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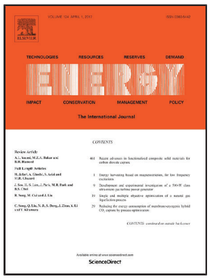

A comparison of an energy/economic-based against an exergoeconomic-based multi-objective optimisation for low carbon building energy design

Iván García Kerdan, Rokia Raslan, Paul Ruyssevelt, David Morillón Gálvez

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Highlights

- The study compares an energy-based and an exergy-based building design optimisation
- Occupant thermal comfort is considered as a common objective function
- A comparison of thermodynamic outputs is made against the actual retrofit design
- Under similar constraints, second law optimisation presents better overall results
- Exergoeconomic optimisation solutions improves building exergy efficiency to double

A comparison of an energy/economic-based against an exergoeconomic-based multi-objective optimisation for low carbon building energy design

Iván García Kerdan[a,c,d*], Rokia Raslan[b], Paul Ruyssevelt[a], David Morillón Gálvez[c]

[a] Energy Institute, University College London, 14 Upper Woburn Pl, London, WC1H 0NN, U.K.
[b] Environmental Design and Engineering, University College London, 14 Upper Woburn Pl, London, WC1H 0NN, U.K.
[c] Departamento de Mecánica y Energía, Instituto de Ingeniería, Universidad Nacional Autónoma de México, México, México
[d] Centre for Process Systems Engineering, Imperial College London, Roderic Hill Building, South Kensington Campus, London, SW7 2AZ, UK

Abstract

This study presents a comparison of the optimisation of building energy retrofit strategies from two different perspectives: an energy/economic-based analysis and an exergy/exergoeconomic-based analysis. A recently retrofitted community centre is used as a case study. ExRET-Opt, a novel building energy/exergy simulation tool with multi-objective optimisation capabilities based on NSGA-II is used to run both analysis. The first analysis, based on the 1st Law only, simultaneously optimises building energy use and design's Net Present Value (NPV). The second analysis, based on the 1st and the 2nd Laws, simultaneously optimises exergy destructions and the exergoeconomic cost-benefit index. Occupant thermal comfort is considered as a common objective function for both approaches. The aim is to assess the difference between the methods and calculate the performance among main indicators, considering the same decision variables and constraints. Outputs show that the inclusion of exergy/exergoeconomics as objective functions into the optimisation procedure has resulted in similar 1st Law and thermal comfort outputs, while providing solutions with less environmental impact under similar capital investments. This outputs demonstrate how the 1st Law is only a necessary calculation while the utilisation of the 1st and 2nd Laws becomes a sufficient condition for the analysis and design of low carbon buildings.

Keywords:
optimisation; building simulation; energy; exergy; low carbon buildings; exergoeconomics.

*Corresponding author at: CPSE, Imperial College London, UK., United Kingdom. Tel: +44 (0) 7867798730
E-mail addresses: i.kerdan.12@ucl.ac.uk , i.garcia-kerdan@imperial.ac.uk (I. Garcia Kerdan)

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1. Introduction

In industrialised countries, buildings are responsible for approximately 20-40% of the national primary energy utilisation [1] and 25-30% of the global CO_2 emissions [2, 3]. Therefore, the sector holds a great opportunity for energy reduction and carbon abatement by delivering cost-effective building energy retrofit (BER) strategies. As the energy issue is becoming more evident in the building sector, developing techniques for designing efficient and cost-effective energy systems is still a challenge that practitioners and researchers face in today's building industry. Optimisation is a technique that is commonly used in research and engineering applications. Buildings' energy design optimisation is an inherently complex technique involving disciplines such as engineering, mathematics, enviro-economic science, and computer science [4]. Three basic types of algorithms are used in optimisation problems applied to buildings: enumerative, deterministic, and stochastic [5]. Stochastic methods based on genetic algorithms (GA) can be regarded as the most popular method for building optimisation. Other popular algorithm methods are 'Direct Search', 'Simulated Annealing', and 'Particle Swarm optimisation' [6].

Evins [6] conducted a comprehensive review of 74 optimisation research studies, providing a list of the most typical objectives used in sustainable building design. He found that the most common objective was energy use (found in 60% of the studies), followed by costs and occupants' thermal comfort. While multi-objective optimisation (MOO) methods are usually used during early designs [5] they have also been applied for retrofit projects. As MOO studies have been increasing in number in recent years, several tools have been developed, using typical building energy simulation tools, such as TRNSYS and EnergyPlus (as the core calculation engines) combined with optimisation toolboxes from MatLab, R, C++ and Python [4]. Taking the advantages from these tools, BER optimisation studies have become more common, considering different decision variables, objective functions, and constraints. Table 1 presents a comprehensive review of the most notable contributions in the field in the last decade.

[Table 1 around here]

1.1 Exergy and exergoeconomic optimisation

As shown, the basis of typical optimisation process has been the 1st Law of thermodynamics or the ‘conservation of mass and energy’ principles. Energy analysis typically shows limitations when it comes to assessing the characteristics of energy conversion systems. With the current high dependency on high-quality energy sources, such as natural gas, oil, and fossil-fuel based generated electricity, combined with the low thermodynamic efficiency of current building system technologies (e.g. at T_0 = 5 °C and T_i= 20 °C, electric heater Ψ: 0.05; air source heat pump Ψ: 0.15), new approaches to improve the selection of optimal BER measures are required. In this sense, there is an opportunity to redesign typical approaches, where the consideration of the fundamental 2nd Law of thermodynamics under the exergy concept appears to hold some promise. Combining 1st and 2nd Law analysis has significant advantages, as it provides with technical limits that the 1st Law misses and an appropriate link between demand and supply analyses, which is often performed separately. This disengagement has led the decision makers to assume that systems, such as electric-based heating, are the most efficient way to deliver heat as it has an ‘energy efficiency’ of 100%. The problem is that the delivery of electricity to cover a low-quality demand, such as space heating/cooling or DHW, can be considered as irrational because the qualities of the demand and supply do not match. Exergy-based analysis could be the ideal methodological complement for the assessment and comparison of energy designs as it focuses on improving efficiency.

After decades of exergy research in other sectors, the 2nd Law and exergy concepts can be considered well established. However, in the building sector, it still needs to achieve certain degree of maturity that could make the analysis useful. In the last years, exergy analysis research in buildings has significantly increased. Main contributions came from three research groups: IEA EBC Annex 37 [31], IEA EBC Annex49 [32] and the ’LowEx - COSTeXergy’ [33]. The common aim was to provide a standard methodology that could lead to a deeper understanding of using both thermodynamic laws in the built environment and its potential application.

However, decision making in building energy design is still mainly based on typical economic indicators, such as Net Present Value (NPV), Life Cycle Cost (LCC), and Discounted Payback (DPB) [34,35]. In this sense, exergoeconomics, which considers not only the thermodynamic inefficiencies of a system but also the costs associated with these inefficiencies, and the investment expenditure required to reduce them could be considered for a comprehensive analysis. Widely used in process and power generation optimisation [36], exergoeconomic optimisation aims to find a trade-off between the energy streams/product cost and capital investment cost of energy systems within the technically possible limits. Exergoeconomics has been effectively combined with the cost-benefit analysis to improve operation and design. By minimising the Life Cycle Cost (LCC), the best system considering the prevailing economic conditions could be found; and by minimising the exergy loss, environmental impact could also be minimised [37]. The major strengths of combining exergoeconomics is the ability to pinpoint exact sources of inefficiencies, highlight real improvement potential, and provide a robust comparison among designs. Specifically, in building research, exergoeconomic has been applied for the analysis and optimisation of different building energy systems such as district heating networks [38-40], micro cogeneration systems (mCHP) [41,42], heat pumps [43], energy storage [44,45], envelope's insulation [46] and conventional heating systems [47-49]. However, neither study performs an exergoeconomic-based multi-objective optimisation under different objective functions.

After highlighting the research gaps in both building energy design optimisation and exergy/exergoeconomic analysis, with the intention of challenging the established methodology for building energy design optimisation based on the 1st law only, the novelty of this paper comes from performing a comparative study between an energy/economic-based and exergy/exergoeconomic-based multi-objective optimisation. To achieve this, ExRET-Opt [50], an automated simulation tool developed for building energy/exergy design optimisation is used. The aim is to illustrate through a detailed analysis the differences between the methodologies and results. Although it is expected that both approaches would provide a more informed assessment of BER designs than the actual retrofit design of the selected case study, it is also expected that each approach would deliver different BER designs and outputs due to the differences in calculation methods.

2. Case Study

The case study building is based on an 1890s-community centre located in Islington, London (UK) that was retrofitted in 2011 to Passivhaus standards. The actual BER design resulted in the installation of an 8.4 kW ground source heat pump (GSHP) and a 90% efficient Mechanical Ventilation Heat Recovery (MVHR) system. Additionally, 18 kWp PV solar panels were installed together with a 3 kW solar thermal system connected to a 300 litres water storage tank. Triple glazed clear windows to maximise winter solar gains and high levels of envelope insulation were installed, compiling with Passivhaus standards. Building's main characteristics and a diagram of the energy system can be found in Table 2 and Fig. 1.

[Table 2 around here]

[Fig. 1 around here]

For simplification, the building energy model has been divided into six thermal zones, according to the orientation, activity type and the spaces' internal loads: 1) basement floor offices, 2) above ground offices, 3) music studio, 4) main hall, 5) reception, and 6) kitchen area. Heathrow, London weather file (epw file) is used as reference temperature for dynamic energy/exergy analysis. Previously, Garcia Kerdan et al. [51] presented the exergy and exergoeconomic evaluation for the retrofitted building. The model calculated a retrofit investment of approximately £417,028 exclusively for energy related measures. The ratio of passive and active technology investment was calculated at 0.41, where PV/T panels represented almost 37% of the total investment, followed by glazing (17.5%) and roof insulation (10.4%). For a 50-year period, the buildings life cycle cost (eq. A.17) has been calculated at £471,403 considering project's capital investment, annual energy bills, government incentives through the feed-in-tariff (FiT) and renewable heat incentives (RHI), and the salvage cost or residual value. This resulted in a discounted payback of 137 years. Table 3 presents the main energy, exergy and other non-thermodynamic values for the case study building.

[Table 3 around here]

These will be used to design the optimisation studies and as benchmark for comparative purposes. A secondary aim of this paper is to showcase the tool's capabilities of providing more cost-effective designs regardless of the approach.

3. Methods and Materials

3.1 ExRET-Opt

ExRET-Opt [50] is a simulation tool that enhances typical building retrofit-oriented tools with the addition of exergy and exergoeconomic analysis and multi-objective optimisation. The systematic methodology and simulation tool covers an existing gap that limits the introduction of exergy into energy design practice. The tool allows the practitioner to quantify indices of performance of the building retrofit based on the 1st and 2nd laws analyses, among other non-energy indicators. It has been developed by embedding a comprehensive dynamic exergy analysis [52] and a tailored exergoeconomic method [53] into a typical open-source building simulation tool – EnergyPlus [54]. The main exergy and exergoeconomic formulas embedded in the tool can be found in Appendix A.

3.2 Optimisation study design

As mentioned, the MOO studies are designed from two different perspectives: a) an energy/economic-based focus and b) an exergy/exergoeconomic-based focus. Yet, buildings are designed to the primary objective of providing a comfortable environment for its occupants. Therefore, the optimal selection of BER should be a trade-off between the thermodynamic efficiency, capital costs, and most importantly, occupant thermal comfort. Thus, occupants' thermal comfort is the only common objective for both approaches. The first MOO method, based on the 1st Law only (typically used in the building industry and research), optimises building energy use and project's Net Present Value (NPV). From this point in the paper, this approach is referred to as the *energy/economic optimisation*. The second method, based on the 1st and 2nd Laws simultaneously, optimises building exergy destructions and an exergoeconomic index. This approach is referred to as the *exergy/exergoeconomic optimisation*. Fig. 2 shows the methodological approach applied to this study.

[Fig. 2 around here]

Following the finalisation of the optimisation processes, Pareto fronts are obtained for both approaches. In a first level of analysis and to make a comparison of both approaches' main outputs, both the number of constrained solutions and the size of non-dominated solutions (Pareto fronts) are statistically analysed using an independent two sample t-test was. An independent t-test compares the mean values from the two-sample gathered and test the likelihood of the samples originating from populations with different mean values. The t-test calculates the null hypothesis that the means of two normally distributed groups are equal. Similar to Yoo and Harman [55], the null hypothesis in this study (setting an α level of 0.95) is that with two different optimisation approaches, the mean values of the number of non-dominated solutions are equivalent. If a p−values is significant, this would suggest that the null hypothesis should be rejected, meaning that one of the optimisation approaches produces a larger number of Pareto solutions.

3.2.1 Decision variables

Due to the inclusion of the extensive ExRET-Opt technology database, the tool can be applied to analyse a wide range of different BER measures. Table 4 presents the characteristic of the main HVAC systems embedded in the database. The techno-economic values for all other possible retrofit measures can be found in [50,52] and in Appendix B.

[Table 4 around here]

Apart from typical technologies found in the tool, some additional considerations are made. Following the actual retrofit design (up to Passivhaus standards) and due to the building's nature, the envelope is differentiated into six parts: 1) above ground wall insulation, 2) basement wall insulation, 3) basement floor insulation, 4) ground floor insulation, 5) pitched roof insulation, and 6) normal roof insulation. Additionally, thicker insulation technologies have been included to achieve U_{values} per Passivhaus standards (U_{val}<0.15 W/m²K). After discretisation of all variables, the total number of decision variables for the optimisation process are defined in Table 5.

[Table 5 around here]

Therefore, as all possible combinations are more than seven thousand quadrillion (7,099,580,375,363,174,400), presenting an impossible task for almost any computer due to limited number of cores and processing time. However, the optimisation jobs have been subject to the following NSGA-II parameters.

3.2.2 Objective functions

As mentioned, the two approaches, consider three conflicting objectives that must be satisfied simultaneously.

3.2.2.1 Energy/economic-based optimisation

For the energy/economic approach the objectives are the minimisation of building energy use, reduction of occupant thermal discomfort, and maximisation of project's NPV:

I. Building's annual site energy use (kWh/m²-year):

$$Z_1(x)min = EUI_{bui} \quad (1)$$

where EUI_{bui} is the total annual energy used by the building.

II. Occupant discomfort hours (Fanger's model [56]):

$$Z_2(x)min = (|PMV| > 0.5) = \left(\left| (0.303e^{-0.036M} + 0.028)\,(H - L)\right| > 0.5\right) \quad (2)$$

where e is the Euler's number (2.718), M is the metabolic rate (W/m^2), H is internal heat production rate of an occupant per unit area (W/m^2), and L is energy loss (W/m^2). This value is given by ExRET-Opt through EnergyPlus calculations.

III. Net Present Value$_{50\ years}$ (£):

$$Z_3(x)max = NPV_{50years} = -TCI + \left(\sum_{n=1}^{N} \frac{R}{(1+i)^n}\right) + \frac{SV_N}{(1+i)^N} \quad (3)$$

where *TCI* is the initial total capital investment, *R* is the annual revenue cost (composed of the annual energy cost savings minus the operation and maintenance cost), and *SV* is the salvage cost or residual value. Detailed calculation information can be found in Appendix A.2 (eq. A.20). However, for simplification and to encode a purely minimisation problem, the NPV is set as negative $-NPV_{50years}$ (however, results throughout the appear are presented as normal positive outputs).

3.2.2.2 Exergy/exergoeconomics-based optimisation

For the exergy/exergoeconomic approach, the objectives are the minimisation of overall building exergy destructions, reduction of occupant thermal discomfort, and minimisation of the exergoeconomic cost-benefit index:

I. Building annual exergy destructions (kWh/m^2-year):

$$Z_1(x)min = Ex_{dest,bui} = \sum Ex_{prim}(t_k) - \sum Ex_{dem,bui}(t_k) \quad (4)$$

where Ex_{prim} and $Ex_{dem,bui}$ are the total primary exergy supplied and total building exergy demand respectively.

II. Occupant discomfort hours (Fanger's model):

$$Z_2(x)min = \left(\left|PMV\right| > 0.5 \right) = \left(\left| (0.303e^{-0.036M} + 0.028)\,(H - L) \right| > 0.5 \right) \quad (5)$$

III. Exergoeconomic cost-benefit $_{\mathbf{50\ years}}$ (£/h):

$$Z_3(x)min = Exec_{CB} = \dot{C}_{D,sys} + \dot{Z}_{sys} - \dot{R}$$
(6)

where $\dot{C}_{D,sys}$ is the building total exergy destruction cost (eq. A.25), $\dot{Z}_{sys}$ is the annual capital cost rate for the retrofit measure (eq. A.26), and $\dot{R}$ is the annual revenue rate. All three parameters are levelised considering the project's lifetime (50 years) and the present value of money. The outputs are given in £/h. The *exergoeconomic cost-benefit indicator* $Exec_{CB}$ [53] is a novel index for energy system design comparison developed from the SPECO exergoeconomic method [61].

3.2.3 Constraints

The optimisation problem is subjected to three constraints. First, the capital investment of the actual retrofit project of £417,028 [51], requiring the model to deliver cheaper designs. Secondly, a positive NPV or a DBP of less than 50 years is also considered a constraint. Finally, the amount of discomfort hours obtained by the actual retrofit model (853 hours) is considered as the third constraint. Hence, the optimisation problems for both approaches can be generally formulated as follows:

Given a thirteen-dimensional decision variable vector

$x = \{X^{\mathrm{HVAC}}, X^{\mathrm{wall}}, X^{\mathrm{roof}}, X^{\mathrm{ground}}, X^{\mathrm{wall\_BS}}, X^{\mathrm{roof\_Pi}}, X^{\mathrm{ground\_BS}}, X^{\mathrm{seal}}, X^{\mathrm{glaz}}, X^{\mathrm{light}}, X^{\mathrm{PV}}, X^{\mathrm{wind}}, X^{\mathrm{heat}}\}$, in the solution space X, find the vector(s) x^* that:

Minimise: $Z(x^*) = \{Z_1(\mathrm{x}*), Z_2(\mathrm{x}*), Z_3(\mathrm{x}*)\}$
(7)

Subject to follow inequality constraints: $\begin{cases} TCI \leq £417{,}028 \\ DPB \leq 50\ years \\ Discomfort\ \leq 853 \end{cases}$

(8)

Based on compromise programming and equal weight solution, all three objective functions are considered to have the same weight (w1 =0.33, w2=0.33, and w3=0.33).

3.2.4 NSGA-II parameters

Table 6 presents the NSGA-II settings defined for both studies hoping to obtain more variability among simulation results:

[Table 6 around here]

Each procedure should perform approximately 10,000 simulations, or terminate either if the objective functions converge or a time limit is reached. The detailed optimisation algorithm process as well as the modelling environments is shown in more detail in Fig. 3.

[Fig. 3 around here]

It is important to point out that GA presents some limitations. Apart of only operating under a discrete search space, meaning that continuous variables must be discretised, algorithm parameters such as population size, crossover and mutation, can affect the location of the optimal value and convergence rate [57, 58].

4. Results

In an 8-core laptop, following 150 hours of simulation, the energy/economic-based MOO collected 9,815 simulations, while the exergy/exergoeconomic-based MOO simulated 9,747 models. However, the number of constrained solutions are found at 475 and 344 for the energy-based and exergy-based MOO respectively. This demonstrates that around 3-5% of the simulated solutions have a better thermal comfort and economic performance than the actual retrofitted building.

4.1 Single-objective analysis

Each objective from the non-dominated solutions are individually optimised for both approaches. The single objective optimal BER designs are shown in Table 7 for the energy/economic based approach and Table 8 for the exergy/exergoeconomic-based approach.

[Table 7 around here]

[Table 8 around here]

4.1.1 Energy-based single objective results

For the energy-based optimisation, when single-optimising building's EUI, the tool produces a BER design similar to the actual retrofit building. The model is also based on a GSHP, differing in that instead of considering a MVHR, the model suggests the installation of underfloor heating. In addition, the wall insulation is similar to that found in the actual BER, having 0.25m of Polyurethane for the above ground walls and 0.30m of cellular glass for the basement walls. In terms of infiltration rate, again, the model suggests a similar value to the one in the real design (model: 0.50 ach, real: 0.42 ach). However, to lower the capital cost, the model reduces the glazing system to double-glazed air-filled windows instead of the triple-glazed air-filled. The lighting system is based on T8 LFC, similarly to the actual building. The biggest change comes in the PV panels, where the model does not consider their installation, and instead, a 20 kW turbine is proposed. The design is able to lower energy use from 47,293 kWh/year (61.6 kWh/m^2-year) to 44,845 kWh/year (58.4 kWh/m^2-year). It also improves thermal comfort by 1.4% (from 853 to 841 discomfort hours), while delivering a positive $NPV_{50\ years}$ of £8,488. The project's total capital investment is calculated of £271,738, reducing the original budget by 34.8%.

When single-optimising for thermal comfort, the model suggests the installation of H21: GSHP with underfloor heating with similar envelope insulation levels compared to the previous case, but considering double-glazed Krypton-filled windows instead of air-filled. The model also considers an airtight envelope, with a value of 0.6 ach. T5 LFC lighting is considered along the implementation of 3.9 kWp PV panels and a 20 kW turbine. This results in a high-energy use of 50,571 kWh/year (65.9 kWh/m^2-year); however discomfort hours are reduced to 550. This BER has a capital investment of £316,444 and a DPB of 33.6 years.

Finally, by single-optimising NPV, the model considers H31: microCHP and gas boiler connected to a CAV system. The solution considers low insulation levels (with some parts not even meeting minimum Part L2B requirements) and an improvement on the airtightness of the building of just 20% (0.8 ach). In the model, the windows are retrofitted to double-glazed air-filled, while considering a more efficient lighting system of T5 LFCs. It also suggests the installation of 3.9 kWp of PV panels and a 20 kW turbine. With this design, the building demands 209,006 kWh/year (272.4 kWh/m^2-year) while keeping thermal comfort at the same level as the original design (853 discomfort hours). However, it has the best economic performance with a payback of 23.7 years requiring a capital investment of £262,992.

4.1.2 Exergy/exergoeconomics-based single objective results

In the exergy/exergoeconomics-based approach, by single-optimising building exergy destructions, the optimisation procedure delivers a design composed of H15: district heating connected to a wall heating system. From a 2nd Law perspective, district systems (especially waste heat-based) are considered as the most ideal low-exergy supplying systems due to their high efficiency in using low grade heat. The design is combined with medium levels of insulation, where just the basement walls and ground insulation meet Part L2 requirements. The design also proposes a reduction of 20% in the air leakage (0.8%) with no retrofit in the glazing system. The lighting system is changed to T8 LED, with no PV panels and a 20 kW wind turbine. The model is able to reduce thermodynamic irreversibilities from the actual retrofit of 104,918 kWh/year (136.8 kWh/m^2-year) to 78,938 kWh/year (102.9 kWh/m^2-year) and improves exergy efficiency (Ψ) from an already high value of 18.0% to 22.2%. Discomfort levels and the exergoeconomic cost-benefit indicator are also reduced to 791 hours and £0.23/h respectively. This BER design has a capital investment of £179,250 and a DPB of 50 years.

By single-optimising discomfort under an exergy oriented approach, the BER design is based on a H28: biomass boiler with wall panel heating with high envelope insulation values, suggesting the installation of 0.25m of EPS for the above ground walls, 0.14m of cork board for the ground floor and 0.12m of cork board for the pitched roof. It also suggests a 0.07m of EPS for the basement walls. This is combined with a slight improvement in the airtightness of 10% (0.9 ach) and the installation of double-glazed air filled windows. For active systems, it recommends the installation of T5 LFC and 7.8 kWp PV panels. This design reduces exergy destructions to 90,364 kWh/year (117.8 kWh/m^2-year) and improves exergy efficiency to 19.5%. In addition, it reduces discomfort hours to 584 hours and minimises exergoeconomic cost-benefit value to £0.28/h. The design requires an investment of £256,761 delivering a DPB of 43.7 years.

Finally, of great interest are the results obtained from the single optimisation of the novel exergoeconomic cost-benefit indicator. This design suggests an HVAC system based on H29: biomass boiler connected to underfloor heating. The algorithm chooses a low-exergy efficient system but with a high renewability factor and high income from government incentives. The envelope is characterised by high levels of insulation in the roof and ground floors and low levels in the walls and pitched roof. A building airtightness of 0.9 *ach* and the utilisation of the pre-retrofit single glazing is also considered by the model. For active systems, the models suggest the installation of highly efficient T5 LFC lighting and the implementation of 7.8 kWp of PV panels. This design results in exergy destructions of 87,405 kWh/year (114.0 kWh/m^2-year) and an exergy efficiency of 19.9%. Discomfort values are reduced to 666 hours per year. Moreover, the exergoeconomic cost-benefit indicator reaches a value of -£0.11/h, meaning that the project was exergoeconomically efficient. This is supported by a low cost BER design (£180,017) with a payback of 26.7 years; similar to the one obtained by optimising NPV in the energy-based approach.

Table 9 provides a comparative study of other main indicators. As seen in the results, the solution that reduced the most carbon emissions is the single optimisation of the exergoeconomic cost-benefit indicator. This design provides the best overall performance, obtaining the best outcomes in three main indicators without delivering indicators showing unsatisfactory performance. This large reduction is achieved thanks to the installation of the biomass-based boiler (0.039 kgCO_2e/kWh) working with low temperature floor systems combined with the 7.8 kWp of PV panels (0.075 kgCO_2e/kWh). On the other hand, as expected the NPV single optimisation provided the best economic outcomes; however, it presents the worst performance in seven other indicators related to carbon emissions and exergy use.

[Table 9 around here]

4.2 Triple-objective analysis

As mentioned, the 475 constrained models obtained in the energy/economic-based MOO procedure, represent less than 4.8% of all the simulated models. In this case the Pareto front is composed of just nine solutions. The sample is dominated by H21: GSHP and underfloor heating, appearing in 66.6% of the solutions. H31: microCHP with condensing boiler and H28: Biomass boiler and wall heating also appear in the Pareto front. For envelope's insulation, not a single technology appears to dominate the solutions, with XPS and polyurethane being the most common solutions. The rest of the envelope is mainly dominated from high levels of infiltration (>0.7 ach) and single-glazing. For renewable energy, 20 kW turbine and 13.8 kWp of PV panels appear most frequently.

On the other hand, the exergy/exergoeconomics-based optimisation delivers an even smaller constrained search space with 344 models, representing 3.5% of the simulated space; however, it is able to deliver more Pareto optimal solutions with fourteen non-dominated models. This suggests that an exergy/exergoeconomics-based optimisation presents better performance and more variability among models, locating solutions in a wider spectrum. The most frequent HVAC system is H29: biomass boiler and underfloor heating with a frequency of 64.2%. This is followed by H15: district heating with wall heating with a frequency of 21.4%. For the insulation measures, high variability existed among technologies and thicknesses, with XPS and EPS being the most common measures. The air tightness of the building is characterised for solutions with 0.8 *ach*. In terms of glazing systems, double glazing technologies are the most frequent. For renewable technologies, 20 kW wind turbines and 11.7 kWp are the most common measures.

Fig. 4 and Fig. 5 shows a comparison of all the constrained solutions and the non-dominated Pareto fronts for the energy/economics and exergy/exergoeconomics based approaches respectively. For both graphs, the current retrofitted building can be located. In this case, every single Pareto point presents a better overall performance compared to the baseline model.

[Fig. 4 around here]

[Fig. 5 around here]

4.3 Algorithm behaviour – Convergence study

To check convergence in objectives, a comparison in the algorithm behaviour for both approaches is presented. Fig. 6 illustrates the convergence rates for the three studied objectives for the energy/economic optimisation. The results demonstrate that energy use converged rather early reaching the minimum value at the 28th generation. However, the discomfort hours and NPV converged at a much later stage (around the 60th generation). As it can be seen, the minimum value for in-site building energy use, found in the third generation (~70 kWh/m^2-year) is similar to the optimised value. This means that the algorithm selected a 'strong' and 'healthy individual' at an early stage in the simulation. On the other hand, due to the study strict constraints on capital investment and thermal comfort, larger number of generations were required for these objectives to converge within an acceptable value.

[Fig. 6 around here]

Fig. 7 illustrates the convergence rates for the exergy/exergoeconomic optimisation. Although it might seem that exergy destruction rate converged late in the optimisation process (generation 77th), the values at the initial generation already presented similar values to the final optimised value. The same behaviour is found for the discomfort hours, reaching convergence after the 8th generation. In the case of the exergoeconomic cost-benefit indicator the initial value of £0.20/h already represented a major improvement from the actual Passivhaus retrofit (£1.33/h); however, it was after generation 74th when it reached the best outcome (-£0.11/h) due to economic constrains set in the study.

[Fig. 7 around here]

4.4 A statistical comparison of optimisation outputs

Although there is no minimum sample size for a t-test to be valid, it is considered that the Pareto fronts are too small (sample sizes: 9 and 14); therefore, it is decided to perform the analysis in the constrained solutions (474 and 343 samples). For the test, the analysed indicators are the same as presented in Table 9. Fig. 8 presents boxplots for each of these outputs. The boxplots would also help to determine each output's variability, median values (skewness), and outliers. Although not conclusive, the test should provide an initial evidence to exhibit that, on average, either approach delivers better outcomes than the real retrofit. Although the t-test requires normally distributed samples, the test is not sensitive to deviation if the distribution of both samples' outputs is similar and the sample size is large enough (>50). Nevertheless, data transformation is required to make the output samples more normally distributed, meaning to remove some extreme outliers.

[Fig. 8 around here]

The independent t-test results are displayed in Table 10. Beforehand, it was expected that each approach dominates its related outputs, meaning that the energy/economic optimisation would deliver better indicators such as energy, NPV, LCC; while the exergy/exergoeconomic optimisation would perform better in indexes such as exergy destruction cost, exergy efficiency, etc. However, there are outputs such as discomfort and carbon emissions which were of great interest for this study.

[Table 10 around here]

According to the results, discomfort hours and annual revenue p-values demonstrated that the difference between the approaches' means, at a significance level of 5%, do not have statically significant difference from zero; therefore, there is insufficient evidence to suggest that either approach has a better performance. The discomfort hours' indicator p-value was expected, as this objective was optimised for both approaches; however, the fact that the annual revenue's energy/economic optimisation do not seem to outperform its exergy/exergoeconomic counterpart, suggests that exergoeconomic optimisation can also deliver cost-effective solutions without the need to invest larger amounts, as shown in the NPV t-test outputs. However, the indicator that seemed to provide the most meaningful outcome is the annual carbon emissions, where there is an average difference in annual emissions of 7.67 tCO_2 in favour of the exergy/exergoeconomic solutions. The t-test provided a 95% confidence interval of the mean difference between 5.8 and 9.78 tCO_2 and a small p-value of 7.16E-15; therefore the null-hypothesis can be rejected and conclude that the exergy/exergoeconomic optimisation approach, at least for this specific case study, provides larger carbon emission reductions.

5. Conclusions

This paper presented two different approaches (1st Law and combined 1st & 2nd Laws) for the optimisation of building energy retrofit designs under tight economic constraints. A recently retrofitted Passivhaus community centre has been used as case study. The results, although presented for a single case, clearly demonstrate the strengths of exergoeconomic optimisation compared to 1st Law-only optimisation (energy and typical economics). Considering the practical limitations that ExRET-Opt might present, the inclusion of exergy/exergoeconomics as objective functions into the MOO procedure has resulted in models with better overall performance, including non-thermodynamic values such as thermal comfort and carbon emissions.

However, due to the high capital investment constraints and high technological prices for low-exergy systems, some Pareto solutions under the exergy/exergoeconomic optimisation are based on high exergy systems (e.g. biomass boilers). This has deprived the optimisation model from suggesting more thermodynamic efficient designs. In an ideal thermodynamic situation, the BER system design would be based on either a high efficient low-temperature lift GSHP or on a waste-heat or low-carbon-based district system network, combined with low temperature hydronic systems and medium levels of envelope's thermal insulation. Nevertheless, the exergy-oriented approach is able to double the thermodynamic efficiency by focusing on improving exergy efficiency on generation systems and electrical appliances. The optimisation drove BER designs towards low-carbon HVAC systems, allocating limited budget to efficient active systems and suggesting U_{values} (envelope and glazing), and infiltration rates not as strict as government minimum requirements. These results suggest that both 1st and 2nd Law analysis, as they have the capability to locate exact sources of inefficiency, should be used together as objective functions and constraints in optimisation procedures.

Exergy and exergoeconomic optimisation could have an important future role in the building industry if some practical barriers can be overcome. The analysis has demonstrated to provide designs with an appropriate balance between active and passive measures, while consistently accounting of irreversibilities and its exergetic and economic costs along every subsystem in the building energy system. Meanwhile, the application of the exergoeconomic cost-benefit index as an objective function could provide more consistent outputs among a large variety of indicators. This index could be a practical solution as it supports building designers in making informed and robust economic decisions.

The outputs from this study should critically expose the limitations of using energy analysis only, demonstrating how the 1st Law is only a necessary calculation while the utilisation of the 1st and 2nd Laws simultaneously becomes a sufficient condition for an in-depth analysis. It is sought that the lessons learned and conclusions from this study may be useful for future retrofit standards and appropriate taxation across the UK and other countries. Minimising exergy destructions at a larger scale could provide countries with greater energy security as high-quality energy sources can be used more efficiently in sectors such as the chemical industry and transport. Nevertheless, more case studies and optimisation runs are necessary to generalise these conclusions.

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Nomenclature

ach	air change rates (1/h)
BER	building energy retrofit
$\dot{C}_D$	exergy destruction cost rate (£/h)
$\dot{C}_p$	exergy cost balance (£/kWh)
c_f	average cost of fuel (£/kWh)
c_p	average cost of product (£/kWh)
CAV	constant air volume
CRF	capital recovery factor (£)
DHW	domestic hot water
DPB	discounted payback (years)
e	Euler's number
EPS	Expanded Polystyrene
EUI	energy use index (kWh/m²-year)
Ex	exergy (kWh)
$\dot{E}x_D$	exergy destructions (kWh)
Ex_{dem}	exergy demand
Ex_{prim}	primary exergy
$Exec_{CB}$	exergoeconomic cost benefit factor (£/h)

f_k	exergoeconomic factor (-)
F_p	primary energy factor (-)
F_q	quality factor (-)
FiT	feed-in-tariff
$GSHP$	ground source heat pump
H	internal heat production rate (W/m^2)
$HVAC$	heating, ventilation, and air conditioning
i	interest rate (%)
kW	Kilowatt(s)
kWh	Kilowatt-Hour(s)
L	energy loss (W/m^2)
LCC	life cycle cost (£)
LFC	Lampe Fluorescente Compacte
M	metabolic rate (W/m^2)
$MVHR$	mechanical ventilation heat recovery
NPV	net present value (£)
N	project lifetime (years)
NSGA	Non-Dominated Sorting Genetic Algorithm
PMV	predicted mean vote
PW	*present factor (£)*
R	annual revenue (£)
$\dot{R}$	annual revenue rate (£/h)
r_k	relative cost difference (-)
RHI	renewable heat incentive (£)
SV	salvage cost (£)
T_0	reference temperature (K)
T_i	room temperature (K)
TCI	total capital investment (£)
U_{value}	thermal transmittance (W/m^2-K)
VAV	variable air volume
VRF	variable refrigerant flow
$Z_j(\mathrm{x}*)$	objective function
$\dot{Z}_{sys}$	capital investment rate (£/h)
Greek symbols	
ψ_{tot}	exergy efficiency (-)

Appendices

Appendix A. Exergy/exergoeconomic calculation framework [52, 53]

A.1 Exergy analysis for building energy systems

A.1.1 HVAC exergy stream

a) *Detailed thermal exergy demand (heat and matter):*

$$Ex_{dem,therm,\ zone\ i}(t_k) = \Sigma_{i=1}^{n}\left(En_{dem,\ therm\ ith}(t_k) * \left(1 - \frac{T_0\ (t_k)}{T_i\ (t_k)}\right)\right) \quad \text{(A.1)}$$

$$Ex_{dem,vent,\ zone\ i}(t_k) = \Sigma_{i=1}^{n}\left(En_{dem,\ vent\ ith}(t_k) * \left(1 - \frac{T_0\ (t_k)}{T_i\ (t_k) - T_0\ (t_k)} ln\frac{T_i\ (t_k)}{T_0\ (t_k)}\right)\right) \quad \text{(A.2)}$$

b) *Room air subsystem:*

$$F_{q,room}(t_k) = 1 - \frac{T_0\ (t_k)}{T_{emission}\ (t_k)} \quad \text{(A.3)}$$

Therefore, the exergy load of the room is:

$$Ex_{room}(t_k) = F_{q,emission}(t_k) * Q_{emission}\ (t_k) \quad \text{(A.4)}$$

c) *Emission subsystem:*

Referencing to the inlet and return temperature of the system, the exergy losses of the emission system are calculated as follows:

$$\Delta Ex_{emission}(t_k) = \frac{Q_{tot}\ (t_k) + Q_{loss,HS}(t_k)}{T_{in}(t_k) - T_{ret}(t_k)} * \left\{(T_{in}(t_k) - T_{ret}(t_k)) - T_0(t_k) * \ln\left(\frac{T_{in}(t_k)}{T_{ret}(t_k)}\right)\right\} \quad \text{(A.5)}$$

Therefore, exergy load rate of the heating system is:

$$Ex_{emission}(t_k) = Ex_{room}(t_k) + \Delta Ex_{emission}(t_k) \quad \text{(A.6)}$$

d) *Distribution subsystem:*

As a result of the heat losses in the supply pipe, a temperature drop occurs (ΔT_{dis}). The exergy demand of the distribution system is:

$$\Delta Ex_{dist}(t_k) = \frac{Q_{loss,dist}(t_k)}{\Delta T_{dist}(t_k)} * \left\{(\Delta T_{dist}(t_k) - T_0(t_k)) * \ln\left(\frac{T_{dist}(t_k)}{T_{dist}(t_k) - \Delta T_{dist}(t_k)}\right)\right\} \quad \text{(A.7)}$$

Hence, the exergy load of the distribution system is:

$$Ex_{dist}(t_k) = Ex_{emission}(t_k) + \Delta Ex_{dist}(t_k) \quad \text{(A.8)}$$

e) *Storage subsystem:*

The exergy demand of the storage can be calculated as follows:

$$\Delta Ex_{strg} = \frac{Q_{loss,strg}(t_k)}{\Delta T_{strg}(t_k)} * \left\{ (\Delta T_{strg}(t_k) - T_0(t_k)) * \ln\left(\frac{T_{dist}(t_k) + \Delta T_{strg}(t_k)}{T_{dis}(t_k)}\right)\right\} \quad \text{(A.9)}$$

And the exergy load is calculated as follows:

$$Ex_{strg}(t_k) = Ex_{dist}(t_k) + \Delta Ex_{strg}(t_k) \quad \text{(A.10)}$$

A.1.2 DHW exergy stream

Exergy demand for domestic hot water is calculated as follows::

$$Ex_{dem,DHW}(t_k) = Q_{DHW}(t_k) * \frac{\eta_{WH}(t_k)}{q_{fuel}} * \left(1 - \left(\frac{T_0(t_k)}{T_{p_{WH}}(t_k) - T_0(t_k)}\right) * \ln\left(\frac{T_{p_{WH}}(t_k)}{T_0(t_k)}\right)\right) \quad \text{(A.11)}$$

Distribution and storage subsystem in the DHW stream is calculated similar to the HVAC stream.

A.1.3 Electric-based exergy stream

Electric-based equipment such as fans, pumps, lighting, computers, and motors are considered to have the same exergy efficiency as their energy counterpart ($\psi_{elec} \approx \eta_{elec}$) and therefore the same exergy consumption.

$$Ex_{dem,elec,i}(t_k) = En_{dem,elec,i}(t_k) * F_{q,elec} \quad \text{(A.12)}$$

A.1.4 Other end-use streams

Exergy demand for cooking equipment (gas based):

$$Ex_{dem,cooking} = Q_{cook}(t_k) * \frac{\eta_{cook}(t_k)}{q_{fuel}} * \left(1 - \frac{T_0\,(t_k)}{T_{p_{cook}}(t_k)}\right) \quad \text{(A.13)}$$

Exergy demand for refrigeration:

$$Ex_{dem,ref}(t_k) = Q_{ref}(t_k) * COP_{ref}(t_k)\left(\frac{T_0(t_k)}{T_{p_{refr}}(t_k)} - 1\right) \quad \text{(A.14)}$$

A.1.5 Primary Exergy Input

For primary exergy input, the following formula is used:

$$Ex_{prim}(t_k = \textstyle\sum_i \left(\frac{En_{gen,i}(t_k)}{*\,\eta_{gen,i}\,(t_k)} * F_{p,source,i} * F_{q,source,i}\right) + \left(Ex_{dem,elec,ith}(t_k) * F_{p,elec}\right) \quad \text{(A.15)}$$

Fuel primary energy factors and quality factors used in this study are shown in Table A.1

[Table A.1 around here]

A.1.6 Exergy destructions and exergy efficiency

Exergy destructions is obtained by subsystems or whole building is obtained as follows:

$$Ex_{dest,i} = Ex_{IN,i} - Ex_{OUT,i} \quad \text{(A.16)}$$

Therefore, a building's exergy efficiency Ψ_i is obtained as follows:

$$\Psi_{sys,i}(t_k) = \frac{Ex_{out,i}\,(t_k)}{Ex_{in,i}(t_k)} \quad \text{(A.17)}$$

A.2 Economic/Exergoeconomic analysis

A.2.1 Economic analysis

The proposed framework recommends and considers typical economic calculations as a first assessment.

a) *Life cycle cost analysis (LCCA):*

$$LCCA = \sum_{n=1}^{N} \frac{CF_n}{(1 + r_d)^n} \quad \text{(A.18)}$$

where CF_n is the annual cash flow of year *n,* N is the total years of evaluation, and r_d is the discount rate. The annual cash flow is calculated as follows:

$$CF_{\boldsymbol{n}} = \left[C_n^B + O\&M_n^B\right] + \left[C_n + O\&M_n\right] + \left[C_{en} - C_{inc}\right] - SV_N \quad \text{(A.19)}$$

where C_n^B is the baseline capital cost, $O\&M_n^B$ is the baseline operation and maintenance cost, C_n is the incremental capital cost in year *n,* $O\&M_n$ is the incremental operation and maintenance cost in year n, C_{en} is the annual energy cost, C_{inc} is annual income from incentives, and SV_N is the salvage cost or residual value with measures with longer lifespan (considering a common rate of 15%).

b) Net Present value (NPV) and Discounted Payback (DPB)

$$NPV_{Nyears} = -TCI + \left(\sum_{n=1}^{N} \frac{R}{(1+i)^n}\right) + \frac{SV_N}{(1+i)^N} \quad \text{(A.20)}$$

where *TCI* is the initial total capital investment, *R* is the annual revenue cost (composed of the annual energy cost savings minus the operation and maintenance cost). A lifespan (N) of 50 years and a discount rate (i) of 3% [59] are considered. DPB can be calculated by contracting the Taylor Series of the NPV formula and by accounting for the retrofit project annual revenue:

$$DPB = -\frac{\ln\left[\left((1-(1+i)) * \left(\frac{TCI}{R}\right)\right) + 1\right]}{\ln(1+i)} \quad \text{(A.21)}$$

ExRET-Opt accounts for programs such as FiT and RHI. Other economic parameters that are considered are energy price escalation, inflation rate, labor and maintenance cost, taxes, etc. Table A.2 shows energy tariffs including CCL for 'small' non-domestic consumers.

[Table A.2 around here]

An annual energy price escalation until 2035 for gas and electricity is considered. [60]. Prices from 2035 onwards maintain the same value. Additionally, energy price forecasts for other energy sources are not considered.

Table A.3 shoes government incentives considered in the analysis. Price changes are not considered for these schemes.

[Table A.3 around here]

A.2.2 Exergoeconomic analysis (SPECO) [61]

This section shows the main exergoeconomic equations used in this study. Rates are presented in £/h.

An exergy cost stream rate associated with the corresponding stream *i* is calculated as follows:

$$\dot{C}_i = c_i Ex_i \tag{A.22}$$

where c_i and Ex_i are the streams' specific cost and exergy, respectively. A general cost balance expression rate is expressed as follows:

$$\dot{C}_{p,k} = \dot{C}_{D,k} + \dot{Z}_{sys} \tag{A.23}$$

In addition, the exergy destruction cost rate of a component is defined as:

$$\dot{C}_{D,k} = c_{f,K} \dot{Ex}_{D,k} \tag{A.24}$$

To obtain building exergy destruction cost rate, a sum of all subsystems' components is needed:

$$\dot{C}_{D,sys} = \sum_{k=0}^{n} (c_{f,K} \dot{Ex}_{D,k}) \tag{A.25}$$

To account for the component capital investment, we should convert it into an hourly rate dependant also on the project's lifetime:

$$\dot{Z}_{sys} = \frac{PW \cdot CRF}{\tau} \tag{A.26}$$

PW and *CRF* are obtained as follows:

$$PW = TCI - \frac{SV_N}{(1+i)^N} \tag{A.27}$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{A.28}$$

Apart from the basic exergoeconomic evaluation, within the SPECO method, two additional performance indicators can be calculated:

Relative cost difference

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} \tag{A.29}$$

Exergoeconomic factor

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{F,k}(\dot{Ex}_{D,k})} \tag{A.30}$$

Appendix B - ExRET-Opt BER strategies techno-economic characteristics [11]

[Table B.1 around here]

[Table B.2 around here]

[Table B.3 around here]

[Table B.4 around here]

[Table B.5 around here]

[Table B.6 around here]

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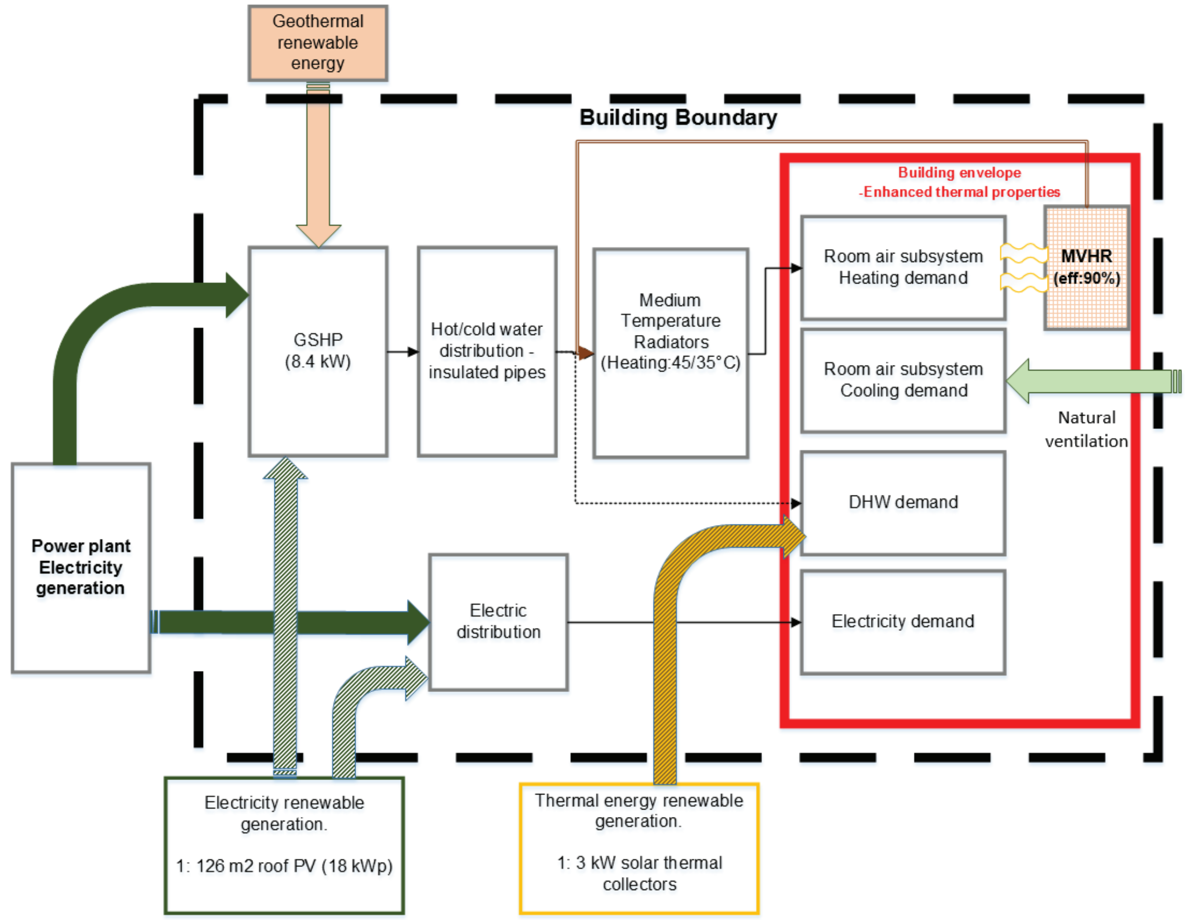
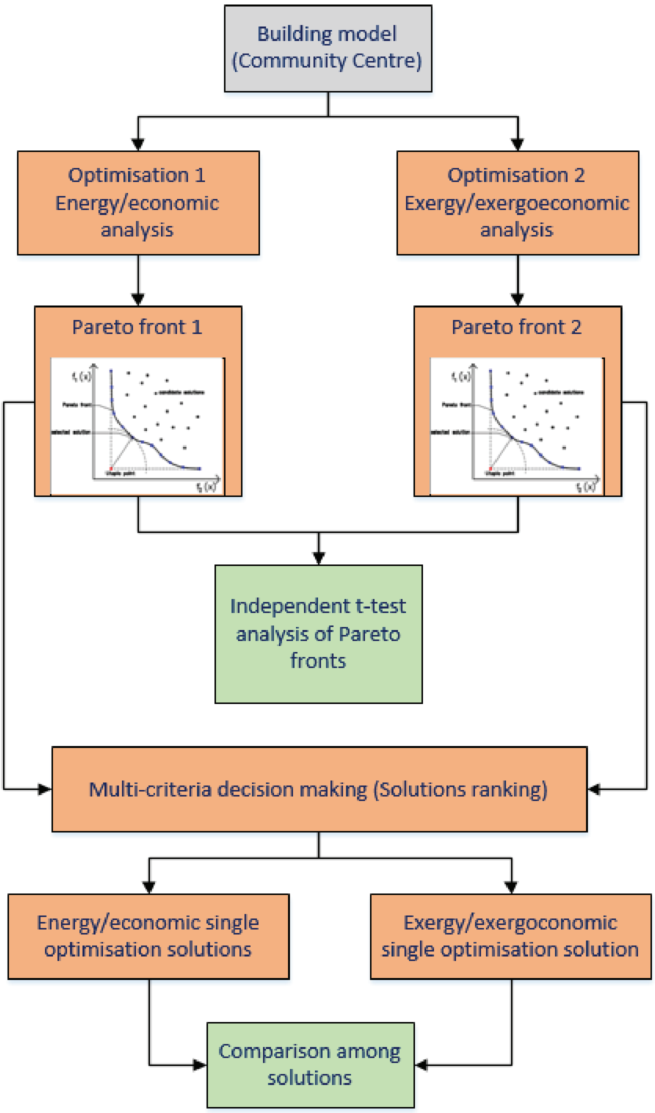
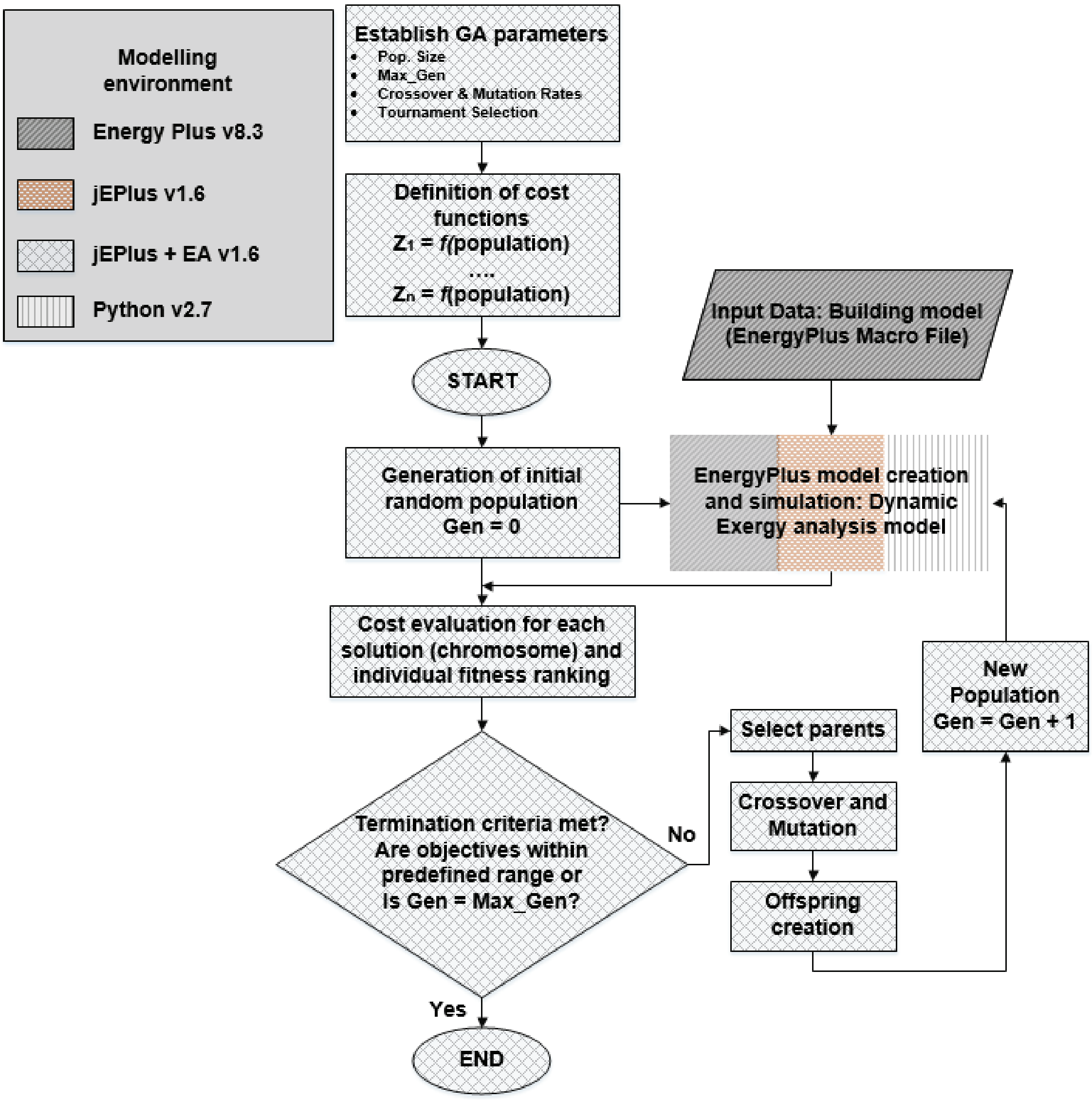


Fig. 1 Schematic layout of the energy system for the post-retrofit Community Centre



877
878 **Fig. 2 Methodological approach to assess the differences between results of both optimisation**
879 **approaches**
880



881
882 **Fig. 3 Genetic algorithm optimisation process applied to the ExRET-Opt tool [52]**

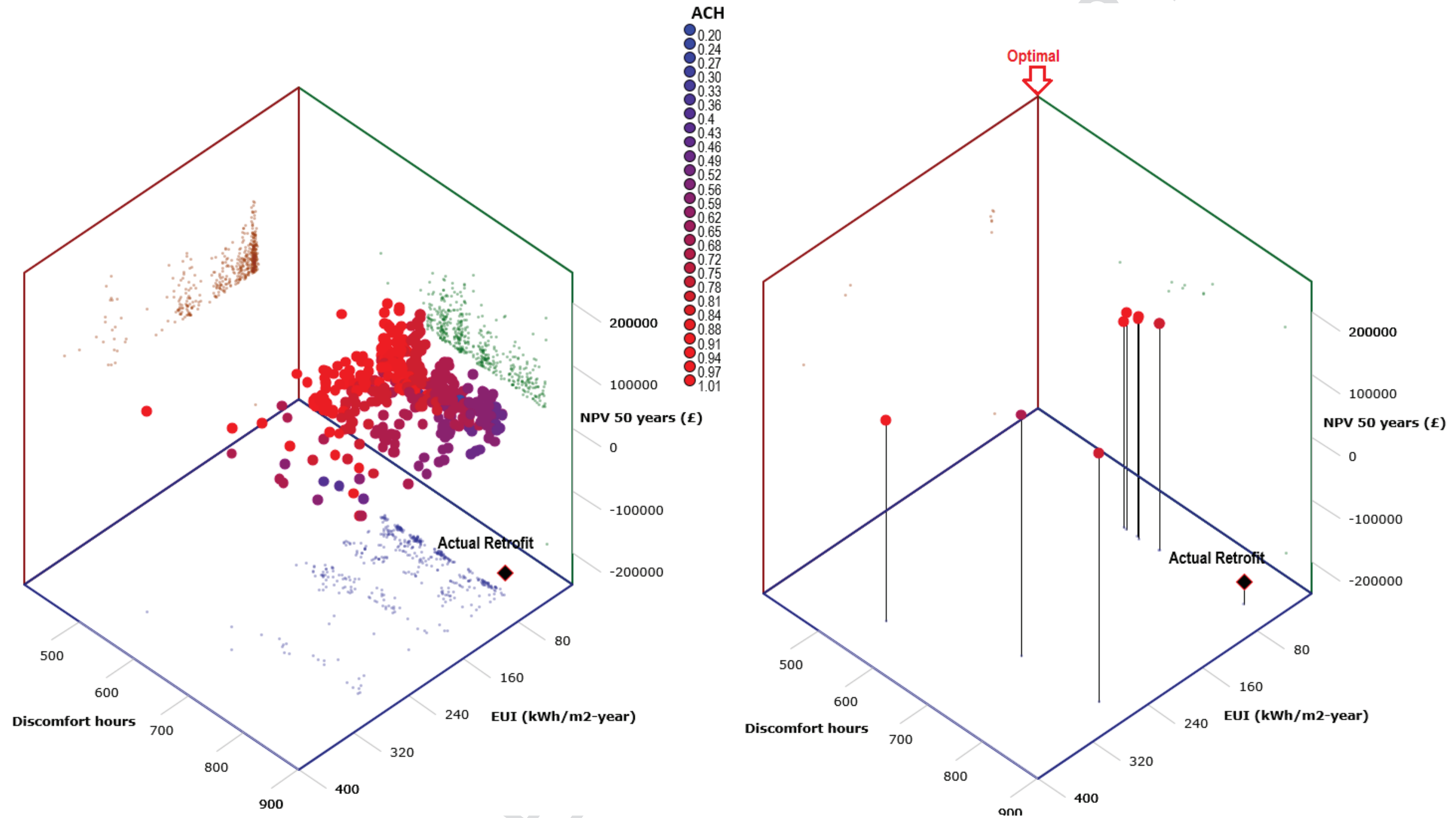


Fig. 4 Constrained results from the multi-objective optimisation (left) and the Pareto optimal solutions (right). Energy/economics- based optimisation

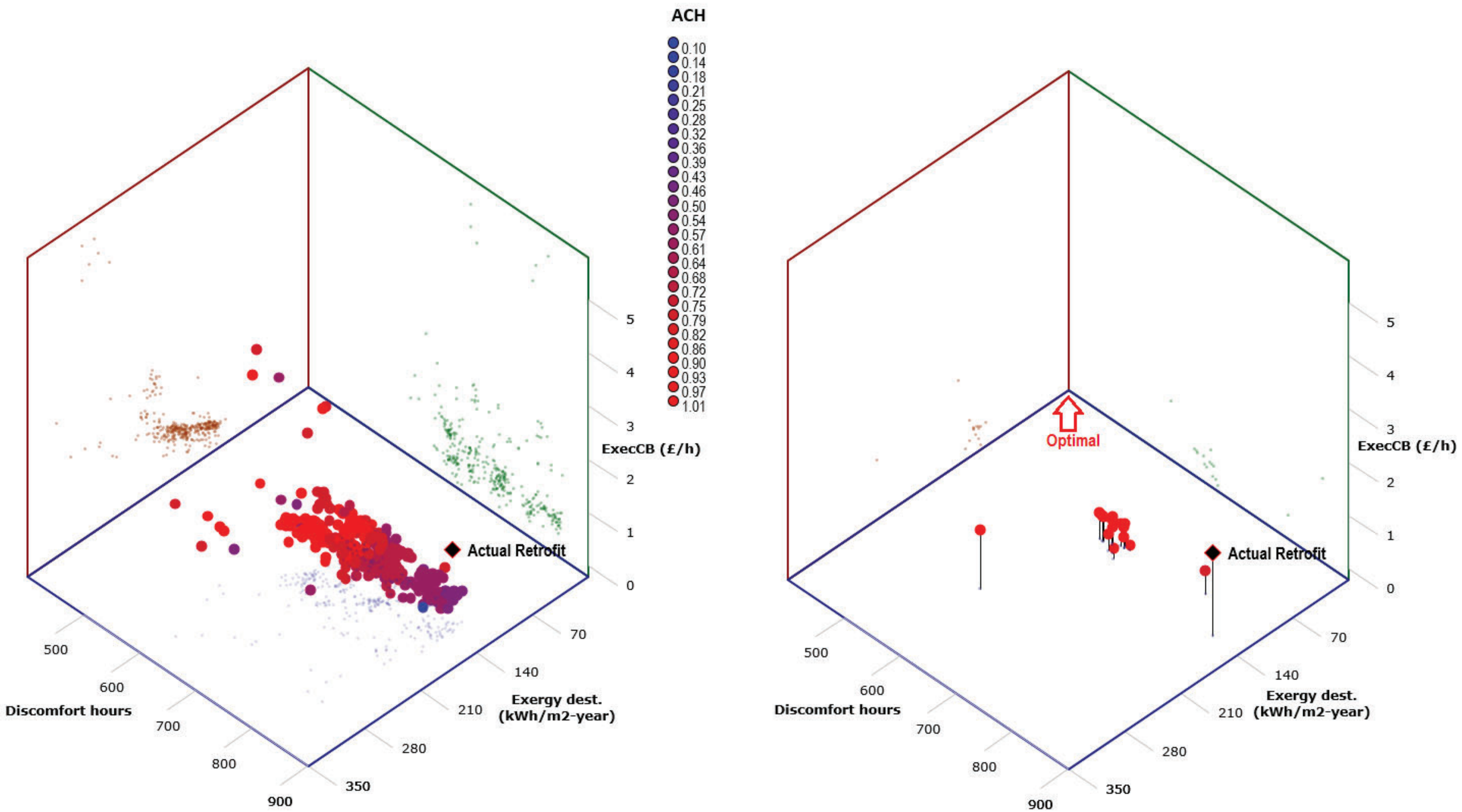


Fig. 5 Constrained results from the multi-objective optimisation (left) and the Pareto optimal solutions (right). Exergy/exergoeconomics-based optimisation

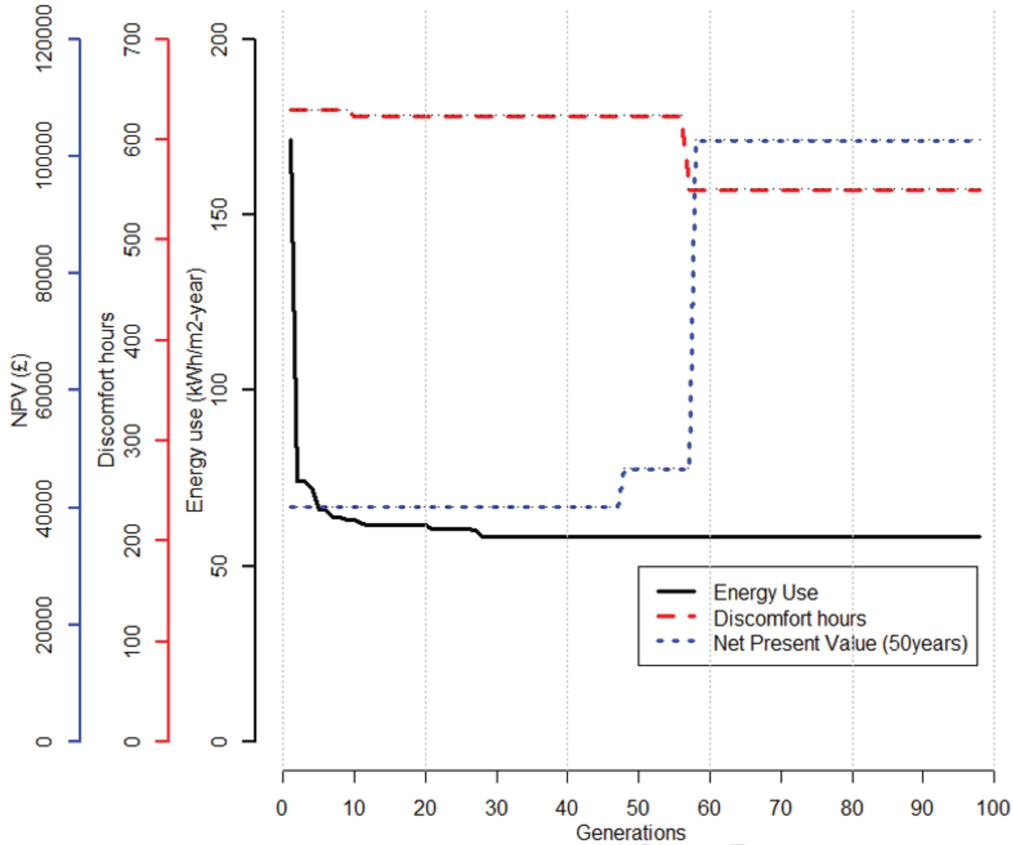


Fig. 6 Convergence of energy/economic optimisation procedure for the three objective functions

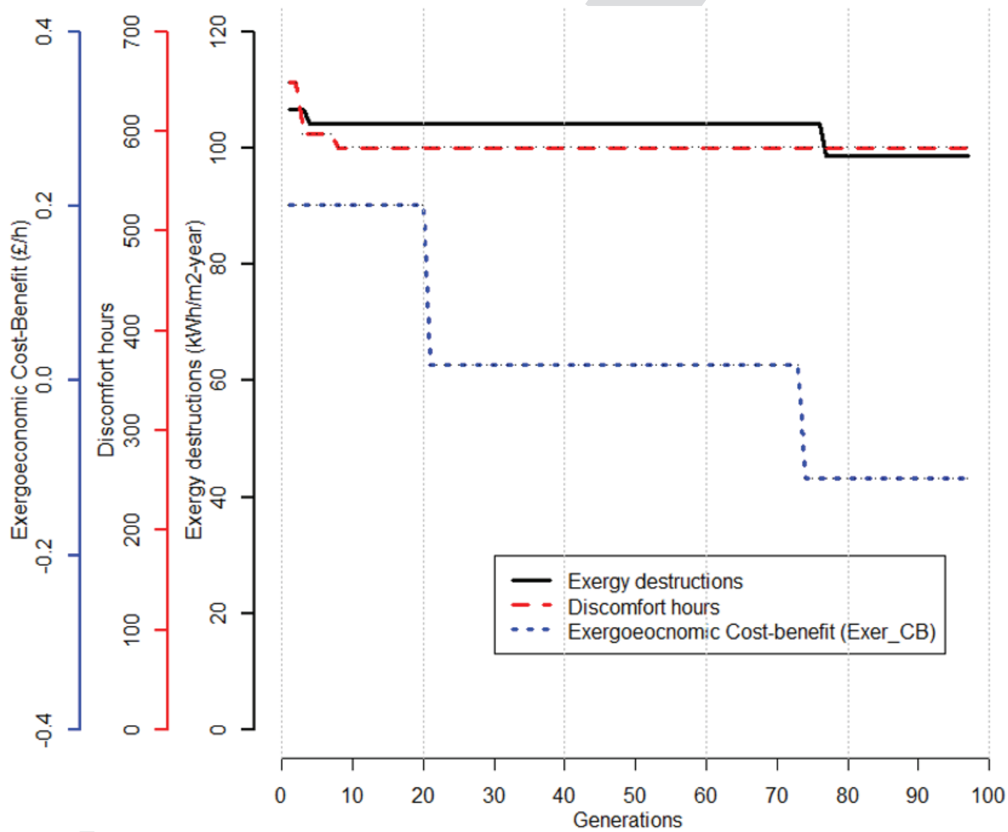


Fig. 7 Convergence of exergy/exergoeconomic optimisation procedure for the three-objective functions

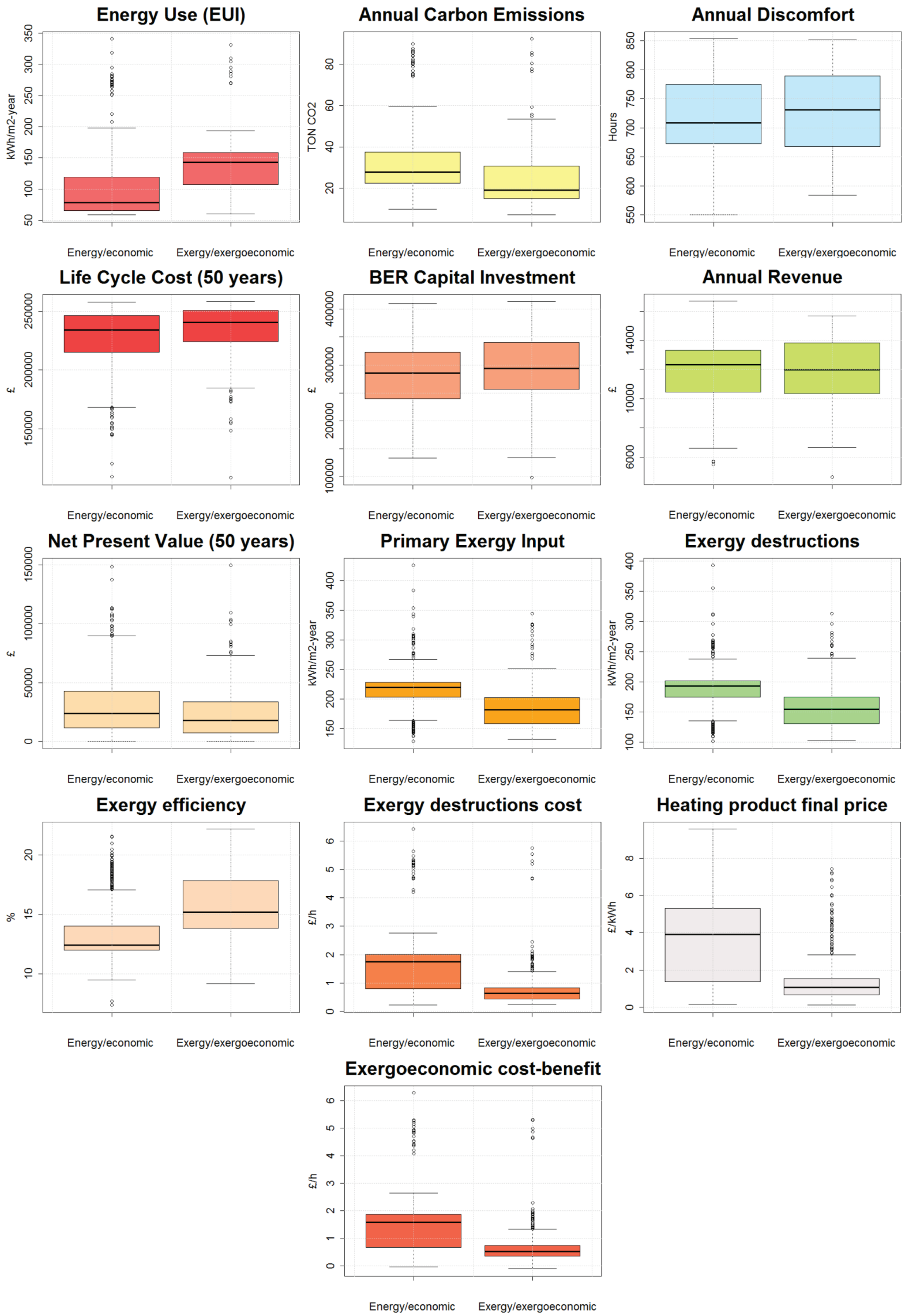


Fig. 8 Boxplots representing each output gathered for both optimisation approach

Table 1 Comparison of several multi-objective optimisation studies applied to building energy design studies

Author	Case study	Location(s)	Simulation engine(s)	Decision variables	Objective functions	Constraints	Optimisation algorithm	Ranking method
Diakaki et al. [7]	Single-zone dwelling (100 m2)	Athens, Greece	LINGO	Windows, insulation type, wall insulation thickness	• Initial investment cost • Building load coefficient	Insulation thickness	Mixed-integer combinatorial optimisation problem	Compromise programming and goal programming
Diakaki et al. [8]	Single-zone dwelling (100 m2)	Athens, Greece	LINGO	HVAC and DHW systems, Solar collectors, and building envelope characteristics	• Primary energy use • Carbon emissions • Initial investment cost	Capital investment	Mixed-integer combinatorial optimisation problem	Chebyshev programming
Siddharth et al. [9]	Office building (3721 m2)	Chennai, India. Maryland, USA. Arkansas, USA	DOE-2.2	HVAC systems, envelope characteristics	• Energy use • Initial investment cost	Non-defined	NSGA-II	N/A
Asadi et al. [10]	Semi-detached dwelling (97 m2)	Coimbra, Portugal	TRNSYS, GenOpt, and MatLab	Envelope characteristics (windows, walls, and roof) and solar collectors	• Initial investment cost • Energy savings • Thermal comfort	Non-defined	Mixed-integer combinatorial optimisation problem	Chebyshev programming
Diakaki et al. [11]	Single-zone dwelling 50m2	Iraklion, Greece	TRNSYS and LINGO	Envelope characteristics and HVAC systems	• Primary energy use • Carbon emissions • Initial investment cost	Technological and budget constraints	Mixed-integer multi-objective combinatorial optimisation problem	Chebyshev programming
Gossard et al. [12]	Single-zone dwelling (112 m2)	Nancy, France Nice, France	TRNSYS, GenOpt, and ANN	Envelope thermo-physical values	• Energy use • Thermal comfort	Comfort conditions	NSGA-II and Particle swarm optimisation (PSO)	Weighted-sum method
Malatji et al. [13]	Facility building (--- m2)	Pretoria, South Africa	N/A	Insulation, lighting, controls, and HVAC systems	• Energy use • Payback period	NPV, initial investment, energy target, and payback period	Integer programming GA	Weighted-sum method

Asadi et al. [14]	School building 9850 m2	Coimbra, Portugal	TRNSYS, GenOpt, and ANN	Envelope characteristics (windows, walls, and roof), solar collectors, and HVAC systems	• Energy use • Retrofit cost • Thermal comfort	Non-defined	NSGA-II	N/A
Murray et al. [15]	University building (--- m2)	Cork, Ireland	Degree-days and BeOpt	Envelope characteristics (windows, walls, and roof)	• Simple payback • Carbon emissions • Energy Cost	Capital investment	NSGA-II	N/A
Shao et al. [16]	Office building (400 m2)	Aachen, Germany	Visual Basic energy model	Envelope characteristics (windows, walls, and roof), and HVAC systems	• Initial capital investment • Energy use, • Carbon emissions	Envelope physical values, annual energy use and envelope air leakage	NSGA-II	Multiple-attribute value theory (MAVT)
Wang et al. [17]	Facility building (--- m2)	Pretoria, South Africa	N/A	Lighting and HVAC systems	• Energy savings • NPV • Evaluation period	% energy use, expected payback period, initial investment	Differential evolution (DE) algorithms	Weighted sum method
Ascione et al. [18]	Apartment flats (110 m2 per flat)	Naples, Italy	EnergyPlus and MatLab	Setpoints, envelope insulation, and HVAC systems	• Initial investment cost • HVAC energy requirement • Thermal comfort	Investment costs	NSGA-II	N/A
Echenagucia et al. [19]	Open space office (first floor) (280 m2)	Palermo, Torino, Frankfurt and Oslo	EnergyPlus	Wall thickness, Number, shape and placement of windows Glazing characteristics	• Heating • Cooling • Lighting	Building physical characteristics	NSGA-II	N/A
Dahlhausen et al. [20]	Office building (6968 m2)	Philadelphia, USA	Open Studio, EnergyPlus, and R	Building enclosure, solar control, plug load/lighting control, and HVAC equipment	• Energy use • NPV	Investment costs	mixed-integer multi-objective combinatorial optimisation problem	N/A

Carlucci et al. [21]	detached single-family house (149.2 m2)	Mascalucia, Italy	EnergyPlus, GenOpt and Java	Envelope characteristics, control strategies, and window openings	• Thermal comfort • Visual comfort	Indoor air quality	NSGA-II	N/A
Lu et al. [22]	Office building (1520 m2)	Hong Kong, China.	TRNSYS and MatLab	Envelope and HVAC systems	• Investment costs • Carbon emissions • Grid interaction index.	Zero energy use	NSGA-II	N/A
Ascione et al. [23]	Apartment flats (110 m2 per flat)	Napes, Italy. Istambul, Turkey	EnergyPlus and MatLab	Solar absorbance and infrared emittance of external plastering, insulation thickness, brick thickness and density, windows' thermal transmittance	• Primary energy for space conditioning • Thermal comfort	Maximum value of admitted discomfort	NSGA-II	Weighted sum method
Ascione et al. [24]	Apartment flats (110 m2 per flat)	Napes, Italy	EnergyPlus and MatLab	Presence and the characteristics (typology and size) renewable systems (type and size of solar collectors, type and size of PV panels, generation system for heating, cooling and DHW)	• Primary energy consumption • Investment cost	Fulfillment of the minimum levels of RES integration per Italian law (minimum production of DHW, minimum size of PV, etc)	NSGA-II	Weighted sum method

Penna et al. [25]	Single-zone dwelling (100 m2)	Milan, Italy. Messina, Italy	TRNSYS and MatLab	Envelope and HVAC systems	• Energy use • NPV • Thermal comfort	Investment costs	NSGA-II	N/A
Delgarm et al. [26]	Single-zone dwelling (9 m2)	Tehran, Iran. Kerman, Iran	EnergyPlus, jEPlus and MatLab	Insulation, glazing, and solar shading	• Annual heating • Cooling • Lighting	N/A	Particle swarm optimisation (PSO)	Weighted sum method
Ascione et al [27]	Residential building (140 m2)	Napes, Italy	EnergyPlus and MatLab	hourly values of set point temperatures in the building thermal zones	• Energy demand • Thermal comfort	Maximum duration of HVAC system daily operation	NSGA-II	Weighted sum method
Schwartz et al. [28]	Council house complex (--- m2)	Sheffield, England	EnergyPlus, jEPlus and jEPlus EA	Envelope characteristics, insulation, windows	• Life cycle cost • Life cycle carbon	N/A	NSGA-II	N/A
Hamdy et al. [29]	Residential house –two floors (143 m2)	Helsinki, Finland	IDA-ICE 4.6	Energy saving measures (envelope, equipment, systems), renewable energy sources (thermal collectors, PV) and mechanical systems	• primary energy consumption • life-cycle cost (LCC) of the design solution	N/A	pNSGA-II MOPSO PR.GA ENSES evMOGA spMODE-II MODA	Normalized generational distance, normalized inversed generational distance and normalized diversity metric
Fan et al. [30]	Residential building – 66 apartments (70 m2 each)	South Africa	Non-linear integer programming problem.	Windows, external wall insulation materials, roof insulation materials, rooftop solar panel	• Energy savings • NPV • Payback period	Total cost of the building envelope retrofitting considering maintenance during a time, and maximum area for solar panel	Genetic Algorithm	Weighted sum method

Table 2 Retrofitted Community Centre main characteristics

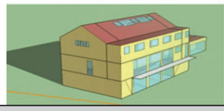
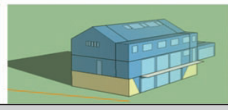
General Description	Three Storey Community Centre - Offices	  		
Building Type	Commercial			
Configuration	Low Rise-Shallow Plan			
Location	London			
Coordinates	51° 33' 03'' N, 0° 04′ 57'' W Decimal 51.550833^0, -0.082489^0			
Weather File	London Heathrow, UK			
Geometry				
Number of Floors	3	Total Floor Area	800m^2	
Opaque Materials	**Construction (from inside layer)**		**U-Value Wm^2/K**	
External Walls (GF/1STF)	400mm Solid Wall – 300mm Extruded Polystyrene		0.109	
External Walls (Basement)	400mm Solid Wall – 200mm Expanded Polystyrene		0.160	
Basement Floor	300 mm Concrete Floor Slab – 80mm Phenolic Foam		0.173	
Ground Floor	300 mm Concrete Floor Slab – 300mm Cellular Glass		0.108	
Pitched Roof	Timber framed - 300mm Cellular Glass - Zinc finish		0.134	
Flat Roof	200 mm Concrete Slab – 300mm Cellular Glass		0.131	
Transparent Materials	**Property**	**U-Value W/m^{2}K**	**SHGC**	**VT**
Glazing Material	6-13-6-13-6 Triple Glazed Air Filled-Low-e	1.598	0.613	0.696
Glazing Area	23% of Total Wall Area			
Skylight Area	5% of Total Roof Area			
Shading	N/A			
Systems				
HVAC System Type	Mechanical Ventilation with Heat Recovery System			
Heating System	Heat Recovery System + 8.4kW Ground Source Heat Pump with radiators			
COP GSHP	4.5			
Fuel Type	Electricity			
Heating System Controls	Main System Thermostat – Thermostatic Valves on Radiators			
Cooling System	N/A (Natural Ventilation and Night Cooling)			
Ventilation	• Winter: Mechanical Ventilation Heat Recovery-Radius Heat Exchanger Eff= 0.75 • Summer: Mixed Mode Ventilation Heat Recovery-Radius Heat Exchanger Eff= 0.75 + Natural Ventilation			
Specific Fan Power	0.7 – 1.5 kPa			
DHW				
Generator Type	Single 3m^2 thermal vacuum tube panel + hot water tank GSHP for top-up			
Fuel Type	Solar energy - Electricity			
Lighting				
Type	T8 LFC			
Controls	manual-on-off			
Loads				
Occupancy	1 person/16m^2 - at average 140 watts= 8.75 W/m^2			
Equipment	73.4 W/m^2			
Lighting	10.6 W/m^2			
Rates				
Infiltration Rate (@50 Pa)	0.42 ach			
Renewables (PV system)				
Available roof space	398.6 m^2			
PV array	125m^2 of PV on pitched surface (inclination 30^o)			
Type	77 modules of 18kWp, c-Si-Monocrystalline			

Table 3 Actual performance for the case study Passivhaus building [51]

Energy and economic indicators	**Values**
Energy use (EUI) (kWh/m^2-year)	61.6
Energy bill (£/year)	4,379
RHI income (£/year)	988.3
FiT income (£/year)	723.6
Retrofit capital investment (£)	417,028
Annual revenue (£/year)	7,415.4
Life Cycle Cost $_{50\ years}$ (£)	471,403
Net Present Value $_{50\ years}$ (£)	-213,436
DPB	137.2
Exergy and exergoeconomic indicators	**Values**
Exergy input (fuel) (kWh/m^2-year)	166.8
Exergy demand (product) (kWh/m^2-year)	30.0
Exergy destructions (kWh/m^2-year)	136.8
Exergy efficiency HVAC	10.4%
Exergy efficiency DHW	2.5%
Exergy efficiency Electric equip.	19.9%
Exergy efficiency Building	18.0%
Exergy cost fuel-prod HEAT (£/kWh) {r_k}	0.12—0.26{1.14}
Exergy cost fuel-prod COLD (£/kWh) {r_k}	----- {---}
Exergy cost fuel-prod DHW (£/kWh) {r_k}	0.12—1.90 {14.82}
Exergy cost fuel-prod Elec (£/kWh) {r_k}	0.12—0.24 {0.97}
D (£/h) Exergy destructions cost {energy bill £; %D from energy bill}	0.38 {2,947.3; 68.2 %}
Z (£/h) Levelised capital cost	1.78
R (£/h) Levelised revenue	0.84
Exergoeconomic factor f_k (%)	0.82
Exergoeconomic cost-benefit (£/h)	**1.33**
Non-thermodynamic indices	**Values**
Occupant thermal discomfort (PMV)	853
Carbon emissions tCO_2	38.6

Table 4 Characteristics and investment cost of HVAC systems [50, 52]

HVAC ID	System Description	Emission system	Cost
H1	*Condensing Gas Boiler + Chiller*	CAV	*Generation systems* • £160/kW Water-based Chiller (COP=3.2) • £99/kW Condensing gas boiler (η=0.95) • £70/kW Oil Boiler (η=0.90) • £150/kW Electric Boiler (η=1.0) • £208/kW Biomass Boiler (η=0.90) • £1300/kW ASHP-VRF System (COP=3.2) • £1200/kW GSHP (Water-Water) System (COP=4.2) • £452/kW ASHP (Air-Air) (COP=3.2) • £2000/kW PV-T system • £27080 micro-CHP (5.5 kW) + fuel cell system Emission systems • £700 per CAV • £1200 per VAV • £35/m² wall heating • £35/m² underfloor heating • £6117 per Heat Recovery system Other subsystems: • £56/kW District heat exchanger + £6122 connection charge • £50/m for building's insulated distribution pipes
H2	*Condensing Gas Boiler + Chiller*	VAV	
H3	*Condensing Gas Boiler + ASHP-VRF System*	FC	
H4	*Oil Boiler + Chiller*	CAV	
H5	*Oil Boiler + Chiller*	VAV	
H6	*Oil Boiler + Chiller*	FC	
H7	*Electric Boiler + Chiller*	CAV	
H8	*Electric Boiler + Chiller*	VAV	
H9	*Electric Boiler + ASHP-VRF System*	FC	
H10	*Biomass Boiler + Chiller*	CAV	
H11	*Biomass Boiler + Chiller*	VAV	
H12	*Biomass Boiler + ASHP-VRF System*	FC	
H13	*District system*	CAV	
H14	*District system*	VAV	
H15	*District system*	Wall	
H16	*District system*	Underfloor	
H17	*District system*	Wall+Underfloor	
H18	*Ground Source Heat Pump*	CAV	
H19	*Ground Source Heat Pump*	VAV	
H20	*Ground Source Heat Pump*	Wall	
H21	*Ground Source Heat Pump*	Underfloor	
H22	*Ground Source Heat Pump*	Wall+Underfloor	
H23	*Air Source Heat Pump*	CAV	
H24	*PVT-based system (50% roof) with supplemental Electric boiler and Old Chiller*	CAV	
H25	*Condensing Boiler + Chiller*	Wall	
H26	*Condensing Boiler + Chiller*	Underfloor	
H27	*Condensing Boiler + Chiller*	Wall+Underfloor	
H28	*Biomass Boiler + Chiller*	Wall	
H29	*Biomass Boiler + Chiller*	Underfloor	
H30	*Biomass Boiler + Chiller*	Wall+Underfloor	
H31	*Micro-CHP with Fuel Cell and Electric boiler and old Chiller*	CAV	
H32	*Condensing Gas Boiler and old Chiller. Heat Recovery System included.*	CAV	
H33*	*Ground Source Heat Pump + Heat Recovery System*	MT Radiators	

* H33 represents the actual post-retrofit HVAC system installed

Table 5 Decision variables and vector ID used for the case study

Decision variables - BER measures	Number of possible solutions	Vector ID
HVAC system	34	X^{HVAC}
Wall insulation (above ground)	116	X^{wall}
Roof Insulation	116	X^{roof}
Ground floor Insulation	111	X^{ground}
Basement Wall insulation	116	$X^{\mathrm{wall\_BS}}$
Pitched Roof Insulation	116	$X^{\mathrm{roof\_Pi}}$
Basement Ground Insulation	111	$X^{\mathrm{ground\_BS}}$
Sealing (infiltration rate)	10	X^{seal}
Glazing	13	X^{glaz}
Lighting	4	X^{light}
Photovoltaic panels	12	X^{PV}
Wind turbines	3	X^{wind}
Heating set-point	5	X^{heat}

Table 6 Algorithm parameters and stopping criteria for optimisation with GA

Parameters	
Encoding scheme	Integer encoding (discretisation)
Population type	Double-Vector
Population size	100
Crossover Rate	100%
Mutation Rate	40%
Selection process	Stochastic – fitness influenced
Tournament Selection	2
Elitism size	Pareto optimal solutions
Stopping criteria	
Max Generations	100
Time limit (s)	10^{6}
Fitness limit	10^{-6}

Table 7 BER retrofit design for single-objective optimisation using energy/economics-based approach

Obj.	X^{HVAC}	X^{wall} Wall Insulation (m) {U-value}	X^{roof} Roof Insulation (m) {U-value}	X^{ground} Ground Insulation (m) {U-value}	X^{wall_BS} Basement Wall Insulation (m) {U-value}	X^{roof_Pi} Pitched Roof Insulation (m) {U-value}	X^{ground_BS} Basement Ground Insulation (m) {U-value}	X^{seal} Infiltration Reduction % (ach)	X^{glaz} (glass-gap-glass, in mm)	X^{light} Light tech	X^{PV} % Roof panels	X^{wind} (kW)	X^{heat} (°C)	EUI_{bu} (kWh/m²-year)	*Discom-fort* (hours)	NPV_{50y} (£/h) {DPB-years}
[min] EUI_{bui}	H21: GSHP + Underfloor Heat.	Polyure-thane (0.25m) {U: 0.09}	Phenolic (0.03m) {U: 0.32}	Phenolic (0.05m) {U: 0.15}	Cellular Glass (0.30m) {U: 0.13}	Phenolic (0.08m) {U: 0.25}	Phenolic (0.10m) {U: 0.11}	50% (0.9 ach)	Double glazed Air (6-6-6)	T8 LFC	0	20	21	**58.4**	841	+8,488 {50.0}
[min] *Discom-fort*	H21: GSHP + Underfloor Heat.	EPS (0.14m) {U: 0.22}	XPS (0.10m) {U: 0.33}	Cellular Glass (0.12m) {U: 0.14}	XPS (0.25m) {U: 0.13}	EPS (0.12m) {U: 0.27}	Polyure-thane (0.10m) {U: 0.11}	40% (0.6 ach)	Double glazed Krypton (6-6-6)	T5 LFC	10	20	21	65.9	**550**	+79,773 {33.6}
[max] NPV_{50y}	H31: mCHP + Boiler + CAV	Glass Fibre (0.15m) {U: 0.21}	XPS (0.08m) {U: 0.85}	Cork Board (0.14m) {U: 0.18}	XPS (0.04m) {U: 0.60}	XPS (0.03m) {U: 0.41}	Phenolic (0.04m) {U: 0.26}	20% (0.8 ach)	Double glazed Air (6-13-6)	T5 LFC	10	20	21	272.4	853	**+148,667** **{23.7}**

Table 8 BER retrofit design for single-objective optimisation using exergy/exergoeconomics-based approach

Obj.	X^{HVAC}	X^{wall} Wall Insulation (m) {U-value}	X^{roof} Roof Insulation (m) {U-value}	X^{ground} Ground Insulation (m) {U-value}	X^{wall_BS} Basement Wall Insulation (m) {U-value}	X^{roof_Pi} Pitched Roof Insulation (m) {U-value}	X^{ground_BS} Basement Ground Insulation (m) {U-value}	X^{seal} Infiltration Reduction % (ach)	X^{glaz} (glass-gap-glass, in mm)	X^{light} Light tech	X^{PV} % Roof panels	X^{wind} (kW)	X^{heat} (°C)	Ex_{dest} (kWh/m²-year)	*Discom-fort* (hours)	$Exec_{CB}$ (£/h) {DPB (years)}
[min] $Ex_{dest,bui}$	H15: District Heating + Wall Heat.	Polyure-thane (0.03m) {U: 0.56}	Phenolic (0.05m) {U: 0.37}	Polyure-thane (0.06m) {U: 0.23}	Glass Fibre (0.20m) {U: 0.16}	EPS (0.09m) {U: 0.37}	Aerogel (0.025m) {U: 0.26}	20% (0.8 ach)	Single glazed (6)	T8 LED	0	20	20	**102.9**	791	0.23 {50.0}
[min] *Discom-fort*	H28: Biomass Boiler + Wall Heat.	EPS (0.25m) {U: 0.13}	Cork board (0.28m) {U: 0.13}	Cork board (0.14m) {U: 0.12}	EPS (0.07m) {U: 0.39}	Cork Board (0.12m) {U: 0.28}	Cellular glass (0.13m) {U: 0.13}	10% (0.9 ach)	Double glazed Air (6-13-6)	T5 LFC	30	0	20	117.8	**584**	0.28 {43.7}
[min] $Exec_{CB}$	H29: Biomass Boiler + Underfloor Heat	Glass Fibre (0.065m) {U: 0.42}	Polyure-thane (0.12m) {U: 0.19}	Phenolic (0.03m) {U: 0.17}	XPS (0.03m) {U: 0.72}	Polyure-thane (0.04m) {U: 0.57}	Polyure-thane (0.07m) {U: 0.14}	10% (0.9 ach)	Single glazed	T5 LFC	20	0	19	114.0	666	**-0.11** **{26.7}**

Table 9 A comparison of main indicators among single optimisation models from both MOO approaches (best performance in bold and underlined, worst performance in bold and italic)

Model	EUI (kWh/m² - year)	Annual Carbon (tCO_2)	Discom-fort (hours)	LCC (50 years) (£)	BER Total Capital Invest. (£)	Annual Revenue (with incentives) (£)	NPV (50 years) (£)	Primary exergy input (kWh_{ex}/m²-year)	Exergy dest. (kWh_{ex}/m²-year)	Exergy eff. Building (%)	Exergy dest. cost rate (£/h)	Heating fuel-product price (£/kWh)	$Exec_{CB}$ (£/h)
Energy/economic-based optimisation													
[min] EUI_{bui}	**58.4**	27.5	841	249,478	271,738	10,530	8,489	222.1	194.7	***12.3%***	2.06	0.12--4.24	2.03
[min] *Discom-fort*	***65.9***	28.3	**550**	186,670	***316,444***	14,649	71,297	213.1	185.9	12.7%	1.05	0.12—3.59	1.43
[max] NPV_{50y}	272.4	***81.0***	***853***	**109,300**	262,992	**15,650**	**148,667**	***294.5***	***255.9***	13.1%	***5.05***	***0.12--4.46***	***4.39***
Exergy/exergoeconomics-based optimisation													
[min] $Ex_{dest,bui}$	118.3	53.6	791	***254,123***	**179,250**	***6,878***	***3,844***	**132.2**	**102.9**	**22.2%**	**0.25**	**0.07--0.12**	0.23
[min] *Discom-fort*	121.7	25.0	584	150,796	256,761	11,309	43,005	146.3	117.8	19.5%	0.28	0.04—0.29	0.28
[min] $Exec_{CB}$	123.3	**14.4**	666	177,333	180,018	9,891	80,633	142.2	114.0	19.9%	**0.25**	0.04--0.19	**-0.11**

917 **Table 10 Independent t-test analysis on main indicators from both optimisation approaches**
918 **(best performance in bold and underlined)**

Indicator	Mean energy/ economic approach	Mean exergy/ exergoeconomic approach	Estimation difference	95% Confidence interval		t-value	p-value
EUI (kWh/m²year)	**<u>102.4</u>**	135.0	-32.4	-39.1	-26.0	-9.78	2.2E-16
Carbon emissions (tCO_2/year)	31.65	**<u>23.98</u>**	7.67	5.8	9.6	7.94	7.2E-15
Discomfort (Hours)	726	729	-3	-11.6	6.2	-0.59	0.5507
LCC (£)	**<u>226,694</u>**	233,946	-7252	-10,576	-3,928	-4.28	2.1E-05
BER Capital Investment (£)	**<u>282,047</u>**	292,534	-10487	-18,640	-234	-2.53	0.01177
Annual Revenue (£)	11,802	11,914	-112	-421	198	-0.71	0.4787
NPV (£)	**<u>31,273</u>**	24,021	7252	3,928	10,576	4.28	2.1E-05
Primary exergy input (kWh/m²year)	215.9	**<u>186.4</u>**	29.5	24.4	34.6	11.35	2.2E-16
Exergy destructions (kWh/m²year)	187.6	**<u>158.0</u>**	29.6	24.6	34.6	11.72	2.2E-16
Exergy efficiency (%)	13.4	**<u>15.6</u>**	-2.2	-2.5	-1.84	-12.3	2.2E-16
Exergy destructions cost (£/h)	1.59	**<u>0.80</u>**	0.79	0.67	0.9	13.12	2.2E-16
Heating product final price (£/kWh)	3.64	**<u>1.47</u>**	2.17	1.92	2.42	17.19	2.2E-16
Exergoeconomic Cost-benefit (£/h)	1.15	**<u>0.70</u>**	0.45	0.64	0.87	12.86	2.2E-16

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Table A.1 Primary Energy Factors and Quality Factors by energy sources

Energy source	Primary energy factor (F_p) (kWh/kWh)	Quality factor (F_q) (kWhex/kWhen)
Natural gas	1.11	0.94
Electricity (Grid supplied)	2.58	1.00
District energy[1]	1.11	0.94
Oil	1.07	1.00
Biomass (Wood pellets)	(0.20)[t] 1.20	1.05
Coal	1.01	1.04

The District system was assumed to be run by a single-effect indirect-fired absorption chiller with a coefficient of performance (COP) of 0.7.

[t] Considering a quality factor for renewable based and fossil based separately.

Table A.2 Energy tariffs for small non-domestic buildings in the UK in 2015 (considering CCL)

Energy source	Prices (£/kWh)
Natural gas	0.030
Electricity (Grid supplied)	0.121
District Heating and Cooling	0.066[y]
Oil	0.054
Biomass (Wood pellets)	0.044

[y] Prices taken from Shetland Heat Energy & Power Ltd - Lerwick's District Heating Scheme (Commercial tariffs http://www.sheap-ltd.co.uk/commercial-tariffs) Accessed: 15-October-2015

Table A.3 FiT and RHI tariffs included in ExRET-Opt. Prices are from September, 2015

Incentive Schemes Tariff	Prices (£/kWh)
FiT Electricity Exported	0.048
FiT PV Electricity Generation	0.059
FiT Wind Electricity Generation	0.138
RHI Solar Heat Generation	0.103
RHI GSHP Heat Generation	0.090
RHI ASHP Heat Generation	0.026
RHI Biomass Heating Generation	0.045

Table B.1 Characteristics and investment cost of lighting systems

Lights ID	Lighting technology	Cost per W/m²
L1	*T8 LFC*	£5.55
L2	*T5 LFC*	£7.55
L3	*T8 LED*	£11.87

Table B.2 Characteristics and investment cost of renewable energy generation systems

Renewable ID	Technology	Cost
R1	*PV panels 10-100% roof*	PV: £1200/m² Turbine: £4000/kW
R2	*Wind Turbine 20 kW*	
R3	*Wind Turbine 40 kW*	

*For the case study PV panels roof area were applied in 10% steps (0-100%)

Table B.3 Cooling and heating indoor set points variations

Set-point ID	Set-point Type	Value (°C)	Cost
SH18	*Heating*	18	(-)
SH19		19	
SH20		20	
SH21		21	
SH22		22	

Table B.4 Characteristics and investment cost of different insulation materials

Ins. ID	Insulation measure	Thickness (cm)	Total of measures	Cost per m² (lowest to highest)
I1	*Polyurethane*	2 to 15 in 1 cm steps	14	£6.67 to £23.32
I2	*Extruded polystyrene*	1 to 15 in 1 cm steps	15	£4.77 to £31.99
I3	*Expanded polystyrene*	2 to 15 in 1 cm steps	14	£4.35 to £9.95
I4	*Cellular Glass*	4 to 18 in 1 cm steps	15	£16.21 to £72.94
I5	*Glass Fibre*	6.7 7.5 8.5 and 10 cm	4	£5.65 to £7.75
I6	*Cork board*	2 to 6 in 1 cm steps 8 to 20 cm in 2 cm steps 28 and 30 cm	14	£5.57 to £85.80
I7	*Phenolic foam board*	2 to 10 in 1 cm steps	9	£5.58 to £21.89
I8	*Aerogel*	0.5 to 4 in 0.5 cm steps	8	£26.80 to £195.14
I9	*PCM (w/board)*	10 and 20 mm	2	£57.75 to £107.75

*For the case study, for insulation measures I1, I2, I3, I4, I5, I6, and I7, extra thicknesses (20, 25 and 30 cm) with its respective cost were added. This was done to achieve envelope U-values within the Passivhaus standard

Table B.5 Characteristics and investment cost of glazing systems

Glazing ID	System Description (# panes – gap)	Gas Filling	Cost per m²
G1	*Double pane - 6mm*	Air	£261
G2	*Double pane - 13mm*	Air	£261
G3	*Double pane - 6mm*	Argon	£350
G4	*Double pane - 13mm*	Argon	£350
G5	*Double pane - 6mm*	Krypton	£370
G6	*Double pane - 13mm*	Krypton	£370
G7	*Triple pane - 6mm*	Air	£467
G8	*Triple pane - 13mm*	Air	£467
G9	*Triple pane - 6mm*	Argon	£613
G10	*Triple pane - 13mm*	Argon	£613
G11	*Triple pane - 6mm*	Krypton	£653
G12	*Triple pane - 13mm*	Krypton	£653

Table B.6 Characteristics and investment cost for air tightness improvement considering baseline of 1 *ach @50Pa*

Sealing ID	ACH (1/h) @50Pa Improvement %	Cost per m² (opaque envelope)
S1	*10%*	£1.20
S2	*20%*	£3.31
S3	*30%*	£6.35
S4	*40%*	£10.30
S5	*50%*	£15.20
S6	*60%*	£20.98
S7	*70%*	£27.69
S8	*80%*	£35.33
S9	*90%*	£43.88