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Importance of HVAC System Selection in Reducing the Energy Consumption of Building Retrofits–Case Study: Office Building in London

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Abstract The analysis of the holistic life cycle and energy has become more important due to the escalating energy demands in existing office stock. HVAC system retrofits to save energy are an outstanding way when compared to envelope improvements. The study proposes a parametric workflow to analyze and reduce energy, carbon and cost in HVAC retrofits. Based on the workflow, the energy demands of an existing office building were gathered using energy modelling software. The results then were calibrated with the building's energy data. Using the equation-based modelling workflow, HVAC plant side systems were simulated parametrically to calculate energy, carbon and cost. In total, 5184 iterations of 10 interventions were tested. It was found that heating plant type and heat recovery were the prominent savings inputs in the case study. The study presented a comprehensive approach to the HVAC system retrofit of existing buildings, which uses real energy data calibration, verifiable, and parametric methods.

Keywords HVAC Systems, Operational Energy, Parametric Modelling, Building Retrofit

1. Introduction

It is a well-known truth now that we're at the early steps of a world crisis called Global Climate Change and action requirements to slow down the occurring impacts become crucial. According to The United Nations Framework Convention on Climate Change (UNFCC), one of the important outcomes of mitigation from the Climate Change Conference (COP) 26 in 2021 is to keep 1.5 C degrees and securing the global net-zero by mid-century is vital for all of us [1]. In the UK, non-domestic commercial buildings are using 293 TWh and are responsible for 59% of the total building energy consumption. Commercial office buildings are one of the top three highest energy-consuming building types with 10%. The total number of non-domestic buildings in England and Wales was 1,656,000 at the end of March 2020 and 335,000 of these are office buildings [2].

Besides, these numbers are only indicatives of the energy consumed during the operation of buildings. Energy consumption and emission rates related to the life cycle stages of the buildings are equally important to operate to mitigate global warming and its adverse effect [3]. HVAC systems are the elements that provide heating, cooling and ventilation for the buildings. The primary function of a well-designed HVAC system should be to ensure the required thermal comfort level in the occupied spaces [4]. Within the appropriate condition of this scope achieved, operational and embodied energy consumption, operational & embodied carbon emissions and cost are the main drivers that should be carefully evaluated. The

importance of HVAC system selections in reducing operational energy consumption has been subject to studies and papers over the past decades. Guopeng L. et al [5] developed a calibration methodology and applied it to various case studies. The study showed the importance of the HVAC inputs and calibration approach to optimize energy consumption in energy retrofits. The study developed a calculation methodology to estimate long-term energy usage based on short-term energy measurements. Limited studies prove that the HVAC systems are responsible for 2-27% of the total embodied carbon of a new building. The proportion of the impact is higher in existing building retrofits [6]. It is a sophisticated approach as the required level of thermal comfort and conditions to provide may vary in line with the location, building type, size, function, materials and usage.

Moreover, the calculation of energy consumption, CO_2 emissions and operational cost of HVAC systems are quite diverse and complicated, and selections of the appropriate system require dynamic simulation and informative data libraries for the potential systems. Jinkyun et al [7] examined the impact of cost for HVAC systems in high energy-efficient building design. The study provided a methodology for HVAC systems cost prediction. Multiple matrix models are used to provide a baseline and decision tree analysis to optimize the energy and investment cost of the proposed systems. Sean N. et al [8], proposed a degree day-based simulation with a genetic algorithm combination to optimize the retrofit interventions over a university building. In the study, initial and operational costs along with the carbon emissions are tested against various scenarios. Interventions such as U-values, boiler type and infiltration rates are tested. Degree day-based simulation, most of the time is a circumscribed approach to test the annual behaviour of a building.

Various inputs of systems will require running thousands of simulations for solid decision-making. For this very reason incorporating an optimization of these functions would ideally be essential to obtain the correct results.

This study focuses on a comprehensive and bespoke approach to calculating the operational energy, carbon and cost via analyzing various parameters, design conditions and operation scenarios for an existing office building. It deconstructs a solid modelling approach using dynamic modelling and hourly analysis of the building which provides the extensive potential to test various scenarios and parameters in range. As a result, the data-driven calculation method aims to minimize the operational energy and carbon with parametric functions and enable to test various parameters faster compared to the conventional simulation methods. It also aims to optimize the nonlinear relationship in between.

In this calculation method, hourly heating and cooling demands are generated from a calibrated digital twin of an existing office building. This demand was then introduced to an equation-based HVAC model created using Rhinoceros-Grasshopper to ensure parametric flexibility and bespoke analysis power. The equation-based model incorporates the airside and waterside of various HVAC systems and calculates the operational energy consumption. Concurrently with this, the system variables of each HVAC system are calculated according to a previously generated HVAC system library. The results of parametric combinations of system selections are determined to optimize the relation between operational energy consumption, CO_2 emission and operational cost.

The number of studies is limited which focus on the office HVAC energy retrofits that comprise energy, carbon, cost and the actual operational data calibration at the same time. This study aims to provide a HVAC selection methodology using the calibrated actual building with a main plant side focus to support both HVAC designers and sustainability consultants to unlock the most efficient and appropriate HVAC systems to reduce energy, carbon and cost in their building design.

In line with the aim of this study, the literature review is given in section 2 and in section 3 compromise on an overview of the methodology and framework of the study is introduced. In section 4, the case study has been explained and the results and findings of the parametric study are demonstrated in the 5th section. In the 6th and final section of the study, the conclusion is presented.

2. Literature Review

HVAC systems are must-have building elements to provide thermal comfort in buildings. While small and less complex systems are sufficient to provide this thermal comfort in buildings such as schools and residential, these systems can be very complex in commercial buildings, shopping centres, airports and office buildings.

In complex systems, design is a step-by-step approach. Engineers calculate heating and cooling loads, define main plant and terminal unit selection, complete duct and pipe pressure loss calculation, and analyses dimension and routing. In these calculations, which are done step by step and gradually, each step affects the next. These calculations vary with each project. This is because each building has different needs. As an output of the design, operational energy consumption, operational carbon and cost also vary with these different system selections.

Building performance simulation (BPS) is a widely utilized method to calculate operational energy and associated carbon emissions & cost. It is a concept to analyse and compare the performance of buildings or specific sections of those buildings. It's a computer-based mathematical model that analyses the building performance for a certain period.

In 1963 the first presented software was developed at the Stockholm Royal Institute of Technology for BPS. It

was an iterative approach to calculating room temperature variations using heat balance equations [9]. Along with the increasing performance of simulation engines BPS software started to be commercialized in the late 1970s. With the increase in commercialization and computer computing capacity, the use of holistic building simulation and the number of software serving in this field have also increased [10].

For different needs, parametric modelling studies have been developed and provided convenience when focusing on various inputs in which all or some of these outputs are evaluated together for enhancing performance in this field.

Similarly, software in general developed with the aim of holistic building simulation, which is quite advanced and competent in analyzing building fabric, geometry, lighting and loads. Eleftheria T. and Theodoros T.[11] focused on nearly zero energy buildings in the early design stage and provided a solution to overcome the complexity of tasks using a multi-objective optimization algorithm. The Study mainly targeted the passive design potentials and used grasshopper for parametric analysis.

However, in all these software, HVAC systems modelling falls short in the analysis of comprehensive and bespoke systems due to their simplified system and control capabilities. Optimization and system comparison can be very difficult in software and its modules that enable complex possibilities. Muzaffar A. et al [12], implemented an equation-based object-oriented modelling approach to optimize the system configuration of a chilled water system. In the study number of chillers, cooling towers, temperature and fan speeds are optimized using Modelica with Genopt integration. In another study [13] chilled water consumption was examined using EnergyPlus engine and particle swarm optimization algorithm. Chiller, pump and cooling tower consumptions are tested against a certain period of time over the conventional operational model.

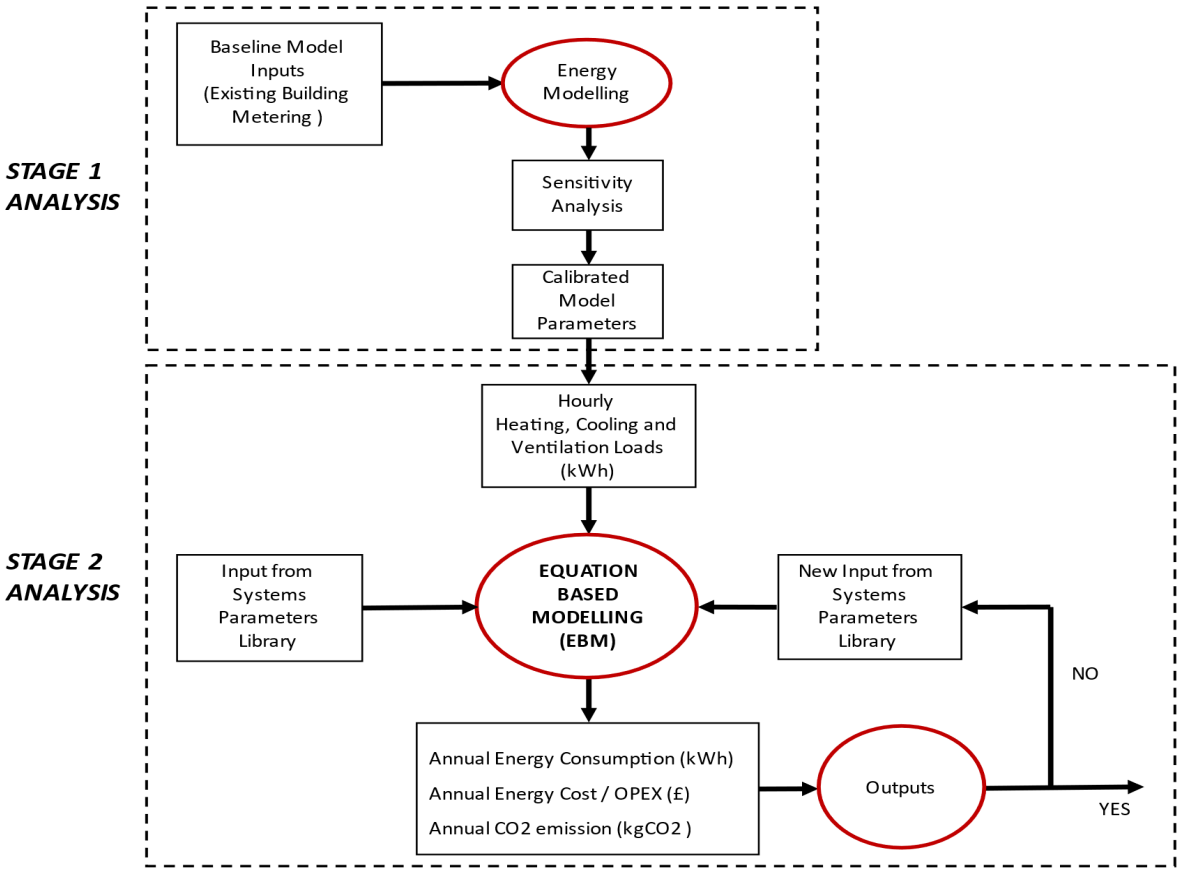


Figure 1. Staged modelling approach calculation workflow

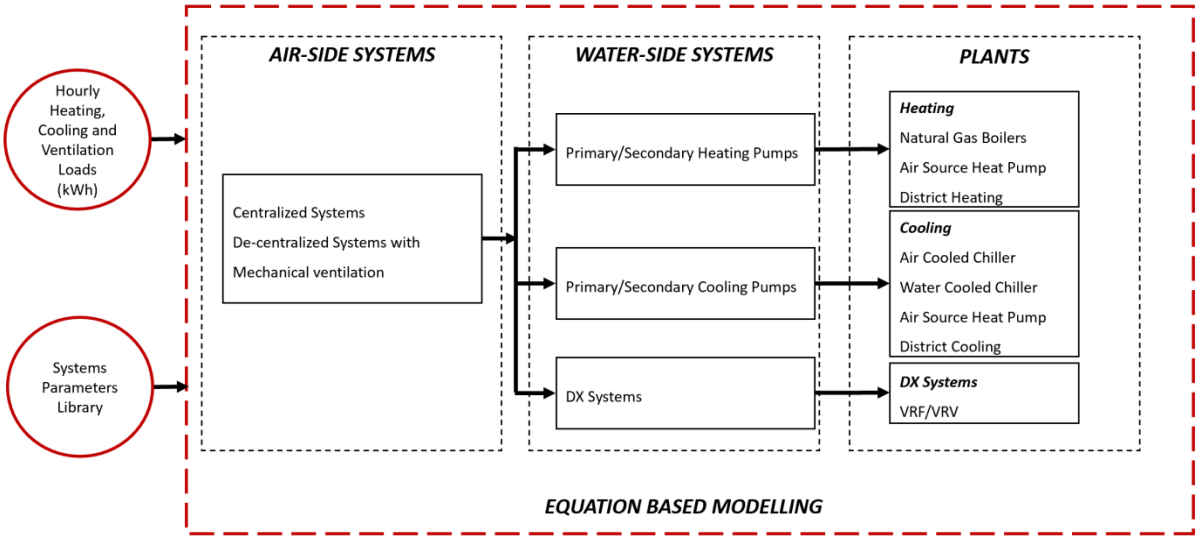


Figure 2. Equation-based modelling workflow

3. Methodology

Considering all the given limitations in the literature review and targeted focus on HVAC systems, the study proposes a staged analysis for the energy consumption evaluation of the building which is divided into demand and supply. The optimization of the supply corresponding to a certain demand is discussed.

The existing office building case study for the analyzing method is given in the next section. The flow chart of the study is shown in figure 1.

The first stage of the method is to calculate the hourly heating, cooling and ventilation demand loads which are needed as input to the equation-based model.

In the case study, this calculation has been done by simulating the building condition with the location, orientation, architectural plans, building envelope, system usage profiles, HVAC and lighting system elements and their control methods with a previously defined energy simulation tool IES-VE. Then the performance data has been calibrated with the actual energy consumption breakdown of the building data which has been taken from the Building Energy Management System (EMS). Sensitivity analysis has been performed using this hourly meter data to execute actually the hourly demand of the building.

In the second stage, the simulation setup for the equation-based model (EBM) has been developed in Grasshopper which is a Rhinoceros plug-in for algorithmic modelling. It's a virtual programming language and allows the model of complex mathematical models. The bespoke calculation algorithm has been developed based on scientific formulas that are been used for HVAC system equations [14].

The calculation algorithm follows the EnergyPlus methodology which is a combination of algebraic energy and mass balance equations with steady-state component methods [15,16]. As the hourly loads for EBM are calculated by dynamic simulation software to meet the certain zone temperature and humidity ratios, the air system equation in the model is solved directly considering the fixed set points and controls. The flow chart of the EBM is shown in figure 2.

EBM consists of three stages of analysis which calculate the size and hourly data for airside systems, waterside systems and plants. It's been designed as a modular tool which allows adding/removal of systems and inputs in both three stages.

In the first stage, airside systems are divided into 2 systems, which are Centralized Systems (CS) and De-centralized Systems with Mechanical Ventilation (DCS). CS contains central heating and cooling coils, central supply and return fans, and controls and meets the whole demand allocated to hourly loads by a centralized approach. In DCS terminal units are responsible for meeting the demand while centralized air units provide mechanical ventilation to the zones. DCS contains both central and local heating and cooling coils, supply and return fans, and controls. The main input for the first stage is the hourly demand from the building and the weather information from the climate data such as the dry-bulb temperature, wet-bulb temperature and relative humidity. The variables are unit types to define the size and capacity of central and terminal units, air supply/ return temperatures (°C), air heat exchanger efficiencies (%) and coil sizing factors.

Coil sizes and hourly coil demands calculated in the Airside systems are used as input for the Waterside systems. Waterside systems are representing the primary/secondary circulation pumps for heating and cooling systems. Additionally, the VRF system is for transferring the output from Airside systems to Plants.

Pumps are categorized as primary and secondary for both heating and cooling systems based on the sub-system introduced in the Airside Systems. Pumps vary due to their control type and the number of used for primary and secondary circuits and systems. The heating or cooling design return water temperatures and Delta T's are calculated based on the heating or cooling supply water temperature and the pump control inputs.

In the third stage of calculations, Plants are referring to the energy generation required by the systems, based on the staged demand (from building to airside, airside to the waterside and then the waterside to plants). Plants are sized for the peak condition of heating and cooling. They are modelled to respond to different numbers of plants, water and outdoor air temperature, part-load conditions and controls. The variables are plant types, fuel type, number of plants, water supply/ return temperatures (°C) and controls.

An adaptable database is generated based on the sizing information from the building for the efficiency and energy performance of the systems. Efficiency and energy performance measures for each system are considered as a cost function to optimize the performance. In the study, some of the system selections were influenced by the [17] study that covered the research topics on energy-efficient HVAC systems.

For each combination, the database is linked to the design interventions. In airside systems, hourly energy consumptions (kWh) of central and terminal fans are calculated with calculated hourly air flow rates and the efficiency input from the database. In waterside systems hourly energy consumption (kWh) of primary and secondary pumps are calculated with calculated hourly water flow rates and the efficiency input from the database. In the Plants hourly energy consumption (kWh) of heating and cooling plants to generate the energy required are calculated with hourly coil demand, hourly water flow rates, outdoor air temperature, water supply/return temperatures, controls, plant type and numbers and the efficiency input from the database. Annual energy consumption, operational CO_2 emissions and operating expenses (OPEX) based on the fuel type of each consumption are analyzed.

4. Case Study

The EBM approach given under section 2 is applied to a central London office building constructed in 2013. The case study aims to perform an energy retrofit considering only HVAC renewal. The building is a 5700 m2 office building and has 2 basements, a ground floor and 8 office floors. The longest building axis is oriented toward the north and south due to the plot boundary's configuration. The building has large, fixed glazing panels for well-lit offices on the east and west elevations. The north elevation has a simpler version of the same, with small, fixed side panels. The south façade is shaded with the columns disengaged from the façade to form a 3m deep balcony on every level to reduce the cooling demand. The baseline model for the case study is shown in figure 3.

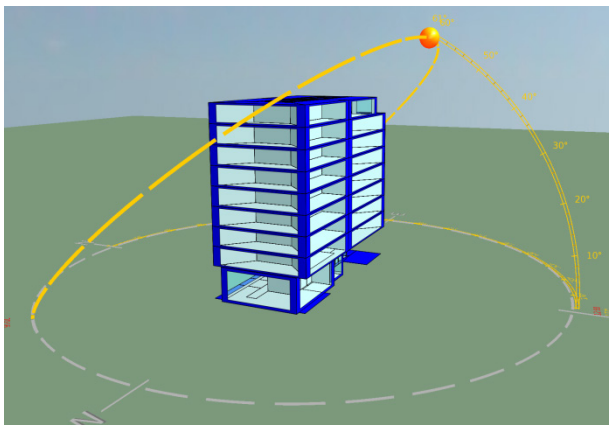


Figure 3. Case study baseline model

The outlined U-values are critical for reducing energy consumption and carbon emissions, and early design consideration is equally important for practically achieving these U-values and g values. Design criteria's set by the mechanical services contractor along with the system selections. Inputs related to internal temperature set points, occupancy and inter gains are calibrated as explained in the methodology and used to remodel the building to generate the loads required to run EBM. In the table.1 baseline model input parameter; weather data, envelope, internal temperature set points, occupancy and internal gains are shown.

The building is served by three Air Handling Units (AHUs) with Constant Air Volume Boxes (CAVs). Two AHUs serve the office areas, and one serves the remaining building. On each floor and individual Chilled Beams serve the office areas. Variable speed drive circulation pumps transfer the energy required in zones from the plants through Low-Temperature Hot Water (LTHW) and Chilled Water (CHW) loops in these areas. The building is connected to a high-efficient district heating network which provides 100% heat demand and 2 Air Cooled chillers (ACC) located on the roof serve the building to meet the cooling energy demand. As-built energy-related HVAC system information for the baseline building is shown in table 2.

Table 1. Baseline Model Input Parameters

Type	System	Design Inputs		Calibrated value after in Stage 1 Analysis
Weather File	Weather Data Used	London DSY05		No change
Envelope	External wall U-Value	0.25	W/m².K	No change
	Roof U-Value	0.25	W/m².K	No change
	Floor U-Value	0.22	W/m².K	No change
	Glazing U-Value	1.26	W/m².K	No change
	Glazing g value	0.36	N/A	No change
	Air tightness	4.9	$m^3/h.m^2$ @50 Pa	No change
Internal temperature set points	Office cooling	22	°C 1.5°C set back (+/-)	22°C no set back
	Office heating	21	°C 1.5°C set back (+/-)	22°C no set back
	Toilet heating	18	°C	No change
	Basement showers / changing heating	18	°C	No change
	Stairwells/ circulations heating	18	°C	No change
	Plantrooms temper heating	10	°C	14°C
Occupancy	1 person per 10 sqm			based on interior layout
Table 1 Continued				
Internal gains	Occupancy sensible	90	W/person	No change
	Occupancy latent	50	W/person	No change
	Lighting	12	W/m^2	6.75 W/m^2
	Small power	25	W/m^2	7.15 W/m^2
	Upgrade allowance	10	W/m^2	No change
Central plant diversities	Occupancy	1		No change
	Lighting	0.9		No change
	Small power	0.8		No change
	Additional capacity	1		No change
Fresh air supply and ventilation rates	Base provision	1.6	l/s per sqm	1.35 l/s per m^2
	Toilets, showers and changing areas	10	ach	No change
	Storage areas	1	ach	No change
Infiltration	Summer	0.25	ach for 4.5m from perimeter	No change
	Winter	0.5	ach for 4.5m from perimeter	No change

Table 2. HVAC Baseline Model Input Parameters

System	Type	As-built Design Inputs
Plants/Heating	Plant Type	District Heating
	Number of Plants	1
	Plant Efficiency	100%
	Distribution Loss	20%
	System Water Temperatures (Flow and Return)	80/60°C
	Plant Control Type	N/A
Plants/Cooling	Plant Type	Air Cooled Chiller
	Number of Plants	2
	Plant Efficiency	SEER :6.4 EER:3.86
	Distribution Loss	10%
	System Water Temperatures (Flow and Return)	6-12°C
	Plant Control Type	Staged
Waterside/ Heating Pumps	Heating Circulation Pump Efficiency	5.2 kW
	Heating Circulation Pump Control	Variable Speed Drive
Waterside/ Heating Pumps	Cooling Circulation Pump Efficiency	39 kW
	Cooling Circulation Pump Control	Variable Speed Drive
Airside	System Type	De-centralized Systems with Mechanical ventilation
	Central Unit Energy Consumption	1.35 W/l/s
	Central Unit Heat Recovery	70%
	Central Unit Air Supply Temperature	22°C
	Central Unit Control Type	Variable Speed Drive
	Terminal Unit Efficiency	0.2 W/l/s
	Terminal Unit Air Supply Temperature	18°C
	Terminal Unit Control Type	Variable Speed Drive

Table 3. HVAC Systems Interventions

System	Type	Intervention range	Number of Iterations
Plants/Heating	Plant Type	NG Boiler/ ASHP/ District Heating	3
	Number of Plants	1,2,1	2
	Plant Efficiency	Vary based on the type	3
	Plant Operation	Equal Load / Sequenced	2
Plants/Cooling	Plant Type	ACC/ WCC/ ASHP	3
	Number of Plants	1,2,1	2
	Plant Efficiency	Vary based on the type	3
	Plant Operation	Equal Load / Sequenced	2
Airside	System Type	Decentralized	1
	Central Unit Fan Energy Consumption	1.6,1.8,0.2	2
	Central Unit Heat Recovery	Off, 70	2
	Terminal Unit Air Supply Temperature	H: 28,36,4 C: 14,18,2	3 3

Table 4. CO_2 factors and unit cost per fuel type

Fuel Type	CO_2 Factor ($kgCO_2$)	Fuel Unit Cost (£/kWh)
Electricity	0.136	0.19
Natural Gas	0.21	0.08
District Heating	0.116	0.05

Ref: SAP 10 Technical paper: CO_2 and primary energy factors for SAP v1.1.(2020)

At the stage 1 analysis, the baseline building energy model has been created with the as-built information given above. To replicate the actual performance of the building in the digital model and generate the hourly heating, cooling and ventilation loads according to this replica, the model was calibrated following a manual method using the operational metadata from the actual metering. Building information and data have been collected between 2014-2020 for over a 6-years period. The metering data is collected from over 130-meter points such as main electric and heat meters also from lighting, small power, chiller and fan systems submeters. The geometry, thermal properties, HVAC, lighting, vertical transport, security, and server room systems have been modelled with dynamic simulation software. The inputs used for these systems are collected from the as-built data information. Simulated data compared with measured data and simulation parameters such as lighting and small power gains and user schedules are fine-tuned for calibration.

At the end of these steps, hourly space heating, cooling and ventilation demand values of the building for the whole year have been calculated. These addressed heating and cooling values that are necessary to be met in order to achieve the desired thermal comfort criteria of the building under the conditions specified above. As defined in the previous section the calculated values in stage 1 analysis are hourly demand and are used in stage 2 analysis as the next step of the study by means of the EBS HVAC systems modelling which is created as a mathematical model using parametric modelling. The HVAC system interventions are shown in table 3.

Limit values of these systems, system type options and energy and operational costs related to these options will be calculated for all possibilities.

5. Results and Discussion

HVAC systems for an existing office building have been analyzed to understand the impact on energy consumption, CO_2 emission and cost. In stage 1 analysis, the baseline model is generated with the as-built building information and then calibrated with the metering data provided by the building management system. Hourly results of the heating and cooling demand were used to test 5184 iterations of 10 interventions in the study for the whole year. Staged analysis and equation-based modelling approach enabled to test bespoke options when needed in a shorter period of time compared to full-scale energy models.

The results of the tested HVAC retrofit interventions are shown in figure 4 to see the impact of each combination in the study.

Results analyzed are also presented as trade-offs to see the actual impact of each intervention parameter on the energy consumption, CO_2 emissions and cost. For each intervention parameter, average energy consumption, CO_2 emission and cost of inputs are compared to have a better understanding of the breakdown. It's shown in table 5.

Best and worst performing scenarios were tested for understanding the range of benefits achievable. Results for best and worst-performing interventions are shown in table 6.

Heat recovery in air systems is a highly effective way to save energy in office buildings. In the airside system, change is not proposed in the study. Only the base building system in the existing building (given under the case study section) was tested for improvements in air supply temperature, Air Handling Unit heat recovery efficiency and specific fan powers. From the study results, one of the importance of airside systems is the impact on heat recovery efficiency. In trade-offs, 70% heat recovery saved 18% energy, reducing CO_2 emission by 20% and operational cost by 10%.

A significant saving potential was observed in the plant replacement option in the study. The proposed scenarios for heating and cooling plants with the number and operational type saved up to 31% energy, reducing the CO_2 emission by 45% and operational cost by 6%. The impact of several plants and plant operations is not observed as satisfactory as expected due to the demand of the building and the size of units accordingly.

As a result of interventions, the study shows the noticeable impact of energy-saving potential through HVAC systems in an existing office building. In the interventions HVAC systems saved 31 to 46% in energy, 31 to 46% in CO_2 and 23-26% operational costs between best and worst-performing scenarios. Also, the best performing scenario saved 24 to 41% in energy, 24 to 41% in CO_2 and 9-13% operational cost over the existing building.

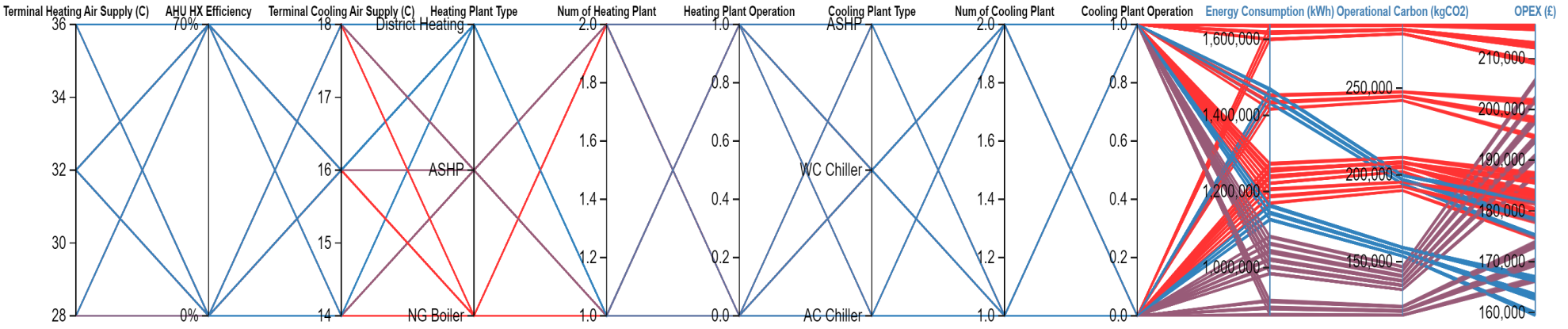


Figure 4. HVAC retrofit intervention results

Table 5. HVAC Systems Intervention Trade-Offs

Intervention	Input	Total Energy Consumption (kWh)	Total Operational Carbon ($kgCO_2$)	Total Operational Cost (OPEX) (£)
Terminal Heating Air Supply (C)	36	-	-	-
	32	0.12%	0.11%	0.15%
	28	0.18%	0.16%	0.22%
FA AHU HX Efficiency	0	-	-	-
	70%	18.25%	20.58%	10.30%
FA AHU SFP (W/l/s)	1.8	-	-	-
	1.6	1.53%	1.40%	1.93%
Terminal Cooling Air Supply (C)	18	-	-	-
	16	0.09%	0.08%	0.11%
	14	0.14%	0.13%	0.17%
Heating Plant Type	NG Boiler	-	-	-
	District Heating	7.37%	25.89%	12.51%
	ASHP	30.56%	44.44%	5.43%
Number of Heating Plant	1	-	-	-
	2	0.20%	0.92%	-0.85%
Heating Plant Operation	Equal	-	-	-
	Sequenced	0.42%	1.23%	-0.71%
Cooling Plant Type	ACC	-		-
	ASHP	1.03%	0.36%	0.36%
	WCC	1.43%	1.30%	1.81%
Number of Cooling Plant	1	-		
	2	0.03%	0.02%	0.03%
Cooling Plant Operation	Equal	-	-	-
	Sequenced	0.06%	0.05%	0.08%

Table 6. HVAC Systems Best Intervention Trade-Offs

Intervention	Total Energy Consumption (kWh)	Total Operational Carbon ($kgCO_2$)	Total Operational Cost (OPEX) (£)
Worst Case Energy and CO_2	-	-	-
Best Case Energy and CO_2	46.69%	58.54%	23.39%
Worst Case OPEX	-	-	-
Best Case OPEX	31.38%	46.63%	26.46%

6. Conclusions

Existing office stock in London is an area that requires focus on improving energy efficiency. Due to the design, application and cost, envelope retrofits are not always feasible to improve energy. HVAC systems energy retrofits is an effective way for energy, carbon and cost improvements.

The study has established a methodology for the HVAC energy retrofits of an existing office building to reduce energy, carbon and costs. The bespoke methodology has been followed to test the design interventions and analyzed the annual energy, CO_2 and operational cost comparison. In the first step of the two-staged approaches, hourly heating, cooling and ventilation demand are calculated via dynamic simulation and calibrated with the

collected data from the existing building management system (BMS). The calibrated hourly demands were used as the input of the Stage two analysis. Parametric equation-based modelling methodology was used in the next step as Stage two. Stage two analysis was used to calculate the impact on energy, CO_2 and cost in every intervention via the bespoke parametric tool.

The study shows that the use of EBM workflow is an enhanced and fast way to analyze the impact of the parameters in HVAC systems when there is no change in demand. HVAC systems design is bespoke for every building topology. The successfully implemented HVAC retrofits have a noticeable impact on energy saving. It requires detailed analysis to measure the energy performance, carbon and cost.

HVAC systems are complex elements of building design. They have impacts on building design, environmental, financial aspects and thermal comfort. The selection of systems and variables related to these systems have an influence on these. In existing buildings, this influence can be extended to the whole system or be limited to a part of the building.

This content of the study is limited to operational energy consumption, carbon emissions and cost as a part of a comprehensive approach to HVAC energy retrofits. It focused on a limited HVAC energy retrofit. Tested 10 interventions are only a part of the holistic HVAC systems and modelling approach and there is further saving allowance with other systems and components. Further research is needed in the study for the integration of the embodied carbon, investment costs and optimization of the conflicting systems and outputs.

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