A Multi-Criteria Decision-Making Approach to Optimising Hospital Estate Refurbishment

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Abstract

The UK health sector has one of the highest energy consumption levels among non-domestic buildings, with hospitals showing particularly high energy use and emissions due to intensive operations. NHS Trust hospitals are diverse in design and function, complicating energy efficiency efforts across the entire stock. With a net-zero target by 2040, sustainable solutions are critical for existing facilities.

This study presents an approach to optimise refurbishment scenarios for energy, carbon and cost reduction, using a deep-plan tower hospital typology, known for high energy consumption, as a case study. Through multi-criteria decision analysis, stakeholders participate in optimizing solutions tailored to building needs. Results show that stakeholder engagement in optimisation process supports robust, balanced outcomes in carbon reduction, energy and cost-efficiency.

Keywords: Multi-objective optimisation, Healthcare buildings, Energy Consumption, Multi-criteria decision analysis, Refurbishment

1.0 Introduction

Across the UK, there are plenty of redundant, under-utilised non-domestic buildings that need to be brought up to a standard suitable for extending their economic life (1). Non-domestic building stock account for about 5% of the UK energy consumption while all commercial buildings are responsible for around 10% (2). The health sector occupies a significant place in the non-domestic building stock. Given that hospital buildings have higher operational activity than other non-domestic sectors, higher energy consumption and emissions are expected. In England, 4% of the total carbon footprint is produced by the National Health Service (NHS) (3).

NHS building stock consists of a wide range of building archetypes built over the past century (4), with the majority of structures built between the 1950s and the 1980s. There are several types of hospital building constructed with different design features under the NHS Trusts. Each Trust has various types of hospital buildings with different uses, which creates a challenge in applying energy efficiency measures across the stock. Deep-plan/tower hospitals (DPTHs), characterised by a deep central core design and costly construction, are among the most energy-intensive hospital types, requiring mechanical ventilation and lighting that consume around twice the energy of naturally ventilated, narrow-plan hospitals (5,6). In order meet the UK's commitment to achieving net zero emissions by 2050, the NHS has set a target of ensuring that all buildings to be low carbon (7).

There are various strategies such as adaptation and mitigation of the building sector, using renewable energy, refurbishment, and multi-optimization approaches to improve the sustainability of the built environment. For the existing hospital stock, the key requirements have been identified as refurbishment and the implementation of optimal design solutions (8). In order to select the optimal solution, several studies have applied a variety of optimisation techniques (9–12). It is recommended that simulation-based optimization be adopted in order to reduce the time required and to achieve greater precision in the results obtained (13). However, decision making in the selection of building refurbishment measures is a complex process influenced by multiple factors, including building type, occupancy, cost, and sustainability.

Multi-Criteria Decision Analysis (MCDA) can be described as a problem-solving method through the division of problems into smaller parts. The method assists participants in making decisions in accordance with their preferences when presented with a set of conflicting criteria (14). Since there are various MCDA methods available in the literature, deterministic approaches compromise of Weighted Sum Model (WSM), Analytic Hierarchy Process (AHP), Weighted Product Model (WPM), ELECTRE, and TOPSIS method are the most widely used ones (15).

The Analytic Hierarchy Process (AHP) has gained popularity due to its straightforward, user-friendly interface, and ability to validate subjective judgments effectively. AHP accommodates small sample sizes while maintaining a high level of consistency, making it well suited for capturing expert opinions and evaluating the relative importance of criteria through stakeholder input and votes (16). It is a valuable mathematical tool for decision-making that integrates both logical and intuitive expert perspectives to select the optimal from several alternatives (17).

Buildings are complex systems and interact with the environment, users, equipment and mechanical systems, creating uncertainty (18). However, around 20-30% reduction in energy consumption is an achievable goal through building optimisation (13). Since there are more than one criterion in planning the building refurbishment, simulation-based multi-objective optimisation approach is implemented in analysing the case study DPTH building. This paper, therefore, seeks to explore the impact of the stakeholder engagement on the development of realistic and comprehensive refurbishment strategies through the combination of multi criteria decision analysis and simulation-based multi objective optimisation approach. The goal of the study is to identify the difference between including decision-makers in finding the optimal refurbishment strategy for the DPTH building and not including them in the formulation of the refurbishment solutions.

2.0 Methodology

The following section outlines the methodologies adopted to develop realistic and strategic optimal refurbishment solutions, aligned with the identified priorities of key stakeholders.

2.1 Case Study Building

The case study hospital building was a typical DPTH building built in the 1960s with a corridor ward design. Firstly, the real energy consumption data was collected from the stakeholders. Based on the available information, the current building performance data was calculated and converted to CO^2 emissions to find out the emission rate per m^2. All emissions are calculated using conversion factors for gas and electricity in the UK, taken from the recent BEIS report (19). This data is used to develop a baseline model for calibration and comparison of results, presented in Table 1. Compared to average deep plan/tower hospital electricity usage data according to ERIC 2018/19 report, the case study tower building consumption result slightly exceed a typical tower building average data but comply with the deep plan average data. Therefore, the case study hospital is considered as a DPTH building type.

Table 1 – The real building performance data

Annual Consumption	kWh	kWh/m2	kgCO2e	kgCO2e/m2
Electricity	6,368,374	158.37	1,484,722.71	36.92
Steam boiler	14,189,417	352.87	2,398,862.84	59.66
Total	20,557,791	511	3,883,585.55	96.58

2.2 AHP Exercise Summary

The decision-making process for defining refurbishment measures was informed by an AHP based approach. AHP has been applied as a first step of identifying the optimal refurbishment solution to determine the priorities of the stakeholders concerning the refurbishment of the DPTH building. The NHS Estates and Facilities team, responsible for managing the refurbishment and delivering effective solutions, were involved in the decision-making process. The full details of the AHP process is detailed in (6) and key outcomes informing the simulation-based multi-objective optimisation of Case Study are summarised in Table 2 below.

In the AHP study (6), the hierarchy criteria that will be ranked by stakeholders were divided into three main categories: selection of refurbishment measures, hospital zones, and sustainability targets. The selection of refurbishment measure category involved:

- Building Systems: Heating, ventilation, air conditioning (HVAC), Electric Lighting, Natural Ventilation, Natural Lighting
- Building Envelope: Windows, Shading, External Wall/Cladding, Internal Wall, Doors, Roof, Floor/Ceiling
- Cost and Disruption

The hospital zones as the second category were defined as follows: Accident and Emergency, inpatient wards, outpatient departments, operating theatres, diagnostic and laboratory, intensive care units, public areas, and staff offices. The final category, aimed at establishing sustainability targets within the AHP study, included seven criteria: Minimise life cycle carbon footprint, minimise life cycle costs, achieve the NHS's overall net-zero target, achieve the net-zero target within the NHS Trust, apply renewable technologies, reduce energy demand, and comply with Health Technical Memorandum (HTM), Health Building Notes (HBN), and building regulations.

Table 2 – AHP key outcomes informing optimisation stage

Goal	Selection of refurbishment measures		Hospital zones	Sustainability targets
Hierarchy Criteria	50% Building Systems	50% Building Envelope	18% Intensive Care Unit (ICU)	25% Comply with HTM, HBN and Building Regulations
			17% Operating Theatres	
Hierarchy Sub-criteria	37% HVAC	22% Windows		
		21% Shading		

In Table 2, the key outcome for each category is presented. For the selection of refurbishment measures category, building envelope and building systems are ranked equally important by the stakeholders. Thus, both of the criteria were taken into consideration and sub-criteria selections were also included in the optimisation stage. Cost and disruption criteria were also ranked with cost being prioritised for refurbishment solutions.

Table 2 presents the key outcomes for each category. For the selection of refurbishment measures, the building envelope and building systems were identified by the stakeholders as being of equal importance. Consequently, both criteria were taken into consideration and sub-criteria results were also included in the optimisation stage. Similarly, cost and disruption were also ranked, with cost being prioritised for refurbishment solutions. In terms of hospital zones, both the intensive care unit (ICU) and operating theatres (OT) were categorised as high-priority areas, with a slight difference in ranking. Given that these departments are linked and situated on the same floor in the case study hospital, both were included in the next stage.

2.3 Simulation-Based Multi-Objective Optimisation

Given the aim of this study, energy efficiency, life cycle carbon emissions (operational and embodied) and cost efficiency objective functions are chosen in the optimisation process. A dynamic simulation model using DesignBuilder is adopted to calculate Pareto front. The building layout and energy data were collected and transferred into DesignBuilder to create baseline building model for energy analysis. The input model data consisted of building dimensions, simplified windows, material data, building activities, operational schedule, temperature setpoints, as defined in Table 3. The energy analysis was set to hourly calculations to improve accuracy of the results. By comparing the building model calculations with the actual energy data, presented in Table1, the results are considered accurate within an acceptable margin of error, with a discrepancy of approximately 6.07%.

Table 3 – Baseline model building parameters

	Baseline Energy Model	
Number of floors	North block	South block
	4	15
Floor height	3.5m	3.5m
Usage	Clinics, operational theatres, labs, offices, screening, nursing rooms, A&E	Clinics, nursing rooms, wards
Operational schedules	Hours / Factors	Hours / Factors
	07:00-12:00 / 0.25- 0.5	07:00 - 12:00 / 1
	12:00 - 18:00 / 0.75 - 1	12:00 - 24:00 / 1
	18:00 - 24:00 / 0.5 - 0.25	24:00 - 07:00 / 1
Heating setpoint temp (Celcius)	22.0 - 12.0	
Cooling setpoint temp (Celcius)	24.0 - 28.0	
Power density (W/m2)	12.85	

The overall methodology steps were illustrated in Figure 1. Following the data collection and the calibration of the baseline model (Stage 1 and 2), the outcomes from the AHP study, as detailed in section 2.2, were introduced to inform the multi-objective optimisation model.

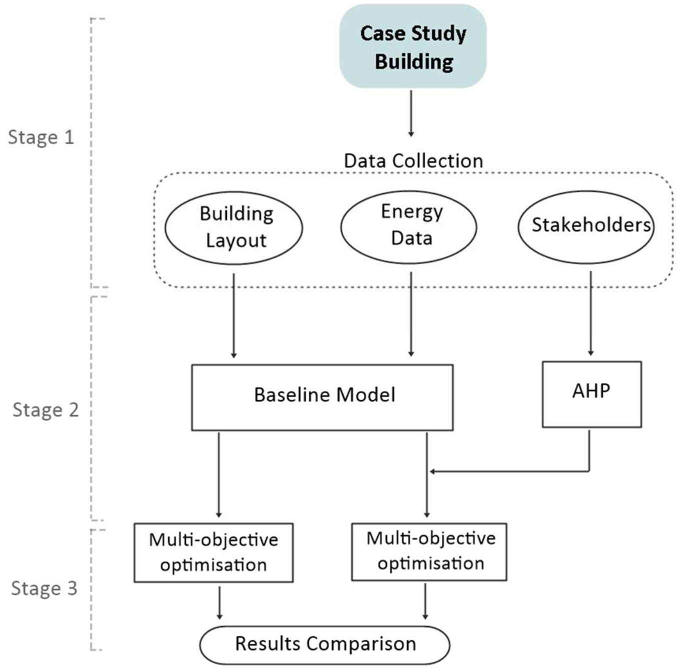

Figure 1 – Methodological workflow of analysis

The multi-objective optimisation functions were set as net site energy consumption, life cycle analysis (LCA) and total construction cost. Nevertheless, the optimisation software was limited to handling two objective functions for each optimisation analysis set. Therefore, energy consumption and LCA objectives were applied in the first set of analyses, while LCA and cost objectives were used in the second set of optimisations. This strategy was applied in the AHP-informed optimisation analysis. The uninformed optimisation was conducted with only two objectives: energy consumption and LCA. At this stage, the cost option was excluded. The reason for this approach was to enable a comparison of the outcomes in order to identify the impact of the stakeholders on the selection of refurbishment solutions.

The whole building of the case study hospital was modelled for the energy analysis, but only the third floor is included in the optimisation in this paper, as the ICU and OTs areas are located on this floor, shown in Figure 2. The energy model of the 4,394 m^2 third floor, consists of seven zones, excluding the plant room and the public circulation area, so that the best possible renovation solution can be identified for the chosen zones. However, the remaining zones are retained in the model structure as they are adjacent to the targeted zones and might have an impact on energy performance

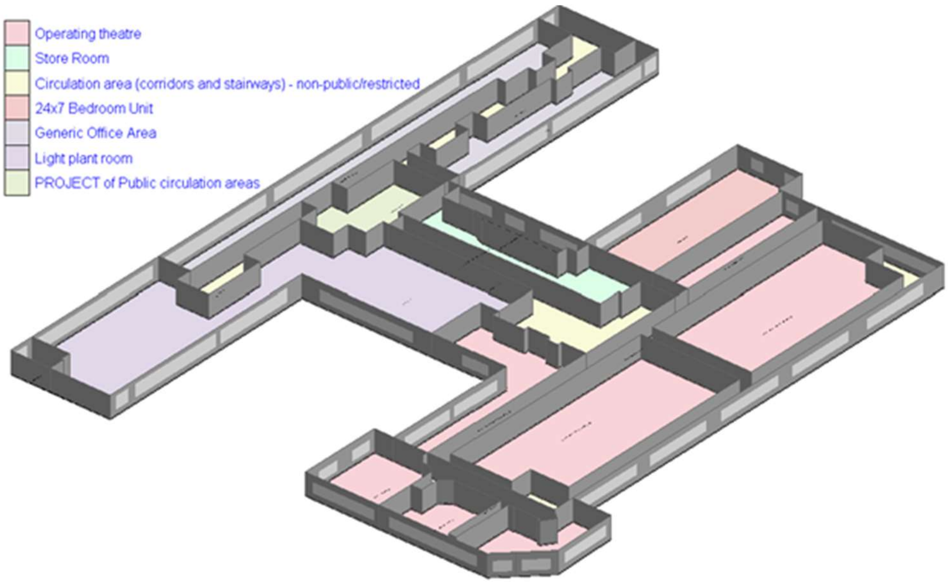

Figure 2 – Case study building third floor model

The design variables for the AHP-informed optimisation were selected based on the design requirements of HTM, HBN and building regulation, in accordance with the stakeholders' preferences. The details of the design variables, selected options and target building objects are presented in Table 4. A total of 17 HVAC, 23 window glazing, and 3 shading options were applied in the simulation-based multi-objective optimisation model. Considering that the target hospital zones were an ICU and OTs, where particularly sensitive patients are treated, the natural ventilation option was excluded to ensure that the indoor air quality is under control with mechanical systems.

Table 4 – Design variables for selected refurbishment criteria

Refurbishment Criteria	Design Variables	Number of Options	Options	Target Objects
Building Systems	HVAC	17	•CAV, air cooled chiller •CAV, Air cooled chiller, 4-pipe induction units •CAV, electric heating •CAV, gas heating •CAV, Water cooled Chiller, Boiler HW •CAV, Water cooled Chiller, Electric Heating •Cooled Beams, Air cooled chiller, DOAS •Cooled beams, DOAS, displacement ventilation •Fan coil unit, air cooled chiller, DOAS •GSHP Unitary water to air heat pump •VAV, Air cooled chiller, HR, Outdoor air reset •VAV, Air cooled chiller, HR, Outdoor air reset mixed mode •VAV, Air cooled chiller, Reheat •VAV, Dual duct, Air cooled chiller •VAV, Dual duct, Water cooled chiller •VAV, Water cooled chiller, full humidity control •VRF (air cooled), Heat recovery, DOAS	Intensive care unit and operating theatre zones
Building Envelope	Windows (Glazing)	23	•Triple Clear 3mm/13mm Air •Triple Clear 3mm/13mm Argon •Triple Clear 3mm/25mm Air for mid pane blinds •Tripple Low-E Clear 3mm/13mm Air •Tripple Low-E Clear 3mm/13mm Argon •Tripple Low-E Film Clear 6mm/13mm Air •Tripple Low-E Film Clear 6mm/6mm Air •Double Clear 3mm/13mm Air •Double Clear 3mm/13mm Argon •Double Elec Ref Bleached 6mm/13mm Air •Double Elec Ref Bleached 6mm/13mm Argon •Double Low-E Clear 3mm/13mm Air •Double Low-E Clear 3mm/13mm Argon •Double Low-E Clear 6mm/13mm Air •Double Low-E Tint 6mm/13mm Air •Double Low-E Tint 6mm/13mm Argon •Double Low-E Spec Sel Clr 3mm/13mm/6mm Air •Double Low-E Spec Sel Clr 3mm/13mm/6mm Argon •Double Ref-D Clear 6mm/13mm Air •Double Ref-D Clear 6mm/13mm Argon •Double Ref-D Tint 6mm/13mm Air •Double Ref-D Tint 6mm/13mm Argon •SageGlass Climaplus Classic SR2.0 no tint	Windows
	Shading	3	•0.5m protection Louvre •0.5m Overhang •No shading	Windows

In the next stage, the design variables for the uninformed optimisation were set based on the problems identified in similar building types in previous studies, and the evaluated condition of the case study building. For this reason, HVAC, windows and external wall construction were considered to be included in the optimisation analysis.

3.0 Results and Discussion

The AHP-informed optimisation process supported with genetic algorithm was performed. The initial populations size and maximum generations recommended by DesignBuilder were applied, 20 and 100 respectively. Nevertheless, the mutation rate was reduced from recommended default value of 0.4 to 0.1 to allow the optimisation engine to create more diverse combinations. This reduction can increase the simulation time but leads to more accurate optimal strategy results. The simulation time for the first optimisation analysis with energy consumption and LCA objective functions, was completed in 18 hours. The second optimisation run for energy consumption and cost reduction, was completed in 21 hours. As a result of the first and second optimisations, ten optimal strategies were found. While only one optimal strategy was spotted in the first run of the optimisation, nine of them was identified in the second run.

It should be noted that LCA and energy consumption are conflicting objective functions, hence the Pareto front was generated in linear form, see Figure 3. As the analysis include only the third floor ICU and OT zones, the results were less diverted. The only optimal strategy appeared in the first set of optimisations included triple low-E glazing, no shading and VAV, air-cooled chiller system, presented in Table 5.

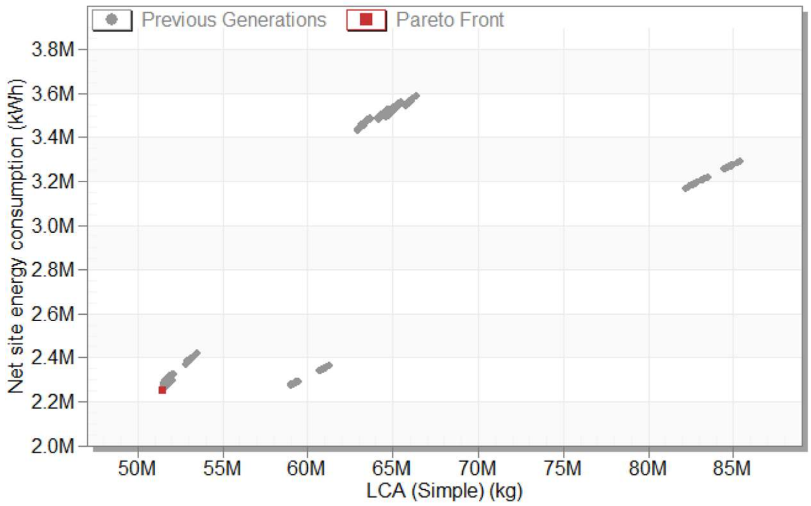

Figure 3 – Pareto front results of first set AHP-informed optimisation

The Pareto front analysis of the second optimisation set, shown in Figure 4, indicated that the energy and cost efficiency strategy produced more diverse outcomes and a wider range of optimal strategy selections. There were three different cost-efficient strategy identified in this optimisation set. The cost-efficient optimal strategy with slightly less than 4.9M GBP, required no shading, Fan Coil Unit with DOAS system, and SageGlass glazing. However, this strategy resulted in higher energy consumption levels around 3,511,896 kWh compared to other six optimal solutions.

The optimal strategy provided both cost efficiency and energy consumption reduction required SageGlass glazing, no shading and GSHP water to air heat pump.

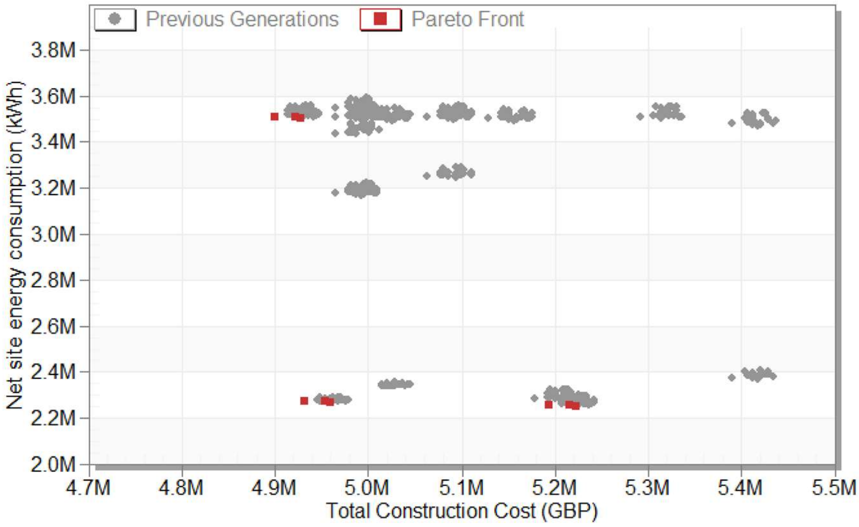

Figure 4 – Pareto front results of second set AHP-informed optimisation

In summary, ten optimal retrofit solutions were identified out of 2,000 combinations of selected design variables, applicable to the intensive care unit and operating theatre departments. These solutions result in reduced energy consumption, cost, and carbon emissions. If there is a priority for the application of cost-effective solutions, it should be considered to apply the three cost optimal strategies which also provide lower energy consumption. In the case of prioritising energy reduction for refurbishment, the first set of optimisation results should be considered as the only optimal strategy, providing the lowest energy consumption rate of 2,252,301 kWh.

Table 5 – Optimal refurbishment solutions - first and second set

	Objective Functions	Optimal Solutions		
		Windows	HVAC	Shading
First Run	Net site energy consumption & LCA	Triple Low-E (e2=e5=.1) Clear 3mm/13mm Argon	VAV, Air-cooled Chiller, HR, Outdoor air reset + mixed mode	No Shading
Second Run	Net site energy consumption & LCC	Trp LoE (e2=e5=.1) Clr 3mm/13mm Air	VAV, Air-cooled Chiller, HR, Outdoor air reset + mixed mode	No Shading
		Trp LoE (e2=e5=.1) Clr 3mm/13mm Arg	Fan Coil Unit (4-Pipe), Air cooled Chiller, DOAS	No Shading
		SageGlass Climaplus Classic SR2.0 No Tint	GSHP Unitary Water-to-air Heat Pump	No Shading
		Trp LoE (e2=e5=.1) Clr 3mm/13mm Arg	GSHP Unitary Water-to-air Heat Pump	No Shading
		Trp LoE (e2=e5=.1) Clr 3mm/13mm Arg	VAV, Air-cooled Chiller, HR, Outdoor air reset + mixed mode	No Shading
		Trp LoE (e2=e5=.1) Clr 3mm/13mm Air	Fan Coil Unit (4-Pipe), Air cooled Chiller, DOAS	No Shading
		SageGlass Climaplus Classic SR2.0 No Tint	Fan Coil Unit (4-Pipe), Air cooled Chiller, DOAS	No Shading
		SageGlass Climaplus Classic SR2.0 No Tint	VAV, Air-cooled Chiller, HR, Outdoor air reset + mixed mode	No Shading
		Dbl LoE (e2=.1) Clr 3mm/13mm Arg	GSHP Unitary Water-to-air Heat Pump	No Shading

The final stage to compare the optimal solutions to identify the impact of stakeholders included uninformed optimisation performed with two objective functions, excluding cost. In Figure 5, the results showed that there was only one optimal strategy similar to AHP-informed optimisation result. However, a slightly lower the energy consumption was achieved with 2,237,051 kWh. The uninformed optimisation resulted in a slight decrease in both operational and embodied emissions, achieving a reduction of approximately 200,000 kg CO_2e.

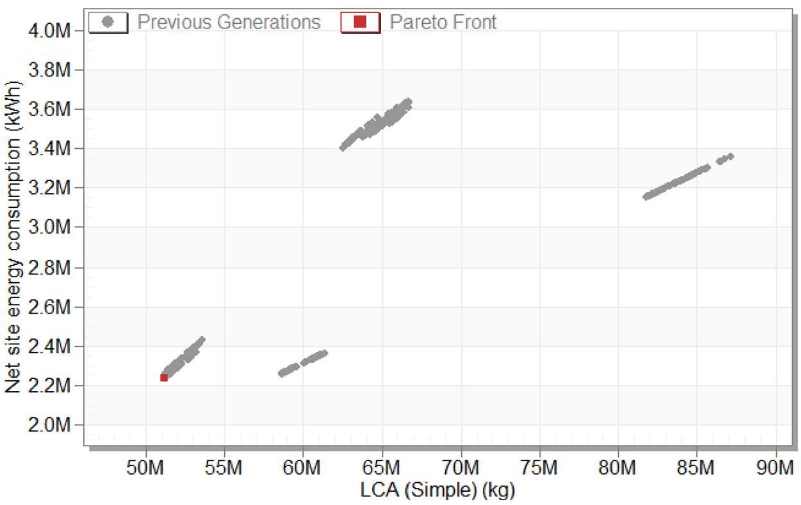

Figure 5 – Pareto front optimisation result of uninformed optimisation

4.0 Conclusions

This paper presents a methodology that explored the impact of stakeholder involvement in the decision-making process in formulating realistic optimal refurbishment measures for a DPTH building. Hospitals are complex building types that need to be active day and night. Therefore, the application of a refurbishment strategy can be more challenging than for other non-domestic buildings. The implementation of multi-criteria decision analysis was found to be a useful approach as it helps to facilitate the refurbishment process, identify the current condition and problems of the building, as well as understanding the decision-making process within the NHS. Starting with the areas of greatest need and prioritising the preferred areas of the building, rather than focusing on the whole building analyse at once, provides reliable and problem-focused solutions.

Engaging stakeholders in the formulation of refurbishment strategy, resulted in a more informed and targeted solution. While there was a slight difference between the reduction of energy consumption and carbon emissions compared to the optimisation analysis performed without stakeholder involvement, the results were quite similar meaning both the decision-makers have a consistent opinion on the building needs and the optimal performance can be achieved with the including stakeholders.

This study will be extended to whole building optimisation to be able to compare the optimal strategies and evaluate the outcome to identify differences in results if they occur, along with the application of the same methodology to two other DPTH type buildings. The next step will also include obtaining feedback from stakeholders and analysing satisfaction to highlight if their requirements are met and the possibility of real-life application of any of the optimal strategies highlighted in the study.

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Acknowledgements

This research has been funded by the Republic of Turkey Ministry of National Education. We also thank to NHS Estates and Facilities team for being part of this study.