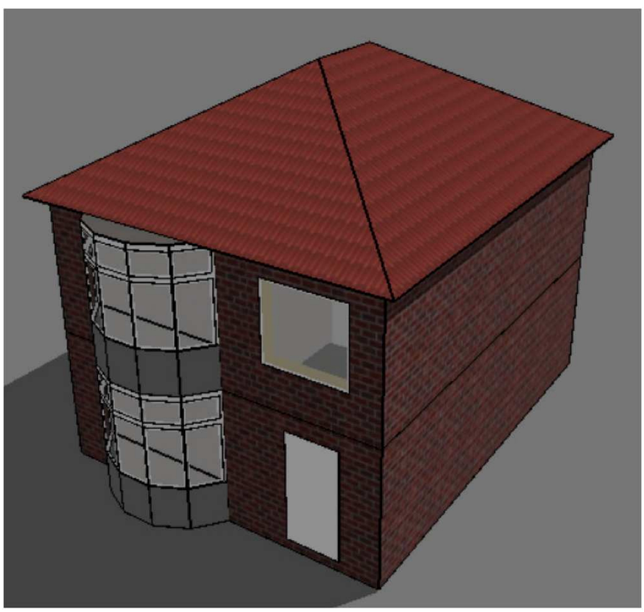

Figure 3. 3D views of the model used for simulations.

Table 2. Simulated house specification.

Construction types	Brick and Block
U-Value for External Walls	0.35 W/m^2K
U-Value for Roof	0.34 W/m^2K
Model Infiltration	5 ac/h
Heating System	Gas with boiler CoP 0.580
Glazing Types	Double-glazed 6 mm Argon filled U-Value 2.5 W/m^2K

3. Results and discussion

Step 1: Glazing

There is a very limited number of studies that measure the significance of different glazing types in the context of refurbishment. (Ganji Kheybari et al. 2022) focused on smart glazing systems in a multi-objective optimisation approach and found even though such technology reduces operational carbon but high embodied carbon made it not a favourable option compared to static systems available in the global market. A study by (Bizonova, Darula, and Dubnicka 2022) offered insight on light transmission in the refurbishment process when low-emission glass pane with hard coating were used. Low Emissivity coating glazing has also been used for various refurbishment studies (Somasundaram et al. 2020; Urbikain 2020; Bougiationi, Alexandrou, and Katsaros 2023) in isolation and also in combination with other elements such as insulation and shadings and all found the strategy effective with various energy savings even though no consideration of embodied carbon was noted.

The refurbishment process in this study starts by looking at 220 glazing types from single-glazed to triple glazed available in the global market. Variations in types include the conductivity rate, light transmission, total solar transmittance and direct solar transmission. 5 optimal designs were found as shown in Figure 4. The three with the lowest operational carbon (between 12K-12.5 K) are shown in Table 3.

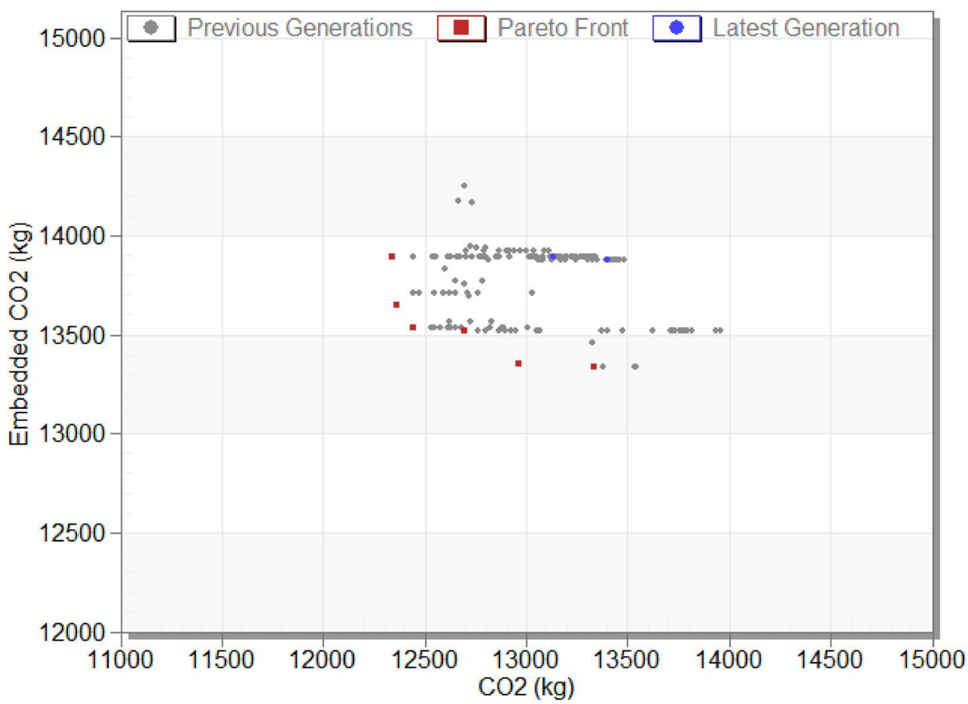

Figure 4. Optimisation analysis results, minimisation of CO2 and Embodied CO2.

Table 3. 3 optimal choices for glazing systems and the specifications.

Types	u-value	Cost	Light transmission	Total solar transmittance SHGC	Direct solar transmission
Generic Double Glazed 6 mm/13 mm Argon filled DesignBuilder Library Reference: Dbl Elec Ref Bleached	1.323	210 GBP/m^2	0.657	0.48	0.364
SGG PLT XN 4/16/4 Reference: https://www.saint-gobain-glass.co.uk/en-gb/sgg-planiclearr	1.44	100 GBP/m^2	0.819	0.649	0.595
Generic Double Glazed LoE 3 mm/13 mm Argon	1.51	180 GBP/m^2	0.769	0.649	0.538

Table 4. Optimal choice for insulation thickness.

Internal insulation	Embodied carbon (kg)	Operational carbon (kg)
U-Value 0.232 XPS Internal 50mm	14247.4	12862.7
U-Value 0.11 XPS internal 200mm	15317.7	12744.0
U-Value 0.173 XPS internal 100mm	14606.2	12803.1
No added insulation	13892.1	13020.4

Step 2: Internal insulation

The existing model has XPS insulation. Mixing different types of insulation materials may lead to uneven thermal performance due to differences in thermal conductivity. This will lead to variations in heat transfer and could potentially affect moisture absorption and air infiltration (Koenders and Knaack 2018). Therefore, the same insulation with different thicknesses within the boundaries of existing building regulations before the 2023 update was used for optimisation. Table 4 shows the embodied and operational carbon in each studied case and Figure 5 demonstrates the outcome of the analysis. The optimal choice with insulation appears to be with 50 mm thickness to reach a U-Value of 0.232.

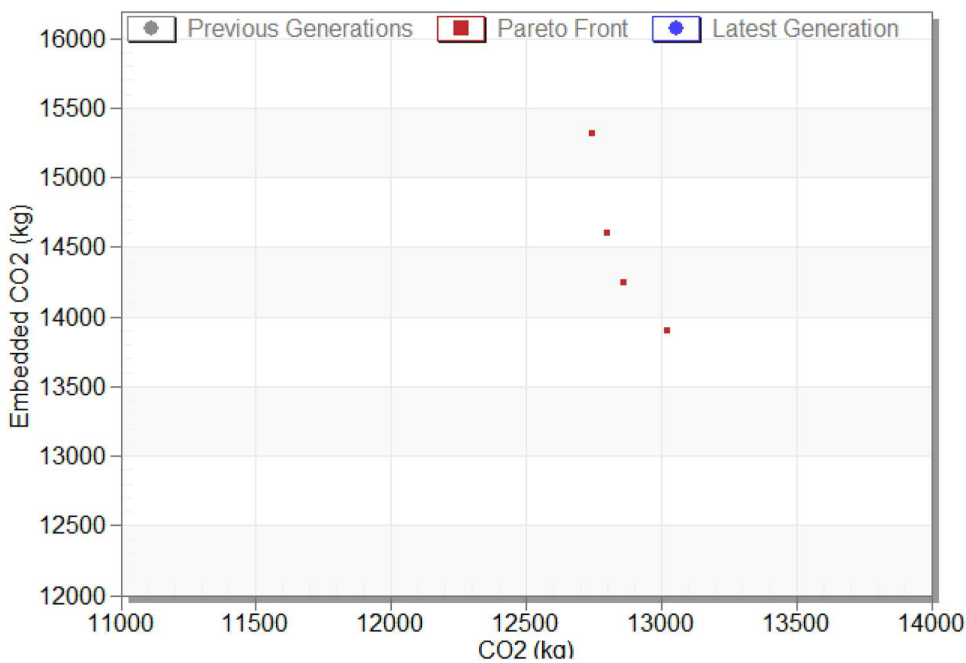

Figure 5. Optimisation analysis for U-Value and added internal insulation.

Table 5. Optimal choices in LCA and Operation compared to the existing system.

	LCA	Operational CO2
Solar Assisted Absorption Chiller	175,477.4	3509.5
GSHP with Ground Heat Exchanger	292,470.2	5849.4
GSHP Water to Water – Heated Floor	351,954.6	7039.0
Existing* – Radiator Heating and Boiler	509,284.7	10185.6

Step 3: HVAC Systems

The decarbonisation of heating and cooling is complex and progressing slowly and the emissions limit at each stage should be considered in the optimisation process. In light of this, this paper assesses the environmental performance of 52 AC systems used across the UK by considering a comprehensive approach like the Life Cycle Assessment (LCA). The selection include suitable HVAC systems for UK houses based on their heating and ventilation functions. Heating Systems include gas central heating (combi and system boilers), electric heating options (electric radiators and storage heaters), heat pumps (both air-source and ground-source), renewable and hybrid Systems. A similar approach was used by (Kathiravel, Zhu, and Feng 2024) in Canada who found the colder the climate the better ASHP could be in LCA analysis. (Smith, Bevacqua, Tembe, & Lal, 201) found GSHP an optimum solution when LCA is analysed in the USA. Simulation results as shown in Table 5 and Figure 6 found Solar Assisted Absorption Chiller with the lowest, and GSHPs as the second and third most favourable solution. All three systems demonstrate significantly lower carbon emissions in operation and LCA compared to the existing system with gas boiler and radiators.

Step 4: Shadings

Shading devices intercept solar radiation when it reaches the building envelope and reduce the amount of heat absorbed by interior spaces. By minimising heat transfer, shading devices could potentially contribute to maintaining stable indoor temperatures and reducing energy consumption for climate control when radiation is at a high level. Shadings can also influence natural daylighting within a building while minimising glare and excessive brightness.

A simplified parametric analysis was used to observe if 0.5, 1, 1.5 and 2 m overhang can offer any reduction in carbon emission throughout the year. The embodied carbon of the shadings is neglectable in the simulation and the results demonstrate the longer the shading the higher the emissions in the model and the design option offers no performance enhancement in the model as shown in Figure 7. This is due to the reduced solar gain during the year and no significant cooling load reduction for the HVAC system. The climate of Edinburgh is temperate and oceanic. Proximity to the sea mitigates significant variations in temperature. The climate records from 1991 to 2020 for Edinburgh indicate an average minimum temperature of 1.67 °C in January and a maximum average temperature of 19.29°C in July. Sunshine hours are at their lowest in December, with 49.15 hours, and peak in May at 194.66 hours. Annually, the average rainfall amounts to 727.7 mm (Met Office n.d.).

Upgrading existing dwellings to improve their environmental performance requires balancing the multiple objectives involved in the process which can often be very complex. There are several trade-offs between environmental factors and often a refurbishment may not reduce overall carbon emissions. One effective approach utilised in this study is the concept of Pareto optimality, which originates from economics. A solution is considered Pareto optimal if no other solution can make one objective better off without making at least one other objective worse off. In the context of sustainable refurbishment, this means finding refurbishment strategies where improving one aspect (e.g. energy efficiency) does not significantly weaken from others (e.g. embodied carbon).

A Pareto optimal approach helps identify refurbishment strategies that provide the best balance for environment performance. Enhancing such performance (e.g. reducing carbon footprint) involves sophisticated modelling and optimisation techniques. This requires accurate data and computational resources to analyse various refurbishment scenarios effectively. Building performance and refurbishment outcomes can vary significantly based on location, building type, and usage patterns. Pareto optimal solutions need to be tailored to specific contexts to be truly effective. There is also some immediate matters to consider such as costs which could add more complexity for decision makers. Evaluation of trade-offs and the inclusion of multiple objectives can lead to better acceptance in the journey toward net zero. Solutions identified through Pareto optimality are more likely to achieve effective sustainability by balancing the goals.

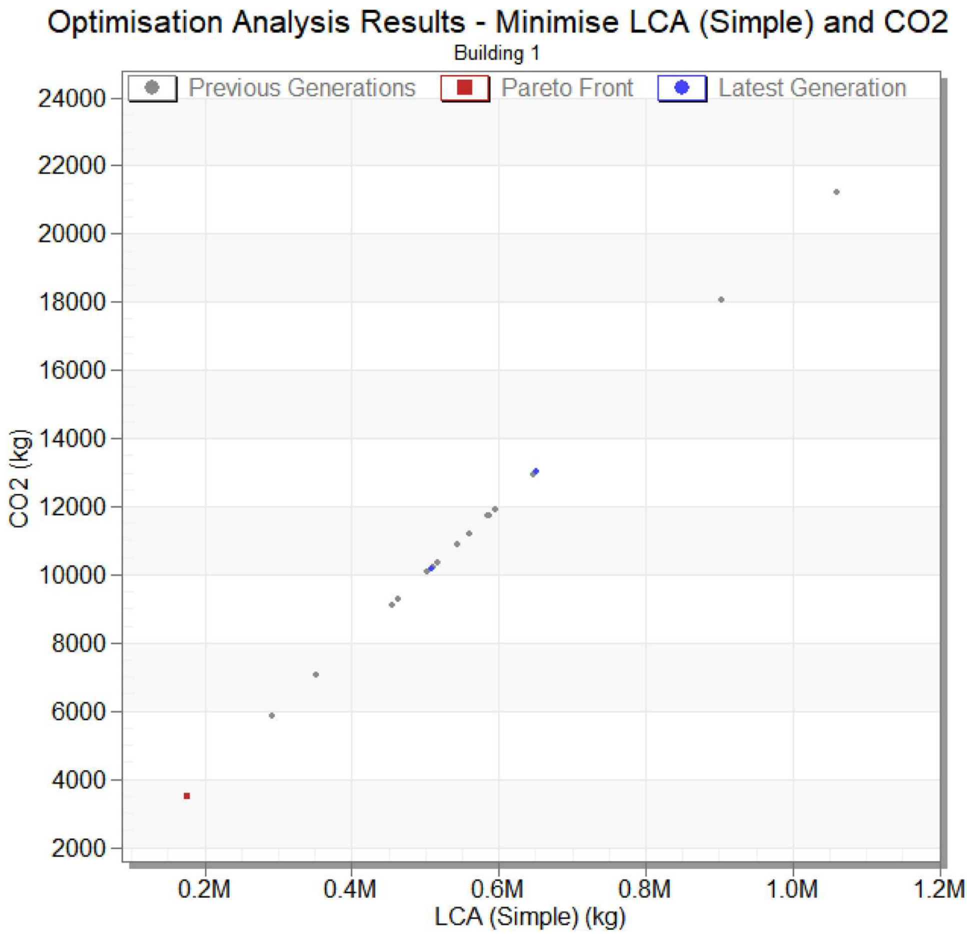

Figure 6. Optimisation Analysis LCA and CO2.

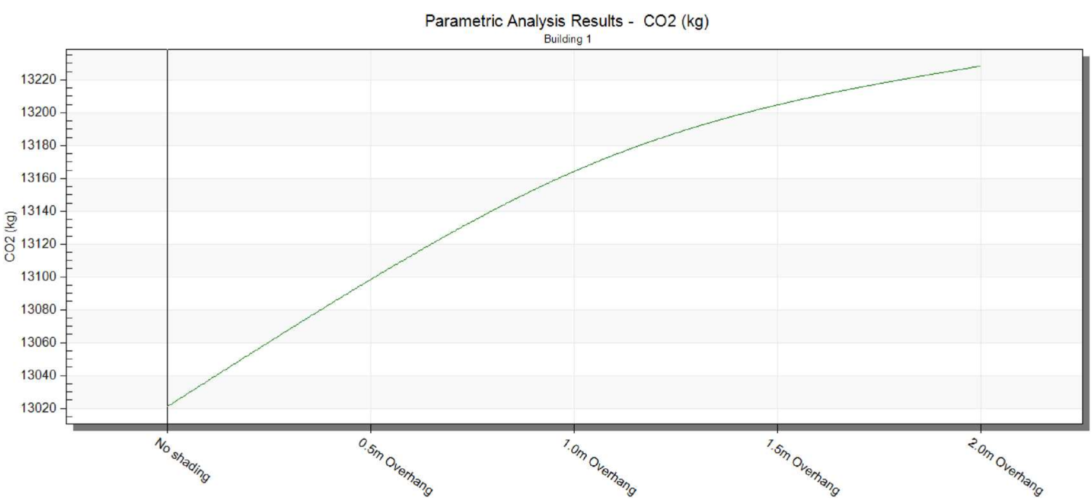

Figure 7. Parametric analysis for CO2 emissions in the model with Shadings.

This study shows residential building refurbishment can benefit from applying Pareto optimal frameworks in upgrading glazing types, insulation materials and HVAC systems. The approach can be expanded to other building types at bigger sizes with more complexities, e.g. where Pareto optimal solutions can also ensure that environmental performance improvements do not compromise other factors such as indoor air quality and occupant comfort.

4. Conclusion

The refurbishment of existing housing stock is key for net zero targets in the UK. This paper proposed a new approach in refurbishment to ensure the minimisation of carbon footprint both in operational and embodied carbon is considered in the planning for sustainable refurbishment. The fundamental idea behind the study was finding 'the best' for carbon reduction and what could also be 'good' in the process. The study utilised the power of simulation in a case study in Edinburgh. The key findings and contributions from this study are:

1. The importance of glazing in embodied and operational carbon is overlooked and despite market development in the triple-glazed system and the condition of building standard systems e.g. Passivhaus to use them, they may not offer low carbon emission compared to double-glazed ones.
2. Achieving the lowest u-value may not necessarily offer the lowest carbon emissions when embodied carbon of added insulation is considered in refurbishment.
3. The highest environmental impacts are associated with the HVAC systems. Solar Assisted Absorption Chiller and GSHP are the optimum solutions to lower carbon emissions in the model.
4. Shadings provide no performance improvement in the model. The greater shading caused increased emissions within the model.

The method used in this study is critical for sustainable refurbishment because of the following reasons:

1. Visualisation of trade-offs between different objectives in the context of decarbonising homes in the UK.
2. Development of a decision support system by highlighting a set of non-dominated solutions, the Pareto-optimal front offers decision-makers a range of viable options to choose from.
3. Avoiding suboptimal solutions by considering interdependencies even though some solutions are recommended by standards and are commonly known as low-carbon solutions.
4. Flexibility and robustness, the solutions are robust and are not sensitive to small changes and more likely to perform well in similar situations and contexts.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Notes on contributor

Dr. Seyed Masoud Sajjadian is a Lecturer and the Programme Leader for the MSc in Architectural Technology and Sustainable Building Performance at Edinburgh Napier University in the UK.

References

ASHRAE. 2020. *Environmental Health Committee (EHC) Emerging Issue Brief: Pandemic COVID-19 and Airborne Transmission*. Atlanta: ASHRAE Environmental Health Committee (EHC).

Bennadji, A., M. Seddiki, J. Alabid, R. Laing, and D. Gray. 2022. "Predicting Energy Savings of the UK Housing Stock under a Step-by-Step Energy Retrofit Scenario towards Net-Zero."

Bizonova, S., S. Darula, and R. Dubnicka. 2022. *Novel Windows for Refurbishment - Impact on Optical Properties and Interior Daylighting*. Bratislava: 5th Central European Symposium on Building Physics.

The Board of Trustees of the University of Illinois and the Regents of the University of California through the Ernest Orlando Lawrence Berkeley National Laboratory. 2010. *Getting Started with EnergyPlus Basic Concepts Manual - Essential Information You Need about Running EnergyPlus*.

Bougiationi, F., E. Alexandrou, and M. Katsaros. 2023. "Sustainable Refurbishment of Existing, Typical Single-family Residential Buildings in GREECE." *International Journal of Building Pathology and Adaptation*. https://doi.org/10.1108/IJBPA-09-2022-0157.

Carpino, C., R. Bruno, and N. Arcuri. 2020. "Social Housing Refurbishment for the Improvement of City Sustainability: Identification of Targeted Interventions based on a Disaggregated Cost-optimal Approach."

Department for Business, Energy and Industrial Strategy. 2020. "Improving the Energy Performance of Privately Rented Homes in England and Wales."

Department of Business, Energy and Industrial Strategy Committee. 2022. "Decarbonising Heat in Homes."

Erlandsson, M., and P. Levin. 2004. "Environmental Assessment of Rebuilding and Possible Performance Improvements Effect on a National Scale." *Building and Environment* 40:1459–1471.

Fahlstedt, O., A. Temeljotov, J. Lohne, and R. Andre Bohne. 2022. "Holistic Assessment of Carbon Abatement Strategies in Building Refurbishment Literature — A Scoping Review." *Renewable and Sustainable Energy Reviews* 167. https://doi.org/10.1016/j.rser.2022.112636.

Ganji Kheybari, A., M. Alwalidi, C. Hepf, T. Auer, and S. Hoffman. 2022. "A Multi-objective Evaluation for Envelope Refurbishments with Electrochromic Glazing." *Results in Engineering* 14:100417. https://doi.org/10.1016/j.rineng.2022.100417.

Higney, A., and K. Gibb. 2022. "A Cost-benefit Analysis of a Traditional Glasgow Tenement Net Zero Retrofit."

House of Commons Environmental Audit Committee. 2021, March 22. "Energy Efficiency of Existing Homes." Accessed November 1, 2024. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://committees.parliament.uk/publications/5171/documents/52521/default/.

Kathiravel, R., S. Zhu, and H. Feng. 2024. "LCA of Net-zero Energy Residential Buildings with Different HVAC Systems across Canadian Climates: A BIM-based Fuzzy Approach." *Energy and Buildings* 306:113905. https://doi.org/10.1016/j.enbuild.2024.113905.

Koenders, E., and U. Knaack. 2018. *Building Physics of the Envelope: Principles of Construction*. Basel: Birkhauser.

Li, X., H. Arbabi, G. Bennett, T. Oreszczyn, and D. Densley Tingley. 2022. "Net Zero by 2050: Investigating Carbon-budget Compliant Retrofit Measures for the English Housing Stock." *Renewable and Sustainable Energy Reviews* 161. https://doi.org/10.1016/j.rser.2022.112384.

Lingard, J. 2020. "Residential Retrofit in the UK: The Optimum Retrofit Measures Necessary for Effective Heat Pump Use." *Building Service Engineering Research and Technology* 42 (3): 279–292.

McCormack, M., A. Belli, D. Waugh, E. Matsui, R. Peng, D. Williams, et al. 2016. "Respiratory Effects of Indoor Heat and the Interaction with Air Pollution in Chronic Obstructive Pulmonary Disease." *Annals of the American Thoracic Society* 13 (12). https://doi.org/10.1513/annalsats.201605-329oc.

Met Office. n.d. "UK Climate Averages." Accessed February13, 2024. https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-climate-averages/gcvwqum6h.

Pareto, V. 2014. *Translation of Manuale di economia politica* [Manual of Political Economy]. Oxford University Press.

Power, A. 2008. "Does demolition or refurbishment of old and inefficient homes help to increase our environmental." *Social and Economic Viability?* 36:4487–4501.

Public Health England. 2018. "Chapter 5: Inequalities in Health." Accessed August 3, 2022. from https://www.gov.uk/government/publications/health-profile-for-england-2018/chapter-5-inequalities-in-health.

RICS. n.d. "Retrofitting to decarbonise UK existing housing stock RICS net zero policy position paper. Retrieved 01 16, 2024, from file:///Users/Mohsen/Downloads/retrofitting-to-decarbonise-the-uk-existing-housing-stock-v2%20(1).pdf.

Royapoor, M., A. Allahham, S. Hosseini, N. Rufa'l, and S. Louise Walker. 2023. "Towards 2050 Net Zero Carbon Infrastructure: A Critical Review of Key Decarbonization Challenges in the Domestic Heating Sector in the UK."

Schwartz, Y., R. Raslan, and D. Mumovic. 2022. "Refurbish or replace? The Life Cycle Carbon Footprint and Life Cycle Cost of Refurbished and New Residential Archetype Buildings in London." *Energy* 248. https://doi.org/10.1016/j.energy.2022.123585.

Scottish Government. n.d. "Energy Efficiency." Accessed January 15, 2024. Scottish Government: https://www.gov.scot/policies/energy-efficiency/energy-efficiency-in-homes/.

Semprini, G., R. Gulli, and A. Ferrante. 2017. "Deep Regeneration vs Shallow Renovation to Achieve Nearly Zero Energy in Existing Buildings Energy Saving and Economic Impact of Design Solutions in the Housing stock of Bologna." *Energy and Buildings* 156:327–342.

Shah, S. 2012. *Sustainable Refurbishment*. Sussex: John Wiley and Sons.

Smith, M., A. Bevacqua, S. Tembe, and P. Lal. 201. "Life Cycle Analysis (LCA) of Residential Ground Source Heat Pump Systems: A Comparative Analysis of Energy Efficiency in New Jersey." *Sustainable Energy Technologies and Assessments* 47:101364. https://doi.org/10.1016/j.seta.2021.101364.

Somasundaram, S., A. Chong, Z. Wei, and ThangaveluSundar Raj. 2020. "Energy Saving Potential of Low-e Coating based Retrofit Double Glazing for Tropical Climate." *Energy and Buildings* 206. https://doi.org/10.1016/j.enbuild.2019.109570.

UK Energy Research Centre. 2020. "The Pathway to Net Zero Heating in the UK."

Urbikain, M. 2020. *Energy Efficient Solutions for Retrofitting a Residential Multi-Storey Building with Vacuum Insulation Panels and Low-E Windows in two European Climates*. Cleaner Production.

UKGBC, J. Wheeler, J. Alker, and P. Box. 2021. "The Retrofit Playbook Driving Retrofit of Existing Homes – A Resource for Local and Combined Authorities."

Whitehead, M., D. Taylor-Robinson, and B. Barr. 2022. "Fuel Poverty is Intimately Linked to Poor Health." *British Medical Journal* 376:o606. https://doi.org/10.1136/bmj.o606.