Proceedings of 6th Masters Conference: ***People and Buildings***
London Metropolitan University, Sir John Cass Faculty of Art, Architecture and Design,
London, UK, 23th September 2016.
Network for Comfort and Energy Use in Buildings: http://www.nceub.org.uk

Multi Objective Optimisation analysis of non-domestic building retrofit strategies in the UK, under climate change uncertainty: A Passivhaus case study approach

Alkyoni Papasifaki[1*], Iván García Kerdan[2], Dr. Marcella Ucci[3]

[1] MSc Environmental Design and Engineering, University College London
*Corresponding author. *E-mail address:* alkyoni.papasifaki.15@ucl.ac.uk
[2] Energy Institute, University College London, 14 Upper Woburn Pl, London, WC1H 0NN, UK
[3] Institute of Environmental Design and Engineering, University College London, 14 Upper Woburn Pl, London, WC1H 0NN, UK

Abstract

This study, examining a Passivhaus retrofit in London, investigates optimum pathways for non-domestic low energy retrofits in the UK, capable of preserving their low energy status in future changing climates. A methodological framework is deployed, utilizing multi-objective optimisation (MOO) techniques and setting three conflicting objectives: building's annual energy use, occupants' discomfort, and retrofit's Net Present Value. The results highlight the potential of this methodological framework to provide an essential aid to the early-stage decision-making phase of building retrofits, identifying solutions which would be more resilient in future climates. Findings emphasize the capability of MOO analysis to demonstrate distinct differences between widely preferred energy-efficient measures and solutions considered "optimum", whilst analysing the Pareto optimums obtained for future climates, gradual adaptation measures can be identified.

Keywords: climate change, multi-objective optimisation, non-domestic buildings, low-energy retrofits, Passivhaus

1. Introduction

In the UK, in 2012, the building sector was responsible for the 37% of its total GHG emissions, due to direct and indirect energy use (CCC, 2014). In the broader direction of achieving an ambitious 80% reduction until 2050, compared to 1990 levels (Climate Change Act 2008, c.27), the construction industry follows strategies to deliver energy efficient buildings (Gething B., 2010). New domestic and non-domestic buildings must be certified as "zero carbon" from 2016 and 2019, respectively, and Passivhaus Standard, an international design, and construction standard for new build and retrofits offers a way to achieve this zero carbon policy (Binns et al. 2013). Nevertheless, some changes to the future climate cannot be avoided, due to the existing GHG emissions in the atmosphere, impacting significantly overall buildings' performance. Therefore, adaptation policies, based on calculated future climate's projections, are essential, adapting design, construction and retrofit approaches (Gething B., 2010). It is essential, though, to ensure that climate change adaptation strategies act complementary with mitigation measures, by taking adequate care regarding future climate change.

This study focuses on the balance between climate change mitigation and adaptation strategies, investigating a Passivhaus certified retrofit in London. The main aim is to deploy a methodological framework to demonstrate optimum pathways for low-energy retrofits of non-domestic buildings in the UK, which would not compromise their effectiveness in future climates, setting environmental, social and financial criteria. The proposed methodological framework intends to integrate climate change into non-domestic building retrofits in the UK, either by identifying solutions that would be resilient in future climates or by concluding that gradual adaptation measures should be applied through the lifespan of the building.

2. Methodology

2.1 Case Study Building

Figure 1: Mildmay community centre after the Passivhaus retrofit

The Mildmay Community Centre, located in the London Borough of Islington, was retrofitted to Passivhaus Standard requirements and design principles, including high insulation and air tightness levels, high-performance glazing, efficient lighting system, MVHR system and a large PV array (Bere Architects, 2015). Focusing on the energy-related retrofit measures, a post-retrofitted energy model of the building has been created. The building's final layout consists of a double-height sports hall, a reception area, a dining area, a commercial kitchen and a music studio, while office spaces exist in the basement, ground floor, and first floor.

2.2 Multi-Objective Optimisation (MOO) Analysis

2.2.1 Modelling Tools and Optimisation Parameters

For the MOO analysis, an optimization framework was used, which relies on a recently developed tool named EXRETOpt, created to evaluate the implications of various retrofit options on non-domestic buildings (Garcia Kerdan et al., 2016). The framework used in this study consists of two main modules: an energy simulation and economic analysis, and a retrofit optimisation module, utilising different sub-tools. More specifically, the building's energy model, created in EnergyPlus software (U.S. Department of Energy, 2015), is exported to the jEPlus parametric tool (De Montfort University, 2015), to define the parametric project. Then, the jEPlus+EA (De Montfort University, 2015) optimisation tool couples the genetic algorithm NSGA-II with the jEplus parametric tool, helping to run the simulation, optimizing the outputs according to the desired objectives. The parameters defined for the optimisation procedure are:

- Population Size: 20
- Maximum Generations: 75
- Crossover Rate: 100%,
- Mutation Rate: 20%
- Tournament Selection: 2

Therefore, for each climate period, 1500 simulations were run for approximately 72h.

2.2.2 Retrofit Variables and Objective functions

The optimization framework, included a large variety of retrofit options, alongside their capital cost, covering a wide range of passive and active measures typically used in non-domestic retrofit projects in the UK. Therefore, they constitute the retrofit variables of the parametric project. The three conflicting objectives defined for the optimisation analysis are:
Energy Use Intensity: Total annual Energy Use Intensity refers to the total energy consumption of the building per square meters over a year (KWh/m^2-yr).
Discomfort Hours: The annual discomfort hours were calculated as the average value of discomfort hours occurred in the two offices and the main hall, using the extended to 0

humidity ratio ASHRAE 55-2004 PMV method (ASHRAE, 2004), and counting the hours per year which are outside the comfort range; comfort zone for PMV -0.5 < PMV < +0.5.

Net Present Value (NPV): The variables needed for the economic analysis and the calculation of the NPV index (for building's lifespan of 50 years) were obtained from Garcia Kerdan's et al research study (2016), which includes a very comprehensive and robust economic research for non-domestic building retrofits in the UK.

Finally, after the Pareto solutions were obtained, a multi-criteria decision-making technique was applied, in order to compromise the objectives; as more optimum defined the solutions which equally weighted the three analysed objectives.

2.3 Future Weather Files

A team at the University of Exeter, working on a project called PROMETHEUS (University of Exeter, n.d.), used the UKCP09 weather generator's outputs to develop probabilistic future weather files. For this study, the Test Reference Year (TRY) weather files for Heathrow, London, in four different climate periods, current [1960-1990], 2030s [2020-2049], 2050s [2040-2069] and 2080s [2070-2099] at High Emissions Scenario and the 90th percentile of air temperature change were used.

2.4 Pareto Fronts

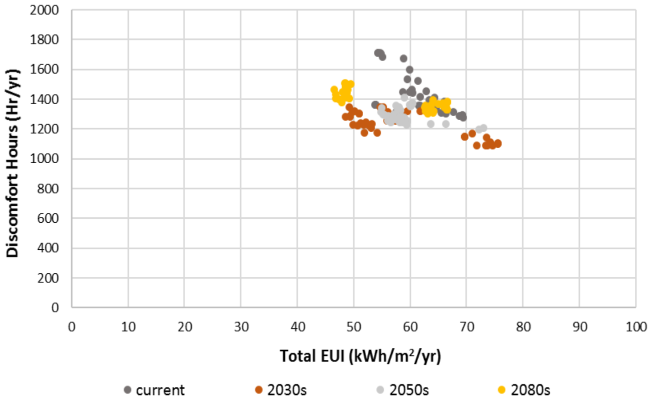

Figure 2: Discomfort Hours and Total EUI Pareto fronts

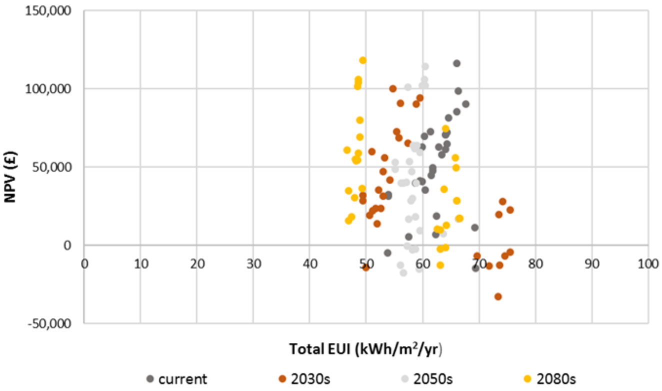

Figure 3: NPV and Total EUI Pareto fronts

Analysing the best 40 optimum solutions obtained from each climate period Pareto optimums (Fig. 2,3,4), it appears that all solutions take advantage of the future temperature rise to drop winter discomfort hours; by providing only space heating, they manage to balance low energy use with positive NPV.

More discomfort hours occur for the solutions of the current climate period, with the setpoints' variation affecting the associated energy use. This trend can be explained by the lower winter external temperatures in current climate conditions.

For the 2030s the solutions with lower set-points (19-21°C), show lower energy use, higher economic profitability but more discomfort hours. For the 2050s, the profitable solutions show generally higher energy consumption and more discomfort hours compared to those of the 2030s, due to the higher summer temperatures. For the 2080s, lower energy use, more discomfort hours and higher NPVs appear with the heating set-point set at 18°C, whilst the opposite trends appear with set-points at 20-21°C.

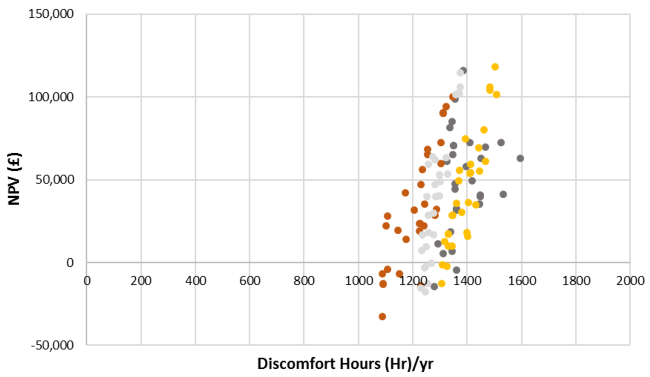

Figure 4: NPV and Discomfort Hours 40 most optimum solutions of the Pareto fronts

These results show that analysing the optimums of the future climates, the decrease of the heating set point in future can be demonstrated as a useful adaptation measure; this measure can reduce energy use without compromising the internal conditions.

2.5 Near Optimum Solutions

Aiming to identify a near optimum solution that could perform ideally in current and future climates, one solution was selected from each climate period's Pareto optimum, imposing the heating and cooling set points included to be 21°C and 24°C, respectively. The heating set-point was selected to have a fair comparison with the base case (the existing Passivhaus retrofit), which includes the same set-point, whilst the cooling set-point do not have any impact; however, it was considered wiser to examine solutions with same features.

A predominance of a GSHP with a underfloor distribution system for space and water heating, high-efficiency lighting systems emerges and wind turbine to provide renewable electricity emerges; a very small PV array is included, aiming to avoid high capital costs. With regards to the building fabric, lower insulation levels, and dramatically higher infiltration rates were included, indicating that heat losses would be minimised during winter, thus lower insulation levels and sealing measures are needed. At the same time, during the higher future summer temperatures, higher rates of heat flow through the fabric help to release the increased internal heat gains.

Table 1: NPV of the optimum solutions in current climate period for heating set- point at 21°C, and comparison with the base case

	NPV$_{50\ years}$ (£)
Base case	-219,864
Optimum_current	98,585
Optimum_2030s	15,401
Optimum_2050s	62,565
Optimum_2080s	13,141

Comparing the NPV of the optimum solutions to the Passivhaus retrofit (Tab.1), it is highlighted that the investment for the energy related retrofit measures of the existing Passivhaus retrofit is financially unviable. This result denotes the unsuitability of reaching Passivhaus targets that refer to new builds when retrofitting an old building, as the high investment cost ensuing would result in a net loss.

Generally, for all optimums, similar downward trends appear through the periods, in terms of energy use (Fig. 5), with higher values emerging in the current period and lower in the 2080s, due to the drop in space heating demand. A substantial difference of 10-15% in energy use emerges between the base case and the optimum for the 2030s, whilst the discomfort hours are 15-20% less (Fig. 6). The optimums of current climate and for the 2050s, seem to perform very similarly, showing 15% more energy consumption than the 2030s optimum, and slightly higher discomfort hours. The 2080s optimum shows the highest energy consumption, 25-30% more than the base case, as the measures selected to deal with the high external temperatures of 2080s are not appropriate for the rest climate periods which have lower external temperatures.

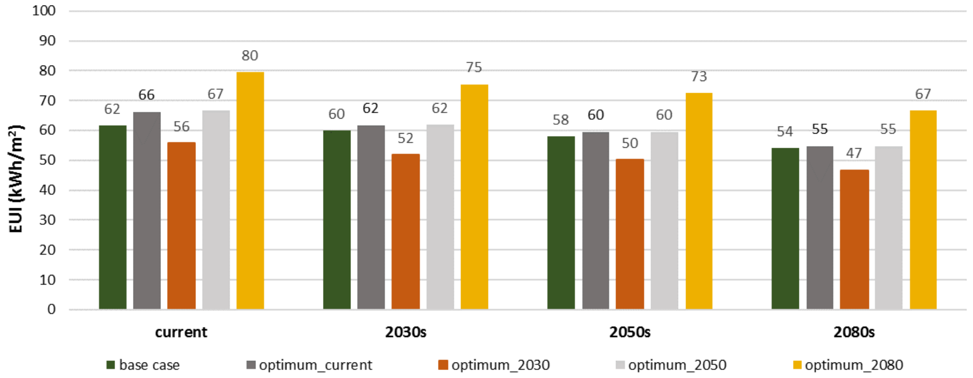

Figure 5: Total annual EUI (kWh/m^2) of the optimum solutions in current and future climate periods for heating set point at 21°C, and comparison with the base case**.**

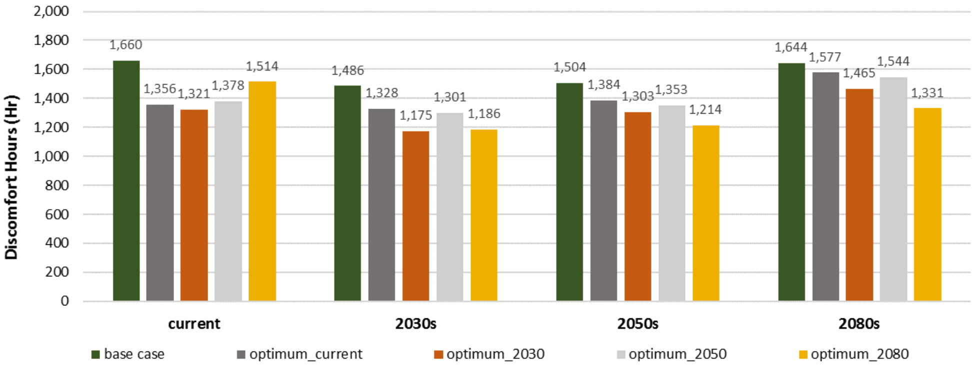

Figure 6: Discomfort Hours of the optimum solutions in current and future climate periods for heating set point at 21°C, and comparison with the base case

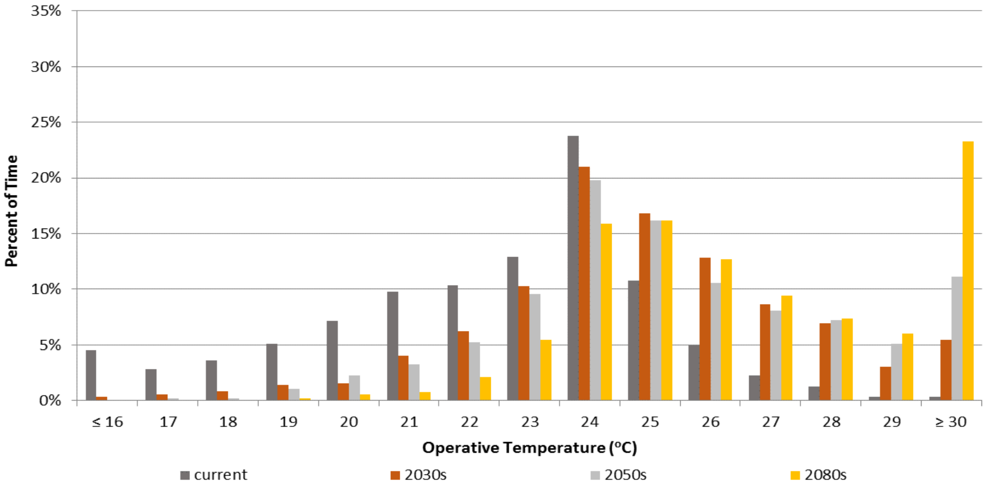

Figure 7: Annual distribution of average hourly operative temperatures of the optimum solution in current and future climate periods for heating set- point at 21°C

Finally, the optimum solution obtained from the optimisation analysis for the 2030s appeared to have more robust performance through the climate periods, constituting also an economically feasible solution. However, examining the prevailing temperatures of the solution in future climates, increased frequency of high temperatures emerges (Fig. 7), whilst low temperatures are significantly reduced. This output highlights the need for active cooling, as an adaptation measure to mitigate future discomfort hours. With the positive NPV value of the solution, though, it could be claimed that there is space left for a future investment.

3. Conclusions

Deriving the ways for low energy retrofits, by itself necessitates a series of decisions, involving several retrofit variables and objectives. The consideration of climate change and the investigation of retrofit solutions which would be resilient to the future climate constitutes an essential step to establish a range of best solutions, without compromising the results in future climates.

The proposed methodological framework, employing MOO techniques, as this is the nature of most building engineering problems, appeared to have a potential to integrate mitigation measures with adaptation strategies and to provide an essential aid to the early-stage decision-making phase of low energy building retrofits. Following the proposed methodology, useful information can be obtained in terms of the desired objectives and future climates. However, there is a potential of being upgraded, examining more climate change scenarios, including a wider range of retrofit or design parameters and optimising more objectives, such as life cycle carbon footprint. Additionally, suitable thermal comfort criteria could be established, which can be used as constraints of the optimisation analysis, in order to ensure that occupants' thermal comfort is not compromised. Analysing further and deeper the Pareto datasets obtained, this framework could constitute a comprehensive and useful tool that could be integrated into the decision-making phase of building retrofits or new builds.

4. References

ASHRAE. ANSI/ASHRAE Standard 55-2004. Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating and Air-conditioning Engineers

Bere Architects, 2015. Mildmay Centre-FINAL REPORT-Technology Strategy Board funded research [online] Available from: http://www.bere.co.uk/research/mildmay-centre-final-report-technology-strategy-board-funded-research

Binns, B., et al, 2013. *Be Passive: Lessons Learnt for the Belgian Passivhaus Experience*. UK: Centre for the Built Environment, University of East Anglia.

CCC (Committee on Climate Change), 2014. *Meeting Carbon Budgets – 2014 Progress Report to Parliament*. Committee on Climate Change: London, UK.

Climate Change Act, 2008. (c.27), London: HMSO

De Montfort University, 2015. *je+.org*

Gething, B., 2010. Design for future climate: opportunities for adaptation in the built environment. Swindon: Technology Strategy Board.

Garcia Kerdan, I., Raslan, R., Ruyssevelt, P., Galvez D. M., 2016. An exergoeconomic-based parametric study to examine the effects of active and passive energy retrofit strategies for buildings. *Energy and Buildings*. In Press, corrected Proof, http://dx.doi.org/10.1016/j.enbuild.2016.09.029

Garcia Kerdan I, et al., 2016. An exergy-based multi-objective optimisation model for energy retrofit strategies in non-domestic buildings. *Energy*. In press, Corrected Proof, http://dx.doi.org/10.1016/j.energy.2016.06.041

University of Exeter, n.d. PROMETHEUS: The Use of Probabilistic Climate Change Data to Future-proof Design Decisions in the Building Sector. Exeter: University of Exeter.

U.S. Department of Energy, 2015. *U.S. Department of Energy - Energy Efficiency & Renewable Energy*