REPUBLIC OF TÜRKİYE

YILDIZ TECHNICAL UNIVERSITY

GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

AN APPROACH FOR ACTIVE ENERGY SYSTEM OPTIMIZATION IN OFFICE BUILDINGS

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DOCTOR OF PHILOSOPHY THESIS

Department of Architecture

Building Physics Program

Supervisor

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A thesis submitted by Baran TANRVERDI in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY is approved by the committee on 23.08.2023 in Department of Architecture, Building Physics Program.

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Baran Tanriverdi

Dedicated to Cinar and Melis

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Baran TANRIVERDI

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LIST OF SYMBOLS

ach	Air change hour
m3/h.m2	Air permeability
Mp	Average of the measured data
cfan	Central fan
ccpump	Condenders circulation pump
cpump	Cooling circulation pump
p/kWh	Cost per kilowatt-hour energy
Cdi	Crowding distance
Fi	Crowding distance assignment
J	Current trajectory
°C	Degree Celsius
EC	Embodied carbon
kWh/m2/yr	Energy use intensity
W/m2	Energy use per area
W/person	Energy use per person
Np	Entire number of values
l/s /m2	Flowrate per area
hpump	Heating circulation pump
kgCO2	Kilogram of carbon Dioxide
kgCO2e/kWh	Kilogram of carbon dioxide emission per kilowatt-hour energy
kW	Kilowatt
kWh	Kilowatt-hour
μ	Mean, sensitivity measure
Mi	Measured data
Rt	Non domination sort model
k	Number of input parameters
N	Number of randomised sets of k parameters
OCE	Operational carbon emission

OEC	Operational energy consumption
I	Parameter analyzed
Δ	Sampling distance interval
Si	Simulated data
W/l/s	Specific fan power per air flow
σ	Standard deviation, sensitivity measure
m2	Square meter
tfan	Terminal fan
W/m^2. K	Thermal heat transfer coefficient

LIST OF ABBREVIATIONS

AAHS	All-air HVAC System
ACC	Air Cooled Chiller
AHU	Air Handling Unit
AM	Application Manual
ASHP	Air Source Heat Pump
AUP	Analytical Uncertainty Propagation
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
BEIS	Department for Business, Energy and Industrial Strategy
BOH	Back of House
BS	British Standard
BMS	Building Management System
CAPEX	Capital Expenditure
CAV	Constant Air Volume
CIBSE	Chartered Institution of Building Services Engineers
COP	Coefficient of Performance
CS	Centralized System
CV(RMSE)	Coefficient of Variation of the Root Mean Square Error
DCS	De-centralized System
DCV	Demand Control Ventilation
DE	Direct Electric
DH	District Heating
DHS	Dedicated Outdoor Air HVAC System
DOAS	Dedicated Outdoor Air System
EBM	Equation Based Modelling
EeB	European Environmental Bureau
EPD	Environmental Product Declaration
EC	Embodied Carbon

EE	Elementary Effect
EER	Energy Efficiency Ratio
EN	European Norm
EP	Energy Plus
EPD	Environmental Product Declaration
EUI	Energy Use Intensity
FCU	Fan-coil Unit
GWP	Global Warming Potential
GHG	Greenhouse Gas Emissions
HX	Heat Exchanger
HVAC	Heating, Ventilation and Air Conditioning
IES-VE	Integrated Environmental Solutions Virtual Environment
LCA	Life Cycle Assessment
MBE	Mean Bias Error
MEP	Mechanical, Electrical, Public Health
MM	Morris Method
NG	Natural Gas
NSGA	Non-dominated Sorting Genetic Algorithm
NZEB	Net Zero Energy Building
ODP	Ozone Depletion Potential
OPEX	Operational Expenditure
RICS	Royal Institute of Chartered Surveyors
SA	Sensitivity Analysis
SCOP	Seasonal Coefficient of Performance
SEER	Seasonal Energy Efficiency Ratio
SFP	Specific Fan Power
TM	Technical Memoranda
TRY	Test Reference Year
VAV	Variable Air Volume
VRF	Variable Refrigerant Flow

WCC	Water Cooled Chiller
WLC	Whole Life Carbon
WLV	Whole Life Value

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ABSTRACT

An Approach For Active Energy System Optimization In Office Buildings

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Doctor of Philosophy Thesis

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The importance of analyzing the overall carbon emission, energy consumption and usage throughout a building lifecycle has increased due to the growing energy demands and carbon sensitivity in buildings within the scope of the global climate emergency evaluation. This content eventually has gained even more importance as the provision of thermal comfort in office buildings has become a necessity in the human centric design. Therefore, the decisions that are supporting the reduction of carbon emission and energy consumption at the early stages of a design or retrofit, make a significant contribution to these aspirations. CAPEX and OPEX due to the increase in the cost of materials and energy prices are two other important contributors in the decision-making process.

The literature review presents that the number of research on energy efficiency optimization in buildings has increased significantly in recent years. Yet the vast amount of these studies is focused on passive design approaches like building form, orientation and building envelope. In these studies, considering the function of the buildings and climatic conditions, the effect of building form, facade transparency ratios, shading elements and insulation values were optimized, and important findings were revealed. Typically, the main goal of these studies was to reduce the operational and embodied carbon using passive measures. Another driving factor is

building energy efficiency in HVAC systems. Building envelope improvements are of primary importance in new buildings. However, these improvements are limited to the existing buildings. While the improvements related to orientation and form are not possible, the improvement of the building envelope can be complex and over cost. In such cases, it is important to focus on the active systems such as HVAC used to provide the required comfort.

This study focuses on the impact of the operational energy, embodied carbon, and CAPEX of different HVAC systems on an existing office building in London. It is aimed to evaluate the operational energy consumption and carbon emissions of these systems, as well as the embodied energy and carbon analyses. In addition to the energy consumption numbers from the whole life cycle, also it is aimed to compare the initial investment and operating costs.

The study follows a two staged modelling approach. In the first stage, a baseline building energy simulation model is generated using an existing office building information in London. The model is calibrated using the BMS data from building. Calibrated heating and cooling demand are used to generate libraries for alternative HVAC systems and components, embodied carbon, and CAPEX libraries. Due to the complexity of the exercise, impact of different HVAC solutions and components are analyzed through NSGA-ii optimization algorithm within the bespoke developed mathematical parametric model EBM. The study focused on minimizing 3 objective functions: operational energy consumption, embodied carbon and CAPEX of the proposed HVAC systems and components.

The stage 1 analysis proves the importance of accuracy of the inputs for modelling and calibration of the modelling with the metering data. The results show the importance of this step to understand the actual demand of the building. The cooling demand difference between baseline and calibrated model is 30%.

The stage 2 results indicate the complexity of a HVAC design when conflicting objective functions are considered together. In these cases, results show that there is more than a single optimum solution in HVAC design due to system and component variables.

It’s concluded that the electrification of the heating is giving the best overall performance due to the carbon and cost factors in the long-term future prediction.

The individual proposed solutions resulted savings of up to 45% in operational energy, 35% in embodied carbon, and 48% in CAPEX.

ASHP is giving the overall best performance within the proposed plants when the heating and cooling are considered together.

For air-side DOAS system is in average uses 9% less energy and requires 21% less CAPEX than the AAHS system.

The impact of air supply temperatures within the design limitation has less effect on the overall consumptions when compared to the water supply and return temperatures.

Furthermore, it given the operational energy impact of the HVAC system lies in the range 12-16% of the overall energy consumption of the existing building.

Key Words: HVAC systems, operational energy, embodied carbon, CAPEX, NSGA-ii multi-objective optimization

ÖZET

Ofis Binalarinda Aktif Enerji Sistemleri Optimizasyonuna Yonelik Bir Yontem

Baran TANRIVERDI

Mimarlık Anabilim Dalı

Doktora Tezi

Danışman: Prof. Dr. Gülay ZORER GEDİK

Küresel iklim acil durum değerlendirmesi kapsamında, binalarda artan enerji ve karbon emisyonu talepleri nedeniyle, genel karbon emisyonunun, enerji tüketiminin ve binanın yaşam döngüsü boyunca kullanımının analiz edilmesinin önemi artmıştır. İnsan merkezli tasarımda ofis yapılarında ısıl konforun sağlanması bir zorunluluk haline geldiğinden bu içerik zamanla daha da önem kazanmıştır. Bu nedenle, bir tasarımın veya renovasyonun erken aşamalarında karbon emisyonunun ve enerji tüketiminin azaltılmasını destekleyen kararlar, bu hedeflere önemli bir katkı sağlar. CAPEX ve OPEX calismalari , malzeme maliyetlerindeki ve enerji fiyatlarındaki artış nedeniyle karar alma sürecindeki diğer iki önemli katkıdır.

Literatür taraması, binalarda enerji verimliliği optimizasyonu ile ilgili araştırma sayısının son yıllarda önemli ölçüde arttığını göstermektedir. Yine de bu çalışmaların büyük bir kısmı bina formu, yönlendirme ve bina kabuğu gibi pasif tasarım yaklaşımlarına odaklanmıştır. Bu çalışmalarda, binaların işlevi ve iklim koşulları dikkate alınarak bina formunun etkisi, cephe şeffaflık oranları, gölgeleme elemanları ve yalıtım değerleri optimize edilmiş ve önemli bulgular ortaya konulmuştur. Tipik olarak, bu çalışmaların temel amacı, pasif önlemler kullanarak operasyonel ve gomulu karbonu azaltmaktır. Diğer bir itici faktör, HVAC sistemlerinde bina enerji verimliliğidir. Bina kabuğu iyileştirmeleri, yeni binalarda

birincil öneme sahiptir. Ancak bu iyileştirmeler mevcut binalarla sınırlıdır. Yönlendirme ve form ile ilgili iyileştirmeler mümkün olmamakla birlikte, bina kabuğunun iyileştirilmesi karmaşık ve maliyetli olabilir. Bu gibi durumlarda gerekli konforu sağlamak için kullanılan HVAC gibi aktif sistemlere odaklanmak önemlidir.

Bu çalışma, Londra'daki mevcut bir ofis binası üzerindeki farklı HVAC sistemlerinin operasyonel enerjisinin, gomulu karbonunun ve ilk yatirim maliyetinin etkisine odaklanmaktadır. Bu sistemlerin işletme enerji tüketimleri ve karbon emisyonları ile gömülü enerji ve karbon analizlerinin değerlendirilmesi amaçlanmaktadır. Tüm yaşam döngüsündeki enerji tüketim rakamlarının yanı sıra ilk yatırım ve işletme maliyetlerinin karşılaştırılması da amaçlanmaktadır.

Çalışma iki aşamalı bir modelleme yaklaşımı izlemektedir. İlk aşamada, Londra'daki mevcut bir ofis binası bilgisi kullanılarak temel bir bina enerji simülasyon modeli oluşturulur. Model, binadan alınan BMS verileri ullanılarak kalibre edilir. Kalibre edilmiş ısıtma ve soğutma talebi, alternatif HVAC sistemleri ve bileşenleri, gomulu karbon ve CAPEX için kutuphane oluşturmak üzere kullanılır. Alıştırmanın karmaşıklığından dolayı, farklı HVAC çözümlerinin ve bileşenlerinin etkisi, calisma geliştirilmiş matematiksel parametrik model EBM içinde NSGA-ii optimizasyon algoritması aracılığıyla analiz edilir. Çalışma, 3 hedef fonksiyonunu minimize etmeye odaklandı: önerilen HVAC sistemleri ve bileşenlerinin operasyonel enerji tüketimi, gomul karbon ve CAPEX.

Birinci asama analizi, modelleme için girdilerin doğruluğunun önemini ve ölçüm verileriyle modellemenin kalibrasyonunu kanıtlar. Sonuçlar, binanın gerçek talebini anlamak için bu adımın önemini göstermektedir. Temel ve kalibre edilmiş model arasındaki soğutma talebi farkı %30'dur.

Ikinci asama sonuçları, çelişen amaç fonksiyonları birlikte değerlendirildiğinde bir HVAC tasarımının karmaşıklığını gösterir. Bu durumlarda sonuçlar, sistem ve bileşen değişkenleri nedeniyle HVAC tasarımında birden fazla optimum çözüm olduğunu göstermektedir.

Uzun vadeli gelecek tahmininde karbon ve maliyet faktörlerinden dolayı ısıtmanın elektrifikasyonunun en iyi genel performansı verdiği sonucuna varılmıştır.

Önerilen çözümler, işletme enerjisinde %45'e, karbonda %35'e ve ilk yatirim maliyetinde %48'e varan tasarruf sağladı.

ASHP, ısıtma ve soğutma birlikte düşünüldüğünde, önerilen sistemler arasinda genel olarak en iyi performansı vermektedir.

Hava tarafı için DOAS sistemi, AAHS sistemine göre ortalama olarak %9 daha az enerji kullanır ve %21 daha az CAPEX gerektirir.

Tasarım sınırlaması içindeki hava besleme sıcaklıklarının etkisi, su besleme ve dönüş sıcaklıkları ile karşılaştırıldığında toplam tüketimler üzerinde daha az etkiye sahiptir.

Ayrıca, HVAC sistemlerinin işletme enerji tuketimini mevcut binanın toplam enerji tüketiminin %12-16'sı aralığında yer aldığı göz önüne alındığında.

Anahtar Sözcükler: HVAC sistemleri, işletme enerjisi, gömülü karbon, CAPEX, NSGA-ii çok amaçlı optimizasyon

1
INTRODUCTION

Climate emergency in the early 21st century refers to the urgent need to address climate change topics which require carbon emission reduction to eliminate the adverse impact on the planet. For mitigating the effects of climate change, it is important to take immediate and decisive actions to reduce greenhouse gas emissions and transition to renewable energy sources. The importance of limiting the global warming temperature raise to 1.5 °C is one of the prior outcomes and goals of the Climate Change Conference (COP) 26 in 2021.[1]

The World Green Building Council (WGBC) has outlined a roadmap that requires all new buildings to be net zero carbon by 2030 and all existing buildings to be net zero carbon by 2050 in order to achieve these goals as a part of the initiated Net Zero Carbon Buildings Commitment.

The climate emergency is a unique global challenge, and one that requires immediate affirmative action at all levels; international, national, local, and personal. In order to meet our commitments to the 2016 Paris Agreement, with the aim of staying below a 2°C temperature increase against pre-industrial levels and aiming to limit this further to just a 1.5°C change, stakeholders at all of these levels must work together to mitigate climate change.

Deep and significant cuts to greenhouse gas (GHG) emissions are required by 2030, with many national governments aiming for zero carbon by 2050. In July 2019, the UK declared its intent to achieve net zero carbon by 2050. The built environment will contribute heavily to the success of this goal. It is estimated that 40% of total United Kingdom (UK) GHG emissions are resultant from the built environment, through the construction, operation and demolition of buildings and infrastructure. Therefore, immediate steps must be taken within the industry to ensure that this goal is delivered.

In the UK, buildings are responsible for 49% of the annual carbon emissions [2]. This carbon emission is attributed to construction and the operation of the built environment [3]. As a part of it, non-domestic commercial buildings are responsible for 59% of the total building energy consumption in the UK. In England

and Wales, existing office buildings represent 20% of the non-domestic building stock and one of the highest energy-consuming building types with 10% [4].

This study assesses the potential carbon, energy and cost performance of an existing office building in London. With a focus to Heating, Ventilation and Air Conditioning (HVAC) systems, it compares the impact of carbon, energy and cost to the potential energy retrofits. While carbon (operational and embodied) and energy are important to address the emission targets, the cost is an indisputable factor for all construction projects. Therefore, the study proposes a solution considering all these three targets.

The modelling concept is named as equation-based modelling (EBM) and calculates the objectives using a mathematical model. The approach is fundamentally a calculation method to optimize operational energy, embodied carbon and Capital Expenditure (CAPEX) in office buildings.

A range of potential options are developed for supplying the energy retrofit of the with its heat and cooling requirements over a year, and their comparative financial and environmental attributes are calculated based on stated assumptions. The exercise starts with the establishment of energy demand and equipment sizing and culminates in parametric HVAC system modelling and optimization of the derived scenarios. The approach and outcomes are outlined below.

1.1 Stages of the Study

The proposed method is developed in a staged form. It follows a two staged approach to calculate the outcomes.

The first stage analysis is a baseline model generation to calculate the hourly heating and cooling demands. Baseline model is calibrated with actual building metering data. Based on the calibrated baseline heating and cooling demand, HVAC system proposals for efficiency, embodied carbon and CAPEX are generated.

In the second stage analysis, a parametric mathematical equation-based model is developedand the impact of the system variables are calculated. The model calculates the operational energy, embodied carbon and CAPEX of each HVAC system combinations.

Finally, the impact of each combination as objective functions analyzed using an optimization algorithm.

1.1.1 Stage 1 Analysis

- Baseline building energy modelling

The baseline building energy model is created using dynamic simulation modelling approach with the available input data. It's an important step to model the building accurately to reduce the performance gap between modelling results and actual building operation.

- Baseline building model calibration

The baseline building energy modelling results calibrated with actual building metering data. The metering data is regularized before the calibration step.

- Calibrated heating and cooling hourly load analysis

The hourly heating and cooling loads are extracted from the calibrated simulation results. The loads extracted from the building energy model for heating and cooling includes all the conditions, systems and equipment that have an impact on it.

- HVAC systems decision drivers

HVAC system selection is a key element for the purpose of the study due to many different criteria. The building type, size, climate, thermal comfort and indoor air quality, building regulations, energy and cost are the main decision drivers that have been involved in the decision-making progress of HVAC system selections.

- HVAC systems input data library generation

An outline of the key theoretical attributes of the main HVAC systems and technologies (e.g., boilers, chillers, heat pumps, centralized and decentralized air distribution systems) is given, together with a commentary on the likely efficiency, embodied carbon and the initial cost of the systems when applied to the existing office building. These are broadly applicable solutions across the options and are peripheral to the way the options are developed.

- HVAC embodied carbon library

Embodied carbon analysis is a relatively new area in the building services industry and limited knowledge and environmental product declarations (EPDs) are available from the HVAC manufacturers. It's due to both a lack of market demand and the complexity of the systems. CIBSE Technical Memorandum (TM) 65 Embodied carbons in building services: a calculation methodology provides guidance on EPDs as well as the calculation approach for the product ranges with no available EPDs. The calculation approach is a guide to understanding the estimated embodied carbon of these products rather than an EPDs replacement. Embodied carbon for the selected HVAC systems and components is calculated following the TM65 methodology.

- CAPEX and OPEX library

Once suitable options are established, an economic appraisal of their relative financial and carbon impacts is carried out. In the cost library generation, a similar approach with embodied carbon is followed and a product-based library generated.

1.1.2 Stage 2 Analysis

The stage 2 is the analysis of the proposed HVAC systems and components in the developed mathematical model to test the impact of energy, embodied carbon and CAPEX.

- Parametric modelling with Grasshopper

In stage 2, using the calibrated hourly heating and cooling loads, HVAC system data libraries, embodied carbon and CAPEX libraries the mathematical model is developed. Arriving at a suitable energy strategy using equation-based modelling methodology and optimization for the existing office building requires decisions over suitable energy supply technology combined with the choice of appropriate distribution options (e.g., centralized or local, high or low temperature). The number of options and combinations available is reduced by considering some preliminary analysis and practical considerations.

- Mathematical modelling – EBM concept

Iteration based parametric model developed using the optimization algorithm presents the results in both tabular and graphical forms. Each individual component of these sub-categories, based on their system definition energy, carbon and cost is calculated and optimized to inform the decision-making process for the existing office building.

1.2 Scope of Thesis

Significant research has been carried out on buildings considering operational energy, cost and embodied carbon individually. The studies from various countries are mainly focused on the envelope and passive building elements that affect energy, carbon and cost. These studies have focused on the outcomes together and individually in the areas of energy, carbon and cost.

However, the number of studies examining this impact of HVAC systems is limited. These studies are not focused on revealing the integrated effect of the systems. Also, the number of studies in which Whole Life Carbon (WLC) and cost are considered together is limited in the literature. In HVAC systems, consideration of combined operational energy embodied carbon and cost is an important criterion for system selection. This thesis, it is aimed to develop a design support method in which these three criteria, which are evaluated by different disciplines, are evaluated together with a holistic design approach for existing and new office buildings.

This thesis, it is aimed to develop a design support methodology for these three criteria, which normally are evaluated by different disciplines, together with a holistic modelling approach for existing and new office buildings. By using optimization methods, these different variables are driven, and conflicting criteria have been transformed into a decision-making algorithm for design. The approach aims to vulgarize cost-supported whole-life carbon assessment in office buildings by promoting its benefits on energy, carbon and economics.

In addition, it will contribute to the target of reducing greenhouse gas emissions and energy consumption, promoting the environmental impact by the common evaluation of all variables in the system selection. It is aimed to provide the opportunity for to designers choose the systems on a project basis by visualizing the optimum system selections with different weights.

1.3 Hypothesis

The energy consumption and office utilization associated with it should be approached with a holistic design in order to analyze the energy, carbon, and cost impact of HVAC design on buildings due to increased embodied-operational carbon emissions. The operational energy efficiency of HVAC systems is a characteristic that can be analyzed through energy modelling software in the design of new and existing buildings. These software programs allow for the evaluation of thermal comfort and energy efficiency together and enable users to maintain desired levels of comfort.

However, the main challenge is that it requires an interdisciplinary approach that includes embodied carbon and cost analyses. An approach that evaluates the technical, economic, and environmental performance of HVAC systems according to building-specific priorities at an early design stage is required. The energy, carbon, and cost performance of HVAC systems depend on design parameters such as system choices, air and water supply temperatures, fuel type, and the number of plants. It is expected that these parameters will be decisive for analysis, as they affect energy performance indicators as well as carbon and cost.

1.4 Research Objectives

The general research question of the study has been proposed as; “In HVAC design, how should the balance between operational energy, embodied carbon and cost performance be achieved from a technical, environmental and economic point of view?” Other sub-questions investigated during the study to answer this question are listed as below.

- What are the HVAC system selection criteria in office buildings?
- How to evaluate operational energy and embodied carbon impact in office buildings?
- What is the impact of HVAC system selections in office buildings on operational energy, embodied carbon and cost?
- What is the relationship between operational energy, embodied carbon and CAPEX variables?
- What is the relationship between operational carbon and embodied carbon?
- What is the relationship between CAPEX and Operational Expenditure (OPEX)?
- What is the effect of multi-objective optimization on the analysis of HVAC design combinations?

- How to make HVAC design decisions influenced by operational energy, embodied carbon and CAPEX?

- How to develop HVAC selection recommendation environment for office buildings with the EBM method?

1.5 Structure and Progress of the Thesis

Within the scope of the thesis, an approach that is believed to be necessary for the EBM design process and offers an interdisciplinary evaluation has been developed.

- **Introduction**

In the introduction section, the problem and the structure of the study is proposed. The HVAC systems related energy consumption, carbon emissions and cost of the existing and new commercial office buildings are mentioned, and solution proposals are searched. The aim of the thesis and the hypothesis were defined in line with the research questions for the problem and its barriers.

- **Literature Review**

Literature focused on, factors and performance indicators affecting the performance of office building HVAC systems that unlocks the energy efficiency, carbon and cost savings and methodologies for assessing in office buildings have been investigated. Equation based modelling design criteria were investigated and the section providing optimum performance for both systems was determined in accordance with the literature review. In addition, international WLC, operational energy assessment and cost modelling application examples are given.

- **Conceptual Models for the Methodology**

For an approach to optimum HVAC design for an office building, the steps, basic principles and the impacting parameters and methods have been determined.

- **Methodology**

This chapter focuses on putting Office HVAC system optimization concepts into a systematic framework and turning it into a computational tool in all domains.

In the first stage of the methodology, a baseline model was generated using holistic building energy simulation. This baseline definition can be as-built design information for an existing building, or any baseline test scenario defined for a new building. The system definitions embodied carbon and cost libraries were created in line with the findings and recommendations of the conceptual study and the outputs of the holistic energy modelling demands.

In the second stage of the study parametrically developed EBM tool is used to calculate the impact of the parameters that effecting energy, carbon and cost variables. The inputs are optimized using the Non-dominated Sorting Genetic Algorithm II (NSGA-II) optimization algorithm to achieve the Pareto front results that support the decision-making process of designing the HVAC systems.

- **Case Study**

In this section, the developed EBM decision support tool is applied in a real building case. An existing office building in London was determined for the study, and the impact of the different HVAC systems on operational energy embodied carbon and cost variables were examined. By determining the optimum Pareto front results, the energy, carbon and economic performance of the selections were examined.

- **Results and Discussion**

Field studies and all the steps and finally the results are discussed. The original value and widespread impact of the study are included.

- **Summary And Conclusion**

The major findings of the study are summarized. The limitations of the study were examined and suggestions for future studies were made.

2
LITERATURE REVIEW

In the literature review of the study, different aspects of the recent studies that focus on building whole-life carbon assessment, building performance modelling, HVAC modelling, HVAC energy efficiency, operational energy, sensitivity analysis and multi-objective optimization are reviewed. After examining more than 200 papers and thesis studies, the evaluation of the literature on the focused study is exhibited and the originality of the thesis work is presented. Key studies influenced the study are presented in the literature review section below.

2.1 Literature Review on Whole Life Carbon Assessment

Christina Kiamili et al. in their study remarked on the limitations of the cases for HVAC systems whole lifecycle assessment in the building industry. It focused on an Life Cycle Assessment (LCA) for an HVAC system using data from the building information modelling (BIM) of an office building in Switzerland. In the study, embodied carbon impact of the HVAC systems was calculated as three times higher than the national benchmarks and indicates a correspondence of 15-36% of the total embodied carbon of the building. Swiss KBOB and Ecoinvent databases are used to calculate embodied carbon of the systems and components that were extracted from the BIM model using Dynamo visual programming software. Material weight calculation methods are applied to the categories based on the material % and weight.[5]

Michal A. in his study focused on the complexity of the HVAC services embodied carbon emissions estimations. It proposed a methodology using analytical uncertainty propagation (AUP) unified with a parametric modelling approach for HVAC system embodied carbon based on case studies. It proposed an alternative uncertainty analysis approach to Monte Carlo Method to support early design stage decisions. The uncertainty happens to analyze input parameters of HVAC system embodied carbon numbers an iterative process used to support the parametric estimations.[6]

B. Rodriguez et al. in their research study identified typical HVAC systems used in an office building in Washington State and explored the effects of current practice on total energy use, and operational and embodied carbon emissions. In the study in total 20 existing LEED-certified buildings in different locations, HVAC systems and certification levels have been analyzed by the data available. Operational CO2 intensity for each building was calculated along with the post-processed metered energy data. However only refrigerant intense equipment embodied CO2 intensity considered. Duct, pipes, terminal units, refrigerant and insulations were not a part of the comparison.[7]

Chendong W. et all, in their study examining the LCA for office buildings with a focus to heating and cooling systems in China. It examines the environmental for heating and cooling technologies. The study evaluates the factors such as embodied carbon and operational energy determine the overall environmental impact of each system. In total 7 combinations for heating and cooling source are tested for the cold regions in China.[8]

Mehdi R. Et all, in their study focus on a net-zero energy building in Australia. In the study a method for building materials, analyzing the uncertainty analysis of the WLC is developed. The carbon footprint of the construction materials are examined using uncertainty analysis. The uncertainty analysis helps to provide to increase the accuracy of the embodied carbon emissions estimation. [9]

The article presents a method of uncertainty analysis for assessing the whole-life embodied carbon emissions (CO2-e) of building materials used in a net-zero energy building located in Australia. The objective is to understand and quantify the environmental impact of construction materials over their entire life cycle, including extraction, production, transportation, use, and disposal.

The research proposes the contribution of different materials embodied carbon which increase the accuracy of estimating the figures using the Monte Carlo method. The factors driving the results exhibit the impact of factors of material types, manufacturing methods and locations. The study shows the difference in between data bases and the simulated results.

Xing S. et al. in their research focus on a building in hot summer and cold winter climate in China. In the study, embodied carbon and operational energy for sustainable materials and technologies investigated to minimize the energy consumption. [10]

The research investigates the impact of passive building considering the materials and systems by analyzing embodied and operational energy and carbon emissions.

The study demonstrates that embodied carbon is higher than the conventional buildings however the operational energy consumption is higher than the conventional buildings.

Agneta G. et al in their study asses the life cycle impacts of the retrofits for existing office buildings achieve the New Zealand 2050 climate change mitigation target. The main observation of the study is the contribution of energy retrofits to existing building to achieve energy efficiency and understand the environmental implications. In the study stock aggregation modelling is used to analyze the LCA impact associated with various building upgrades, including insulation, energy-efficient HVAC systems, and renewable energy. The research highlights the impact of existing office building retrofits in New Zealand climate change mitigation targets. Existing office stock has a potential to reduce around 40-98% kgCO2 emissions in New Zealand. [11]

Eleftheria T. and Theodoros T. in their study introduces a workflow that uses generative design tool to optimize operational energy consumption to achieve nearly zero energy buildings. It highlights the potential of employing advanced computational techniques to optimize building designs, enhance energy efficiency and achieve Net Zero Energy Building (NZEB) standards. [12]

In the study parametric design coupled with energy simulation and optimization algorithm is proposed to unlock the potential of energy performance of the buildings. It introduces generative design as a powerful approach to achieve NZEB.

Afaf A. et al in their study demonstrate the LCA of energy conservation measures for office buildings in London during the early stage over a mid-rise office case study. The study is focused to structure, envelope and operational systems. Following the London plan energy hierarchy in operational energy, embodied carbon savings are introduced to the design. Savings through the energy efficiency measures and embodied carbon are presented in the study. The authors also highlight the operational energy and carbon significance as having higher impact than embodied energy and carbon over a 60-years building lifetime. [13]

2.2 Literature Review on Operational Energy Consumption and HVAC Modelling

Hussam J and Junjing Y. in their study is a qualitative analysis for the innovative and efficient HVAC systems in buildings. It covered different Heat Pump technologies, heating and cooling systems, ventilation systems, energy storage and regenerative process and highlights the impact of the controls to achieve higher energy efficiency.[14]

Muzaffar A, et all, presents a simulation- based optimization method that analysis energy consumptions of different chilled water system configuration. The study focuses on the optimization of the energy performance of different configurations to define the most efficient setup for cooling. The methodology allows calculations of various system parameters, optimizing the chilled water system performance while minimizing energy consumption. By analyzing different configurations, the research aims to provide insights that can help design engineers and building operators make informed decisions to achieve higher energy efficiency and cost savings in cooling systems. [15]

Kuei-P. et all, in their study propose a method to improve the energy efficiency of chilled water systems thorough optimization. The proposed methodology integrates optimization to building simulations to analyze energy performance of these systems. Study focuses on the parameters such as chilled water temperature, pumps and cooling towers to reduce the operational energy consumption without changing the cooling capacity. [16]

George P. et al, reviews the public office buildings in UK and discuss a method to assess building performance for low carbon building design. [17]

The study focuses to the performance gap, combines project management operations and building energy use analysis to evaluate the building's environmental impact and energy efficiency. HVAC system efficiencies, lighting, set points, occupational hours are tested through trade-offs. Using the dynamic model coupled operations, study shows the annual energy consumption and operational CO2 emissions.

Xiaofei H. Et al, in their study employ a model that optimize the performance o of Heating, HVAC systems with room temperature ramp rates. [18]

The study proposes a data-driven model that uses artificial intelligence and machine learning algorithms. The particle swarm optimization is used to optimized proposed solutions to enhance the efficiency and impact of HVAC systems. System parameters such as control strategies, air flow, air and water temperatures are tested and energy consumption patterns to achieve improved HVAC system performance is presented.

Sokratis P. et al, discusses the impact of users in commercial buildings. The study proposes the impact of HVAC indoor set point temperatures to achieve zero-cost energy savings. [19]

The adjustment can be done to the temperature setpoints with wider set point ranges can bring significant operational energy reductions without any additional cost using multi-objective optimization.

Study proposes analyzing temperature set point in different climate zones, identifying the potential for energy savings and thermal comfort improvement.

Wanqi X. and Jiandong W. developed a mathematical model to optimize the operational energy consumption of the HVAC systems. The model is developed using thermodynamic principles using an in-out relation of variables to optimize the consumptions. Metering data compared with the calculated figures and using an ANN model the results are calibrated, including outdoor weather conditions, building profiles and occupant preferences. [20]

Through extensive testing and simulations, the researchers demonstrate the effectiveness of the model in optimizing power consumption. The results show that the semi-physical static model can significantly reduce HVAC energy usage while still meeting the comfort requirements of the building occupants.

The study highlights the importance of advanced modelling techniques in achieving better HVAC systems energy consumptions subjected to maintain indoor air temperatures.

Shuo C. et al in their study compares three different HVAC systems in an office building with a focus to life cycle assessment. Air systems such as conventional VAV, chilled beam and underfloor air distribution compared for energy saving potential and environmental impact over a 50-year time frame. [21]

Throughout the study, various parameters were evaluated, including energy consumption, greenhouse gas emissions, and resource usage associated with each HVAC system over its life cycle. Based on the results, the adoption of chilled beam systems in office buildings is encouraged for projects with a focus on environmental responsibility and long-term energy efficiency.

Andrew K. et al, provide a data-driven modelling and optimization of HVAC systems in an office building. The study aims to increase the accuracy by using a predictive HVAC operational energy model and optimize system performance to achieve energy efficiency and cost savings. [22]

Data mining algorithm used to understand the relationship of the parameters. And multiple-linear perceptron is used to test chiller, pump and fan performance. Particle swarm optimization is used for energy optimization and results provide a 7% energy reduction on HVAC systems.

Cristina B. et al, in their study explores the correlation in between envelope and HVAC system configurations in different cities with different climates for minimizing operational energy consumption towards achieving NZEB. The study essentially focuses on the importance of HVAC system selections for specific climatic conditions to enhance energy efficiency and reduce environmental impact on the selected residential buildings. [23]

Study highlights the significance of NZEB to reduce carbon emissions, emphasizes the pivotal role of HVAC systems and incorporation of renewable energy sources into HVAC systems in building energy consumption.

Mieczysław P in his study proposes an optimization method for HVAC systems from a holistic perspective, with an energy consumption focus. He highlights the importance of whole building simulation, using it as universal set of constant parameters and constraints to optimize HVAC systems for achieving energy efficiency. The study proposes a bespoke hourly calculation methodology with a focus to air and primary energy systems. The mathematical model allows a matrix calculation to optimize the HVAC system combinations. The study emphasizes the need for a comprehensive approach that addresses the interactions between different HVAC systems for effective energy performance. [24]

Hyo S. et al propose an energy benchmark for the operational rating system of office buildings. To generate the database, study utilizes data-mining techniques to analyze and process data related to energy consumption in office buildings. The aim of the study is to generate accurate benchmarking system to support identification of the areas for improvement of energy efficiency in office buildings. Correlation and decision tree analysis with analysis of variance is used to generate the data base from 1072 office buildings in South Korea. [25]

Energy benchmarks are created based on floor area and building use ratio. The study highlights the impact of improved operational rating system based on this benchmark, which can bring more accurate and insightful information on energy performance, leading to better-informed decisions, increased energy efficiency, and the promotion of sustainable practices in the commercial building sector.

Liu G. and Liu M. in their study present a calibration process for the simplified building energy simulation. The method is tested over case studies with different functional purposes. [26]

The methodology proposes a two staged calibration process to improve the effectiveness. It provides long term annual energy consumption predictions using only couple of weekly hourly measured data. Model tolerances for monthly and hourly consumptions are also introduced within the given constraints.

Authors remark the impact of calibration in HVAC energy consumption studies with a focus to heating and domestic hot water.

2.3 Literature Review on Cost Modelling of HVAC Systems

Jinjyun Cho et al. in their research focused on the optimization of energy consumption and the initial cost for the HVAC systems in the early design stage. Study declared the initial investment cost information in the early design stage can be inadequate and proposed a method that formulates predictive models. The energy performance and investment cost are optimized through decision tree analysis for the office HVAC systems. The HVAC systems are divided into 3 main categories from 33 basic elements. The cost associated to each sub-category is used to analyses different combinations. Calculated cost is tested against pre-calculated energy use intensity numbers in the optimization step.[27]

Jinkyun C. et al, explores a methodology to conduct the operational energy and CAPEX analysis of HVAC systems in office buildings. The researchers aim to develop a multiple prediction methodology for estimating the cost of HVAC systems, taking into account various factors that influence both energy consumption and cost. [28]

The cost method is developed using a generative library by collecting the data on HVAC systems. They analyzed the data to identify correlations between different parameters and HVAC system costs.

Decision making for options are provided using decision tree analysis of energy-cost of HVAC systems.

Jie W. et al in their study explore the correlation in between operational energy and LCC performance of high-rise office buildings. In the study authors draw the strong correlation between operational energy efficiency and life cycle cost performance. [29]

The temperature set points, enhanced HVAC systems, lighting, glazing, and renewable energy is analyzed. The simulation results are compared against the real energy use for Energy Use Intensity (EUI), HVAC, equipment and lighting energy consumptions. As a result, lower operational energy consumption demonstrates better life cycle cost performance.

Jinkyun C. et al propose a HVAC system cost estimation methodology using a multi prediction methodology. The introduced methodology is used to test office buildings energy-cost analysis. Predictive models are used to estimate cost, due to inadequate information in most of the projects. [30]

Authors aims to provide a methodology for the energy consumption and inlined costs of HVAC systems. The findings demonstrate that the energy-cost analysis can provide insights into the economic implications of HVAC system selections.

2.4 Literature Review on Multi-Objective Optimization

Hayrettin O. Bektas in his study focused on the multi objective optimization NSGA-II to assess the impact of storage tank sizing against the pipe diameter changes on the network's strength. These inputs used to test the cost/ networks strength together. It explicitly proved the power of the NSGA-II evaluating the conflicting cost functions.[31]

Kotek Petr et al. focused on the HVAC system comparison using uncertainty and sensitivity analysis. Fan-coil and VAV systems tested the randomization using the Monte Carlo, Latin Hypercube sampling and Morris method. In the study, uncertainty analysis investigated the heating and cooling load derivatives under uncertain conditions. It allowed calculating the deviations in the heating/ cooling demand and energy consumption. Also, the sensitivity analysis helped to assess the strongest and weakest input parameters to reduce the number of simulations.[32]

In another study, V. Zeferina et al. focused on the sensitivity analysis applied to the cooling demand of an office building. They tested Morris elementary effect and Sobol to understand the impact of different inputs on building peak cooling demand and the annual cooling demand. The study exhibited the main contributors affecting the demand using SA by looking into a total of 14 different inputs. One of the major findings was on the impact of the ventilation rate in both peak and annual demand shown as a major contributor. The second major finding was the limited impact of the occupancy density on both results. Last but not least, it proposed that the change in the peak demand is larger in most of the changes when compared to the annual demand.[33]

Andrew K. et al proposed a data-mining driven optimization approach to minimize HVAC systems operational energy consumption while maintaining the indoor thermal comfort. In the study, application of an evolutionary computation algorithm for multi-objective optimization of various user defined variables in HVAC systems are tested. [34]

The study focuses on the controllable inputs such as supply air temperature and fan static pressure configurations. Having multiple objectives, energy consumption and thermal comfort are optimized to identify the optimal solutions.

Optimization provided 21.4% energy saving without effecting the indoor air quality results and with occasionally effected indoor air quality the saving increased to 22.6%

Yaohui et al. in their study discusses the application of predictive modelling and optimization techniques for a multi-zone HVAC system. The study proposes a data-driven approach which utilizes data mining and firefly algorithms to improve the HVAC system performance. Operating parameters such as room temperature and relative humidity, controlled parameters such as supply air temperature and static pressure set point used in the predictive model to minimize the energy consumption of the operation. [35]

Data mining is used to predict thermal comfort conditions and firefly algorithms used for optimization. Th enabled the authors to enhance HVAC system for occupant comfort and reduce energy consumption. The approach is a pathway to improve efficiency in the real-world HVAC system management applications.

Matti P. et al implement NSGA-ii algorithm to develop an optimization method for envelope and HVAC systems. The authors point the importance of considering the building envelope and HVAC system together during the multi-objective optimization process. The study also highlights the potential OPEX savings and carbon emission reductions. [36]

2.5 Evaluation of the Literature

Although there are studies in the international literature that focus on energy, embodied carbon and cost in HVAC systems individually or two at a time in different countries, no detailed study investigates these three together has been found internationally and in Turkey. In the previous studies that were examined, it is seen that the research was carried out only individual focus to these functions.

The study presents a decision support model that examines the energy, carbon and cost for HVAC systems together to guide designers and developers to achieve their energy and sustainability goals.

Although there are studies on the form of energy and carbon in the literature, studies evaluating various performance measures centering the embodied carbon and cost are limited. In studies, also defined parameters of the HVAC systems is usually inadequate. This study provides a wider perspective to understand the performance indicators of HVAC systems and components with both embodied carbon and cost measures.

While the main focus of this research is operational energy, embodied carbon and CAPEX, it provides researchers to compare this analysis with long term OPEX and operational carbon projections.

The results of this thesis can help to predict the effects of HVAC system parameters and components for an existing office building on the energy, carbon and cost performance. It is thought that this methodology with its comprehensive extend will guide the decision makers and designers through design processes.

3
CONCEPTUAL MODELS FOR THE METHODOLOGY

In this section definitions that have been used to generate the calculation methodology is explained. The methodology indentified in the introduction section, is a holistic approach that has been structrured by connecting individual assesments. These assesments are operational energy/carbon, embodied carbon and CAPEX-OPEX. Alongside the definitions of the assessments, this section detirmines the limitations and the constraints of these. These definations inheritely have different constraints that require separate calculations. Further calculation steps on the methods is given under section 4.

It is important to comprehend the holistic Whole Life Carbon (WLC) approach to estimate the building and carbon relationship. WLC approach allows to understand to have a better perspective on embodied-operational carbon and energy. This also supports the desicion making process and the appropriate actions are considered in order to minimise these. WLC Assessments measure and report on embodied carbon and operational carbon. [38]

Embodied carbon accounts for the emissions associated with:

- the construction of a building including extraction, manufacture and transportation of materials;
- the energy and water consumption used to construct a development;
- maintenance, replacement, refrigerant leakage and end-of-life stages (demolition and disposal).

Operational carbon describes carbon emissions associated with the use of a building, for example, lighting and heating.

EN 15978:2011 is the European framework setting out the principles for whole life assessment of the environmental impacts of built projects based on life cycle assessment. [39]

The life cycle embodied emissions resultant from manufacture, construction, operational material replacements and deconstruction have traditionally not been assessed. As the industry continues to drive down operational emissions, so the overall proportion of embodied emissions in a development increases. The Royal Institute of Chartered Surveyors (RICS) Professional Statement provides a robust and thorough assessment method for calculation of the embodied carbon impacts of a development's life cycle. [40] However, it is still important that neither of these emission sources are considered in isolation; the intent of the Whole Life Carbon (WLC) study is to ensure that the life cycle emissions are considered as a whole, helping to identify overall combined opportunities for reducing emissions. To be successful, the WLC thought process should be integrated into the project delivery process from the earliest stages and be closely monitored and evaluated throughout design and construction.

In the study the modular methodology and set of calculation rules which should be followed when completing WLC assessment, is set following the RICS Professional Statement which is largely based on the methodology set out in EN 15978:2011. Aspects of the implementation of EN 15978:2011 have been erratic, and the RICS Professional Statement notes that this has caused significant discrepancies in the way in which WLC assessments are undertaken. This undermines the reliability of carbon measurement and the confidence of stakeholders in the process. The Professional Statement sets out a clear and informed methodology which can be applied to multiple construction projects, providing the required level of repeatability and cross-comparability between assessments.

EN 15978:2011 takes a modular approach to different parts of the life cycle. In WLC assessments, the scope of the carbon assessment can be set during the construction stages and should cover all modules within British Standard (BS) EN 15978:2011 which is given in figure 3.1.

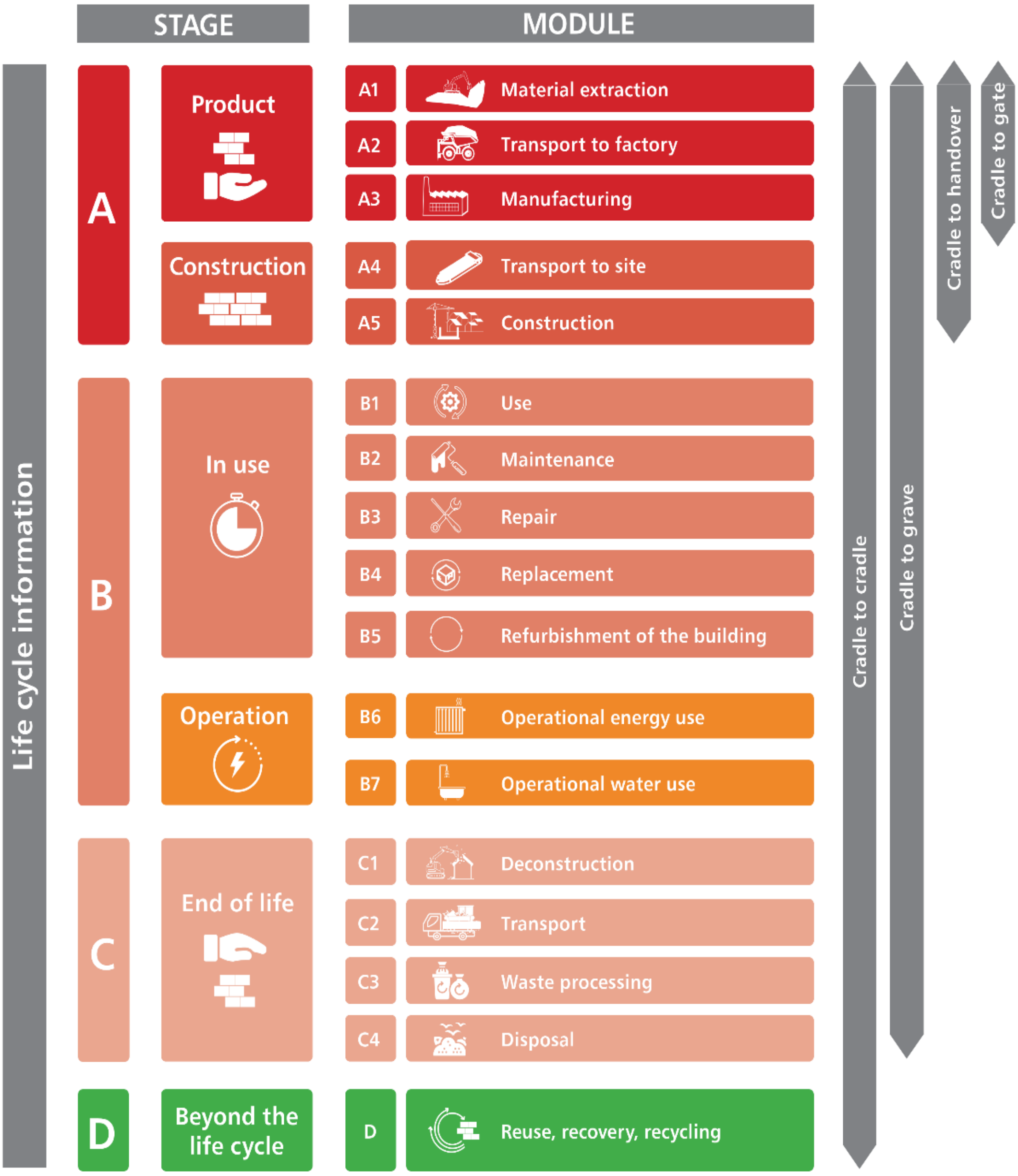

Figure 3.1 Stages of the WLC assessment

In the study stages of the WLC as defined above is followed to describe the operational and embodied carbon definitions.

3.1 Operational Energy and Carbon

The operational energy is the end-use energy consumption during the operation of a building. This includes the regulated and unregulated usage such as heating, cooling, hot water, ventilation, lighting, electrical equipments and vertical transportation in the building systems during the operation. The operational carbon refers to the emissions associated with these energy consumptions.

The definations and calculation methodologies for the operational energy and carbon are outlined in international standards and guidelines. Eventhough these standards and guidelines are mostly focused on the local aspects, the intention will the commonly recongnized standards and guidelines that has been used to define the methodology in this study is given below.

ASHRAE Standard 90.1: The standard establishes the minimum energy efficiency requirements for buildings expect low-rise residential buildings. The standard provides requirements for building envelope, HVAC, domestic hot water, power, lightinh and other equipments. It also specifies performance approach for energy comparison [41]

ASHRAE Standard 189.1: The standard provides a standard for the design of high-performance green buildings: except low-rise residential buildings. It stipulates a comprehensive requirement for high-performance green buildings, including energy efficiency, site sustainability, water efficiency, and indoor environmental quality. [42]

ASHRAE Standard 140: The standard provides method for testing of the evaluation in building energy analysis computer programs a framework. Softwares are tested using this framework. [43]

ISO 50001: The standard provides a framework for organizations to establish, implement, maintain, and improve an energy management system. It supports the organizations reduce energy consumption and associated operational carbon emissions. [44]

CIBSE AM 11: The manual provides a methodology for building performance modelling. It focuses on building simulation issues such as quality assurance procedures, compliance with UK and some international building energy efficiency codes, thermal environment and energy, ventilation, lighting and plant modelling. [45]

CIBSE TM54: The techcnical memoranda provides guidance on evaluating the operational energy performance of buildings. It covers methodologies for perfromace modelling, metering, monitoring and improving energy efficiency. [46]

Building Regulations Part L: Part L of the Building Regulations in England sets the minimum energy efficiency requirements for new and existing buildings. It covers areas such as insulation, heating systems, hot water systems, and lighting. [47]

The Energy Savings Opportunity Scheme (ESOS): ESOS is a mandatory energy assessment scheme for large organizations in the UK. It requires eligible businesses to carry out energy audits and identify energy-saving opportunities across their operations. [48]

BEIS Energy Modelling: Department for Business, Energy and Industrial Strategy (BEIS) Energy modelling explains the standards and guidelines given above highlights the significant impact of operational energy and carbon role to meet the climate change targets. To meet the climate change targets it's necessary to target significant reductions on the operational energy consumption in both exsiting and new buildings. Decarbonisation of the grid and electrification became equally important along the operational energy reduction measures to meet the climate change targets. [49]

3.1.1 Impact Of HVAC Systems On Operational Energy And Carbon For Office Buildings

For operational energy consumption in commercial office buildings, HVAC systems are one of the largest systems that use energy. Therefore, the operational energy impact of HVAC systems can have a significant impact on OPEX and carbon emissions. UKGBC in their net zero operational carbon roadmap [50] defines the requirements for the new and existing commercial office buildings. Low energy usage, measurement and verification and low carbon energy supply are 3 key requirements for a zero-low energy commercial office building. Total EUI of 70 kWh/m2/yr(NLA) for UK commercial office buildings, reporting and verifcation of annual energy use and on-site energy generation at system level, and systems such as heationg and hot water generation that not using fossil fuel will help the projection to achieve the climate goals. It is important to design and operate the systems in an energy-efficient manner to reduce the operational energy impact of HVAC systems. This can include using energy-efficient and proper equipment and plants. Also, appropriate controls are important to reduce operational energy and related carbon and cost in buildings.

Both American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) 90.1 and Chartered Institution of Building Services Engineers (CIBSE) TM54 define the methodologies to calculate the operational energy related to systems given above. The energy consumptions are calculated with validated softwares follow the thermal building performance simulation methods.

In the study, the carbon dioxide and equivalent global warming potential (GWP) of other gases referring to the greenhouse gases emitted by a building during its operation is calculated using these building performance simulation softwares. These gases are typically associated with the energy used for heating, hot water, cooling, ventilation, lighting and equipment.

In this particular study, operational carbon refers specifically to the carbon emissions that result from generating heating and cooling energy.

3.1.2 HVAC Systems For Office Buildings

HVAC systems use some source of fuel conversion to generate cooling and heating energy to satisfy the thermal comfort and indoor air quality for occupants in office buildings. Combustion solutions such as burning natural gas, oil and coal has been the most common solutions for heating while the cooling is mostly dependant to cooling cycles for cooling energy. [51], [52], [53], [54]

The generated energy distrubuted with pipes and ducts to rooms through air terminals. The energy generation and distrubition systems vary on the functional and thermal comfort requirements of the building types.

HVAC systems can be grouped as air-side systems, water-side systems and plants.

- Air-side systems: Air systems refer to the sytem and components that distribute the generated heating and cooling energy using air to the rooms and zones to maintain the indoor thermal comfort conditions. The mian components of the air systesm are Air handling units (AHUs), terminal units, fans, ductwork, suppy and return diffusers, variable and cosntant air boxes, filters and mixing units.
- Water-side systems: Water-side systems refer to the sytem and components that distribute the generated heating and cooling energy using water to the rooms and zones to maintain the indoor thermal comfort conditions. Water-side systems uses coils and room emiiters to trasfer the heat into rooms.

Plants are a sub-category of the water-side systems but explianed individually. Circulation pumps, heating and cooling coils, thermal energy stograge tanks, pipework, pressurazation units and explantion vessels are the main components of the water-side systems.

- Plants: Plants as a subcategory of the water-side systems have a very crucial role related to energy consumption carbon emissions in buildings. Plants generates the requird heationg and cooling energy to maintain the maintain the indoor thermal comfort conditions. Chillers, cooling towers, boilers, Air source heat pumps, water source heat pumps, ground source heat pumps ad VRFs are the main components of the water-side systems. Boilers utilizes combustion and transfer heat to water, which could then be used for space heating and domestic hot water purposes. Boilers can use the NG, oil or coal as source of fossil fuel or direct electric to produce heat energy. Efficiency of Ca boiler plant relies on the ability for the system operation times to be maximized and for the full load to be utilized. Air Source Heat Pump (ASHP) system works on the basis of transferring heat from outside air to a heat exchanger which would ultimately deliver heating to indoor spaces, or to DHW systems. This type of system can provide space heating or cooling through a refrigeration loop which operates under the principles of vapour compression. Similar to GSHP, ASHP works best at low temperatures between 35 and 50°C, above which efficiencies drop.

3.2 Embodied Energy and Carbon

In this study, a high-level perspective of embodied carbon reporting, as well as a perspective of the embodied carbon hierarchy associated with each system option is provided for the optimization purpose.

A comprehensive approach is necessary to accurately assess the carbon footprint of a development, including both embodied carbon emissions, which are emissions produced during the construction process, and operational carbon emissions, including both regulated and unregulated emissions, which are emissions produced during the ongoing use of the development.

Calculations of embodied carbon and whole-life carbon assessments are tools used to determine the carbon impact of a building and its carbon footprint. These assessments can be used to evaluate the feasibility of reusing existing buildings and to identify any offsetting requirements that may be necessary.

Design choices can significantly influence embodied carbon. For instance, streamlining and optimizing the structure can reduce embodied carbon from carbon-intensive structural components. Using more insulation and triple glazing may lead to operational energy savings, but it may also increase embodied carbon due to the increased amount of material used or the longer distances that products must be transported if they are not readily available locally. There can also be significant variations in similar products and solutions, with some offering significant embodied carbon savings through the specification and procurement process.

3.2.1 Impact Of HVAC Systems On Embodied Energy And Carbon For Office Buildings

Mechanical, Electrical, Public Health (MEP) systems embodied carbon impact is significant due to the equipment replacement rates during the lifetime of the building.

The embodied carbon impact of HVAC systems can be related to a variety of sources, including the materials used in construction, the energy used to operate the systems, and the refrigerants used in the systems.

HVAC systems that use refrigerants with a high global warming potential (GWP), such as hydrofluorocarbons (HFCs), can also contribute significantly to embodied carbon emissions. On the other hand, refrigerants with a lower GWP, such as hydro-fluoro olefins (HFOs) or natural refrigerants (e.g. ammonia, CO2), can have a lower embodied carbon impact Reducing the embodied carbon impact of HVAC systems in buildings is an important consideration for those looking to minimize the carbon footprint of their construction and operations.[54]

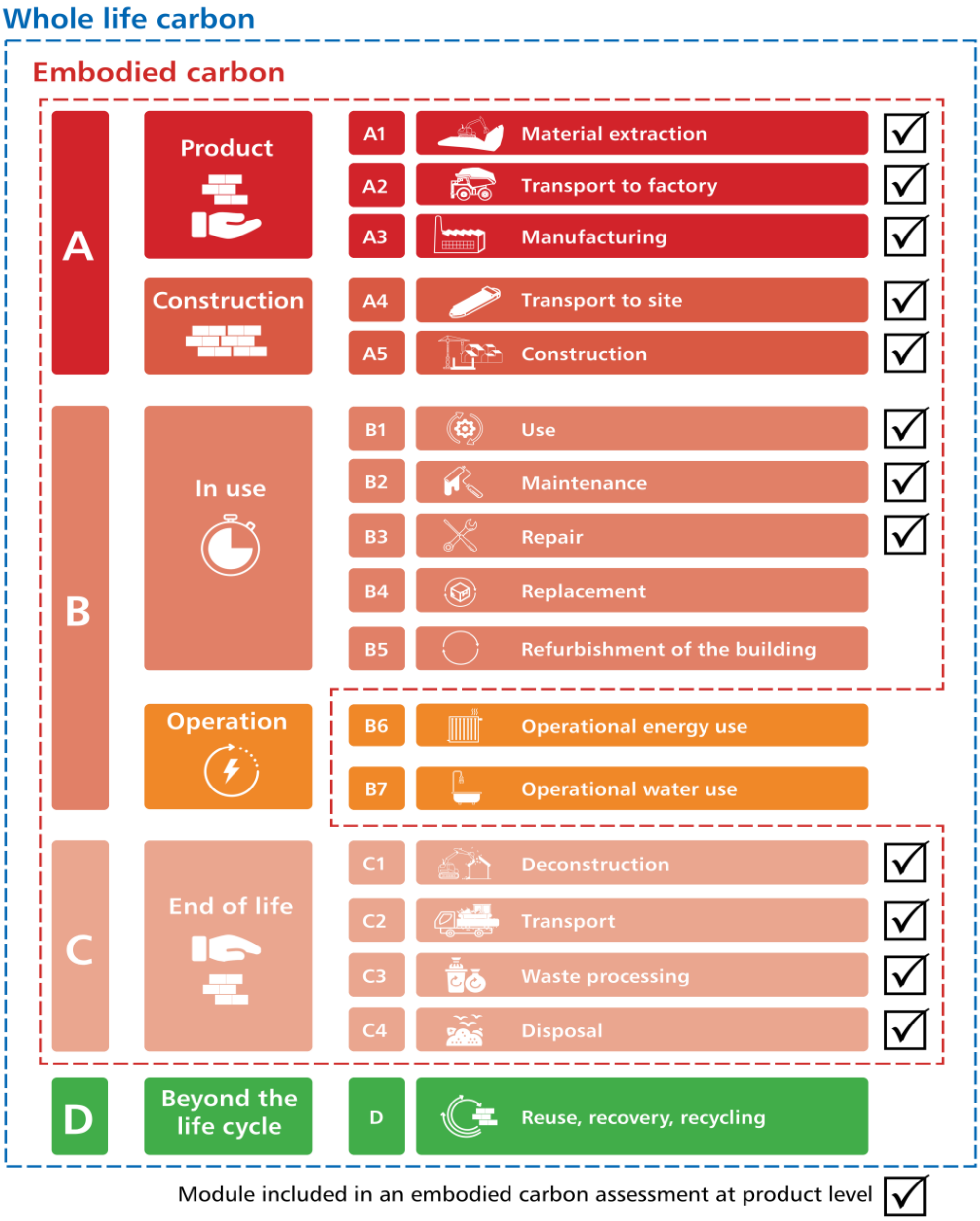

Figure 3.2 Stages of the embodied carbon assessment

3.2.2 Embodied carbon calculation for HVAC Systems

Embodied carbon analysis is considered a part of the whole life cycle (WLC) assessment. The life cycle stages and modules of WLC in building services are defined in BS EN 15978:2011 standard, the European Environmental Bureau (EeB) Guide (Wittstock, et al., 2011) Whole life carbon assessment for the built environment (RICS, 2017) [16].

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. [55]

Environmental Product Declaration (EPDs) is the common way to propound the embodied carbon impact of materials and products in buildings. However, at the time this study was presented, the number of products and manufacturers for these products could offer EPDs.

In 2021 CIBSE publish the TM65 Embodied carbon in building services: a calculation methodology for embodied carbon assessment of mechanical, electrical and public health (MEP) systems. It's a product-based calculation methodology. For this very reason, the TM65 methodology is recommended to be used to calculate the MEP embodied carbon impact for a product unless EPD is available.

In the study embodied carbon calculations consider the individual systems and equipment GHG emissions related to A1-A3(product), A4-A5(construction), B1-B3(in use) and C1-C4(end of life) modules. B4 and B5 modules are excluded as the study is focused on product level rather than the building level. [39]

A1-A3 is the 'product' stage, representing material and product emissions from cradle to factory gate. The level of detail for the building services systems is reflective of the design. Although the majority of equipment is detailed at the study, large-scale items such as pipework and ductwork are excluded in the study.

Module A4 captures the transport emissions of the products and materials from the factory gate to the project site. The carbon emissions associated with this process are calculated as the material mass x transport distance x carbon conversion factor. The transport distance is subject to the supply chain route of each item.

Module A5 covers all on or off-site construction activities, including any energy consumption for the site accommodation, plant use and the impacts associated with any waste generated through the construction process, including treatment and disposal.

The in-use Module B1 accounts for the emissions arising during the life of a building from its components. In this case, the major focus is on the impact of refrigerants, which can have a disproportionately large impact on the overall WLC impact if not managed effectively.

Module B4 covers the replacement emissions associated with key materials over the development's modelled 60-year life cycle and is a mandatory module for inclusion in a WLC assessment.

The emissions associated with operational energy consumption are covered by Module B6.

Module B7 covers the carbon emissions associated with water consumption and use during the development's operational life cycle. This covers the emissions associated with both water supply and wastewater treatment, excluding water use during maintenance, repair and replacement that are reported elsewhere. Any emissions associated with energy expended from water-related systems are captured under Module B6 outputs.

Modules C1-C4 cover the end of life (EoL) emissions. The EoL stage commences when the built asset has reached the end of its life and will no longer be used.

3.3 Expenditure

CAPEX and OPEX associated with the HVAC systems and equipment are evaluated as a part of the study. Methodology followed a simplified cost model to estimate the cost impact of the solutions. First, the unit costs for the construction of the components and operational costs based on the fuel type of the different HVAC systems are calculated in order to determine the investment cost and life cycle cost.

These are interpreted through economic and environmental performance indicators, and a performance ranking is proposed for optimal selection. All costs are calculated in UK Sterling (£). Similar to the operational energy and embodied carbon, cost is only related to the analyised HVAC systems and equipments.

3.3.1 CAPEX

The CAPEX for the proposed solutions is generated using the cost rates provided by a local cost consultant using the 2022 figures for HVAC products. These figures are indicative and can vary based on the project location and different manufacturers.

The CAPEX of HVAC systems, as it is calculated in product base, vary depends on different factors, including the size factor calculated based on the heating and cooling demand, the complexity of the HVAC system, manufacturer, and the location. Generally, the CAPEX for HVAC systems includes the cost of products, equipment, installation and labor costs.

For the CAPEX of HVAC systems, it is crucial to ensure that systems have good long-term system efficiency, resilient and provide the required occupant comfort. Additionally, incorporating energy-efficient technologies and sustainable practices can help mitigate operational costs and provide long-term benefits.

The purchase, installation and maintenance fees are included in the equipment CAPEX library in this study. The CAPEX table is presented in Appendix G.

3.3.2 OPEX

The OPEX is the running cost that associated with the systems or buildings. In other words it is the operating expenses required for energy consumption.

The OPEX definition in the study is limited to the operational fee of the individual solutions only. Each iteration based on the given energy type is calculated annually using UK government's "Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal". This is calculated for the indicated lifespan of the products. [56]

The running costs per the fuel type to generate the OPEX library are presented in Appendix F.

4
METHODOLOGY

4.1 Introduction to Methodology

In this section, the functions of the conceptional methods, that is described in the previous chapter, and the integration of these into the computational methodology of this study are discussed. The developed modelling concept for this study is named as Equation-Based Modelling (EBM) as it's articulated by integrating the operational energy, embodied carbon and CAPEX modelling concepts described in section 3. The approach is a combination of steps which is substantially an optimization calculation method to optimize operational energy, embodied carbon and CAPEX in office buildings. Also supports the decision-making process with suggesting HVAC system proposals for designers and developers. The methodology is applicable for both new and existing office buildings. The calculated or metered peak, hourly and annual thermal demand loads for space heating and cooling can be used for the analysis. This recommendation proposal is based on operational energy consumption, operational carbon, embodied carbon of the HVAC services, initial investment cost and operational cost related to these services.

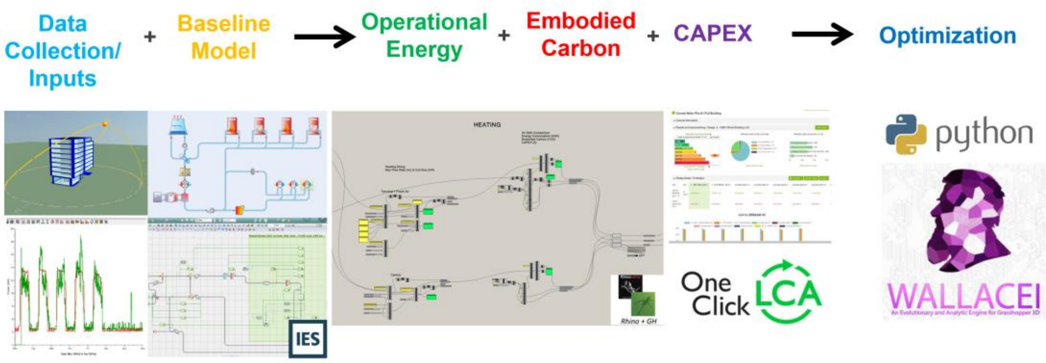

Figure 4. 1 Methodology workflow and associated software

In figure 4.1, methodology workflow and associated software are demonstrated. The detail of the workflow is clarified in the next sub-section of the methodology.

- A baseline model is generated using the system inputs required for a whole building energy simulation. Understanding the existing asset and associated carbon emission on building is an important factor at this step. Data collection, parameter definitions and assumptions, to generate the baseline model, are explained later in the section. IES VE software is used to create the baseline model and generate the thermal demand loads for heating and cooling. The baseline model is calibrated with the existing metering data of the building to increase the accuracy of the calculated loads. These calculated loads as the baseline model outputs lead to the next step that uses the outputs from this first stage.

- In the next step, the first stage outputs are introduced to the parametric mathematical model developed for this study. The EBM is used to calculate operational energy, operational carbon, embodied carbon of the HVAC systems and initial investment cost and operational cost for different to HVAC system selection and intervention scenarios. The bespoke mathematical model is developed using the Grasshopper plug-in in Rhinoceros software. The airside and water side components related to energy consumptions are calculated individually in the model using the iterative parametric input capability. The embodied carbon and CAPEX libraries are developed for each component subjected to the study. The model for each component, calculates the embodied carbon and CAPEX of each system combination through a data mapping process. The connection allows a linked, iterative system selections. For each iteration the model calculates the operational energy, operational carbon, OPEX, CAPEX and embodied carbon for the selected HVAC systems.

- Operational energy, embodied carbon and CAPEX are the objectives to minimize. These are contravening objectives and given the number of combinations, it's hard to interpret manually. Hence the model is connected to an optimization algorithm to generate the optimal set of solutions as the final outcomes of the study. The process is enabled using the Wallecei engine that employs NSGA-ii as the primary evolutionary algorithm to run optimization and clustering and python scripting language to visualize the various results. The optimization allows running a strategic decision-making process using the data to select the preferred collection of measures based on, CAPEX, energy, and carbon savings.

- The objective functions in the optimization that are connected to the model are limited with operational energy consumption, embodied carbon and CAPEX. The NSGA-ii algorithm optimize these objective functions and generates the pareto front optimized solutions cluster. This is given in the figure 4.2 as equation-based modelling optimization system flow chart.

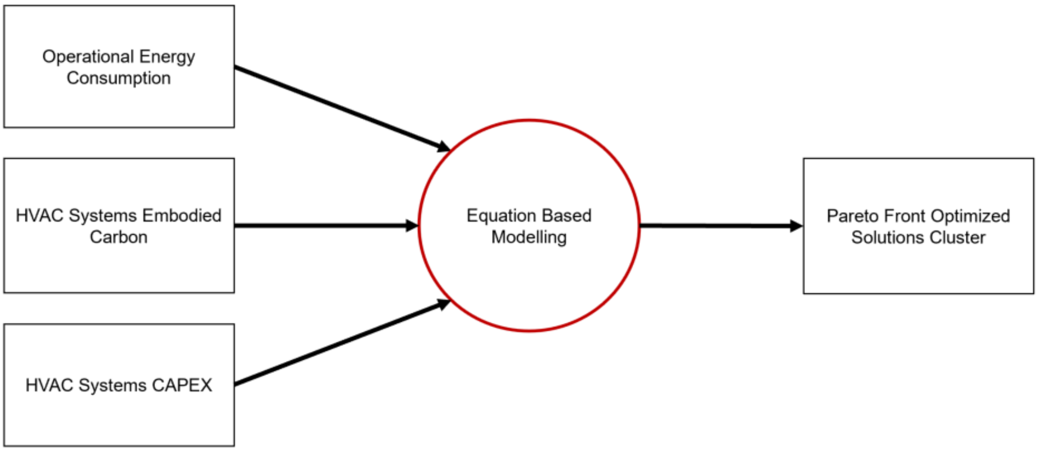

Figure 4. 2 Equation based modelling optimization system flow chart

4.2 Reason To Develop Bespoke Methodology: EBM

In the section 4.2 firstly the reasoning behind developing a bespoke methodology explained. Then in section 4.3 the step of the methodology is described. The Building Energy Modelling (BEM) is a methodology that can be used to calculate the operational energy performance of new buildings in design and existing buildings in retrofit.[57] BEM is a physics-based modelling approach that allows to define inputs related to building models and systems such as geometry, materials, lighting, HVAC, domestic hot water, system variables and control strategies. Then it calculates the energy performance and carbon emissions for one or more of these variables. The software capable of BEM, calculate the building energy consumption on an hourly basis or longer intervals using the parameters such as building geometry, construction materials, HVAC systems, occupancy and usage patterns, lighting systems, fenestration, climate data, internal loads, control strategies and thermal comfort criteria.

One of the areas that BEM used is HVAC energy performance modelling. The HVAC modelling includes.

- HVAC System Type and Configuration
- Equipment Efficiency
- System Controls and Setpoints
- Equipment Sizing
- Ductwork and Air Distribution
- Ventilation Rates
- Thermal Zones and Zoning Controls
- Occupancy and Usage Patterns
- Weather Data

The calculation of different HVAC system options can be complex study in commercial buildings due to the elaborate structure of the HVAC systems and components. BEM can assist the engineering design in the decision-making progress to achieve the most efficient response to thermal demand loads of HVAC systems. Based on this, the calculation of thermal loads and the capacity of the systems to meet those loads and accordingly the energy consumption are revealed.

Even these traditional BEM tools are useful calculating the thermal loads and system capacities (which is also used on this purpose in this study), there are some common limitations when calculating the HVAC systems energy performance. Some of these limitations can be listed as.

- Simplified HVAC System Representation
- Inability to Model Advanced HVAC Technologies
- Limited Control Strategies
- Lack of Integration with Detailed Building Simulation
- Limited Flexibility for Parametric Analysis

In this area, there are studies focused on HVAC modelling using comprehensive tools. These tools enable the model of bespoke systems due to their thorough modelling and control capabilities. The tools enable to calculate the demand hourly consumptions and also the sizing and hydronics of the air and water systems.

It is commonly seen in literature review studies focus on the HVAC system performance modelling or optimization, authors use more comprehensive tools with HVAC focus or develop their mathematical models to solve these problems. As given in the literature review, Wanqi X. et al [20] developed a mathematical model to optimize the HVAC systems operational energy consumption.

However, optimization and embodied carbon integration are not covered in these studies. Muzaffer A. et al [15] used an equation-based object-oriented modelling approach and the Genopt optimization tool to optimize the configuration of a chilled water system. This approach allows for the modelling of complex systems and the optimization of various parameters such as the number of chillers, cooling towers, and fan speeds.

In another study [13], the authors used the EnergyPlus simulation engine and the particle swarm optimization algorithm to examine chilled water consumption over a certain period of time. They tested the consumption of various components such as chillers, pumps, and cooling towers against a conventional operational model.

The given studies demonstrate the alternative methodologies to calculate the energy consumption and the performance of HVAC systems and that various tools and techniques can be used to overcome the limitations of traditional software. The tools and methodologies can propose bespoke solutions for detailed HVAC system representation, advanced HVAC technologies and controls. It also shows that optimization and system comparison can be done by different methods. It depends on the problem and the objective of the study. However, developing these methodologies can be time consuming, non-reproductible and non-scalable.

On the other hand, embodied carbon is another key item in the holistic WLC approach, which requires a product-based calculation for the HVAC systems. To calculate the embodied carbon of HVAC systems, it is necessary to know the approximate dimensions and capacity of the HVAC products in addition to the type of potential systems considered for the building. Embodied carbon of the products can vary based on the capacity and size of the unit. It's calculated based on these design inputs on a product basis. The total embodied carbon of the system is calculated with the sum of the products. This step can be applied to one or more recommended systems. Chendong W. et all, in their study propose an embodied carbon calculation methodology for heating and cooling systems in China. They have testes combinations to understand the embodied carbon impact of individual HVAC technologies. [8]

Similar to embodied carbon calculations, also CAPEX is evaluated on a product basis, and the product unit cost of the systems to be compared is calculated. Following this, the CAPEX for the proposed systems can be compared. Jinkyun C et al, in their study propose a methodology to conduct the operational energy and CAPEX analysis of HVAC systems in office buildings. The researchers aim to develop a multiple prediction methodology for estimating the cost of HVAC systems, considering various factors that influence both energy consumption and cost.[58]

4.3 Stages of the Methdology

The developed methodology follows the alternative solution pathway and is giving a clear and concise answers through the objective functions, operational energy, embodied carbon and CAPEX. The alternative pathway in the study is focused to existing office buildings due to the HVAC system type and configuration, however it's a reproductible and scalable model.

The method is developed in a staged form. The first stage analysis focus to the hourly heating and cooling demands. The heating and cooling loads are calculated using a BEM tool supported by metering data calibrations, systems responding to demand. This allows different building systems and system variables that meet the varying demands of the buildings to be analyzed accurately.

In the second stage analysis, the impact of the system variables is calculated using the parametric mathematical equations. Establishing the method with mathematical equations also provides flexibility in adding and removing different variables to the HVAC system. This method also allows access to the pre-calculated embodied carbon and CAPEX for each variable system with the component libraries created. By this, the mathematical model calculates the operational energy, embodied carbon and CAPEX of each HVAC system combinations.

The impact of these the objective functions is analyzed by the NSGA-II optimization integrated into the methodology. The Pareto-front curves formed as a result of the optimization and provide a set of results where optimal solutions are presented. These results provides resilience and flexibility for the designers and developers in their decision-making process. In this methodology chapter of the study, these two staged calculations are explained individually. The system flow chart of the methodology is demonstrated in figure 4.3 below.

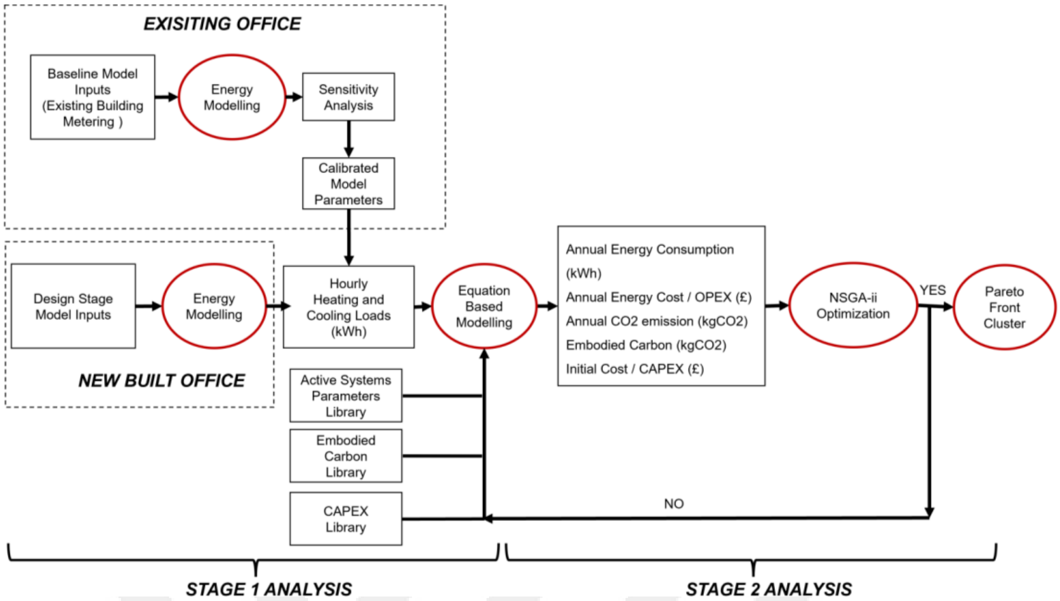

Figure 4. 3 System flow chart

In the study, the methodology is divided into two as visualized in the flow chart presented. The first stage analysis is defined as the calculation of the hourly loads required for the EBM and development of the system, embodied carbon and initial investment cost libraries for the anticipated systems. In the second stage, these aggregated inputs are used in the parametric mathematical model of EBM and analyzed with the optimization method.

4.3.1 Stage 1 Analysis

The Stage 1 analysis is developed to understand the designed/ existing assets and associated demand, operational energy consumption and operational carbon emission on building level. A baseline model and systems associated to the building is generated to calculate the inputs to be used for the second stage in the parametric script. In this stage, the peak heating and cooling loads to use for system and component sizing, embodied carbon and CAPEX libraries; the hourly heating and cooling loads are calculated; and the HVAC system-component, embodied carbon and CAPEX libraries are generated. All these outputs are used as inputs in the stage 2 analysis. In the figure 4.4 the flow chart for stage 1 analysis is demonstrated.

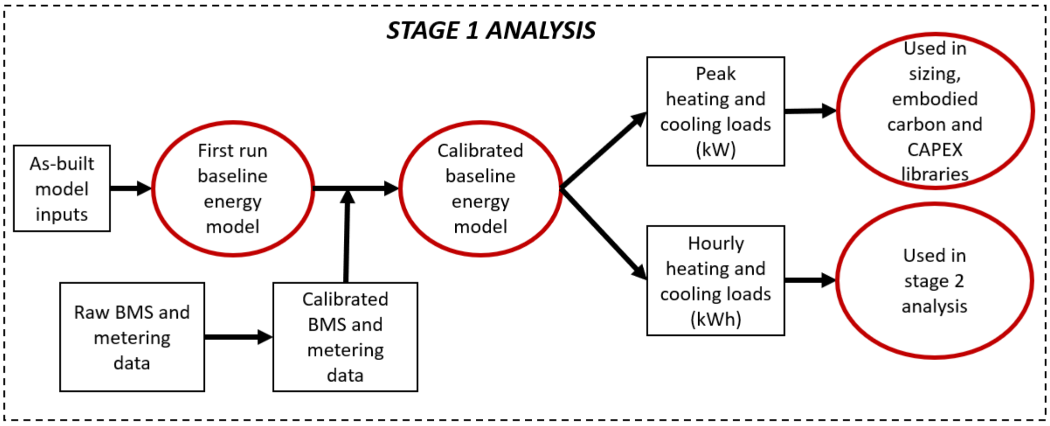

Figure 4. 4 Stage 1 analysis flow chart

The stage 1analysis is grouped under 2 main categories. The first category is the baseline model generation. Input information from actual building related data is collected to generate baseline energy model. Raw Building Management System (BMS) and metering data then regularized to calibrate the baseline energy model. The outputs, peak heating and cooling demand are used in sizing, embodied carbon and CAPEX library generation are used to generate the building energy model accurately. The outputs, hourly heating and cooling loads are used in the stage 2 analysis as inputs. The definition of these outputs is important as they are used to carry out the hourly heating and cooling load demands in subsequent simulations.

The first category inputs follow the consecutive steps to simulate the hourly loads analysis, HVAC plant and system analysis. The simulation results are post-processed following calibration steps with an aim to increase the accuracy of the results. Utility bills, BMS and sensor data and on-site measurements are the inputs used for this calibration step. Even though calibration step is optional, it is incorporated into the study to reduce the performance gap representing the actual energy use with the simulation data.

The second category of the stage 1 analysis is the generation of libraries, in which HVAC systems type and configurations, the embodied carbon and CAPEX information of these systems are defined. In this second step, the embodied carbon and CAPEX libraries in connection with the HVAC systems type and configurations are generated using the peak heating and cooling loads extracted from the calibrated baseline model calculations.

- **Data colection**

Data collection is an important part of building energy modelling. The precision of the data availability, reliability and accuracy affects the model representation against the actual operational energy consumption of the building. More accurate data allows to close the performance gap in between modelling results and actual building operation. [59]

Data collection step in new buildings, can be unclear due to the limited information availability and uncertainties through the design stages. Sensitivity analysis performed on assumptions to test different weather files, user profiles, efficiencies and control scenarios can help to improve the accuracy of the models in early design stages. The building energy models can only reflect the results of the information available at the time being. Adding more data at each stage or increase the accuracy of those data can evaluate the hourly demand loads of each stage. This method allows complex optimizations such as system determination at the concept stage in new buildings, and the decision-making of water and air temperatures, control types, and the number of HVAC plants and equipment in the detailed design stage.

Beside such limitations of new buildings energy modelling, in existing buildings, the accessibility and availability of the modelling input data enables more accuracy in modelling. However, data collection availability is not the only indicator. The metering information and the BMS readings of sub-energy systems, temperature and air flows from the actual building operation is equally important for an accurate model.

When the as-built information is applicable, the performance data then can be calibrated with energy consumption and sensitivity analysis using the hourly meter data to be obtained from the building. Available modelling input data when evaluated together with metering information allows to create more accurate models.

The inputs as design and construction documentation, sensor data, utility bills and BMS data are the fundamental data required for a calibrated energy model of an existing building. This can further be calibrated using occupant surveys and on-site measurements to optimize the energy performance upon the requirement.

In the study the design and construction documentation of the as-built design to generate the energy model and metering data to calibrate it further are considered in data collection.

- **Baseline building energy modelling**

For the stage 1 analysis of the study, baseline building energy model is created using dynamic simulation modelling approach. The building energy modelling has been carried out using Integrated Environmental Solutions Virtual Environment (IES-VE) software which is an approved DSM software by the DCLG (Department for Communities and Local Government), which meets all the requirements in an advanced HVAC system and controls capabilities listed in the CIBSE AM 11 [45]Building Performance Modelling and ASHRAE 140 standard [43] which procedures for evaluating and comparing the energy performance of building energy simulation programs. It provides guidelines for conducting energy simulations and analyzing the results to assess the energy efficiency of buildings.

The IES-VE (Integrated Environmental Solutions Virtual Environment) is a building performance simulation software suite that allows users to model, analyze, and optimize the energy performance and sustainability of buildings. It provides tools for energy, thermal, daylight, and airflow analysis, enabling architects, engineers, and energy consultants to evaluate different design options, identify energy-saving measures. [60]

In the dynamic simulation inputs such as location, orientation, architectural plans, building envelope, system usage profiles, HVAC and lighting system elements, efficiencies and their control methods are used to generate the model. These inputs are modelled and simulated with the tool to assess the building heating and cooling loads. The accuracy of the loads is highly dependent on the accuracy of these inputs. IES-VE modelling is used to calculate the hourly and annual demand and consumptions of the building.

Additionally, a spreadsheet based external calculator, highly integrated with the selected DSM software, has been used to support the calculation. The overall modelling process for the dynamic simulation is given in figure 4.5.

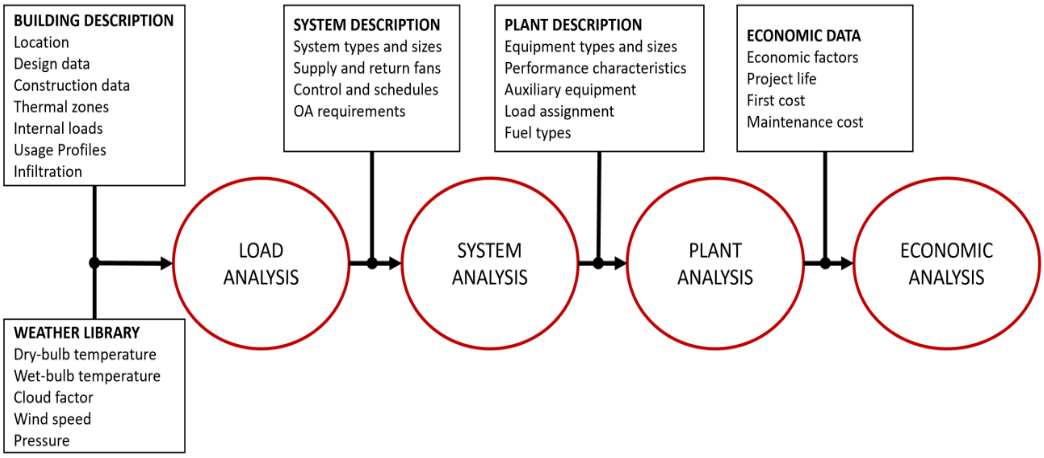

Figure 4. 5 Baseline building energy modelling flow chart [52]

For the baseline modelling, CIBSE TM54 methodology is followed which is described in section 3 for the evaluation of building energy uses. The summary of the required actions at each step s of TM54 methodology is further described with the associated inputs that has used to generate the baseline model. In figure 4.6 steps of TM54 methodology is demonstrated as per the guideline. Each step explains the input requirement to increase the accuracy of the model. The inputs from step 1 to step 13 are followed using the as-built design information. [46]

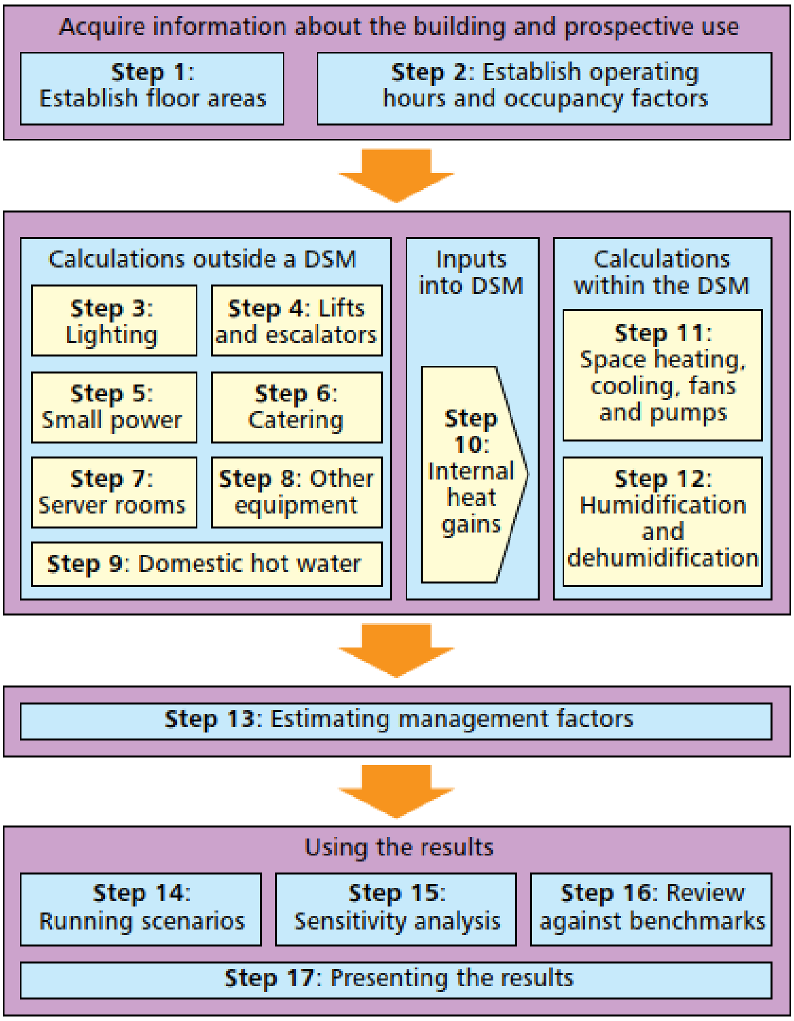

Figure 4. 6 CIBSE TM54 methodology to evaluate operational energy use at the design stage

The potential impact of weather conditions on the operational energy prediction is considered using different weather tapes in the modelling of the different scenarios:

- CIBSE 2016 Test reference Year (London_TRY2020_High50) can be used for scenarios to represent "typical" weather conditions.
- Design Summer Year (London_LHR_DSY2_2020High50) can be used for the worst-case scenario to reflect extreme weather conditions.

DSY2 summer is significantly longer and more intense than the one of the typical Test Reference Year, resulting in significantly higher cooling loads and auxiliary energy consumption for the worst-case scenario building.

Establishing solid figures for the building floor area is of essential importance when comparing the predicted building energy use to the energy benchmarks set out by UKGBC [61], BBP [62] and in CIBSE Guide F.[63]

According to Energy Consumption Guide 19 (EEBPP, 2000) and the Royal Institution of Chartered Surveyors' (RICS) Code of Measuring Practice (RICS, 2007) [40]

- Gross Internal Area (GIA): total building area measured inside external walls.
- Net Lettable Area (NLA): measurement of the total occupiable floor space taken from the inside surfaces of the exterior walls and/or the mid-line of any shared walls and excludes areas such as common stair wells, toilets, lift lobbies and vertical service ducts.

The external envelope of a building can act as an important climatic modifier, with a well-designed façade significantly reducing the building energy demand.

The intended hours of operation of the plant and systems as well as the occupancy patterns is established as far as possible as part of a structured interview process held with the project developer and facilities management coordinator to gather insights on the development operation and management.
It should be noted that the hours of operation of plant and equipment is different from the occupied hours and will vary between different energy end-uses. Therefore, both figures needed to be established. It is also worth noticing occupancy profiles need to be accurately estimated as the internal heat gains related to occupancy patterns strongly affect the building space heating and cooling demands. Energy consumption by unregulated energy uses must be calculated and included in the calculation process to provide a comprehensive figure for the operational energy consumption and to inform the internal heat gains withing the building. Tenant energy consumption is calculated based on the equipment loads predicted and outlined by the design team and discussed during the interview process and the estimated hours of use. "Sleep mode" and weekends energy consumption for common office equipment is considered as well, as outlined in the CIBSE TM54 methodology. As mentioned, internal gains from tenant equipment is included in the DSM when calculating energy use associated with heating and cooling systems.

Fresh air heating and cooling loads for the Air Handling Units (AHUs) are calculated based on hourly external and internal psychrometric conditions for the whole year, considering the efficiency of the unit heat recovery device as well.

Lighting consumption is calculated based on design Lux levels, lamp efficiencies and occupancy schedules. Consumption reductions due to daylight dimming and occupancy sensing controls is also considered as well.

Auxiliary energy demand of the AHUs is calculated based on the fresh air requirements, the occupation and systems operation patterns and the units Specific Fan Power (SFP).

Fan Coil Units (FCUs) is sized based on the peak cooling and heating loads obtained by dynamic simulation. FCUs energy is calculated based on SFP and the calculate flow rates.

Pumps energy is calculated based on the modelling of primary and secondary chilled water and LTHW loops, pumps power consumption curves (part loads have therefore been considered), and the heating and cooling demands that are calculated within the DSM software.

Extract fans energy is calculated based on the required air changes levels, occupancy and systems schedules and SFPs of the selected FCUs.

Estimates of parasitic energy consumption of the lighting controls when the lamps are not operating, and energy consumption of emergency lighting are included as part of the calculation methodology.

Lighting internal gains are included appropriately in the dynamic thermal model as well, with the inclusion of control factors for daylight dimming and occupancy sensing controls.

The design parameters assigned to the base building to establish its space heating, space cooling, domestic hot water (DHW) and auxiliary energy use is another key factor to be considered in modelling.

In the study the building energy modelling process contains inherent simplifications and limitations when compared with the way the real building would operate:

- Building envelope U-values are considered to be static, while in reality they are dynamic values, function of temperature and other climatic conditions.
- The heat flow through the ground floor slab is simplified as it's based on an assumed ground temperature.

- Weather tapes are based on historic data set and predicted future changes and will be therefore different from the conditions in any given year the building will operate.
- Actual system operation and occupancy patterns will always differ from the estimated ones up to a certain extent.
- The specific fan power (SFP) of the AHUs and FCUs used in the thermal model energy consumption estimation is based on as-built design report design for the ducting system and pressure drop of the normal operation.
- Small power loads are assigned following the as-built design report produced by the contractor and might differ from the actual equipment that is installed by the tenants.
- Server rooms electric load is estimated at 10 W/m2.
- Server rooms cooling load, security systems and external lighting energy are not included in the calculation due to lack of available data.
- Lighting energy consumption reduction due to daylight dimming control is simplified. Daylight simulation hasn't been carried out.
- The listed assumptions and simplifications are addressed by presenting the results within a range to illustrate the uncertainty of the calculations.

- **Baseline building model calibration**

The first run of baseline building energy modelling results then calibrate with the BMS and metering data acquired from the building operators. The data for provided sub-systems are analyzed. The annomalies in these data sets are very common due to various issues. The annomalies are detected during the analysis. It’s important to have a regularized and cleaned data from the BMS sytem for accurate comparison. The annomalies that have occured in metering data from the BMS system are regularized using the some manuel steps. First the monthly energy readings are converted into monthly energy consumptions. The submeters are linked to the systems. Monthly energy consumption data over time is visualized in line charts. This help to identify any anomalies or unusual patterns in the data. Anomalies are identified by looking for any data points that deviate significantly from the overall trend or appear as outliers. These points indicate anomalies in the energy consumption. The potential causes for the anomaly are determined witihin the limitation of the information . These anomalies normally can be caused by data entry errors, equipment malfunctions and external factors.

Data entry errors can be manually correct the value with the appropriate value. Equipment malfunctions can either exclude the data point from the analysis or estimate the energy consumption value based on surrounding data points or historical averages. If the anomaly is caused by external factors like extreme weather conditions or other events, it can be adjusted based on known factors or exclude the data point if it is deemed to be an outlier.

Witihin the limitations of the available information in the study, the necessary changes to the energy consumption values are applied. The incorrect or anomalous values are corrected. All the tabular data and charts are updated to visualize the corrected data, ensuring the anomalies are addressed.

Once the regularization steps are followed, the profiles and patterns are generated using this updated metering data. Then the first simulation run results are cross analysed using these profiles and patterns generated from updated metering data.

Using a one parameter at a time approach manually, with further simulations the simulated results are regularized with the metering profiles. This step allows to understand and increase the accuracy of the hourly and peak demands of the building for energy consumption and plant sizing purposes.

- **Calibrated heating and cooling hourly load analysis**

From the calibrated simulation results, the hourly loads for heating cooling are extracted. As the scope of the study is to compare HVAC systems, all remaining inputs such as, geometry, building materials, thermal comfort conditions are considered as fixed inputs in line with the existing design. The loads extracted from the building energy model for heating and cooling includes all the conditions, systems and equipment that have an impact on it. For the accuracy purpose, since the calculation of load demand of the study requires hourly detail analysis, benchmarking analysis using steady-state analysis or similar existing building stock is not considered a sufficient solution at this stage. For this reason, within the scope of this study, as detailed in this methodology section, IES-VE simulation which can perform dynamic simulation is used to extract the hourly loads.

- **HVAC systems decision drivers**

HVAC system selection is a key element for the purpose of the study due to many different criteria. The building type, size, climate, thermal comfort and indoor air quality, building regulations, energy and cost are the main decision drivers that have been involved in the decision-making progress of HVAC system selections. The HVAC systems are the combination of many components. These components are heating and cooling plants, central and terminal ventilation units, the coils inside these ventilation units, pumps, fans and duct and pipe systems that connect these components. These connected components create loops, and the loops create the systems. The necessity for components and connections varies based on the building type and function.

In the study HVAC systems and components that analyzed, are decided using the key drivers given above, the literature on previous studies, CIBSE [54], [63], [64], [65] and ASHRAE [41], [51], [52], [53] guidelines, HVAC technology trends and the UK building regulations. [47]

- **HVAC systems input data library generation**

Considering the given HVAC system decision drivers, an adaptable systems library is generated based on ASHRAE and CIBSE guidelines on office building HVAC design and some of the previous studies [66] focused on the energy-efficient HVAC systems design. Operational energy consumption is one of the key drivers in building design and it is an objective function of this study. Energy performance and efficiency measures of HVAC systems are considered during the HVAC systems data library generation process.

The HVAC systems input data library is divided into 2 systems: airside and waterside systems. Air-side systems split into 2.

In All-Air HVAC systems, conditioned air is distributed into spaces from centralized air units. The Air Handling Units (AHUs) are central units that conditions and circulates the air within the spaces in the building. Fans, heating and cooling coils, filters and heat exchanger are included components within centralized system. The conditioned air is distributed through ducts to different spaces and zones in the building. Properly sized and routed ducts ensure the efficient airflow and reduce the energy loss through distribution. Air control boxes such as constant air volume (CAV) and variable air volume (VAV) installed on supply air ducts enables the control of the airflow to zones based on temperature and occupancy requirements.

Dedicated outdoor air system (DOAS) on the other hand provide a controlled and conditioned supply of fresh outdoor air to a building while maintaining indoor air quality and occupant comfort. It focuses on ventilation, leaving the heating and cooling of the indoor space to terminal units. For offices these terminal units can be water or DX fan-coil units. Fresh outdoor air supplied by AHUs with similar principal to the centralized unit with a limited capacity to fresh air rates. Heating and cooling are delivered by terminal units. The HVAC controls are modelled that includes thermostats, occupancy sensors, CO2 sensors.

The study is only focused to fully air-conditioned HVAC solutions. Natural and mixed mode ventilation solutions are not tested within the scope of the study. Air-side system categories considered within the scope of the study is presented in the figure 4.7.

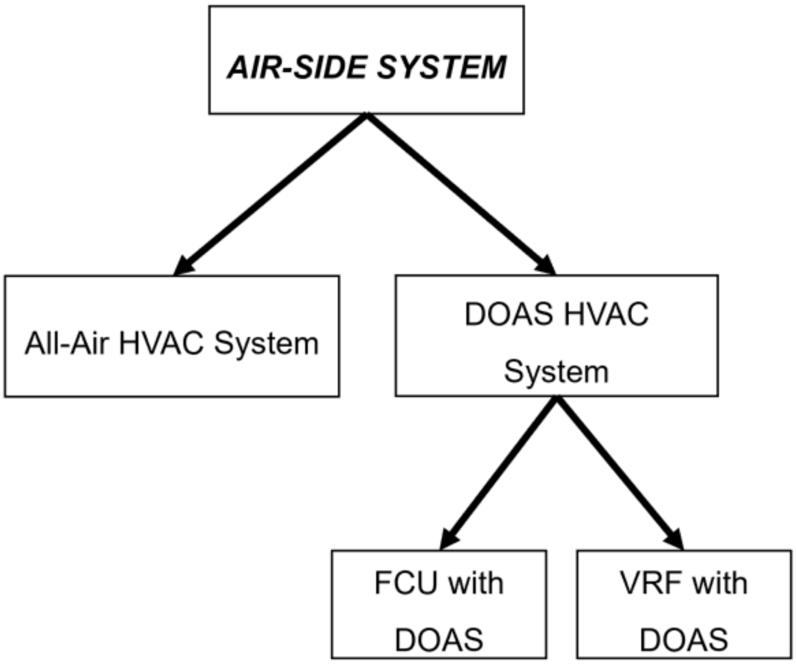

Figure 4. 7 Air-side system categories

The water-side systems in buildings utilizes water or other refrigerants for heating and cooling purposes. There are many components of the water-side systems however in the study, it's categories as heating and cooling plant as these sub-categories which contributes most to the operational energy consumption. Both in heating and cooling 4 main plant groups are considered. For heating electric boilers, natural gas boilers, Variable refrigerant flow (VRF) and Air Source Heat Pumps

(ASHP), for cooling Air Cooled Chillers (ACC), Water Cooled Chillers (WCC), VRF and ASHP are considered within the scope of this study.

The design and configuration of a waterside HVAC system can vary depending on factors such as building size, load requirements, climate, and energy efficiency goals. Decision making process of the waterside HVAC systems are made in consideration with energy efficiency, flexibility in system design for small to medium size office buildings.

The systems and the system parameters that are generated are used in both energy consumption calculations, and mapping of embodied carbon and cost.

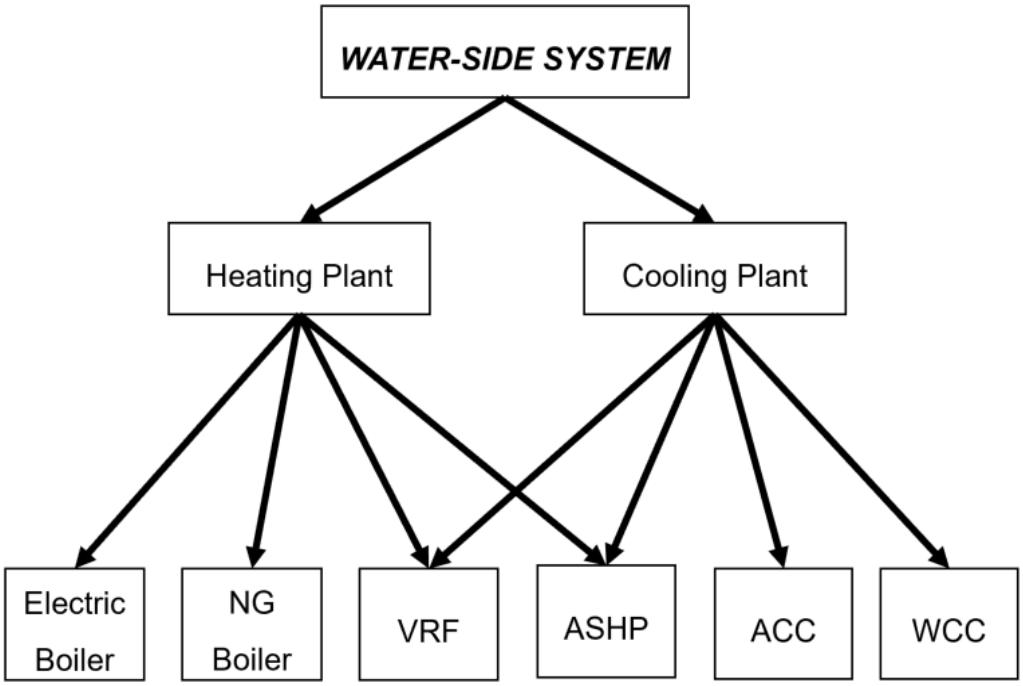

Figure 4. 8 Water-side system categories

Water-side system categories considered within the scope of the study is presented in the figure 4.8.

Details of HVAC system selections and inputs that are used to calculate energy consumptions are presented in the case study section of the study.

- **HVAC embodied carbon library**

GHG emissions that are related to embodied carbon in building systems and components are calculated using the inputs from WLC stages A1-A3, A4-A5, B1-B5 and C1-C4. [x] The definitions and the calculation methodology for embodied carbon assessment is given in section 3. Similar to building systems and components, the methodology for the HVAC systems embodied carbon calculations follows the same approach. In HVAC systems, the equipment is jointed raw components. Manufacturers mostly doesn't share the component information and breakdowns. For this reason, differently from the building systems most of the time embodied carbon requires a solution-dependent calculation based on the product. The HVAC system product information are generated using the HVAC system input library developed. Following the TM65 methodology [55] , the product information required is collected using 3 main sources. Manufacturer's product declarations, TM 65.1 guide and the One Click LCA material library. [67] All information is transferred to embodied carbon data library. The library is connected to the EBM model. It allows the EBM script to map and extract this data for each product that defines the iterative system type. It calculates the total embodied carbon related to the system and system parameters. The embodied carbon-related details of the products are given in Appendix C.

Further details of embodied carbon libraries are presented in the case study section of the study.

- **CAPEX and OPEX library**

Similar to embodied carbon, developing a cost modelling library is a product-based approach. For the CAPEX, the cost of each product is required and for the OPEX fuel type, energy usage by fuel type and the unit rates are required. The cost modelling library information is collected using the manufacturer's information and consultation with HVAC professionals and engineers. All information is transferred to the cost library. The library is connected to the EBM model. It allows the EBM script to map and extract this data for each product that defines the iterated system type. It calculates the OPEX and CAPEX related to the system and system parameters. The cost-related details of the products are given in Appendix D.

Further details of CAPEX libraries are presented in the case study section of the study.

4.3.2 Stage 2 analysis

In stage 1 analysis of the study, peak and hourly heating and cooling loads and associated office HVAC system, embodied carbon and cost libraries are generated.

Stage 2 analysis focus on the optioneering of different HVAC system types and configurations that influence the operational energy and carbon, embodied carbon and CAPEX using a mathematical model with an integrated multi-objective optimization.

In the stage 2 analysis, outcomes of the stage 1 analysis, calibrated peak and hourly heating and cooling loads, HVAC system data libraries, embodied carbon and CAPEX libraries are used to set the mathematical model. The mathematical model is developed using the Grasshopper software[68]. The libraries generated are connected to the simulation setup via the capability of the Grasshopper.

In the next section an overview to parametric modelling in Grasshopper and scripting libraries used to develop the mathematical model is introduced briefly.

- **Parametric modelling with Grasshopper**

For the second stage of the study, an itteration based parametric mathematical model is developed. The components of the model are set of calculations which are linked to calculate the operational energy, embodied carbon and cost of the given combination. These components are explained in detail under "Mathematical modelling – EBM concept" section.

Grasshopper tool is used to develop the parametric model. Grasshopper is a visual programming plug-in for Rhinoceros to perform algorithmic modelling. It's a virtual programming language and allows the modelling of complex mathematical models. Parametric modelling using Grasshopper is a process of designing and analyzing complex systems and structures using visual programming. It allows users to create and manipulate complex geometries and perform simulations and analyses using a set of parametric inputs. [68]

Grasshopper through components allows to create programs and these programs can contain algorithms scuh a numeric, text and other applications. In the figure 4.9 a representation of the script that calculates the peak load from the hourly load results using sorting, recersing and itemization functions is visualized.

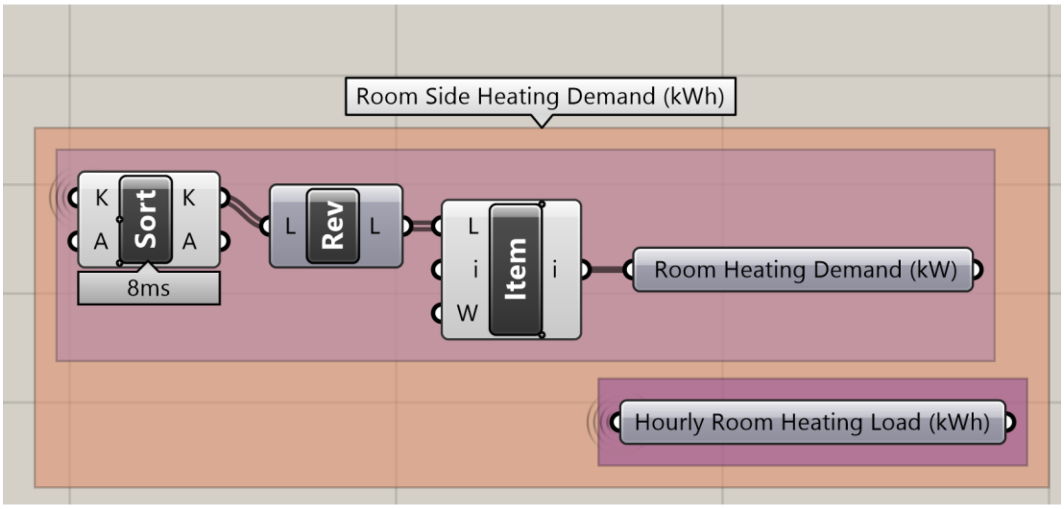

Figure 4. 9 Grasshopper component connection

In parametric modelling, the design of the system or structure is defined by a set of parameters that can be adjusted to explore different design options and optimize the design for specific performance criteria. Using rule-based modelling allows design optimization and makes the decision-making process easier. Grasshopper supports the scripting language Python and C#. This helps users to develop add-ons, functional tools and libraries within the Grasshopper.

There are many third party add-ons have been developed and released for Grashopper in the recent years. In the study third party libraries competible in Grasshopper is used to connect exteranal databases for embodied carbon and cost, data management, time series analysis and optimization is used. The list of libaries are used within the study are listed below.

Bumblebee is used to allow inpteroperabilty in between Grashopper and Microsoft Excel, for acceses to data libaries. The bumblebee library allows to transfer data sets, create charts and data sets. [69]

LunchBox is a comprehesnive libary focused on data in many aspects. It allows data management in different formats, generative geometry and mathematical modelling and machine learning implementations. [70]

Wallacei libary is used for the optimization. Wallacei platform and Wallecei engine is used to perform optimization study. Wallecie is an evolutionary engine and runs in Grasshopper 3D environment. It's based on a doctoral study on design focused utilization of the evolutionary computation as a problem-solving tool. [71]

Wallacei is a tool that helps users run and analyze evolutionary simulations in Grasshopper 3D. It includes features to help users understand and make decisions about their simulations, such as setting up the design problem, analyzing results, and selecting the best solutions. Wallacei also allows users to select, rebuild, and output any phenotype from the population after the simulation is completed. Wallacei X uses the NSGA-2 algorithm and the K-means method for clustering. Further details for the optimization alghorithm is given under section multi-objective optimization section of the methodology. [71]

- **Mathematical modelling – EBM concept**

In this section the mathematical model developed using Grasshopper to perform the Stage 2 analysis is explained in layers. The connection with Stage 1 analysis is defined. The inputs and limitations of this stage is discussed. Then the high-level stage 2 structure with HVAC subsections is explained. Information on the subcategories of the HVAC systems and limitations are reviewed. Further information on the connection in between these subcategories are detailed. Finally, the components and the variable including the intervention ranges are justified.

For the mathematical modelling, a bespoke calculation algorithm is developed based on thermodynamic principles that are been used in HVAC system equations [72]. The calculation steps is divided into 3 subcategories as air-side systems, waterside systems, and plants. For each subcategory, the calculation algorithm follows the EnergyPlus methodology which is a combination of algebraic energy and mass balance equations with steady-state component methods. [73]. Each individual component of these sub-categories, based on their system definition energy, carbon and cost is calculated.

The mathematical model developed for the study focuses on the HVAC system and plant analysis. The thermal comfort conditions set in the baseline energy model is extracted from the heating and cooling load analysis. This pre calculated (in stage 1) load analysis hourly heating and cooling demand loads for the simulation year contains the information about building description and weather library as defined in the stage 1 modelling flow chart in figure 4.10. As is demonstrated in the figure, stage 2 mathematical model uses the inputs from the building energy modelling load results.

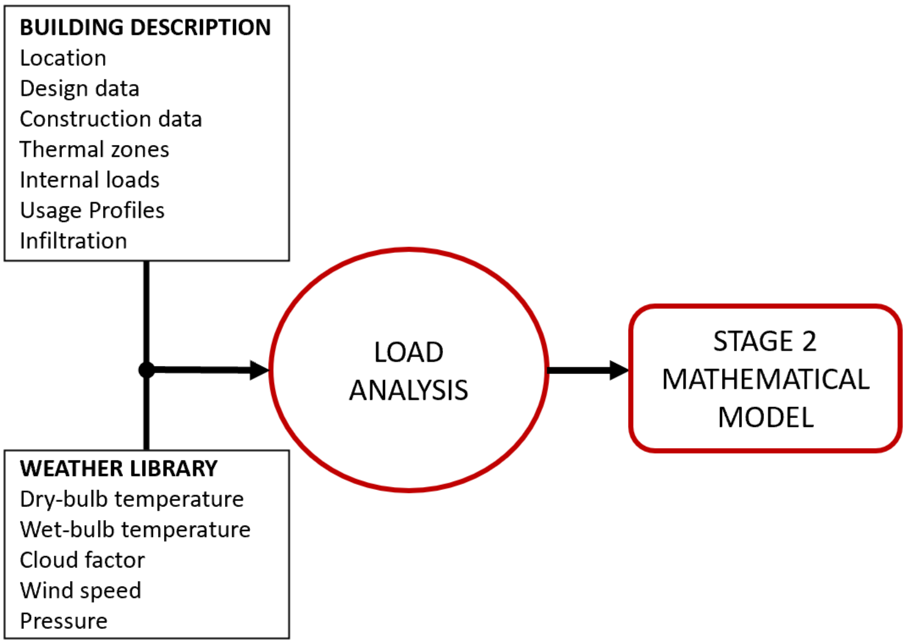

Figure 4. 10 Stage 1 load analysis outputs

Eliminating the load analysis in the further iterations allow to reduce simulations runtimes significantly and a focus on the HVAC system parameters only. However, the model is not capable to capture the changes to be made on whether file, fabric, user profiles, infiltration and lighting.

EBM inputs from load analysis are calculated using a 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 room temperature set points. The load analysis are used in this mathematical model for system and plant calculations as given in the stage 2 modelling flow chart in figure 4.11. System and plant descriptions are intorduced to the model and enables to calculate system and plant performace of the given HVAC configurations.

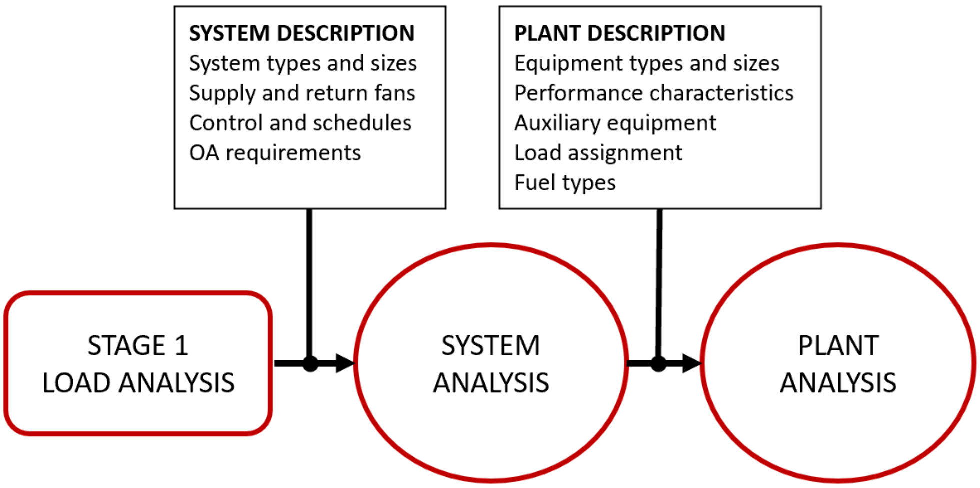

Figure 4. 11 Stage 2 system and plant analysis inputs

Equation based modelling subcategories further divided into components due to the system characteristics as an implementation of HVAC system decision drivers and HVAC systems input data generation sections. The components define the system types and contains to information to be used in the next part of the analysis. Information calculated (loads) and gathered (system, carbon and cost libraries) in Stage 1 is connected to the air system side of the model. The required inputs for waterside systems and plants are calculated in the airside category. These outputs are then used in the waterside and plants calculations.

The airside is divided into 2 categories based on type. These categories are centralized system and de-centralized system with mechanical ventilation. Both categories are fully air-conditioned solutions.

Water systems are categorized as primary and secondary pumps for heating and cooling and no pumps for DX systems. In the last step of EBM heating and cooling plants defined per fuel types. The flow chart of the EBM system components is given in figure 4.12.

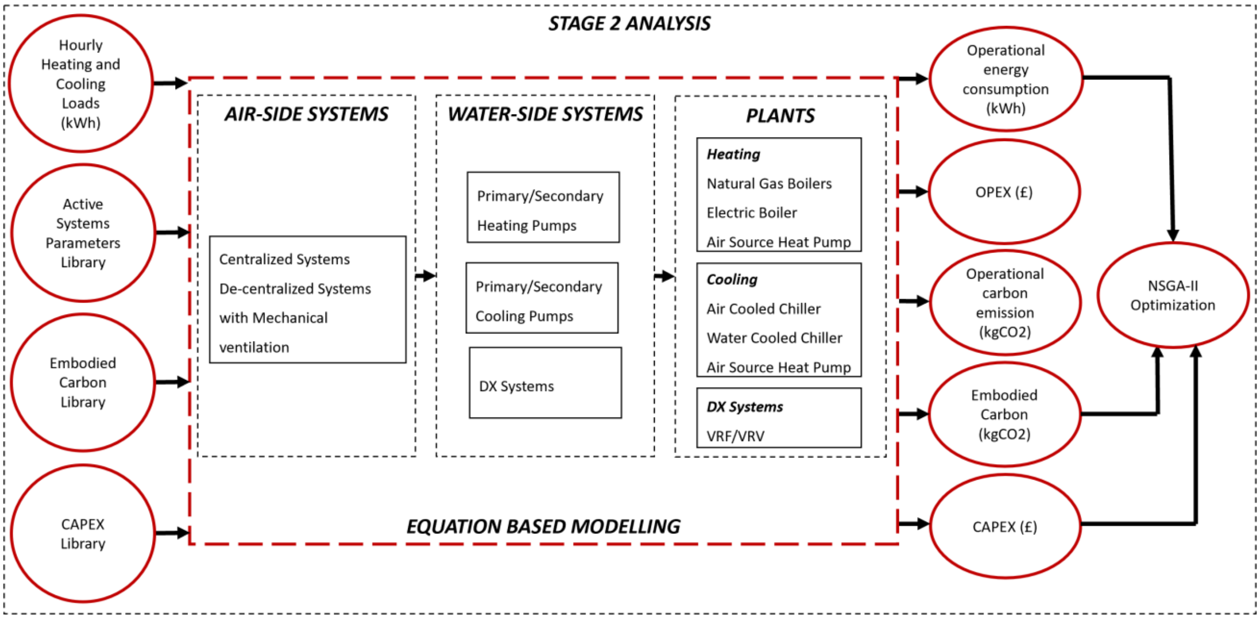

Figure 4. 12 Stage 2 analysis - equation based modelling - flow chart

The system variables of each subcategory are decided as per HVAC system decision drivers and HVAC systems input data generations. The interventions for these variables have impact on the energy, carbon and cost calculations. These system variables are listed in figure 4.13 for each subcategory.

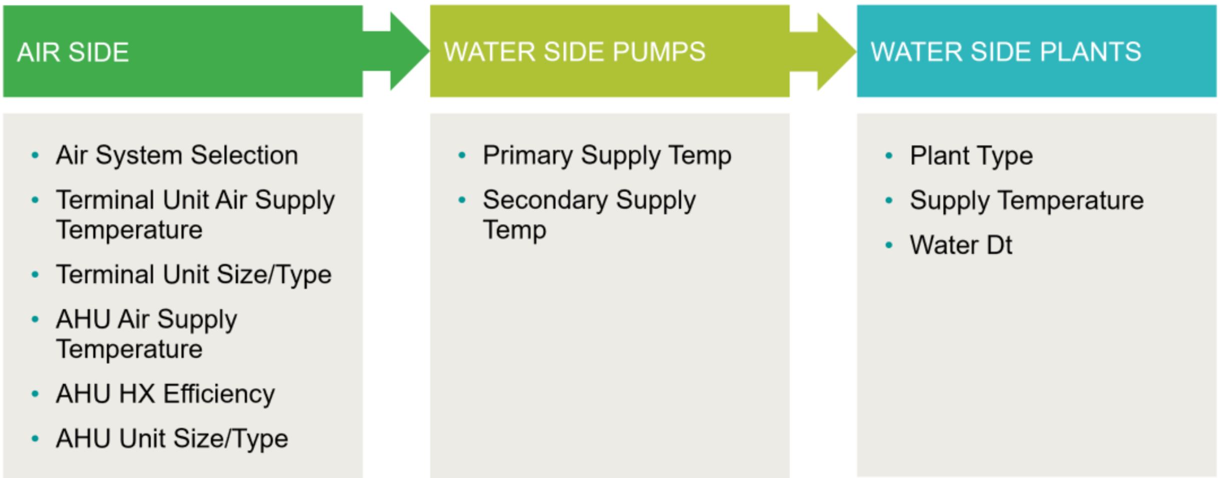

Figure 4. 13 System variables of subcategories

The components in the HVAC systems are connected to others. The inputs and outputs of these components enable the calculation of the fluid behaviors in a component and transfer to the next one. The three stages of analysis that EBM consists of calculating the size and hourly data for airside systems, waterside systems and plants. These are designed as a modular tool which allows adding/removing systems and inputs in both three stages.

The three stages of the analysis are further explained as air-side, water-side and plants in the following subsections.

- **Air-side systems**

In the first subcategory, airside systems are divided into 2 groups. All-air systems (AAHS) and De-centralized Systems with Mechanical Ventilation (DOAS). AAHS contains central heating and cooling coils, central supply and return fans, heat recovery and controls. AAHS, using primary air distributed by ducts, satisfy the whole demand allocated with hourly loads as a standalone solution. The DOAS is a combined solution. The terminal units are responsible for satisfying the demand while centralized air units provide the required fresh air rates by mechanical ventilation to the zones. DOAS contains both central and local heating and cooling coils, supply and return fans, and controls. Schematic view of air-system components is given in the figure 4.14.

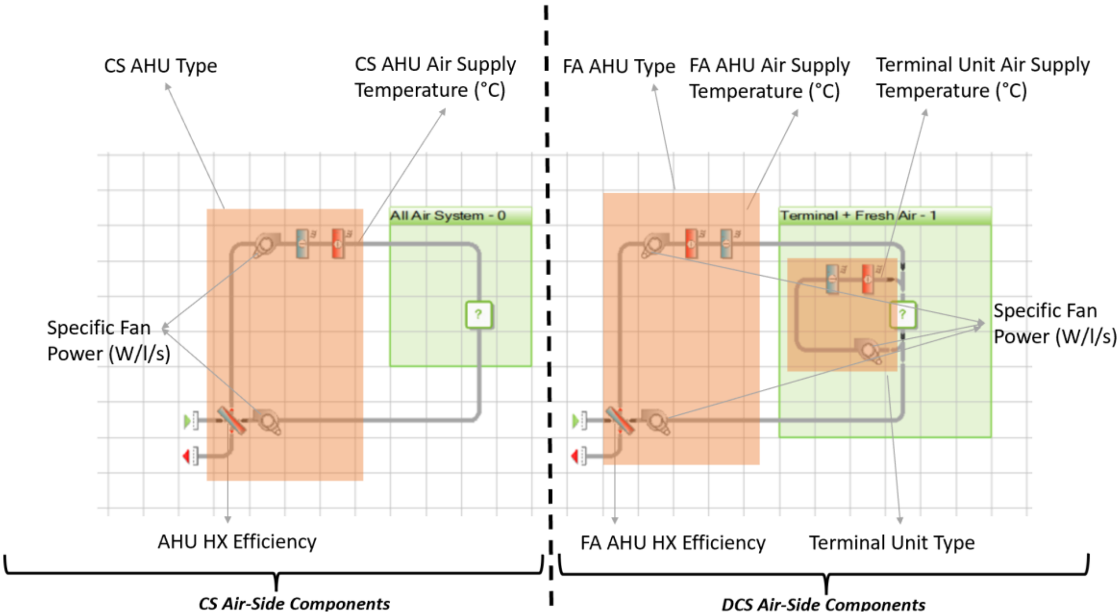

Figure 4. 14 Air-side components

The main inputs required for this subcategory is the hourly heating and cooling loads from the stage 1 analysis building, the weather conditions information from the climate data such as the dry-bulb temperature, wet-bulb temperature and relative humidity and the calculated fresh air rates via hourly profiles. 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 (%), specific fan powers of the supply and return fans and coil sizing factors. All formulas related to this subcategory is given in Appendix K.

In AAHS, for both heating and cooling, the peak and hourly coil loads, and air flow rates are calculated as a function of hourly load (kWh), central unit air supply temperature(°C), room air return temperature (°C), outdoor air dry-bulb and wet-bulb temperatures(°C), central unit heat recovery efficiency (%) and the coil sizing factor. The peak and hourly coil demands that calculated in the AAHS are used as the input for the Waterside systems. The peak demand is additionally used for defining the AAHS AHU unit type and number. The unit type contains the specific fan power information. The airside operational energy consumption due to fans is calculated this SFP information of the unit type and hourly air flow rates. Also, the unit type, which is associated with the externally generated embodied carbon and cost libraries, enables to calculate embodied carbon and CAPEX for the AAHS interventions.

In DOAS, the space and fresh air related coil loads, and air flow rates are calculated separately. For space heating and cooling, the peak and hourly coil loads, and air flow rates are calculated as a function of hourly load (kWh), terminal unit air supply temperature(°C), room air return temperature (°C), and the coil sizing factor. Fresh air rates are calculated via design criteria using hourly profiles. Following this, fresh air related peak and hourly coil loads and are calculated as a function of hourly fresh air flow rates, central unit air supply temperature(°C), room air return temperature (°C), outdoor air dry-bulb and wet-bulb temperatures(°C), central unit heat recovery efficiency (%) and the coil sizing factor.

Similar to AAHS, the peak and hourly coil demands that calculated in the DOAS are used as the input for the Waterside systems. The peak demand is additionally used for defining the DOAS Terminal unit type and number. The unit type contains the specific fan power information. The fresh air AHU unit type is defined by the calculated fresh air rates. For both terminal units and fresh air AHUs, the airside operational energy consumption due to these system fans is calculated this SFP information of the unit type and hourly air flow rates. Also, the unit type, which is associated with the externally generated embodied carbon and cost libraries, enables to calculate embodied carbon and CAPEX for the DOAS interventions.

- **Water-side systems**

The second subcategory, waterside systems are representing the distribution between plants and the coils. For the plants distribute the energy using water as fluid, these are the piping, primary and secondary circulations pumps for heating and cooling systems. The primary and secondary circulation pumps split in the DOAS for the terminal and fresh air AHU coils. Alternatively, in the VRF system which distributes the energy using refrigerant as fluid, there is no circulation pumps. Water-side systems are simplified in the study and uses fixed inputs for energy, carbon and cost. This subcategory calculates the operational energy using standardized heating and cooling pump power for per volumetric flow rate.

The inputs required for this subcategory is the hourly heating and cooling coil demand calculated in the air-side systems, heating and cooling design flow and return water temperatures. These inputs are used to calculate the hourly volumetric flow rates.

Water-side operational energy is calculated as a function of hourly heating and cooling volumetric flow rates and the pump power for per volumetric flow rate. Standardized embodied carbon and CAPEX are calculated based on typical pumps types which is associated with the externally generated embodied carbon and cost libraries. In the interventions that uses VRF in the plant side, this water-side subcategory is negligible. All formulas related to this subcategory is given in Appendix K.

- **Plants**

The third subcategory, plants are divided into 2 groups. Heating and cooling plants. Even the plants are a part of water-side systems, due to their impact on both energy, carbon and cost, they are categorized individually to analyze the standalone impact. Schematic view of waterside system and plant components are given in the figure 4.15.

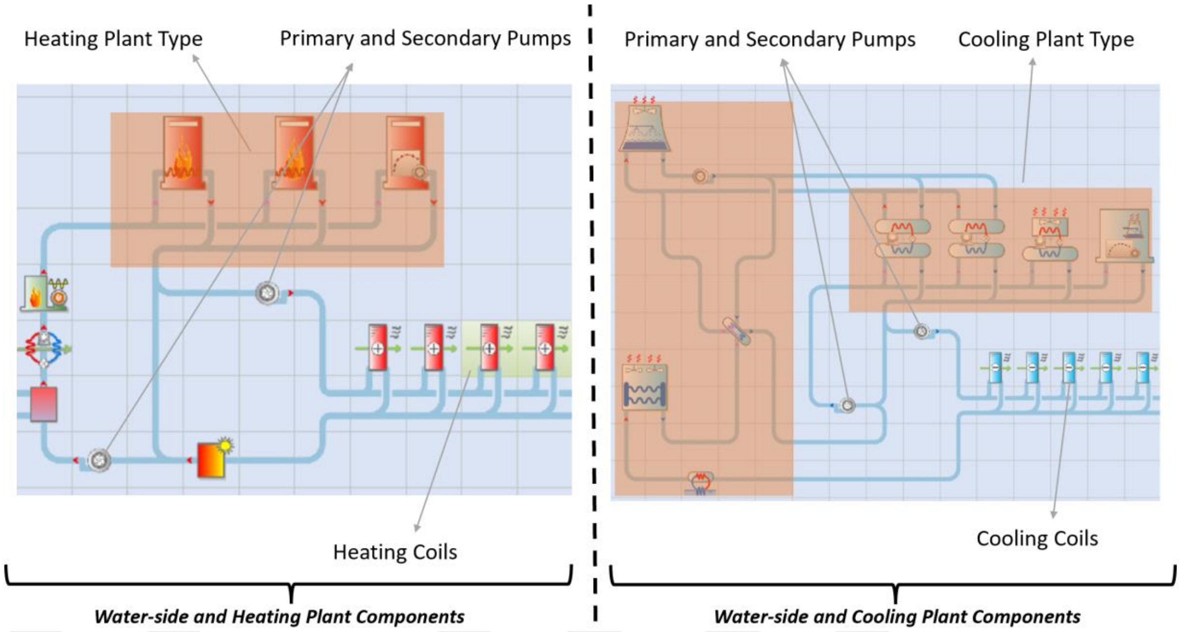

Figure 4. 15 Waterside and plant components

Both heating and cooling plants, are due to generate the energy required at a time from the coils. The effectiveness and the efficiency of this generation depends on the plant type, fuel type, outdoor air temperature (for some plants), full load and part load efficiencies and distribution water supply and return temperatures.

The inputs required for this subcategory is the peak and hourly heating and cooling coil demand calculated in the air-side systems, heating and cooling design flow and return water temperatures.

Plants are referring to the energy generation required by the systems, based on the changing hourly demand (from building to airside, airside to the waterside and then waterside to plants). Plant capacities are defined using the peak coil loads occurring throughout the year for heating and cooling. The part load ratios are calculated using the peak and hourly load. Peak and part load efficiencies are calculated as a function of load ratios, outdoor air temperature and water supply and return temperatures. These load ratios then associated with the hourly coil loads using the mapping function. The plant operational energy consumption due to energy generation is calculated using this hourly efficiency information of the unit type and hourly heating and cooling coil loads. Also, the unit type, which is associated with the externally generated embodied carbon and cost libraries, enables to calculate embodied carbon and CAPEX for the interventions. All formulas related to this subcategory is given in Appendix G.

In both subcategories, an adaptable database is generated based on the sizing information from the building for efficiency, energy performance, embodied carbon and CAPEX of the systems. Efficiency and energy performance measures for each system and total embodied carbon and CAPEX of each combination are considered as a cost function to optimize the performance.

- **EBM calculations summary**

For each subcategory, different types of components and intervention ranges are defined in the study. These design intervention combinations are linked further to the HVAC system database. In figure 4.16 the components-based workflow is explained with inputs and outputs associated to each subcategory.

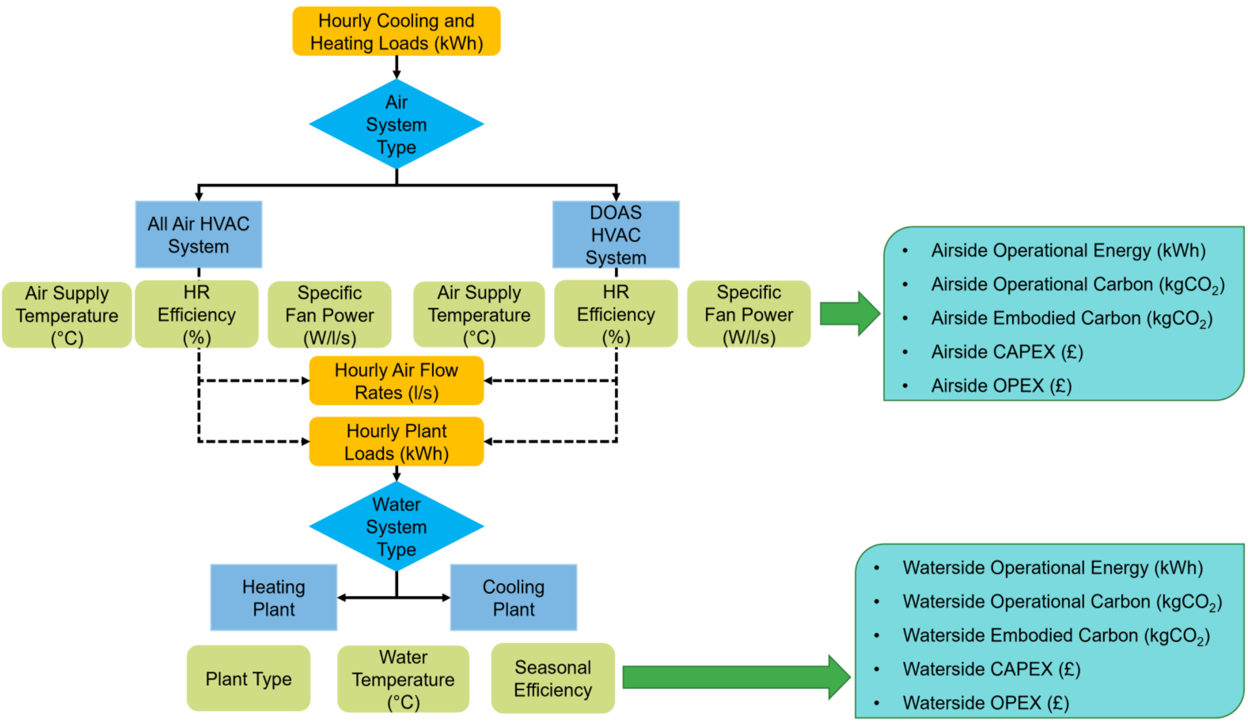

Figure 4. 16 EBM components-based workflow

Hourly cooling and heating loads used as input for the airside systems. Using airside system type, air supply temperatures, heat recovery efficiency, specific fan powers for different interventions, airside operational energy, operational carbon, embodied carbon, CAPEX and OPEX is calculated. Additionally, to transfer to waterside systems and plant, hourly air flow rates and hourly coil loads are also calculated.

In waterside systems hourly energy consumption (kWh) of primary and secondary pumps is calculated using hourly water flow rates and the efficiency input from the database. Plants hourly energy consumption (kWh) of heating and cooling plants to generate the energy required is calculated with hourly coil demand, hourly water flow rates, outdoor air temperature, water supply/return temperatures, controls, plant type and the efficiency input from the database. Using waterside system and plant type, water supply temperatures and seasonal efficiencies for different interventions, waterside operational energy, operational carbon, embodied carbon, CAPEX and OPEX is calculated.

Combined annual energy consumption, operational CO2 emissions and OPEX based on the fuel type of each consumption are analyzed per each iteration.

4.3.3 Multi-Objective Optimization

The optimization is the subcategory and the last stage of the Stage 2 analysis. This stage is directly connected to the EBM and interventions are driven by the optimization. However optimization is introduced as a seperate section under the methdology to enable better clarification on the structure of the study. [74]

As described in the previous chapters the objective functions of the study conflict with each other. In the literature review studies mainly focus on one or two of the operational energy, embodied carbon and CAPEX functions. Due to the complexity of the study, variety of the subcategories, design parameters and intervention, optimization plays a essential role to compare and analyise the outcomes.

The fact that all optimization algorithms and methods have limitation. It is widely recognized, which means that the choice of a suitable algorithm relies on the specific characteristics of the problem being addressed.

The study focus on HVAC system optimization problem and having three objective functions. The literature review exhibits the necessity of multi-objective optimization solution due the multi-dimensional nature, inputs and constraints. Of the study. Multiple cost functions have many key aspects to focus on such as problem formulation, pareto front exploration and practical constraints.

By means of the nature of the problem, the evolutionary computational technique also referred to as evolutionary algorithms (EAs) is chosen as the optimization algorithm. Evolutionary algorithms is a subfield of computational intelligence which is inspired by evolution theory and natural evolution. As a result of multiple solutions, there are multiple solutions can represented in the Pareto optimal solutions and solving such kind of a complex problem can be well handled by using evolutionary computational techniques. [75]

Buildings are complex structures and most of the time, a single set of parameters does not define the optimum solution. EAs techniques help to understand the phenomena with operators. The operators allow generating new solutions to achieve the optimum solution or a near-to-optimum solution. These near-to-optimum solutions provide a range to allow selection in the needs of the design. As EAs' mimics the natural evolution, this happens with variation operators, such as crossovers and mutations. The good solutions which are defined as the fittest results are retained and the bad are eliminated. These good results are transferred from generation to generation until it reaches the optimum solution. Information is coded in genetics. It's a population-based algorithm that generates many solutions and points. [75]

In EAs there are two types genotype and phenotype. Genotype is the information coded internally and phenotype is the physical representation of the result of decoded genotypes. The information is transferred from parents to the next generation by crossover and mutations. The initial population is randomly generated. [75]

The multi-objective optimization is a subcategory of the Evolutionary Algorithms that enables solving more than one objective.

Multi-objective optimization algorithms are generally capable to represent these trade-offs and complexity between mutli-dimensional conflicting objectives. As discussed in the literature review of the study these algorithms are found as an effective way of dealing with conflicting objectives for building studies. These algorithms are able to represent pareto optimal solutions , provode a diverse set of solutions, converge towards the true pareto front, desicion making support, scalibity, robustness and flexibity.

Instead of one optimal solution, multi-objective optimizations generate many trade-off solutions. There are multiple optimal solutions. And the ideal multi-objective optimization approach allows for the generation of multiple optimal solutions (Pareto front) using the multi-objective optimization technique.

There are several multi-objective optimization algorithms that have been developed over the years. NSGA-II, SPEA2, MOPSO, MODE are few examples for these. Each algorithm has its own strengths, weaknesses and characteristics.

In the study after the the comprehensive literature review, NSGA-II (Non-dominated Sorting Genetic Algorithm II) is chosen as a multi-objective optimization algorithm which imitates the genetic operators evolve a population of candidate solutions. In NSGA-II, the population is organized into several levels based on the non-dominated relationship between individuals.

The two important parameters in NSGA-II are the generation size and the generation count. Generation size refers to the number of individuals in each generation of the population. The larger the generation size, the more diverse the population, but it also increases the computational time required for each generation. Generation count is the number of generations that the algorithm will run. The algorithm iteratively improves the population from one generation to the next, and the generation count determines how many times this process will be repeated.

In NSGA-II, it is important to specify both the generation size and generation count before running the algorithm. These parameters have a significant impact on the quality of the solutions found by the algorithm and the computational time required to find those solutions.

Integtration of the NSGA-ii optimization algorithm to the EBM is the last step of the study. Therefore as the first step to this, each parameter relative to the problem of the study is listed. Using the information generated in the previous steps, adjusted/ lessened parameters are introduced to the optimization.

As described in the previously the optimization is based on the search for the design variables, which are defined in detail under the equation-based modelling part, subjected to minimising the three defined cost functions to satisfy the constraints. These three cost functions are operational energy consumption, embodied carbon and the CAPEX. However the study is not limted with this. Calculated operational carbon emissions and OPEX are used to allow a next level of desicion making in the pareto front solutions. Wallecei library which is introduced in the parametric modelling section is used in the visual programming tool Grasshopper to execute optimization using the NSGA-II algorithm. The library is connected to the EBM model. The optimization algorithm runs and generates the Pareto front results. All results are visualized using Wallecei X data analytics module, python programming language and visualization libraries. [71]

In Wallecei X, iterative component sliders for the interventions are connected to the Genes input. Objective functions or fitness objectives, which reads the each intervention results are connect to the Objectives input. Based on the generation size, generation count, crossover probabilty, mutatio probabilty, crossover distrbution index and mutation distribution index, the optimization algorithm run the simulations.

Population parameters are generation size and generation count.

Generation size represents the number of individuals per generation and generation count represents the number of generations in the simulation.

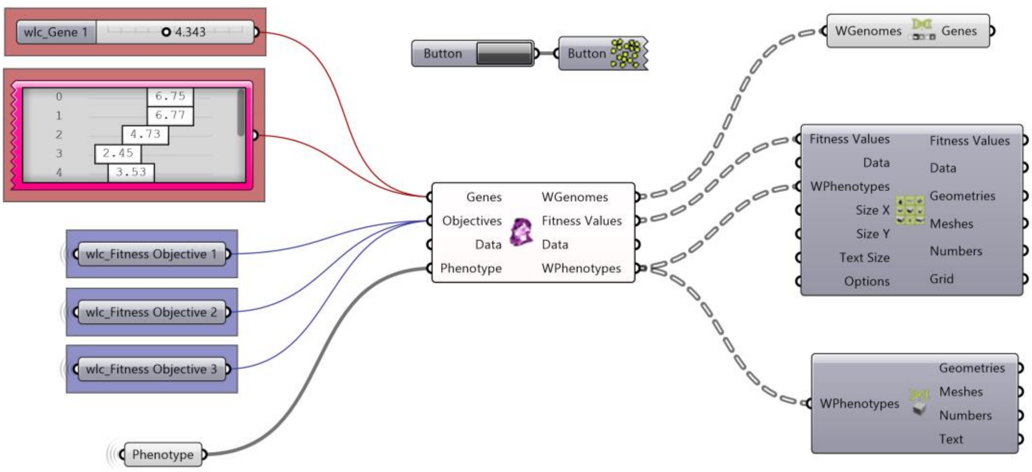

Figure 4. 17 Wallecei X grasshopper representation

Algorithm parameters are crossover probability, mutation probability, crossover and mutation distribution index.

Crossover probability varies in betwen 0.0 and 1.0. It is the percentage of solutions in the generation that will reproduce for the next generation.

Mutation probability varies in betwen 0.0 and 1.0. It is the percentage of mutations taking place in the generation.

Crossover and mutation distribution index varies in betwen 0 and 100. Large distribution index value gives a higher probability for creating offspring near parent solutions and a small distribution index value allows distant solutions to be selected as children solutions.

Selected population and algorithm parameters are presented in the case study section of the study.

5
CASE STUDY: STAGES OF THE METHODOLOGY

In this section, the methodology of the study - equation-based modelling- using the multi-objective optimization is demonstrated over a case study. The methodology developed to support designers and developers on the HVAC system selection decision making process, is explained over an existing office building. The show case implements different HVAC design scenarios and testing their effectiveness against energy, carbon and cost constraints.

The selected office building is in London. It was constructed as a prime office serving technology companies in different floors. It was constructed by following the building regulations, standards and the market trends of the time. It represents the design and construction features of the time it was built. It's also a good representative of the technology that is used and needs to be replaced due to the end of its life cycle in 5-10 years. The impact of the EBM method on the decision-making process has been propounded by evaluating the energy, carbon and cost relationship in an HVAC retrofit of an existing office building.

The corresponding inputs of stage 1 and stage 2 analysis of the EBM, which are described as in section 3and 4, are demonstrated. Firstly, the overall details for the existing office building subjected to the case study is described. Based on the definition of the building model description in Stage 1 analysis, initial reference for the inputs to set up the baseline model and the calibration steps for this model are introduced. In line with hourly heating and cooling demand loads, HVAC system types, components and selections are defined. HVAC system types and components allow to generate the product-based embodied carbon and cost libraries. Al these outputs are fed into stage 2 analysis. In the stage 2 analysis, the parameters of the systems and components to be tested are defined. Depending on the loads calculated by Stage 1 analysis, the functional effect of the inputs has been tested using NSGA-ii optimization algorithm.

5.1 Stage 1 Analysis System Inputs

In the stage 1 analysis, firstly, a dynamic thermal modelling study has been undertaken to determine a baseline for the study. Heating-cooling demand and energy consumptions are calculated in baseline for comparison and evaluation of the next stage analysis. The results are calibrated using the metering data gathered from the building for the subsystems of the building.

The study has been conducted, following the TM54 methodology explained under section 4, using IES VE 2022 software to demonstrate the Enhanced Building Energy Modelling (EBEM). The IES VE software has been approved by the Department for Communities and Local Government (DCLG) for use as a Dynamic Simulation Model (DSM) software package. As part of its approval process, the IES software had to demonstrate that it satisfies all of the tests and other requirements defined in accordance with ISO 90003:2004 – 'Guidelines for the application of ISO 9001:2000 to computer software and accredited with ANSI/ASHRAE standard 140- 2017, "Standard Method of Test for Evaluation of Building Energy Analysis Computer Programs".

The dynamic thermal model includes the details for building for architectural and M&E characteristics. The inputs on envelope, profile and operational patterns, HVAC systems, lighting system and internal gains are represented. Since the described base building is an existing building, the input values used in the baseline modelling were based on the as-built design and the building operation logbooks.

5.1.1 Data Colection And Baseline Energy Modelling

The building used as the base case is an existing office building was constructed in 2013 and has been in operation since then. Total gross internal area (GIA) of the building is 6400 m^2. The building has 2 basements and 9 overground floors. The basements are used for car park, storage and Back of House (BOH). Ground and upper floors are used for office spaces. The building has a simple form rectangular-shaped (20m x 40m), north-to-south oriented and it is heavily shaded from North and East orientations. For a typical level, the floor-to-floor height is 3.5m. Due to confidentiality reasons, floor plans and some further information are not given as a part of the study. The visuals and details that do not affect the modelling and results are anonymized.

- **3D Geometry**

The geometry of the thermal model is generated using as built 2D CAD drawings of the actual building. Site plan, floor plans, sections and elevations are used to build up the model geometry in the software. The 2D drawings are imported into the software and used as a base for defining the geometry. Building form and external shading are modelled as per drawings. In each floor, the open office areas are divided into 6-metre-deep perimeter zones to allow for more accuracy in the thermal and lighting control. Each floor has 6 external and 2 internal zones are modelled. The surrounding buildings area also modelled to allow the impact of external shading.

The graphical 3D representation of the generated model is given in Figure 5.1.

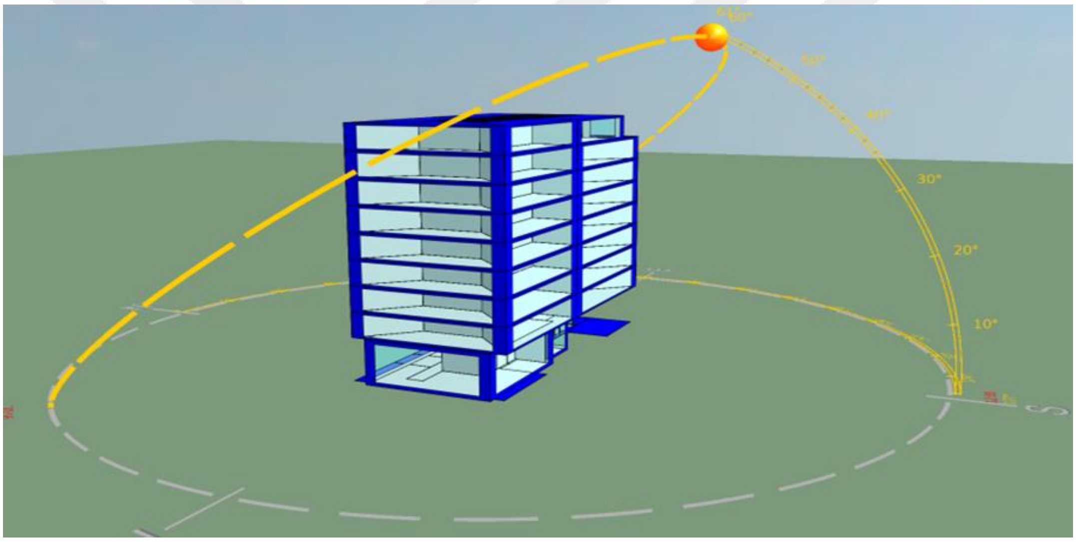

Figure 5. 1 Case study baseline model

- **Area schedules**

The following floor area values are extracted from the dynamic thermal model for the office building.

Table 5. 1 Area schedule

Use	Proposed Gross Internal Area, GIA (m^2)
Office (Class B1)	5,400
Basement (Class B1)	1,000
Total	6,400

- **Climate data**

The potential impact of weather conditions on the operational energy prediction has been considered using weather tapes in the modelling. The baseline analysis is carried out in accordance with CIBSE TM54 (2013) guidelines, using dynamic thermal modelling (DTM) under the Test Reference Year (TRY) for London Heathrow. London Heathrow is the closest weather station to the actual building location.

The CIBSE 2016 Test reference Year weather data "London_TRY2020_High50", which is based on Heathrow Airport weather measures, has been utilized in the annual analysis. The weather file contains the hourly temperature, humidity, wind and solar radiation information for a whole year. In table 5.2 the latitude, longitude, winter and summer design temperatures are given. Design temperatures are used for the equipment sizing calculations.

Table 5. 2 Weather data

Type	System	Design Inputs	Latitude - Longitude	Winter Design Temperature (°C)	Summer Design Temperature (°C)
Weather File	Weather Data Used	London TRY_2020High50.epw	51.48 N - 0.45 W	-2.5	31.5

In figure 5.2 average outdoor dry-bulb temperatures for the whole year is illustrated. Further information on average, maximum and minimum monthly temperatures, hourly tabular temperature, humidity and wet bulb is given in Appendix B.

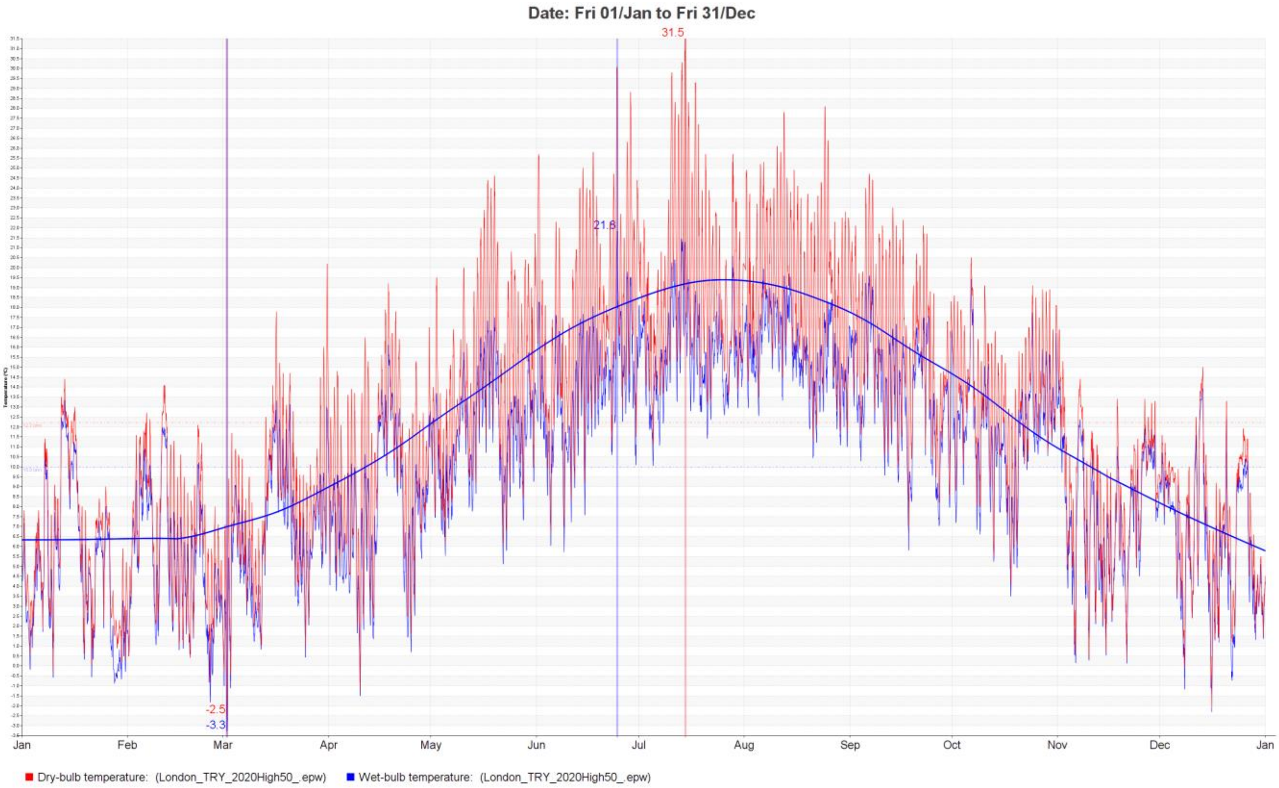

Figure 5. 2 Annual weather profile

- **Building envelope thermal properties**

Elements of the building envelope are external walls, roof, floor and glazing. For all the elements of envelope, thermal performance has been accurately presented in the study as per architects and façade engineer as-built reports. Opaque construction elements are modelled on per layer basis.

The envelope U-Values for the case study building are summarized in the table below:

Table 5. 3 Construction elements thermal properties

Type	System	Design Inputs	
Envelope	External wall U-Value	0.25	W/m². K
	Roof U-Value	0.25	W/m². K
	Floor U-Value	0.22	W/m². K
	Glazing U-Value	1.26	W/m². K
	Glazing g value	0.36	N/A
	Air tightness	4.9	m3/h.m2 @50 Pa

As façade air tightness is specified at 4.9 m3/hr. / m2 @ 50 Pa, referring to CIBSE Guide a Table 4.16, 0.15 air changes per hour (peak value) has conservatively been assumed as winter infiltration rate, while the average figure of 0.1 ACH has been assigned for the summer. These values could be assumed as contractual processes exist to achieve that level of air tightness for the total building.

The thermal properties of the building comply with the building regulation Part L 2010 version as a requirement of the time it was constructed.

- **Internal conditions, operating schedules and occupancy**

In the study, the hours of operation of plant and equipment is taken differently from the occupied hours and will vary between different energy end-uses. Therefore, both figures are established. For the accuracy of the building space heating and cooling demands, temperature set points and occupancy profiles are taken from the as-built design documents. These defined internal temperatures set points, systems operating schedule and occupancy patterns are given in table 5.4.

Table 5. 4 Internal temperature set points, systems operating schedule and occupancy patterns

Thermal Zones	Temperature Set Point (°C)	Systems Operating Hours	Occupancy Hours
Office	Winter 21 °C - Setback 14 °C Summer 22 °C	6 am - 8 pm, off on weekends and holidays	7 am - 8 pm, weekdays only
Entrance	Winter: 21 °C - Setback 14 °C Summer: 22 °C	6 am - 8 pm, off on weekends and holidays	7 am - 8 pm, weekdays only
Toilets	Winter: 18 °C - Setback 14 °C	6 am - 8 pm, off on weekends and holidays	7 am - 8 pm, weekdays only
Circulation and Lift Lobbies	Winter: 18 °C - Setback 14 °C	6 am - 8 pm, off on weekends and holidays	7 am - 8 pm, weekdays only
Plantrooms temper heating	Winter: 10 °C	6 am - 8 pm, off on weekends and holidays	7 am - 8 pm, weekdays only

Customized occupancy patterns have been created adapting the ASHRAE profiles to the building uses that emerged from the as built and operational schedules information. Occupancy density of 10 m^2/person is assumed based on the fresh air design rates of the as-built HVAC calculations. Occupancy sensible and latent gains are taken from ASHRAE fundamentals Handbook, 2021. Further details on occupancy profiles can be found in Appendix A.

- **Lighting and internal gains**

Customized lighting and tenant equipment power consumption profiles have been created adapting the ASHRAE profiles to the building uses that emerged from the as built and operational schedules information. Annual energy use for interior lighting has been calculated outside the DSM software following the LENI approach outlined in the CIBSE TM54 and referenced in the SLL Code for Lighting (SLL, 2010). Area weighted average lighting gains are applied as an outcome of the calculations. These numbers are updated in the calibration step of the Stage 1 analysis. Further details on these profiles can be found in Appendix A. The table below outlines the occupancy and internal gains.

Table 5. 5 Internal gains

Type	System	Design Inputs	
Occupancy	1 person per 10 sqm		
Internal gains	Occupancy sensible	90	W/person
	Occupancy latent	50	W/person
	Lighting	12	W/m2
	Small power	25	W/m2
	Upgrade allowance	10	W/m2

Lighting internal gains have been included appropriately in the dynamic thermal model as well, with the inclusion of control factors for daylight dimming and occupancy sensing controls. Default parameters have been applied to the lighting hours and occupancy control, while daylight dimming control has been modelled using IES VE – Radiance. Default parameters have been applied to the equipment and small power hours and controls.

External lighting calculations are excluded in the study.

- **HVAC Systems Plant and System Diversities**

The following design parameters were assigned to the energy model based on the as built information to establish its space heating, space cooling and auxiliary energy use. Plant and system diversities due to simultaneous usage of the system are given under table 5.6.

Table 5. 6 HVAC systems plant and system diversities

Type	System	Design Inputs
Central plant diversities	Occupancy	1
	Lighting	0.9
	Small power	0.8
	Additional capacity	1

- **Fresh air supply, ventilation, and infiltration rates**

Fresh air supply, ventilation and infiltrations rates are calculated based on the ventilation drawing and the information captured form the as-built documentation and given under table 5.7. The fresh air rates are also used as an input in the stage 2 analysis.

Table 5. 7 Fresh air supply, ventilation and infiltration rates

Type	System	Design Inputs	
Fresh air supply and ventilation rates	Base provision	1.6	l/s per sqm
	Toilets, showers and changing areas	10	ach
	Storage areas	1	ach
Infiltration	Summer	0.25	ach for 4.5m from perimeter
	Winter	0.5	ach for 4.5m from perimeter

- **HVAC Air-side System Parameters**

The HVAC system data to use in the baseline model is collected from the design projects and as-built reports. The data is broken into two subcategories as airside and waterside systems. The existing building HVAC system is also referred to as the baseline for comparison in the results section. The potential improvements through retrofitting determined using this reference model as a benchmark.

The existing building is equipped with heating, cooling and ventilation systems. It’s a fully airconditioned system. District heating networks are common solution in UK that supply heat from a central source to different consumers via underground pipes. The heat is mostly generated by a central boiler or CHP and transferred as hot water. For the existing building, heating energy is supplied by a district heating network system. The system supplies heating energy providing hot water for both space heating and DHW requirement of the building. For space heating, heating energy generated is transferred to heating coils of AHUs and chilled beams via LTHW pipes. Cooling is served by 2 Air Cooled Chiller (ACC) located on roof. ACCs supply chilled water to cooling coils of AHUs and chilled beams via CHW pipes.

Air-side distribution is served by Air handling units (AHUs) with constant air volume boxes (CAVs), and chilled beams. 2 out of 3 AHUs serve the office areas and the last one is for the common and BOH areas. These components work together to provide heating and cooling to the office areas of the building.

The HVAC circuits for airside and waterside systems of the buildings are replicated using the IES VE Apache HVAC module with all details to maximize the accuracy in the simulation. Air-side systems, waterside heating and waterside cooling systems are modelled using the as-built information based on the manufacturer and installation documents.

Airside system is modelled using the IESVE Apache HVAC library. The active chilled beam diagram from the library upgrade in line with the building design. This upgrade contains the circuit and the control changes. In the circuit, air-side heat recovery unit, supply and extract fans, ventilation unit heating and cooling coils, and coils within the conditioned spaces are modelled. Also, all temperature, occupancy, air rate and weather-related controls applied. Moreover, to enable modelling the distribution losses, two additional components added to supply and return nodes. The upgrade schematic is given in the figure 5.3.

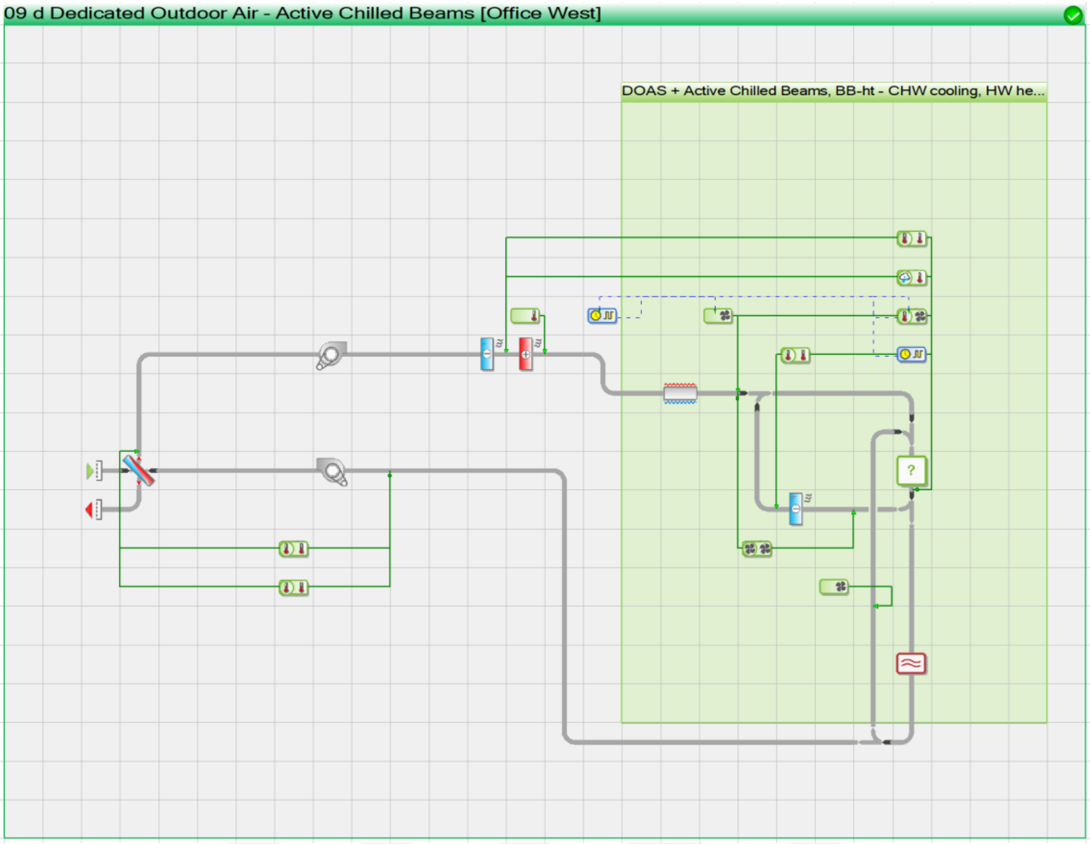

Figure 5. 3 Airside system circuit demonstration

Baseline airside modelling input information is also tabulated in the EBM input format. In the results section, the system simulated using the following inputs are compared with the other system proposals as the baseline definition. The tabulated summary of the baseline airside inputs is given under the table 5.8.

Table 5. 8 Baseline airside HVAC modelling input parameters

System	Type	As-built Design Inputs
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

- **HVAC Water-side System Parameters**

Similar to airside to generate the waterside circuit, IES VE Apache HVAC libraries used. These air and water side circuits are connected via the coils. In the cooling side 2 Air Cooled Chiller (ACC) is modelled with dedicated primary pumps and the secondary pumps. All outdoor air temperatures, chilled water temperatures, plant control and efficiency ratios are applied to the circuit as given in the as-built building information.

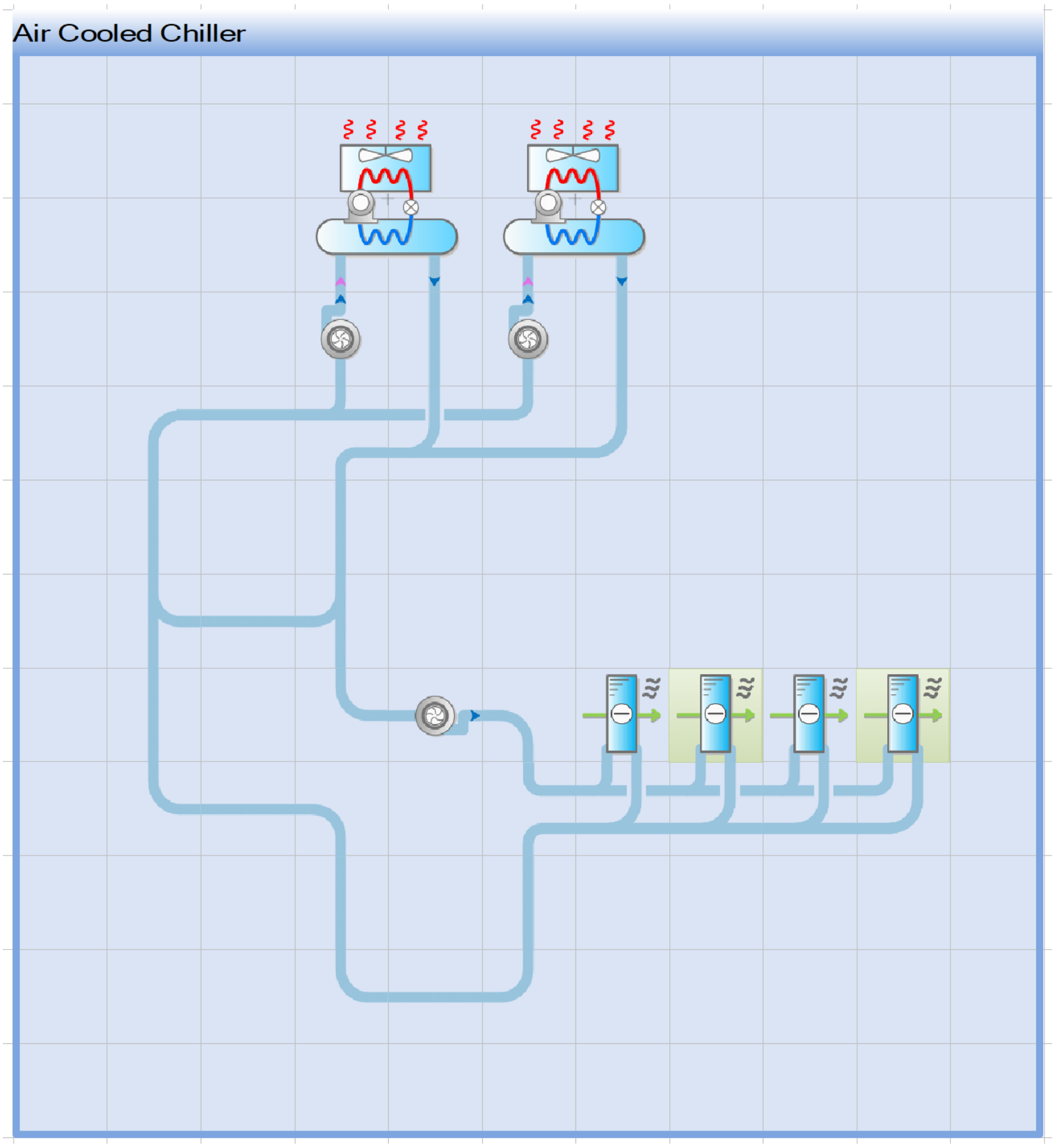

Figure 5. 4 Waterside system cooling circuit demonstration

Heating in the baseline is provided by the district energy network. However, in IES VE Apache HVAC circuit models, District Heating (DH) is not available. For this reason, a single boiler with 100% efficiency with distribution loss used for the heating energy generation. All OPEX and operational carbon emissions are calculated using DH unit rates which is given under table 5.9.

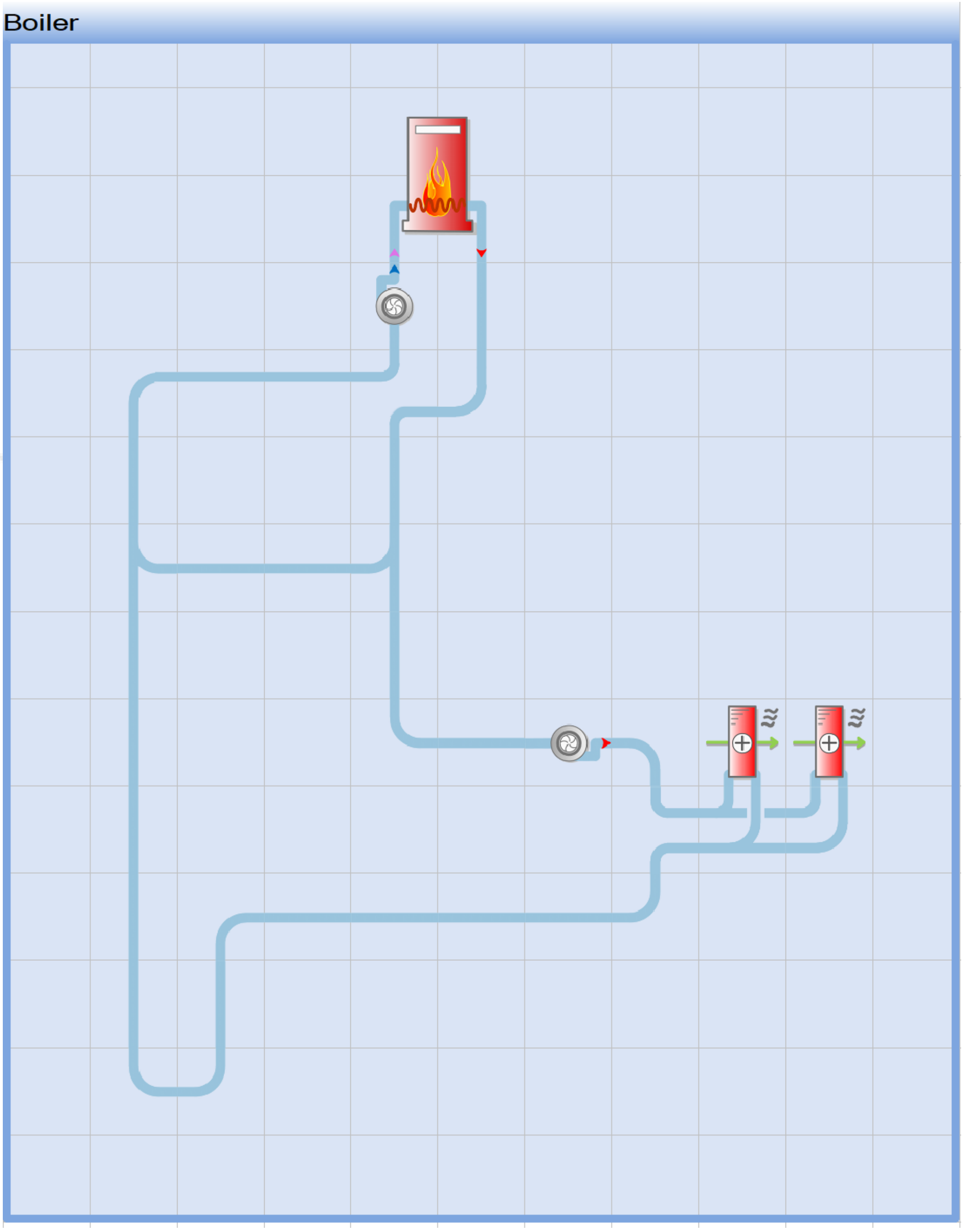

Figure 5. 5 Waterside system heating circuit demonstration

Baseline waterside modelling input information is also tabulated in the EBM input format. In the results section, the system simulated using the following inputs are compared with the other system proposals as the baseline definition. The tabulated summary of the baseline waterside inputs is given under the table 5.9.

Table 5. 9 Baseline Waterside HVAC modelling 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

- **Unit and CO2 rates factors**

In the study, CO2 and fuel rates per fuel type are calculated using the data from BEIS modelling data is used for the fuel rate and carbon factors are demonstrated in figure 5.6 and 5.7 below.

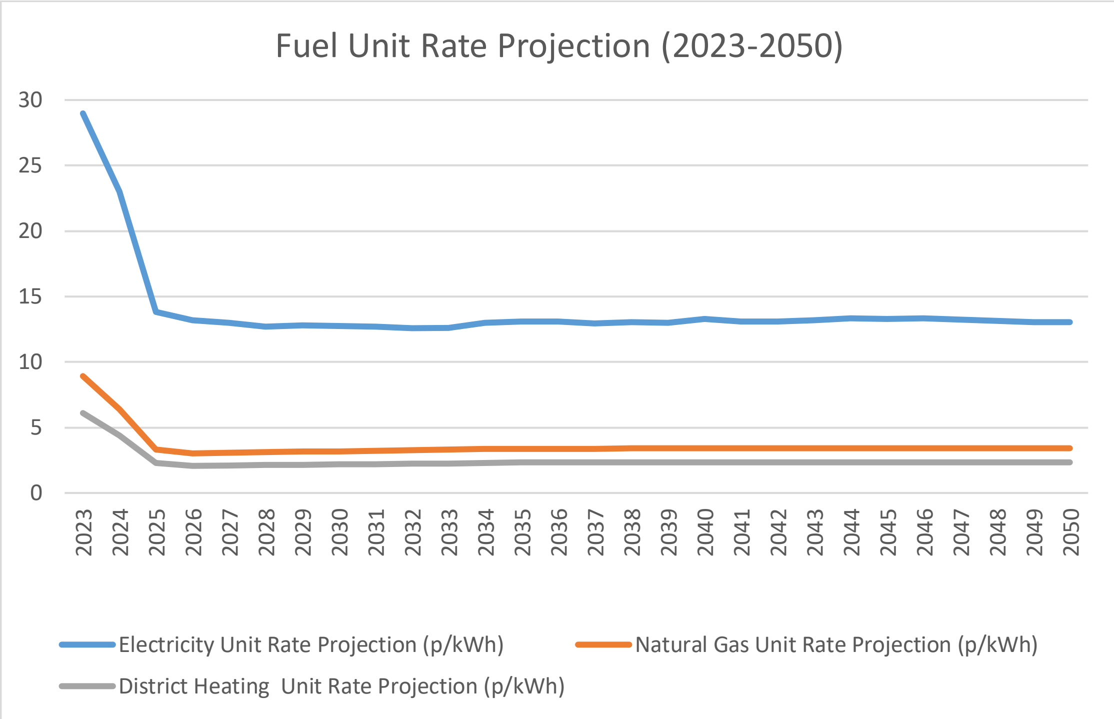

Figure 5. 6 Unit rates factors per unit type 2023-2050[77]

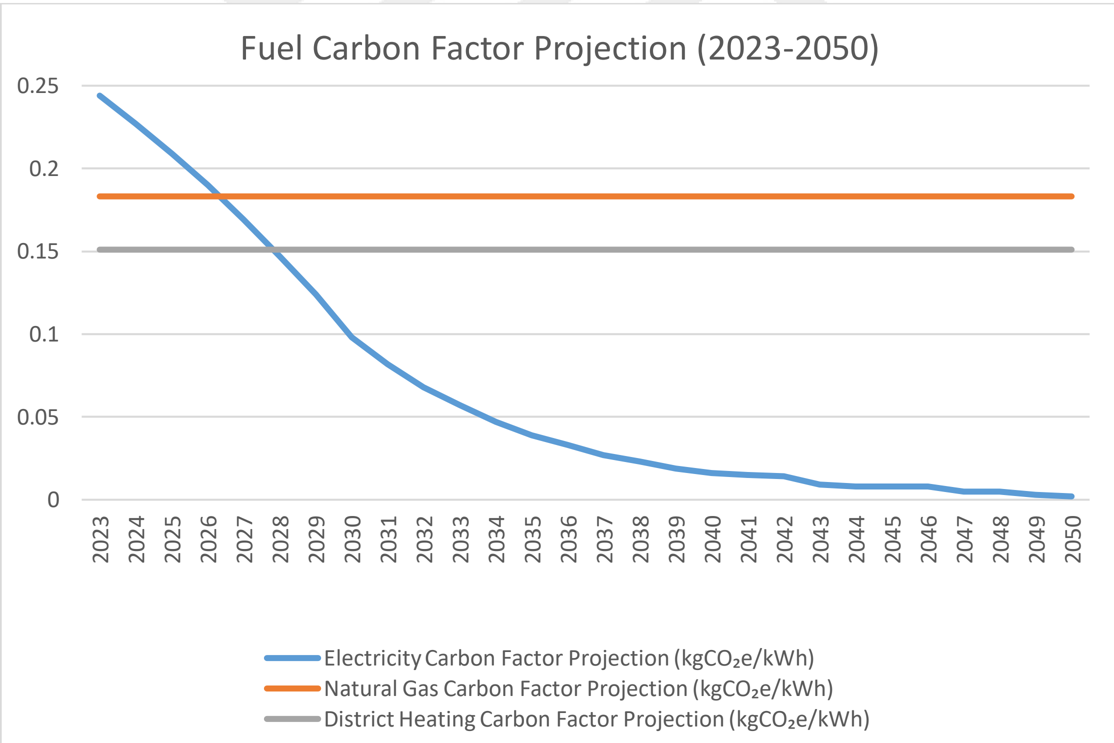

Figure 5. 7 CO2 factors per unit type 2023-2050[76]

5.1.2 Baseline Building Model Calibration

In Stage 1 analysis, the hourly and annual loads and energy consumptions for the existing building are calculated using the defined inputs in section 5.1.1. Even though the modelling inputs contain the as-built information mostly, there are still uncertainties do the limitations of modelling and performance gap as explained in the methodology section. For this very reason, to increase the accuracy of the results, a manual calibration approach is followed using the actual metering data of the existing building. [78]

- **Baseline building model calibration**

The metering data contains the monthly meter readings for electricity and thermal heat. Sub-electric meters for electricity measures the cooling, ventilation fan power, LTHW pump power, CHW pump power, other pumps (booster sets), tenant small power and lighting electricity consumptions. Sub-thermal meters measure the heating and DHW for common and tenancy areas.

The metering data collected contain the information in between 01/2015 and 12/2019. The main data as collected from 2018-2019 is used in the study. In figure 5.8 and 5.9 monthly electricity and heating consumptions are demonstrated.

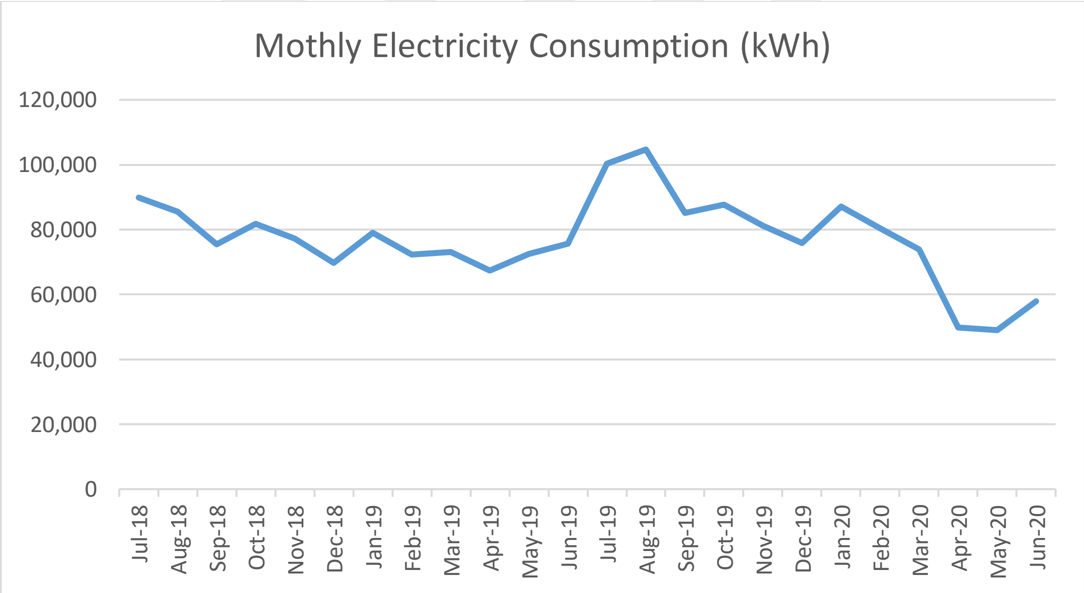

Figure 5. 8 Metering data monthly electricity consumption

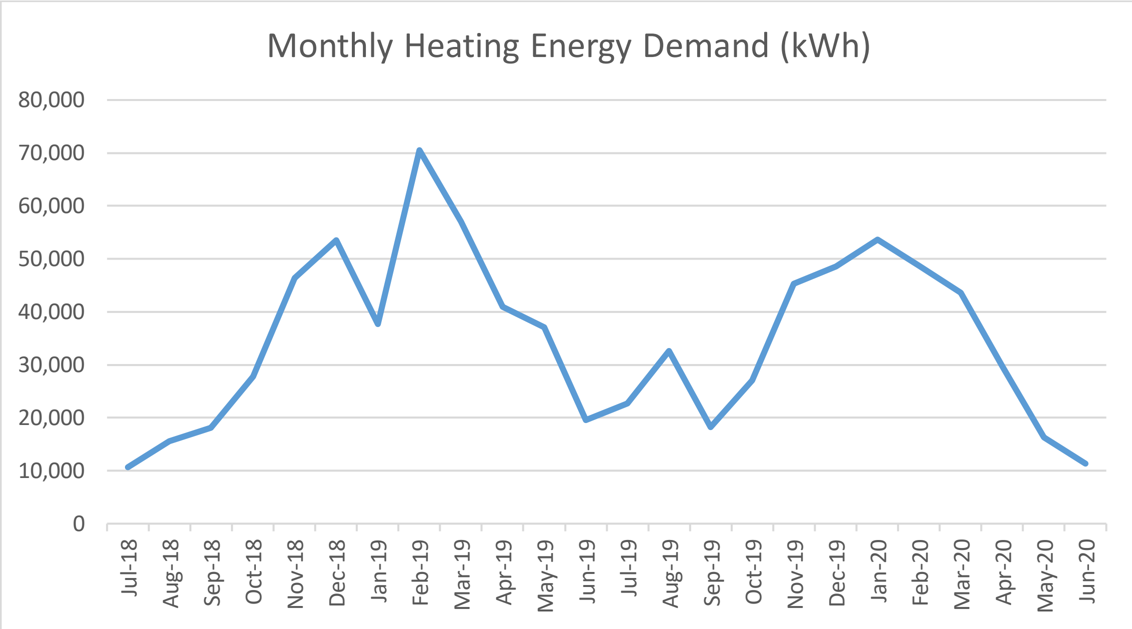

Figure 5. 9 Metering data monthly heating demand

- **Calibrated heating and cooling hourly load analysis**

The results of these calculations were calibrated with the building energy consumption and thermal energy data extracted from building energy management system. The purpose of the calibration is to regularize the electric equipment and usage profiles that are generally uncertain in the design stage. The goal here is to reveal the actual demand for the building and maximize the impact of proposed strategies.

The simulation results were compared with lighting, electric equipment energy consumption, and profiles. Data regularization is achieved in simulations gradually implemented. The lighting, small power load densities, operational and occupancy profiles are updated in the regularization process. The steps and outcomes of the calibration process is given under results section.

Due to the limitations and errors in the building BMS data, this calibration is only carried out to a certain extent within the scope of the study.

5.1.3 HVAC Systems Libraries

The HVAC system libarries are generated based on the literature review and the methodology definitions. There are many other componemts and options can be considered as a part of these solutions however the study is only focused on system compoenets that have significant impact on the energy, carbon and cost together.

In the waterside systems, plant type, nominal and seasonal plant efficiencies, heating and cooling water supply&return temperatures are selected as types to be simulated. Natural gas boiler, electric boiler, Air Source Heat Pump and VRF are the plant types for heating. District heating as a plant solution is also considered for the baseline definition. Air cooled chiller, water cooled chiller, Air Source Heat Pump and VRF are the plants for cooling. Air cooled chiller is also used in the baselining of the study alongside with district heating.

In the airside systems, system type, number of units, specific fan power, ventilation heat recovery, air supply temperatures are selected as types to be simulated. All-Air HVAC system and DOAS HVAC system are the system types. Existing building system is used to calculated the baseline energy and carbon consumptions.

5.2 Stage 2 Analysis System Inputs

- **HVAC System Interventions**

In stage 2 analysis proposed HVAC systems and interventions are simulated to estimate the performance of the potential retrofits. Through the decision-making process, systems, types and interventions related to the types are tabulated in the table 5.10.

Table 5. 10 HVAC system interventions

System	Type	Intervention range	Number of Iterations
Water Side Heating	Plant Type	NG Boiler 70/NG Boiler 50/ Direct Electric 70/ Direct Electric 50 /ASHP70/ ASHP50/ VRF	7
	Number of Plants	1	1
	Plant Efficiency	Vary based on type	1
	Plant Control Type	Vary based on demand	1
	Heating Water Supply Temperature	50, 70	1
	Heating Water Dt	10, 20	1
	Number of Heating Primary Circulation Pumps	1	1
	Number of Heating Secondary Circulation Pumps	1	1
	Circulation Pump Control Type	Variable Flow	1
Water	Plant Type	ACC/ WCC/ ASHP / VRF	7

Side Cooling	Number of Plants	1	1
	Plant Efficiency	Vary based on type	1
	Plant Control Type	Vary based on demand	1
	Cooling Water Supply Temperature	6, 10	1
	Cooling Water Dt	5, 10	1
	Number of Cooling Primary Circulation Pumps	1	1
	Number of Cooling Secondary Circulation Pumps	1	1
	Circulation Pump Control Type	Variable Flow	1
Airside	System Type	All-Air HVAC System/ DOAS HVAC System	2
All Air HVAC System (AAHS)	AAHS AHU Type	type 1 to 6	6
	AAHS AHU Specific Fan Power	1.6, 1.8, 2.0	1
	AAHS AHU Heat Recovery	Off, 70, 80	1
	AAHS AHU Heating Supply Temperature	30,35	2
	AAHS AHU Cooling Supply Temperature	14, 18	2
DOAS HVAC System (DHS)	DHS AHU Type	type 1 to 6	6
	DHS AHU Specific Fan Power	1.6, 1.8, 2.0	1
	DHS AHU Heat Recovery	Off, 60, 80	1
	DHS Number of Terminal Unit (Based on Capacity)	Type 1 to 3	3
	DHS Terminal Unit Specific Fan Power	0.14, 0.17, 0.20 (vary based on type)	1
	DHS Terminal Unit Heating Supply Temperature	30, 35	2
	DHS Terminal Unit Cooling Supply Temperature	14, 18	2

There are 169,344 iterations are foreseen to calculate 31 different components under airside and waterside systems. The intervention ranges are limited by combining one or more components together to minimize the overlaps and number of simulations. The reduction on the overall simulation run time is one of the targeted objectives in the study.

5.3 Multi-Objective Optimization Inputs

The aim of the study, objectives defining the NSGA-II optimization methodology specified under Section 4 in details. In this section the function and compatibility of the methodology will be tested towards a case study in which individual design conditions and scenarios applied. These variables will be tested against energy consumption, life cycle impact, cost and operativity with simulation and optimization techniques.

The three main cost functions that defined in the study are operational energy, embodied carbon and CAPEX. However, operational carbon and OPEX is also calculated as a part of study. These outputs are used as a further step to simplify the decision-making process.

In the grasshopper canvas, the number sliders that define the ranges of the iteration parameters are connected to the Wallacei X component through Genes input parameter. The fitness objectives, operational energy, embodied carbon and Capex are connected to the Wallacei X component through Objective input parameter.

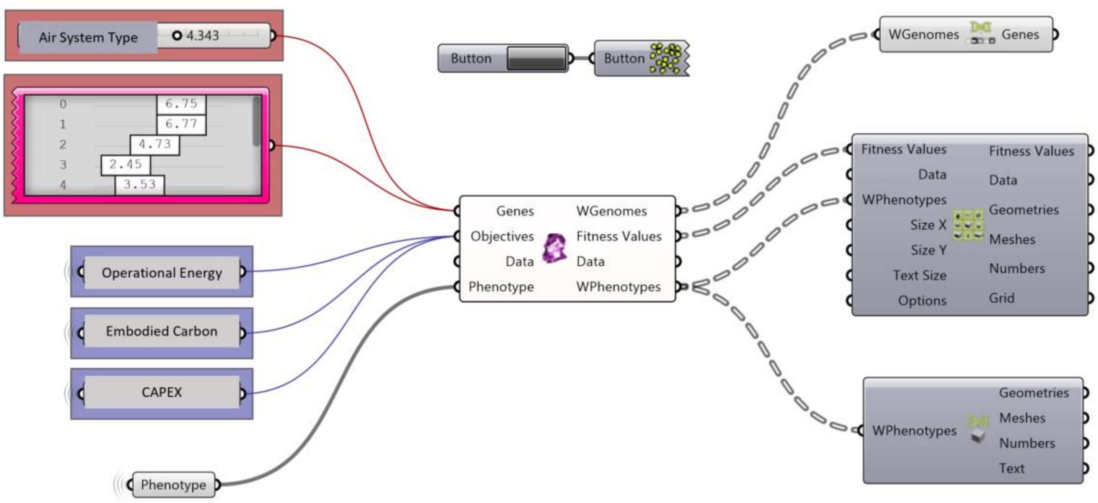

Figure 5. 10 Case study optimization component illustrations

In the Wallacei settings, inputs impacting the population size, runtime and number of pareto solutions are defined. These inputs are generation size, generation count, crossover probability, mutation probability, crossover distribution index, mutation distribution index and random seed. These inputs are explained in detail in section 4. The changes to these inputs allow calibration of the algorithm and simulation setting and enable to monitor the performance. Due to the impact of changing values options and limitations are defined based on the literature review outcome. These values are given in table 5.11.

Table 5. 11 Optimization control inputs

Control Input	**Run1**	**Run2**	**Run3**	**Run4**
Generation Size	40	40	60	40
Generation Count	80	150	150	200
Crossover Probability	0.9	0.9	0.9	0.9
Mutation Probability	1/Crossover Probability	1/Crossover Probability	1/Crossover Probability	1/Crossover Probability
Crossover Distribution Index	20	20	20	20
Mutation Distribution Index	20	20	20	20
Random Seed	1	1	1	1

6
RESULTS AND DISCUSSION

In the 5th section, inputs for the case study are prepared to test the optimization models. These models are used to determine the energy, carbon and cost options for different HVAC system solutions. In this section stage 1 and stage 2 analysis results for the case study is presented. The results on each stage are given in a staged categorization.

In the first stage analysis, firstly the results for baseline model that is developed using the building's as-built information and then the calibrated results with metered data from the building management system are presented. At this stage, hourly heating and cooling demand calculated with the simulation software, comparison in between the simulation results and metered data and steps to calculate the final calibrated results are presented.

In the second stage analysis, the calibrated heating and cooling demand are used to test scenarios developed via the EBM parametric model. Due to the total number of variations, iterative analysis is used to determine the impact of individual types and interventions. The number of iterations is optimized, and results are presented for energy, carbon, cost and as pareto front.

6.1 Stage 1 Analysis

- **Baseline building energy modelling**

Baseline model is generated using the energy modelling software with the input information given in section 5. The dynamic simulation allows to calculate and visualize the energy consumption of the systems in hourly, daily, weekly, monthly and annual basis.

In the study, monthly total heating, cooling demand, lighting, electric equipment and chiller electricity consumptions are extracted from the software for the baseline simulation. Baseline simulation monthly energy consumptions and demands are visualized in the figure 6.1.

The color coding defines the systems and operational energy consumptions throughout the modelling test year.

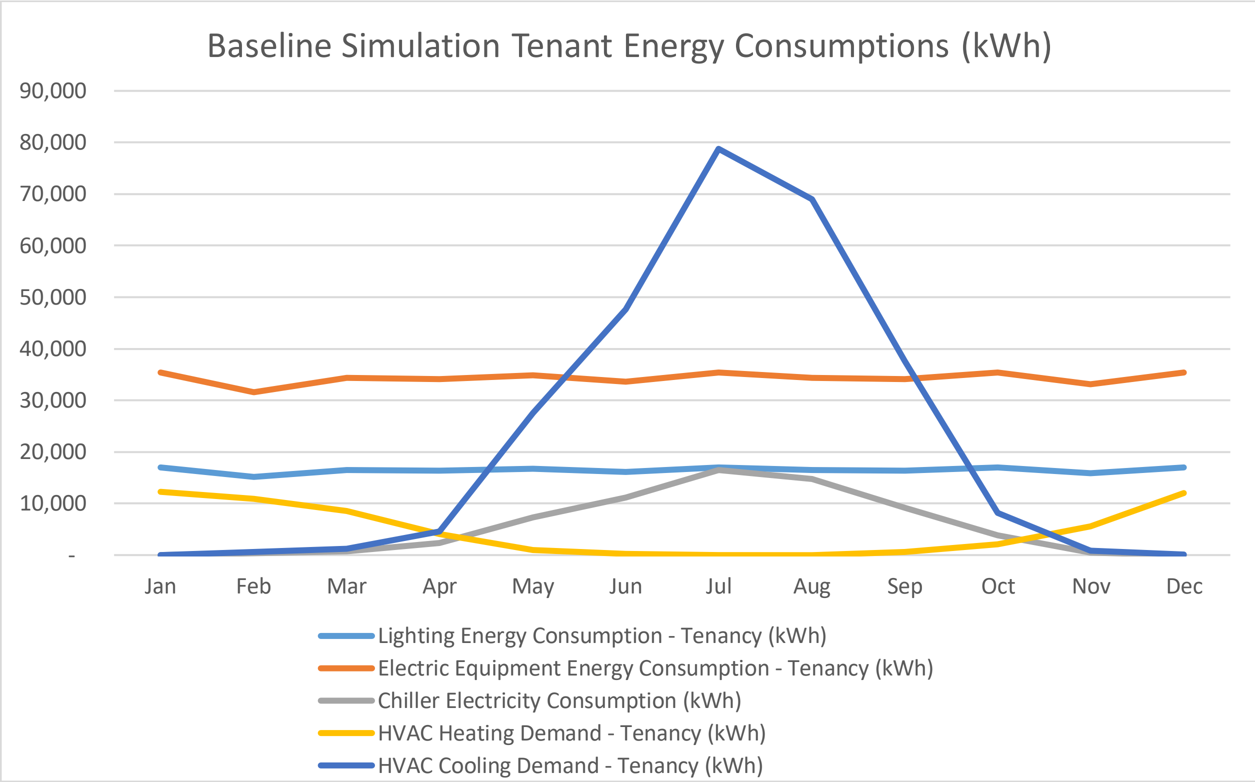

Figure 6. 1 Baseline simulation tenant energy consumptions

- **Metering data regularization**

For the calibration of the model monthly metering data in between 2015-2019 is used. From the data log, heating and cooling energy demand, chiller energy consumption, HVAC systems electricity consumption, lighting and power electricity consumption for both landlord and tenancy areas are extracted. The anomaly in the data is regularized by reasoning steps explained in the methodology section.

In figure 6.2 HVAC demand for heating and cooling is visualized. In both heating and cooling the anomalies over the 4 years trend occurs in the same months of the monitored period.

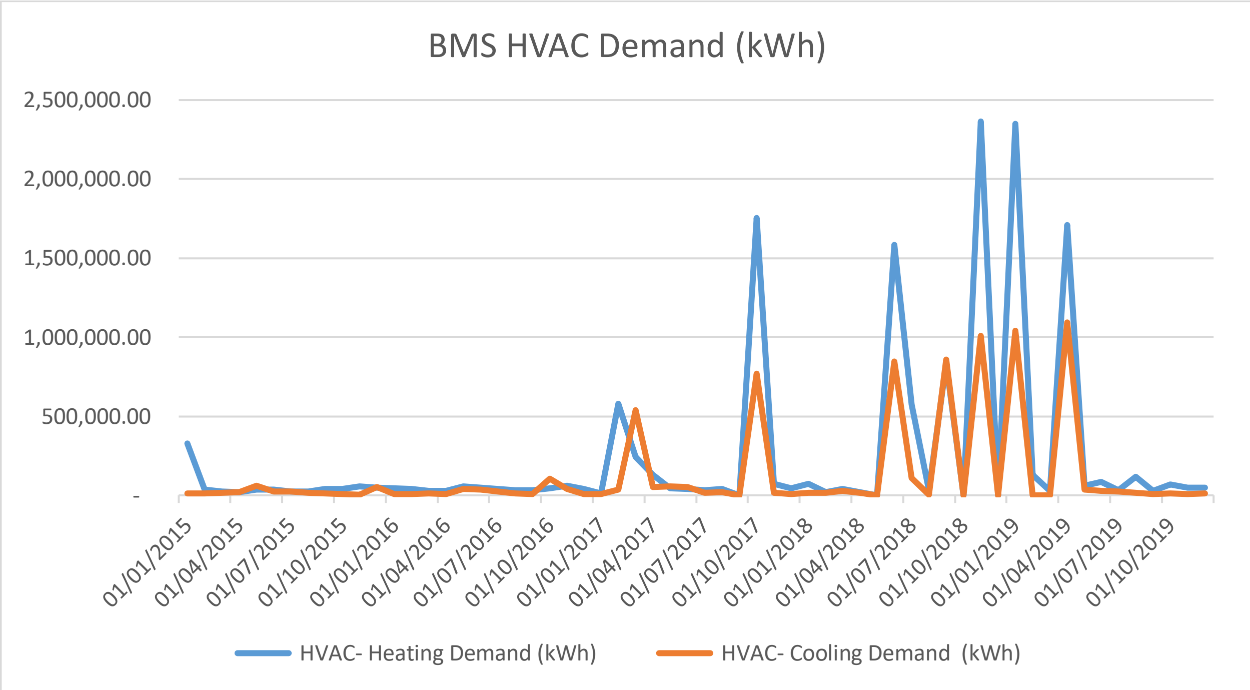

Figure 6. 2 BMS HVAC demand

The trends for heating and cooling are regularized using the overlaps of each month for 4 years using the displayed trend equation. In figure 6.3 regularized HVAC demand for heating and cooling is visualized. Due to the information limitation, further potential anomalies might be caused by building operation couldn't investigated further.

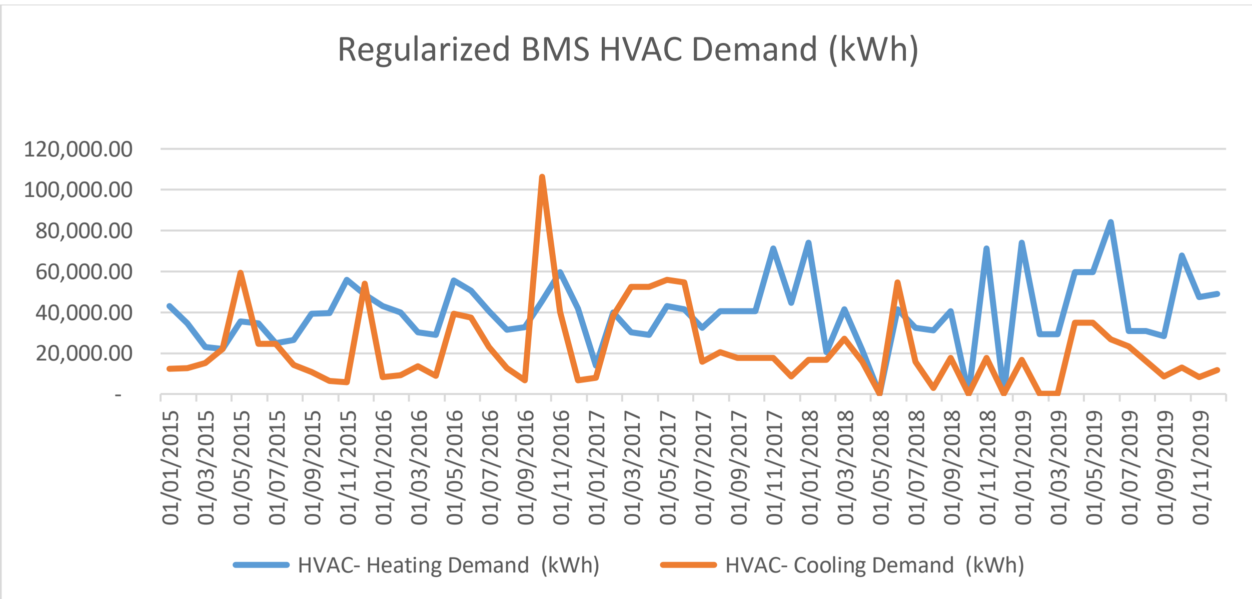

Figure 6. 3 Regularized BMS HVAC demand

In figure 6.4 BMS Chiller Electricity Consumption is visualized. The anomalies are only happened between 10-2017 and 01-2018.

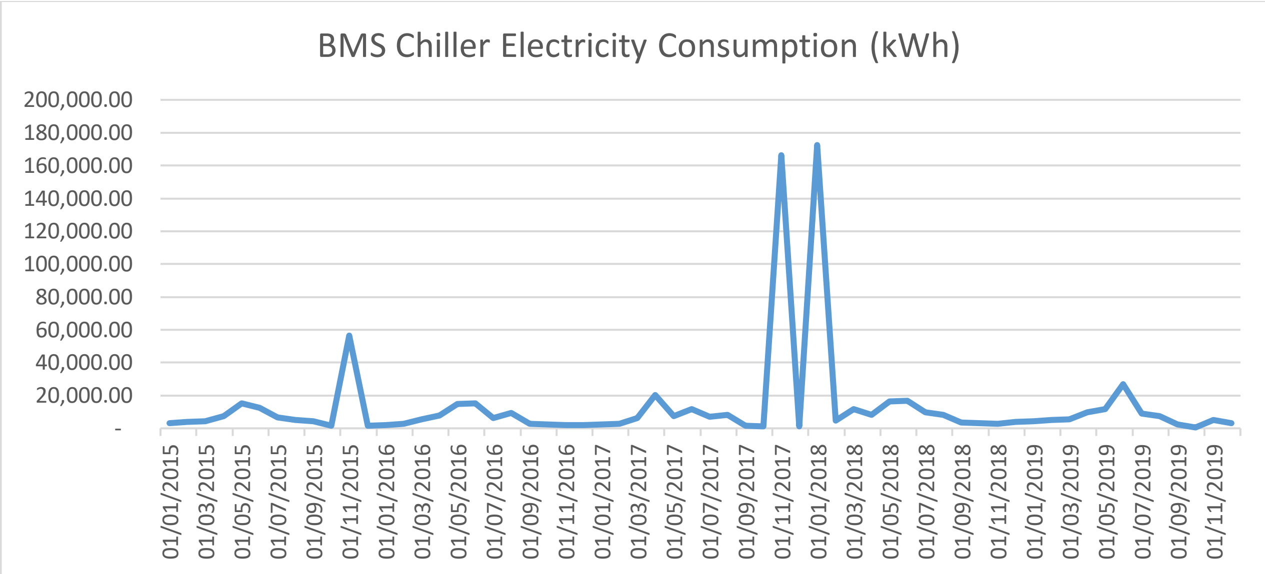

Figure 6. 4 BMS chiller electricity consumption

Similar to demand regularization, chiller electricity consumption is regularized using 4 years using the displayed trend equation. In figure 6.5 regularized BMS Chiller Electricity Consumption is visualized. Regularized chiller energy consumption has an expected trend mainly peaks during the summer months over the 4 years trend.

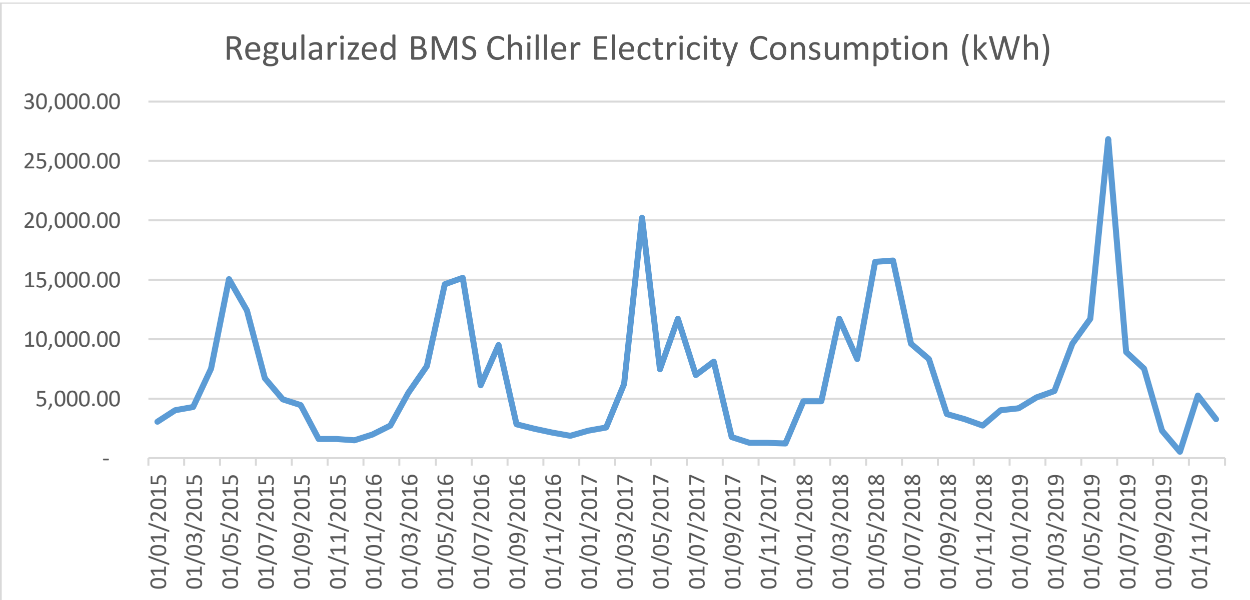

Figure 6. 5 Regularized BMS chiller electricity consumption

In figure 6.6 BMS Airside HVAC Electricity Consumption is visualized. This contains the consumption of all type of fans, circulation and domestic pumps. The only major anomaly is happening between 10-2017 and 01-2018.

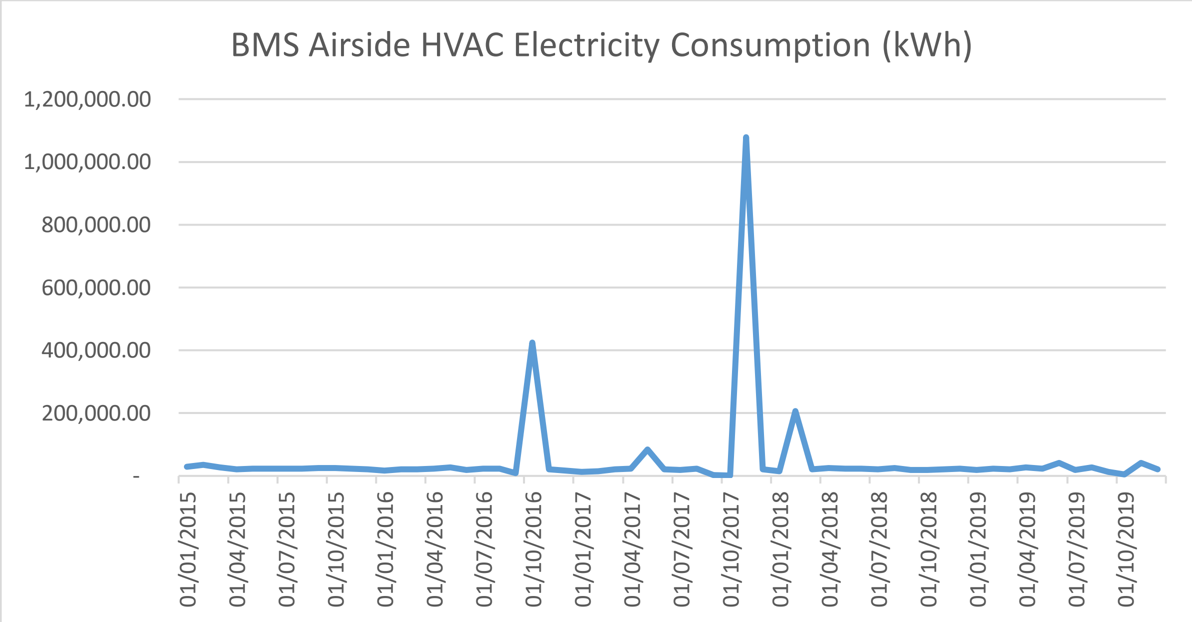

Figure 6. 6 Airside HVAC electricity consumption

Similar to demand regularization, airside HVAC electricity consumption is regularized using 4 years using the displayed trend equation. In figure 6.7 regularized BMS Airside HVAC Electricity Consumption is visualized.

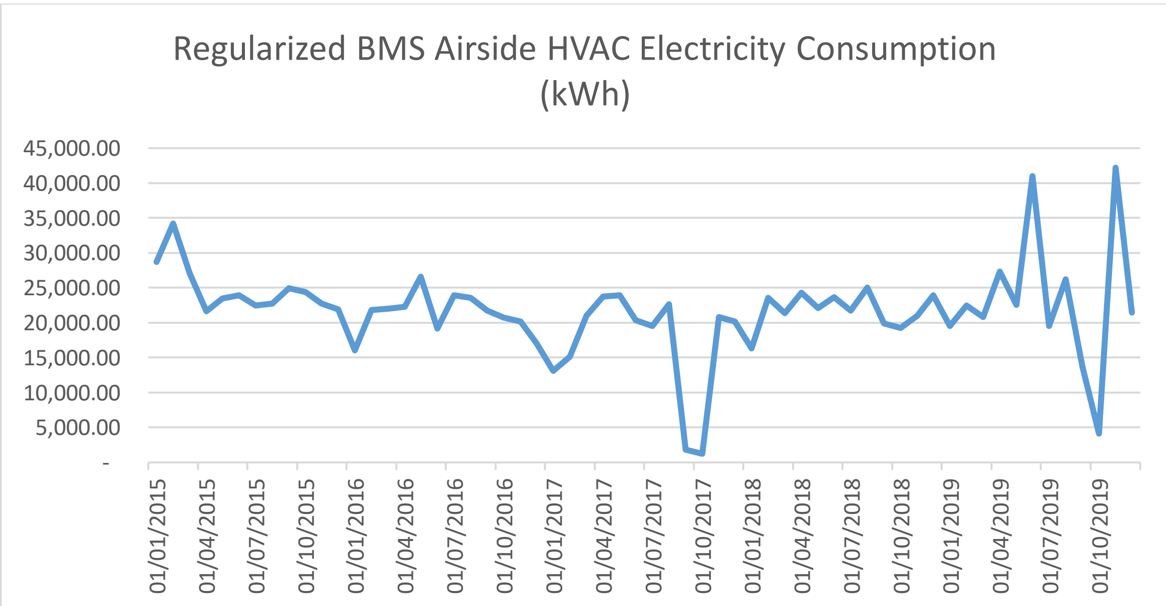

Figure 6. 7 Regularized BMS airside hvac electricity consumption

In figure 6.8 BMS Lighting Electricity Consumption is visualized for both landlord and tenancy lighting energy consumptions. The discrepancies in the lighting consumption happen between 10-2017 to 01-2018 and 01-2019 to 07-2019 in the tenancy areas.

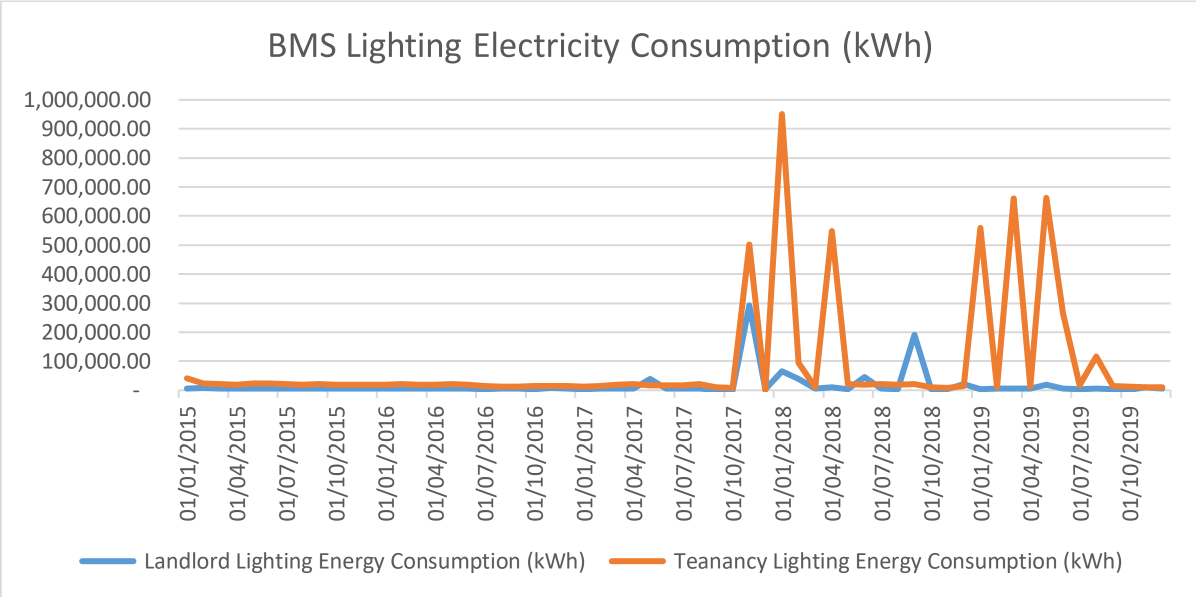

Figure 6. 8 BMS lighting electricity consumption

Previously explained strategy applied to the lighting energy consumptions and the regularized figures are visualized in figure 6.9.

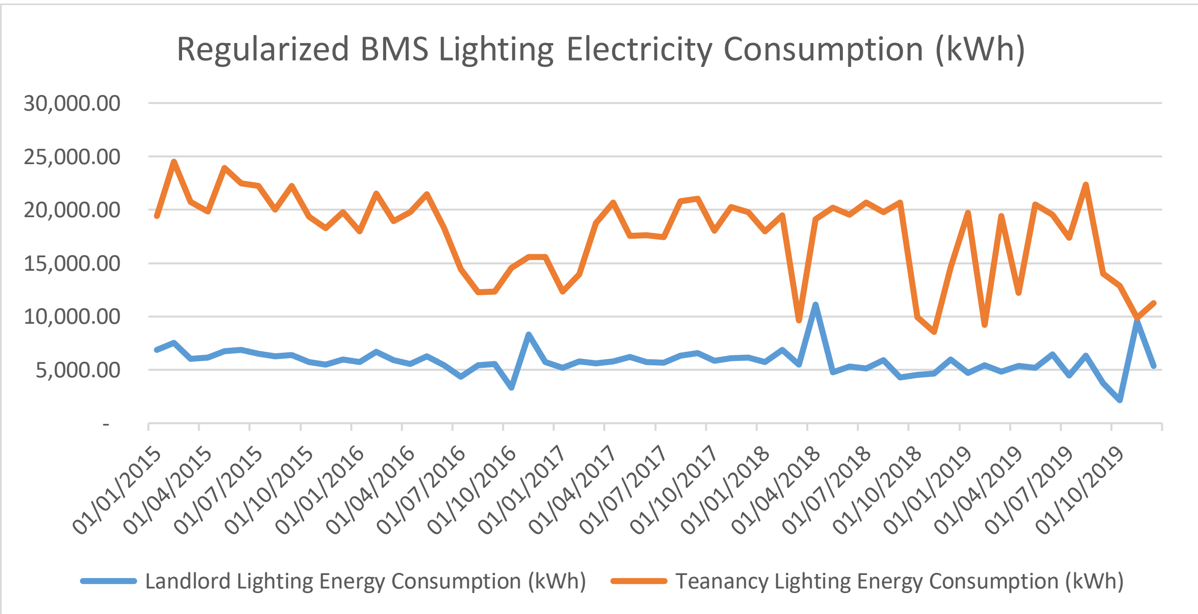

Figure 6. 9 Regularized BMS lighting electricity consumption

In figure 6.10 BMS Electric Equipment Electricity Consumption is visualized for both landlord and tenancy lighting energy consumptions. The discrepancies in the lighting consumption happen between 10-2017 to 01-2018 and 01-2019 to 07-2019 in the tenancy areas.

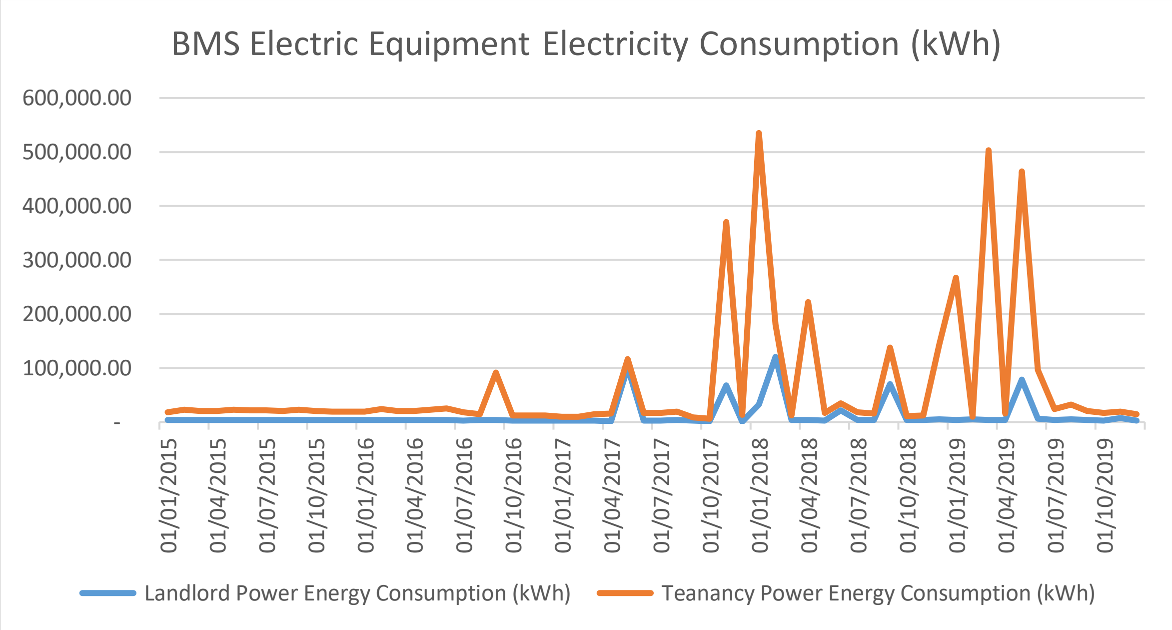

Figure 6. 10 BMS electric equipment electricity consumption

Previously explained strategy applied to the electric equipment energy consumptions and the regularized figures are visualized in figure 6.11.

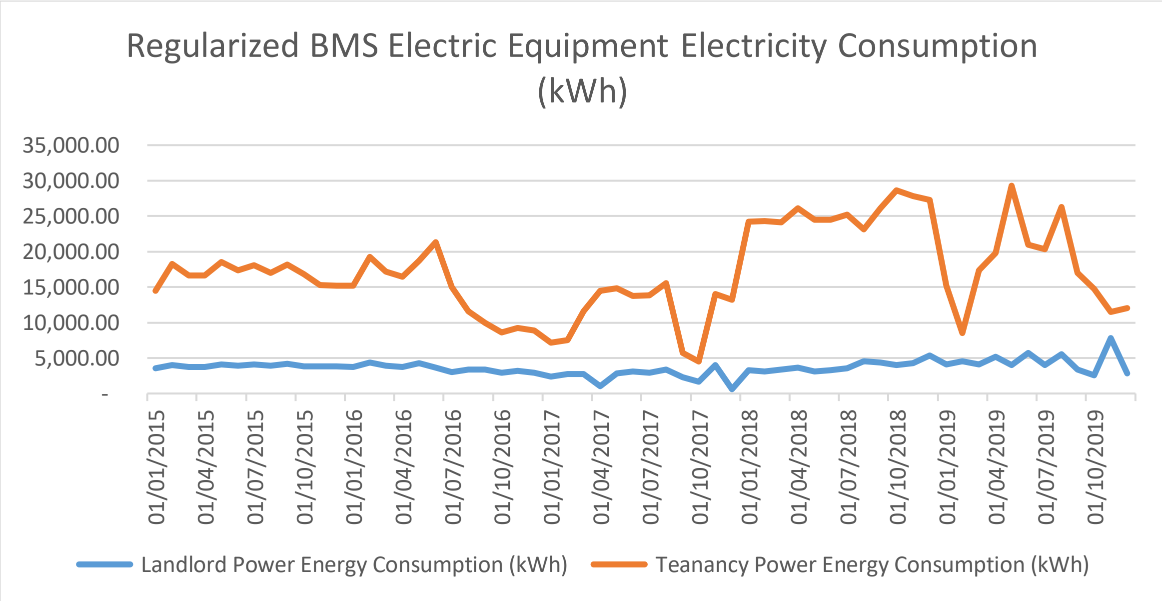

Figure 6. 11 Regularized BMS electric equipment electricity consumption

- **Baseline building model calibration**

After the regularization of the metering data, 2017 is selected as a reference to calibrate the baseline energy model. Model Metered building data and the staged calibration using iterative steps are listed. Total building electricity consumption and heating demand are visualized in the figure 6.12. The electricity energy consumption date is a combination of chiller, ventilation fan power, LTHW pump power, CHW pump power, other pumps (water booster pumps), landlord and tenancy electrical equipment and lighting electricity consumptions.

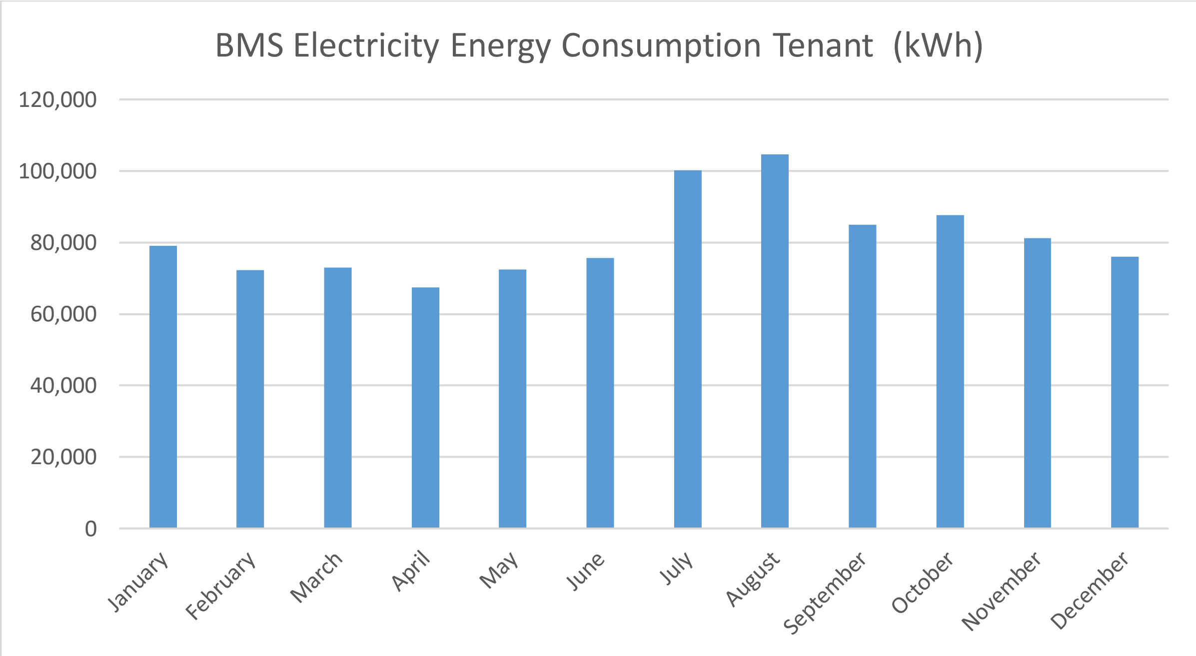

Figure 6. 12 BMS data electricity energy consumption 2017

Heating demand data contains the total energy demand for space heating and domestic hot water. AHU heating coils are calculated within the space heating. Figure 6.13 represents the BMD data for the combined heating energy demand for 2017.

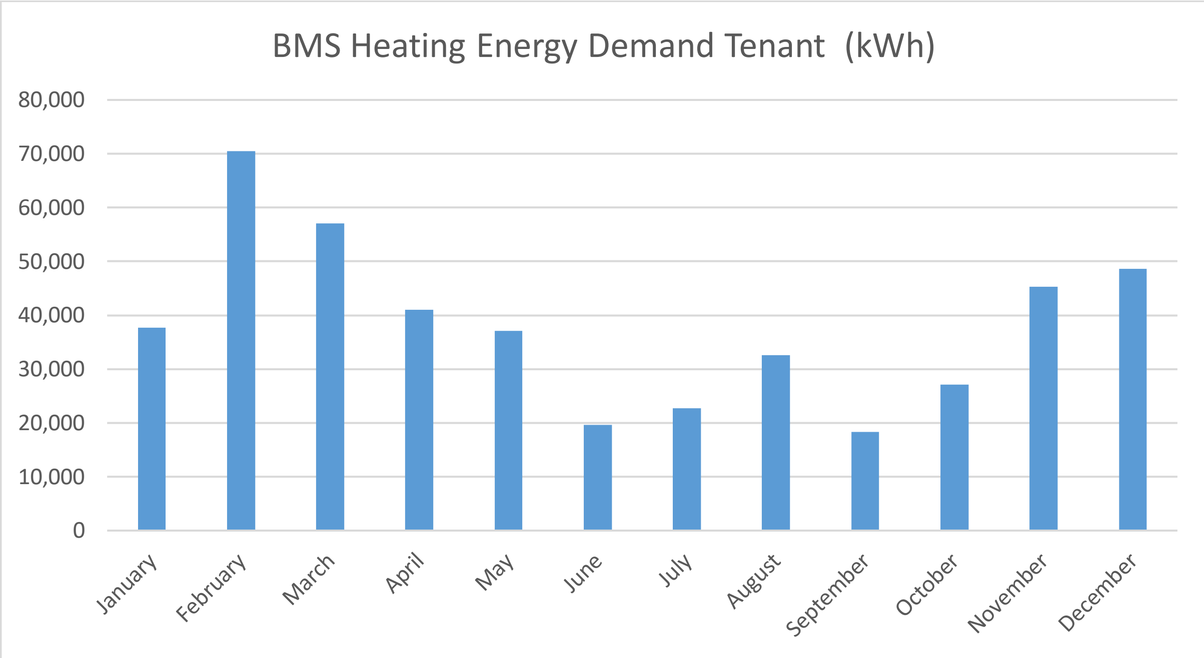

Figure 6. 13 BMS data heating energy demand 2017

Given the fact that there is a limited information available on the building operation, in the calibration only changes applied to lighting, electric equipment and occupancy densities. In total 6 runs, iteratively starting with lighting power density, following electrical equipment power density and occupancy density, are simulated and the hourly simulation data converged to the regularized BMS data.

In average lighting power density is updated from 12 W/m^2 to 6.75 W/m^2, electrical equipment power density is updated from 25 W/m^2 to 7.15 W/m^2 and occupancy density updated from 1 person per 10m2 to 1 person per 8 m2.

The comparison in the lighting and electrical equipment energy consumption between BMS and simulations are visualized in the figure 6.14 and 6.15.

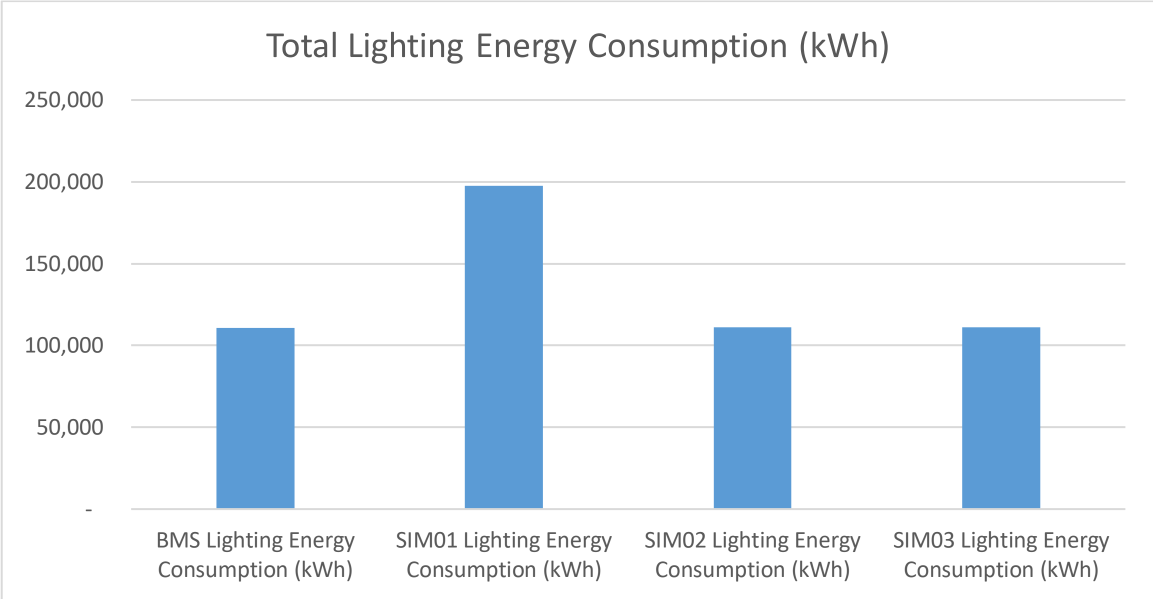

Figure 6. 14 Summarized comparison between BMS and iterations- lighting

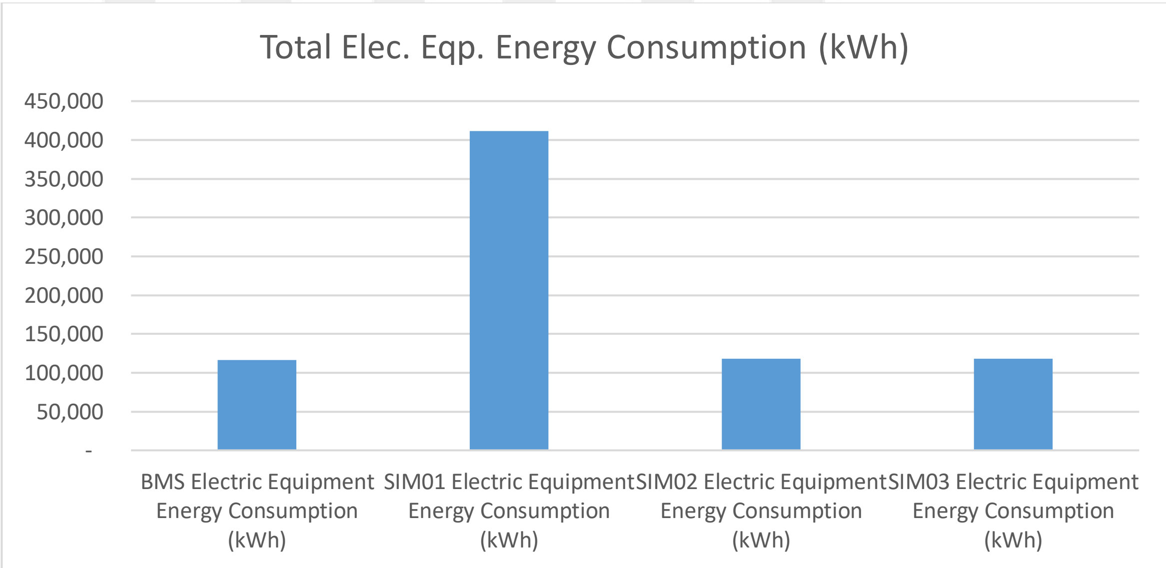

Figure 6. 15 Summarized comparison between BMS and iterations- elect eqp

- **Calibrated heating and cooling hourly load analysis**

The hourly heating and cooling demand to be used in the stage 2 analysis, is generated after the series of iterations of simulations. The results are also visualized and given in the figure 6.16.

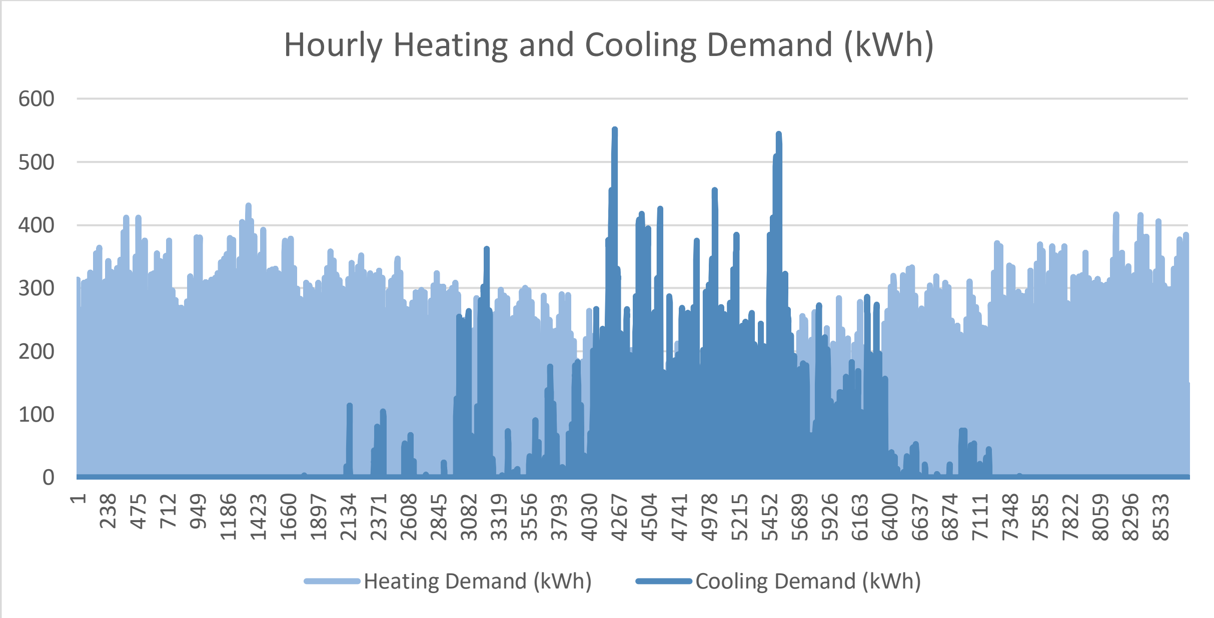

Figure 6. 16 Hourly heating and cooling demand results for the Stage 2 Analysis

In the stage 1 analysis, annual energy consumptions for heating, cooling, fans-pumps, lighting, DHW, lift and other electrical equipment are calculated. This step is important to understand the energy consumption behavior of the building. The tree map for the data consumption is visualized in the figure 6.17. This graph is important visualize the impact of each energy consumption system of the building. The total building energy use intensity is calculated as 164 kWh/m^2.annum. [79], [80]

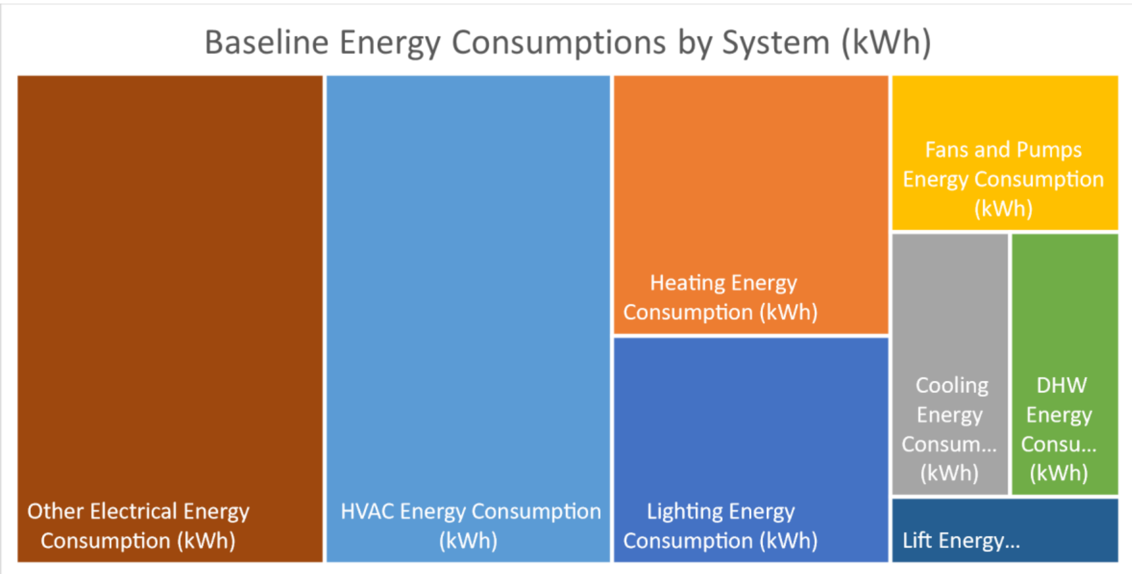

Figure 6. 17 Operational energy breakdown of the systems

The systems breakdown is also extracted from the calculations. In figure 6.18 energy use for regulated and unregulated loads are given alongside with the breakdown of systems included in the study (HVAC energy consumption) and excluded consumptions. Regulated energy that results from HVAC, DHW and lighting represents the 58% of the total building energy. Unregulated energy that results from the electrical equipment, lifts and other systems represents the 42% of the total building energy. The HVAC systems that subjected to this study is represents the 35% of the total building energy. The impact of the HVAC upgrades has bigger contribution to reduce the operational energy and carbon in the buildings. The study shows that the HVAC system selection in existing office buildings is a complex exercise and not only limited to the research area of this study.

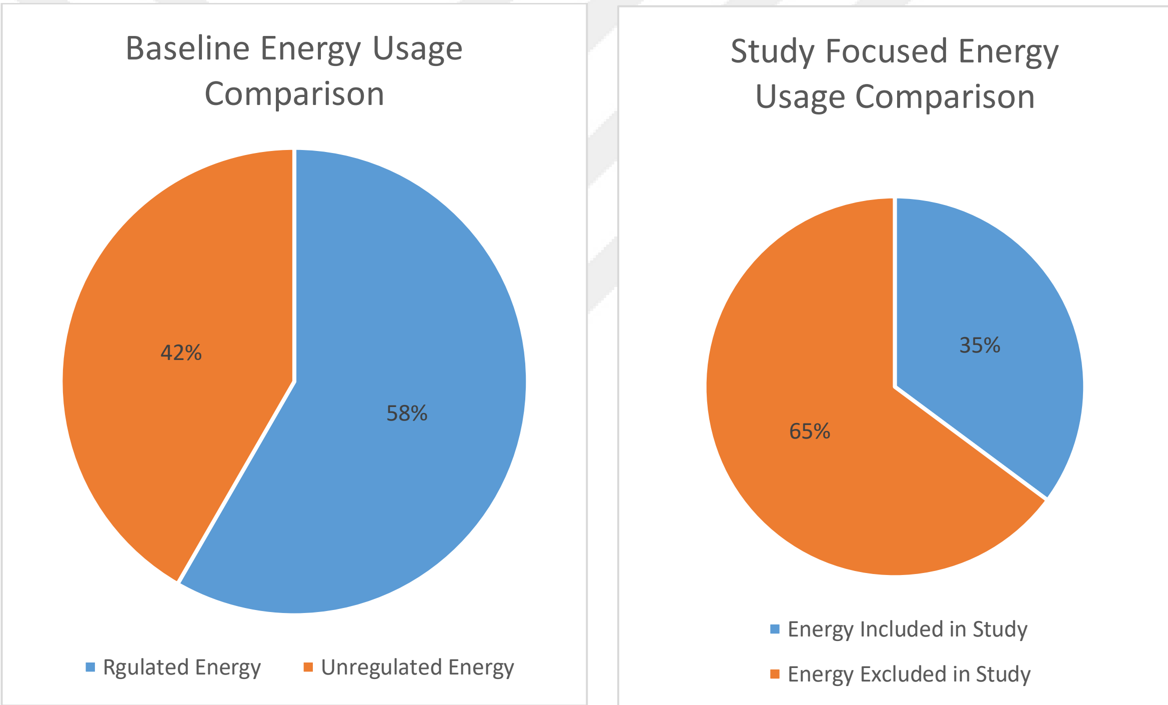

Figure 6. 18 Operational energy split based on energy type

6.2 Stage 2 Analysis - EBM

In the study a hybrid modelling methodology focused only to the HVAC is investigated and optimal solutions within the energy, carbon and cost constraints are analyzed. The study provides a bespoke calculation methodology against using am mathematical post-processing with optimization against the commercial software right along with the capability to compare operational carbon and energy, embodied carbon and cost together.

In the stage 2 analysis, using the outputs from the stage 1 analysis, the NSGA-ii algorithm tested within the EBM.

The algorithm is tested for the cost functions: operational energy, embodied carbon and CAPEX. These results are presented in the Pareto front together and individually. Additionally, operational carbon and OPEX is also calculated in EBM to support the decision-making process. These are not considered as cost functions to minimize the complexity of the optimization.

The results of each cost function are presented individually in the following sections. The results are given as standard deviation, standard deviation trendlines, fitness values and trade-off tables. Also combined results are given as parallel coordinate plots and pareto front space.

- **NSGA-ii Optimization Analytics**

The optimization results are tested with different generation sizes, generation counts, crossover and mutation rates. Only the results of the pareto front run are presented in the study. As explained in the methodology, there is no specific calibration factor can be applicable in the NSGA-ii algorithm. These settings of these control parameters allow to find the appropriate configuration to achieve good results.

Standard deviations for each cost function are visualized in figure 6.19. In each graph, the x-axis represents the objective values that are optimized. The y-axis represents the standard deviation of the objective values across the solutions. The higher value given on the y-axis indicates the larger spread or variability of each objective values for the corresponding objective.

Not like operational energy and embodied carbon, the higher standard deviation for CAPEX suggests that the solutions' objective values for this specific objective is more scattered. This is an important metric for to analyze the diversity of solutions on the Pareto front and a result of similar cost results for the variety of the solutions.

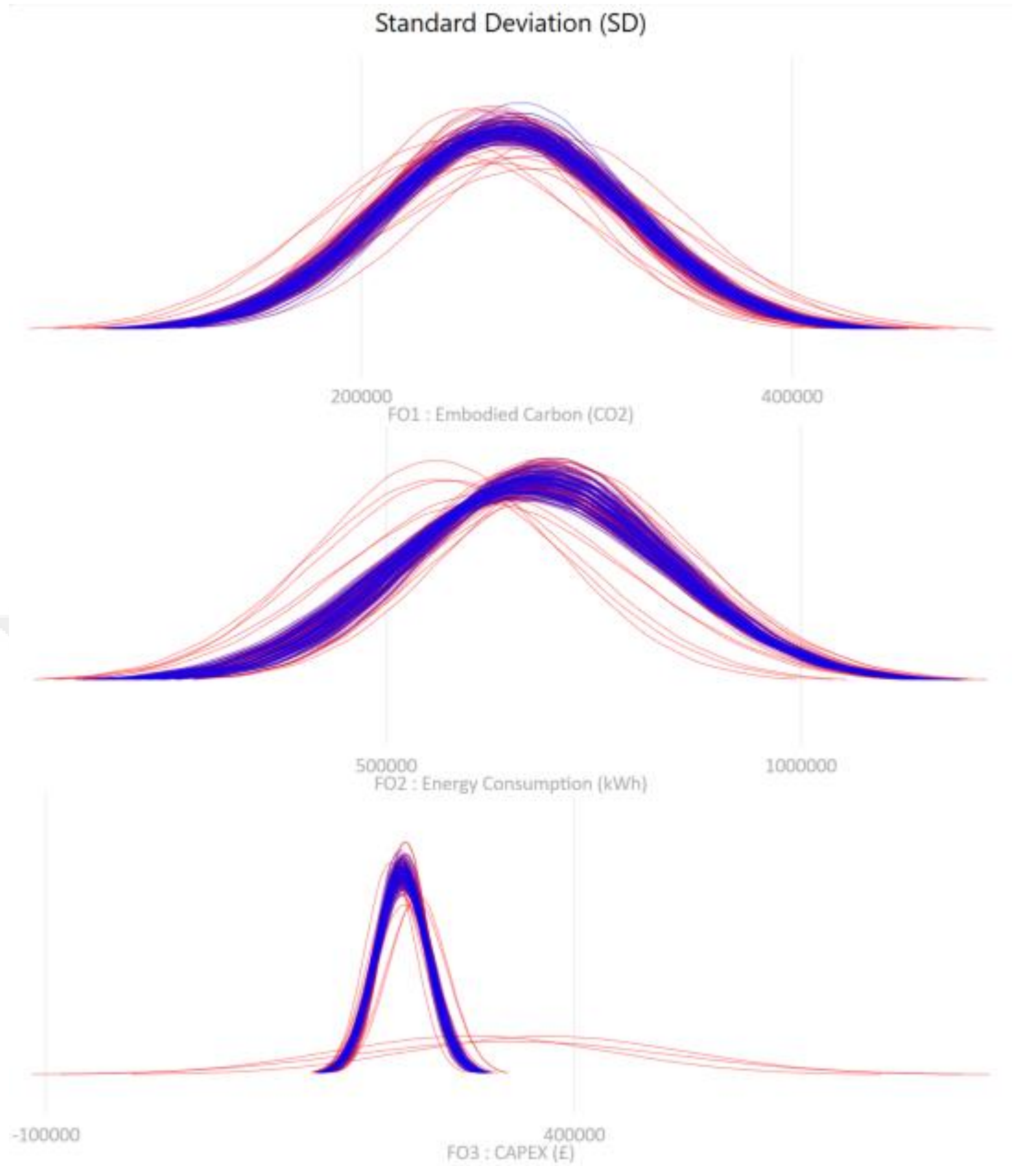

Figure 6. 19 Standard deviation graphs of the cost functions

Fitness values for each cost function are visualized in figure 6.20. In each graph, the x-axis represents the generation count. The y-axis represents the fitness values of the objective values across the generations. The fitness values are the objective values that are optimized. The fitness values are monitored over generations or iterations. The decreasing trend in fitness values over time is the indication of convergence. It's visualizing the trend of finding better solutions towards the true Pareto front.

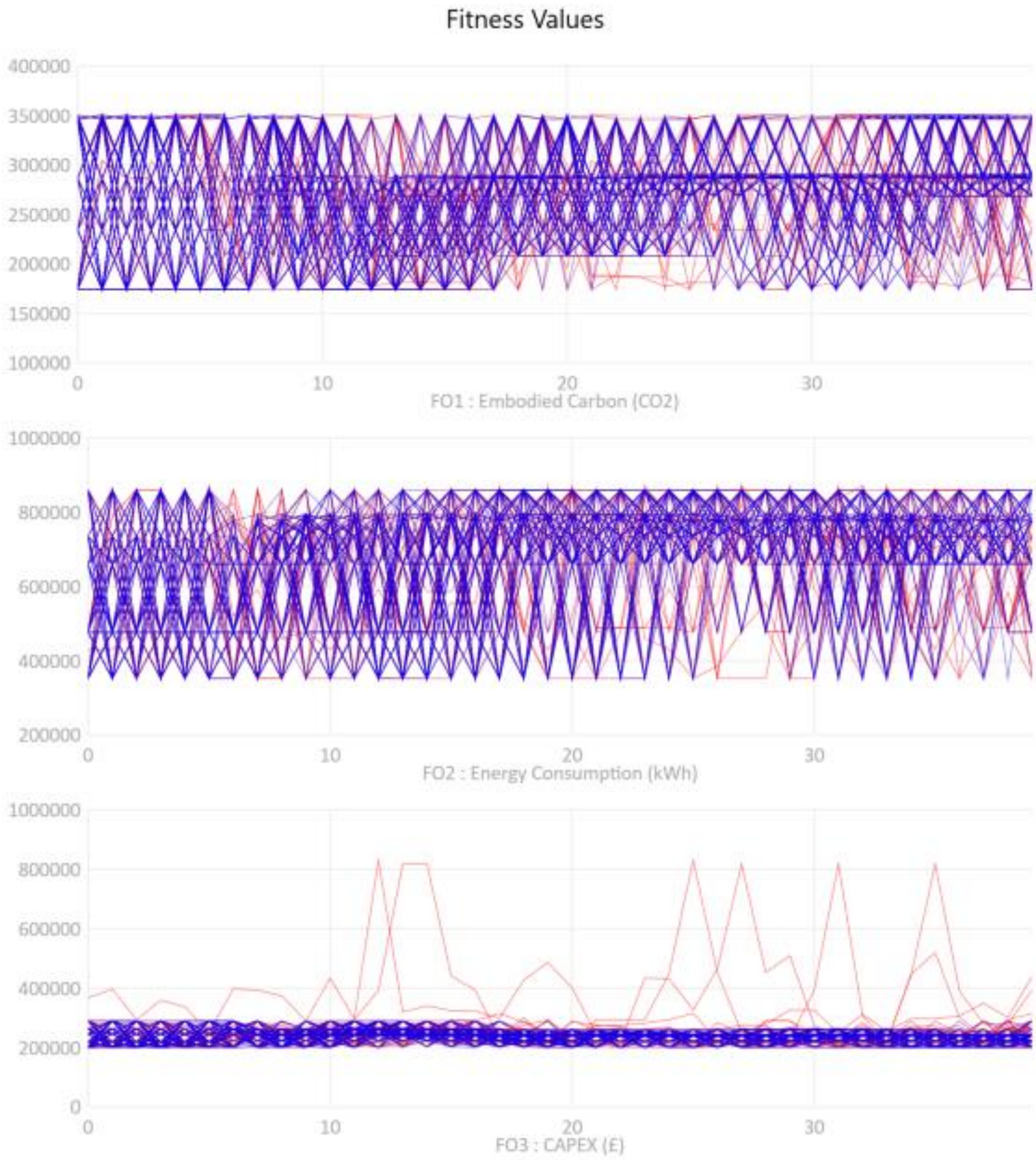

Figure 6. 20 Fitness value graphs of the cost functions

Standard deviation value trendlines for each cost function are visualized in figure 6.21. The x-axis represents the generation count and the y-axis represents the standard deviation of the objective values across the solutions. The standard deviation over generations is monitored to understand the insights into the convergence and diversity of the NSGA-II algorithm. The higher standard deviations observed in the early generation is a resultant of the NSGA-ii algorithms explore on the solution space. The standard deviation decreases for each objective as the algorithm progress as an indication of algorithm is converging towards a more concentrated and diverse set of solutions on the Pareto front.

Figure 6. 21 Standard deviation value trendlines of the cost functions

The mean value trendlines that are represented in figure 6.22 represent the average fitness values of the solutions in each generation of the algorithm. Similar to standard deviation trendline, mean value trendlines provide the insights into the convergence behavior and progress of the optimization process. These mean value trendlines are also used to understand the average impact of the solutions.

Figure 6. 22 Mean value trendlines of the cost functions

The pareto front results are visualized in figure 6.23. Each axis represents the cost functions. These non-dominated optimal solutions obtained from the NSGA-ii algorithm, represents the solutions which doesn't require further improvement with the quality and diversity. The additional layer of operational carbon and OPEX is introduced after this stage to support the decision-making process further. The full list of pareto-optimal solutions is represented in Appendix J.

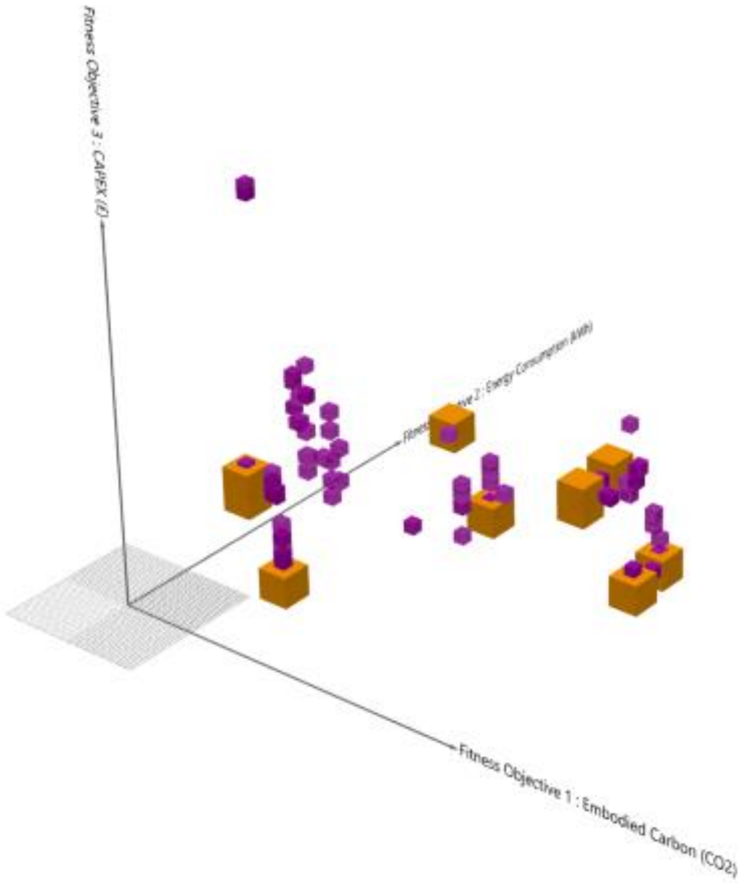

Figure 6. 23 Pareto front selections

- **Simulation Trade-offs**

Trade-off for airside and plants are calculated and given under table 6.1 and 6.2. Trade-offs shows the comparison of the performance for the system interventions. The interventions of each system are compared for operational energy consumption, embodied carbon and CAPEX.

In airside model, the DOAS system in overall 9% more energy efficient and 21% cost effective than the AAHS system. However, AAHS has a better overall embodied carbon performance with 19%.

Lower air temperature for heating and higher air temperature for cooling increase the air flow rate. This increases the fan consumptions for each option.

For DOAS systems, higher heating air supply temperature results with lower flow rates and effects the capacity of terminal units. 35°C heating air flow temperature over 30 °C performs better against 3 cost scenarios. Increased cooling air flow temperature has a negative impact on energy, from 14 to 18 °C the energy consumption is increased by 5%. However, it has a positive impact to embodied carbon and CAPEX.

Similar to DOAS systems in the table 6.1 similar results for air supply temperatures are represented for all 3 cost functions.

Airside supply temperatures have a very limited impact on operational energy and no impact on embodied carbon and CAPEX on their own. However, the impact on the fan energy consumption increases its significance of it.

The number of indoor units in DOAS system is a very important intervention for embodied carbon and CAPEX results. Bigger terminal unit capacity results in better energy results however brings additional embodied carbon and CAPEX.

The study shows the impact of increased unit numbers have a limited impact on operational energy consumption but 8-10% on the embodied carbon and CAPEX. This is also an important driver for the design and the controllability of the thermal comfort.

Heat recovery in ventilation is an effective energy efficiency contributor in office buildings. The impact of HR in ventilation on operational energy depending on the efficiency vary in between 17-26%. It has additional embodied carbon due to increased material and CAPEX.

Table 6.1 Air-side trade-offs

System	**Intervention**	**HVAC Operational Energy Consumption (kWh)**	**HVAC Embodied Carbon (kgCO2)**	**HVAC CAPEX (£)**
Air System Selection	DHS	-	-	-
	AAHS	-9%	19%	-21%
DHS Terminal Heating Air Supply Temp (°C)	30	-	-	-
	35	2%	4%	2%
DHS Terminal Unit Type	1	-	-	-
	2	1%	-8%	-2%
	3	2%	-10%	-10%
DHS AHU Type	1	-	-	-
	2	29%	26%	-41%

	3	43%	23%	-54%
	4	25%	28%	-41%
	5	38%	23%	-54%
	6	41%	24%	-58%
DHS AHU HX Eff	Off	-	-	-
	70%	17%	-7%	-9%
	80%	26%	-7%	-11%
AAHS Heating Air Supply Temp (°C)	30	-	-	-
	35	2%	0%	1%
AAHS AHU Type	1	-	-	-
	2	18%	-8%	-11%
	3	17%	-12%	-18%
	4	21%	-20%	-23%
	5	20%	-19%	-19%
	6	21%	-18%	-23%
AAHS AHU HX Eff	Off	-	-	-
	70%	-2%	4%	5%
	80%	0%	1%	-1%
DHS Terminal Cooling Air Supply Temp (°C)	14	-	-	-
	18	-5%	6%	6%
AAHS Cooling Air Supply Temp (°C)	14	-	-	-
	18	-6%	-1%	-2%

Plant selections takes an important role in design of buildings HVAC systems. It's crucial for both operational energy, embodied carbon and CAPEX. Plant capacity, fuel type, circulated water temperature and the plant efficiency are important in addressing the energy efficiency. Water temperatures are especially important for the plants to interact with outside air to heat/cool the water.

Lower water temperature for heating and higher water temperature for cooling increase the plant efficiency and results with better energy consumption without impacting the embodied carbon and CAPEX.

VRF is providing the overall best plant solution for the operational energy consumption in heating and a decent in cooling. It's 49% more efficient than a Natural Gas (NG) Boiler operating at 70 °C flow temperature. Due to the amount of refrigerant that the system contains, it has a poor embodied carbon performance. CAPEX performance is also low for the VRF system.

ASHP due to the complexity of the systems they have higher CAPEX. The plant performance is a function of the outdoor temperature, load and the supply temperature. The plant performance increase with a lower heating supply temperature and higher cooling supply temperature.

ASHP and VRF systems can be able to do heating and cooling with the same unit. It's an advantage to reduce overall plant space and CAPEX.

VRF for heating with Air Cooled Chiller or ASHP is providing the overall best plant solution for the CAPEX, however, the plant area is not a constraint for the results. This could bring practicality issues in different cases.

Table 6.2 Plant trade-offs

System	**Intervention**	**HVAC Operational Energy Consumption (kWh)**	**HVAC Embodied Carbon (kgCO2)**	**HVAC CAPEX (£)**
Heating Plant Type	NG Boiler 70 °C	-	-	-
	NG Boiler 50 °C	-84%	20%	-8%
	Electric Boiler 70 °C	4%	6%	-19%
	Electric Boiler 50 °C	-2%	9%	-14%
	ASHP 70 °C	36%	4%	-34%
	ASHP 50 °C	39%	8%	-36%
	VRF	49%	-32%	-81%
Cooling Plant Type	ACC 6 °C	-	-	-
	ACC 10 °C	30%	-6%	-17%
	WCC 6 °C	23%	3%	-25%
	WCC 10 °C	29%	1%	-27%
	ASHP 6 °C	19%	12%	9%
	ASHP 10 °C	22%	23%	21%
	VRF	-2%	-8%	-11%

- **Stage 2 Analysis Operational Energy**

Operational energy consumptions for the pareto front solutions are visualized in figure 6.24. X-axis represent the generation count and y-axis represents the operational energy consumption numbers. The pareto front results for operational energy vary between 200,000 – 320,000 kWh. All figures are below the 367,300-

kWh baseline number. Pareto front results figure 13-46% savings over the baseline consumptions.

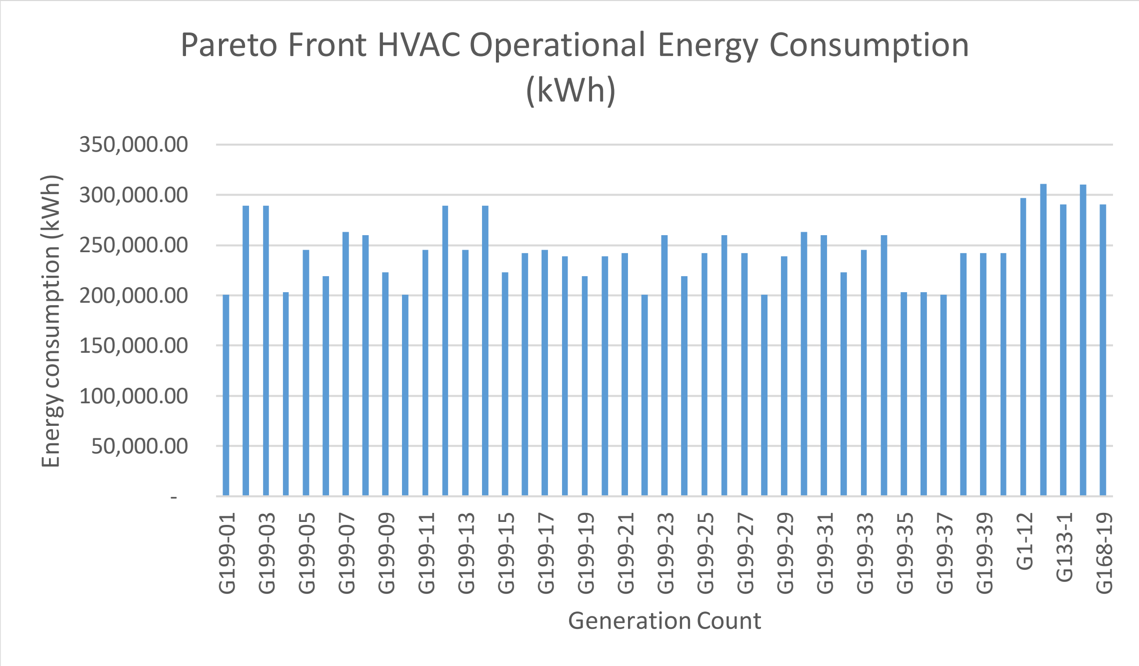

Figure 6. 24 Pareto front solutions HVAC operational energy consumption

Heating and cooling energy consumptions for the pareto front solutions are visualized in figure 6.25. X-axis represent the generation count and y-axis represents the heating and cooling energy consumption for interventions. In the chart color blue represents the heating energy consumptions and color orange represents the cooling energy consumption. Even the cooling demand is higher than heating for the analysis period of a year heating has a higher impact on the energy consumption results due to the longer heating period.

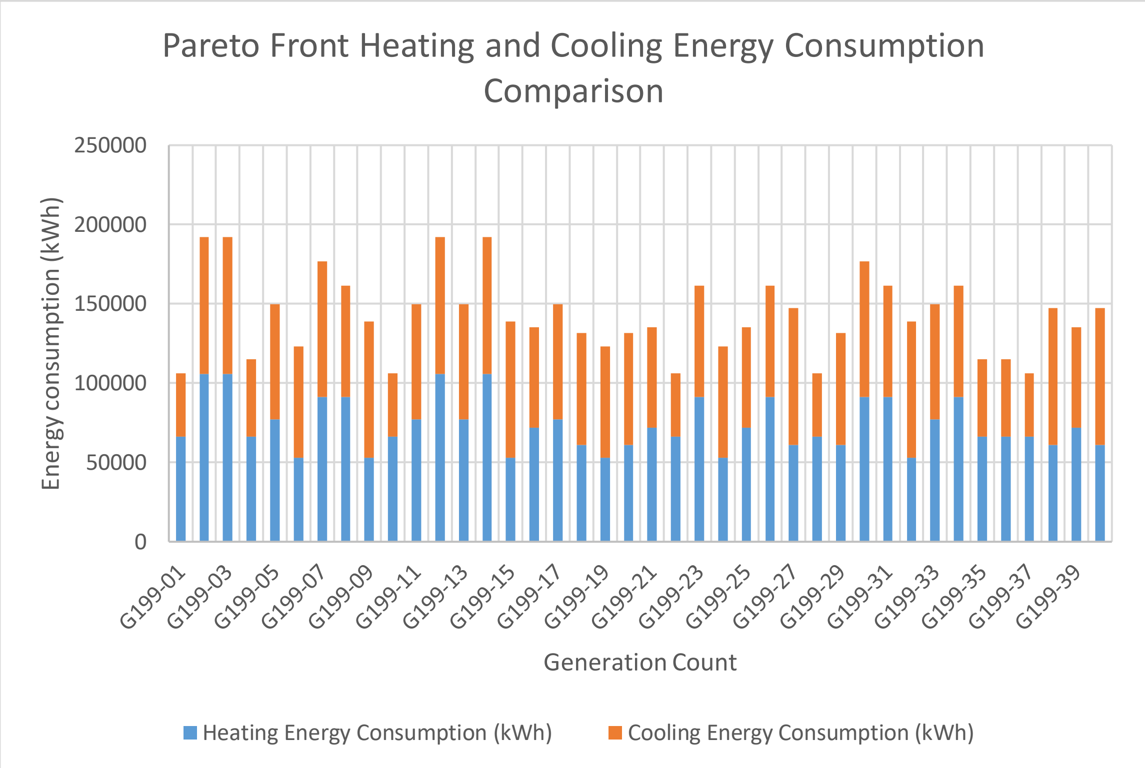

Figure 6. 25 Pareto front solutions HVAC heating & cooling consumption

- **Stage 2 Analysis Embodied Carbon and Operational Carbon**

For the carbon calculations, in all given pareto front iterations operational carbon and embodied carbon are estimated based on the embodied carbon library generated and the fuel carbon prediction calculations. Embodied carbon and operational carbon over a span of 22 years for the pareto front solutions are visualized in figure 6.26. X-axis represent the generation count and y-axis represents the total carbon figures. In the chart color blue represents the embodied carbon and color orange represents the total operational carbon in between 2023-2045.

The pareto front results for embodied carbon vary between 174,000- 350,000 $kgCO_2$ and operational carbon vary between 375,000-581,000 $kgCO_2$.

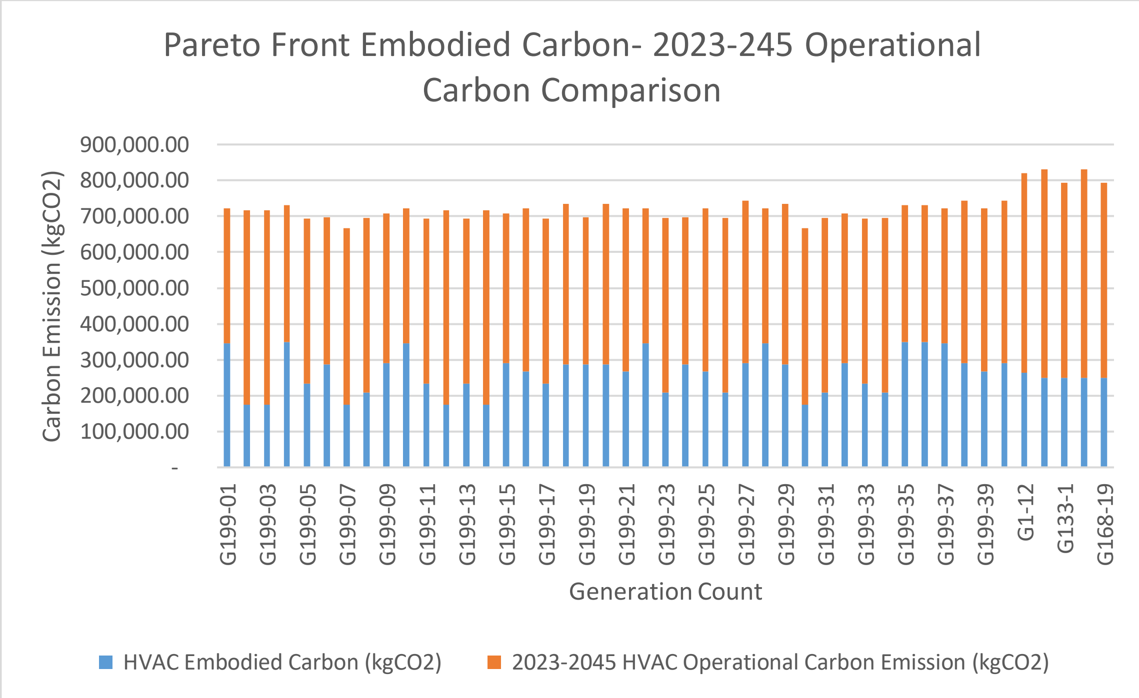

Figure 6. 26 Pareto front embodied carbon- 2023-245 operational carbon

- **Stage 2 Analysis CAPEX and OPEX**

For the cost calculations, in all given pareto front iterations CAPEX and OPEX are estimated based on the cost library generated and the energy unit prices. CAPEX and OPEX over a span of 22 years for the pareto front solutions are visualized in figure 6.27. X-axis represent the generation count and y-axis represents the total OPEX and CAPEX figures. In the chart color blue represents the CAPEX and color orange represents the total OPEX in between 2023-2045.

The pareto front results for CAPEX vary between £ 350,000 – 860,000 and OPEX vary between £ 652,000-1,000,000.

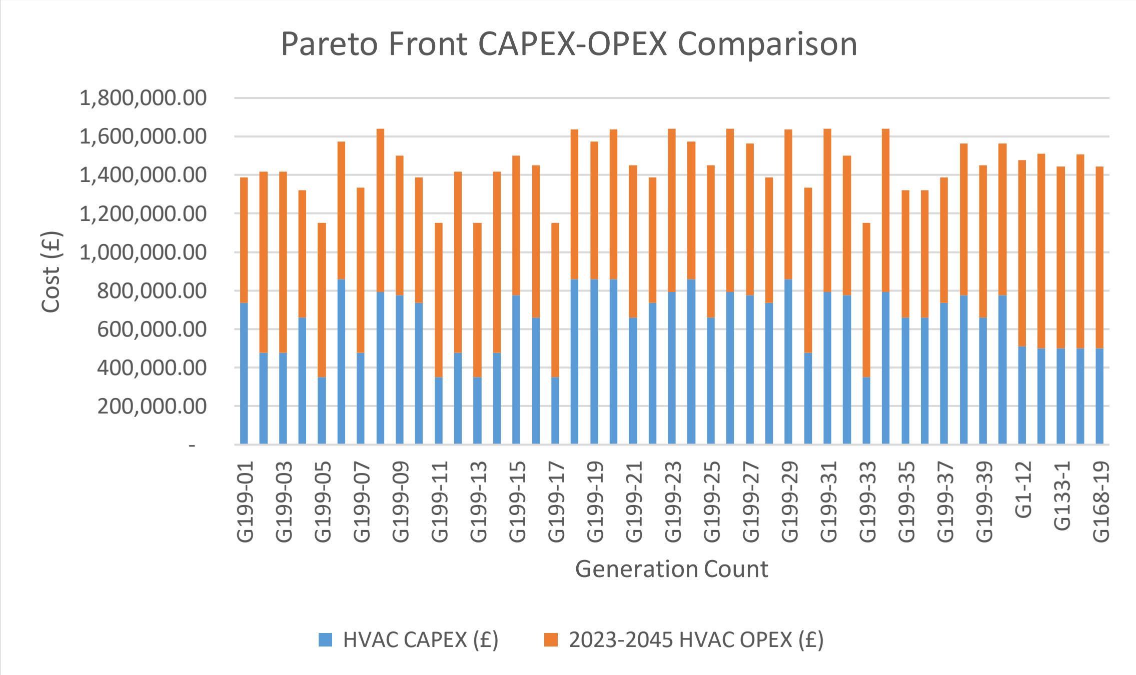

Figure 6. 27 Pareto front CAPEX-OPEX comparison

- **Stage 2 Analysis Combined**

In the study, worst and best performing calculated scenarios are compared against the baseline for operational energy, embodied carbon and CAPEX. Additionally, 2 selected solutions are considered to represent these against the solutions. The first custom scenarios are selected from the pareto front and the second one is selected from the main simulation results which is represents close results to pareto front. At the time that there is no embodied carbon and CAPEX for baseline, the comparison for these is only for interventions. The summary input reference for the selected scenarios is presented in the table 6.3. Further details of the scenarios can be seen in Appendix J using the run reference number of the solution. In the given table scenario reference is given as “run”, and the main drivers as air system selection, heating plant system with supply temperature reference, and cooling plant system reference is represented.

Table 6.1 Test scenarios from results

	Run	**Air System Selection**	**Heating Plant System**	**Cooling Plant System**
Worst Energy	G1-13	AAHS	NG Boiler 50C	Air Cooled C 6C
Worst Embodied Carbon	G1-14	DHS	ASHP Heating 50C	VRF Cooling
Worst CAPEX	G3-25	AAHS	VRF Heating	Water Cooled C 6C
Best Energy	G197-15	DHS	VRF Heating	Water Cooled C 10C
Best Embodied Carbon	G46-13	AAHS	ASHP Heating 50C	ASHP Cooling 10C
Best CAPEX	G4-34	DHS	ASHP Heating 70C	ASHP Cooling 10C
Selected Scenario 1	G199-2	DHS	VRF Heating	Air Cooled C 10C
Selected Scenario 2	G9-23	AAHS	VRF Heating	VRF Cooling

Further details for the comparison scenarios are represented in the table 5.4.

Table 6.2 Additional inputs reference for test scenarios from results

	Run	Heating Air Supply Temp (C)	DHS Terminal Unit Type	DHS AHU Type	AHU HX Eff	AAHS AHU Type	Cooling Air Supply Temp (C)
Worst Energy	G1-13	30	0	0	0	3	18
Worst Embodied Carbon	G1-14	35	0	1	0.7	5	18
Worst CAPEX	G3-25	35	1	1	0.7	1	14
Best Energy	G197-15	35	0	2	0.8	3	14
Best Embodied Carbon	G46-13	35	0	5	0.8	5	14
Best CAPEX	G4-34	30	1	2	0.8	4	14
Selected Scenario 1	G199-2	35	0	4	0.7	3	14
Selected Scenario 2	G9-23	30	0	4	0.7	4	18

In order of figures 6.28 to 6.30, comparison graphs are representing the energy, embodied carbon and CAPEX.

Displayed in Figure 6.28, the bar chart presents a comparison of energy consumption across different scenarios. The data represents the annual energy consumption in kilowatt-hours (kWh). X- axis represents the scenarios and y-axis represents the annual energy consumption of the scenarios.

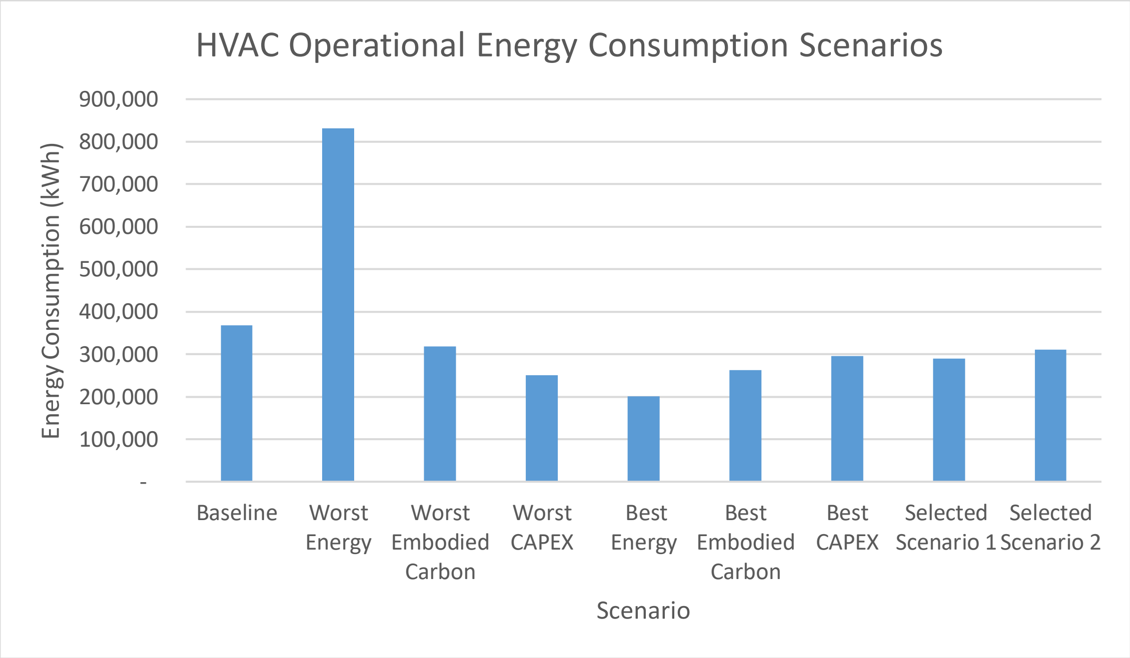

Figure 6. 28 Operational energy split based on energy type

Best energy scenario shows the least amount of energy consumption compared to other scenarios and performing 45% better than the baseline and 16% better than the average simulation results.

Selected scenarios 1 and 2 exhibit moderate energy usage, with values falling between the baseline and the best energy scenarios. Scenario 1 has a 34% better energy performance than baseline and 0.3% better energy performance than the average simulation results.

Worst energy scenario shows the highest energy consumption, exceeding all other scenarios including the baseline.

Figure 6.29 presents a comparison of embodied carbon emissions for the selected scenarios. Embodied carbon represents the total carbon dioxide equivalent (CO2e) emissions associated with the manufacturing, transportation, and installation of materials. The chart aims to highlight the differences in carbon footprints of each solution, aiding decision-makers in making sustainable choices. - axis represents the scenarios and y-axis represents the embodied carbon emissions (CO2e in metric tons) of the scenarios.

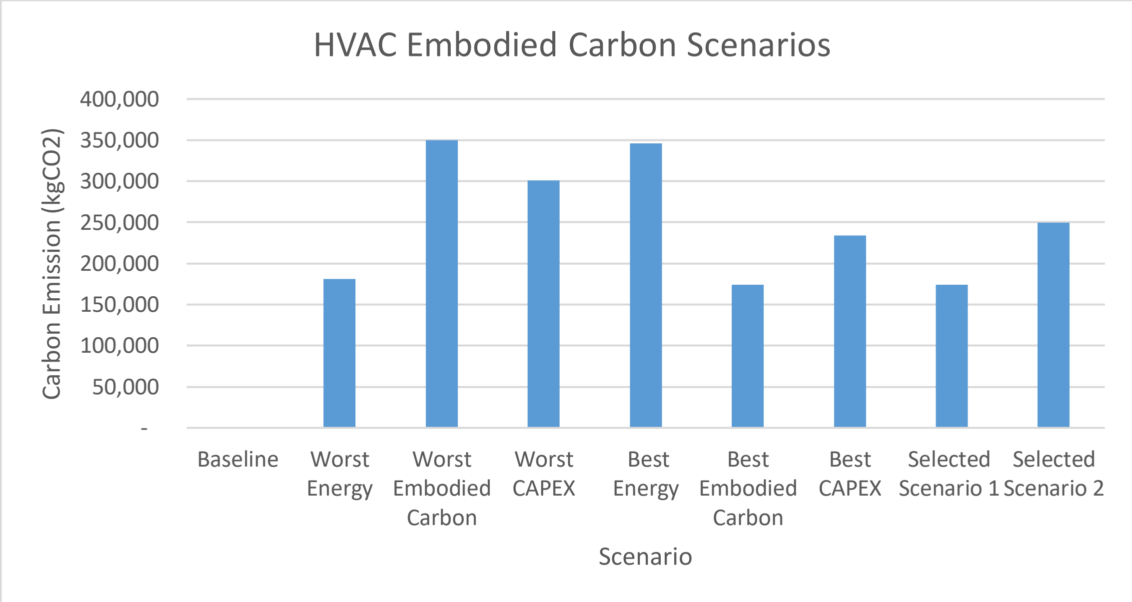

Figure 6. 29 Operational energy split based on energy type

Baseline as it stands doesn't not contribute to any additional embodied carbon emissions.

Worst embodied carbon scenario together with the best energy scenario exhibit the highest embodied carbon emissions, surpassing all other solutions.

Selected scenario 1 and worst energy scenarios have moderate carbon footprints, with values falling between best and worst solutions.

Best embodied carbon scenario has the lowest embodied carbon emissions compared to others with a 35% better performance than the average simulation results.

Figure 6.30 provides a comparison of CAPEX for different scenarios. CAPEX represents the initial capital investment required to fund each solution. X- axis represents the scenarios and y-axis represents the cost associated to the scenarios.

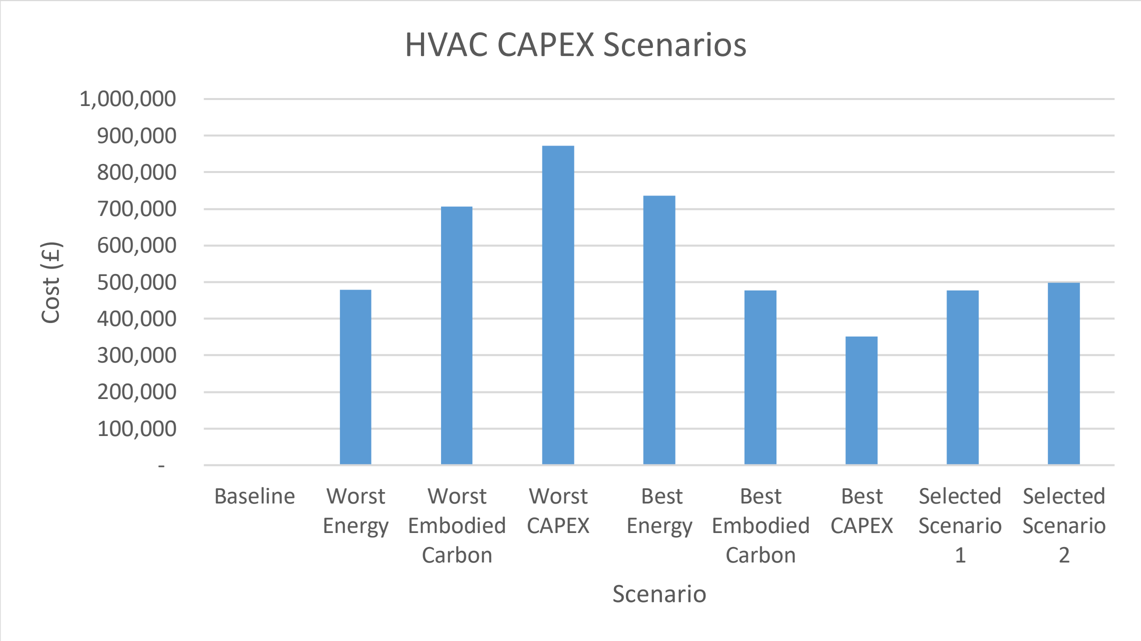

Figure 6. 30 Operational energy split based on energy type

Similar to embodied carbon baseline doesn't not contribute to CAPEX.

Worst CAPEX scenario requires the highest CAPEX, surpassing all other scenarios in cost.

Selected scenarios 1 and 2 exhibit moderate CAPEX, with values falling between the worst and the best CAPEX scenarios. Scenario 2 has a 27% CAPEX results than average however scenario 1 is 14% under the average CAPEX.

The simulation results for the three cost functions specified in the study were evaluated individually and together. A comparison was made between the calculated baseline and the system recommendations. In addition, comparisons are made with operational energy and embodied carbon benchmarks established by the regulations and standards.

In the referenced solutions search space, interventions provided up to 45% saving over the operational energy, 35% embodied carbon reduction and 48% CAPEX reduction.

When considering all 3 together, an average of 30-35% operational energy saving, 7-10% embodied carbon reduction and 20-27% of CAPEX saving can be achieved. It's important to understand the requirements of the project and design and the targeted saving areas.

Reduced consumption targets help to make informed decisions on energy-saving practices.

Evaluating embodied carbon during selection can support sustainable construction practices and align with environmental goals.

Low-CAPEX solutions might present more financially viable options for investment. Consideration of CAPEX alongside project potential and expected returns can help prioritize investment decisions.

Figure 6.31 presents the trend of operational carbon emissions over a span of 22 years for the scenarios, baseline, best and worst operational energy and bespoke scenario 1 and 2. The graph aims to illustrate the trajectory of carbon emissions and identify long-term trends in environmental impact. In the line plot x-axis is representing the analysis period. The y-axis represents the calculated carbon emission trend over this period.

For the interventions, the upgrades are introduced in 2025 to show the representation of offset against the baseline.

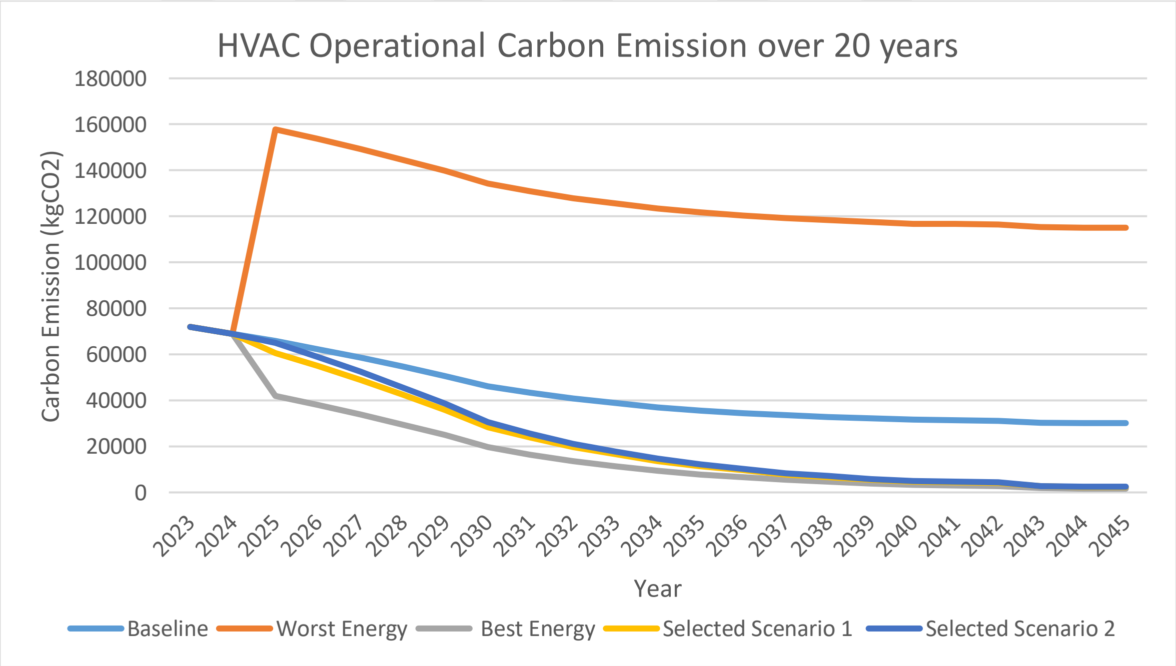

Figure 6. 31 HVAC operational carbon emission over 20 years

The line plot shows the variation in operational carbon emissions over the 20-year duration.

Upward trends indicate periods of increasing emissions, while downward trends represent reductions in carbon emissions for the scenarios.

The increasing emissions trend in the worst energy scenario necessitates the implementation of carbon reduction strategies and sustainability initiatives to mitigate environmental impact.

The decreasing emissions trend in the given scenarios signify successful efforts in adopting eco-friendly practices and energy efficiency measures.

Due to the decreasing trend of the electricity carbon emissions, scenarios rely on electric as a fuel has positive impact on the overall carbon emissions.

Selected scenario 1 in 2045 has an operational carbon reduction by 96% against the 2023 emission numbers.

Figure 6.32 presents the trend of OPEX over a span of 22 years for the scenarios, baseline, best and worst operational energy and bespoke scenario 1 and 2. The graph aims to illustrate the trajectory of OPEX and identify long-term insights on the financial performance and cost trends. In the line plot x-axis is representing the analysis period. The y-axis represents the calculated OPEX trend over this period for baseline and selected intervention scenarios.

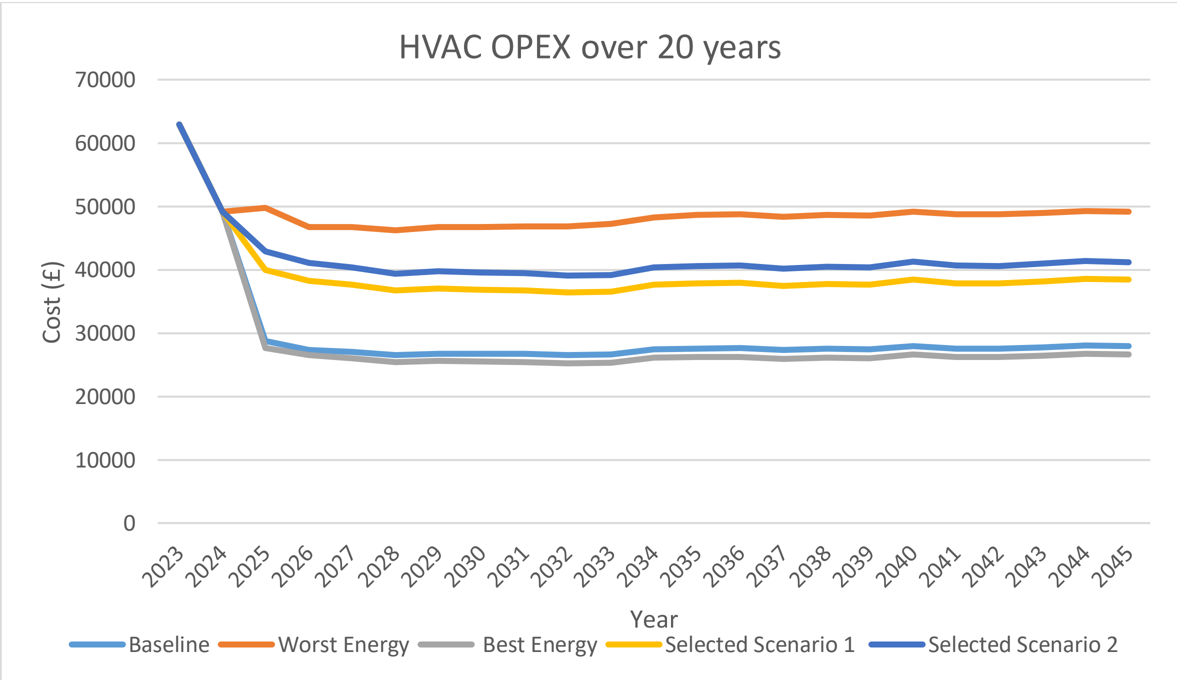

Figure 6. 32 HVAC OPEX over 20 years

Understanding the OPEX trends helps in forecasting future financial needs and setting budgetary expectations.

Analyzing the factors behind expenditure fluctuations can guide decision-makers in optimizing operational costs.

Long-term OPEX data assists in evaluating the financial sustainability and profitability of the project.

7
CONCLUSION AND FUTURE WORK

7.1 Conclusion

Building industry is responsible for 40% of the total energy consumption in UK. They are also an important source of carbon emissions and responsible for the 49%. When it comes to individual functional buildings, the offices are one of the main contributors of the energy consumption and carbon emissions.

One of the biggest energy consuming systems in existing office buildings. The HVAC systems are responsible of 45% of the overall operational energy consumption and 15-23% of the embodied carbon in exiting office buildings in UK.

The decarbonization became a priority and like some other countries UKS set certain frameworks and targets towards to reach net zero before 2050.

In buildings performance targets such as energy, carbon, and cost conflicts in many cases. The need for optimization in between these targets is key when various design alternatives, components and design parameters are considered.

It's been identified that, possible applications of HVAC systems in the building lifecycle while relying on literature review. Beyond, it's highlighted that only few research papers.

The HVAC systems that subjected to this study is represents the 35% of the total building energy. The impact of the HVAC upgrades has bigger contribution to reduce the operational energy and carbon in the buildings.

In this study, an approach for HVAC system optimization for office buildings is explored and analyzed. The investigated approach has shed light on the impact of operational energy, embodied carbon and CAPEX of HVAC systems in existing office buildings.

The study is divided into two stages as stage 1 and stage 2 analysis. The staged modelling approach allowed focusing on the HVAC modelling individually with a better process capacity. In stage 1 analysis a baseline model is generated and calibrated with the existing building metering data. The hourly heating and cooling loads alongside with generated embodied carbon and CAPEX libraries used to test proposed HVAC systems and components in a mathematical calculation model developed for the study that uses NSGA-ii algorithm for optimization. Through rigorous data analysis and simulations, the main contributors and results are demonstrated as below.

The described features of the study make it stand out with an unique perspective on the study area and making a valuable contribution to the literature.

HVAC system retrofits are key indicators on energy, environmental impact and financial improvements for existing office buildings to a certain extent.

Energy, carbon and cost are 3 key performance indicators of an efficient design. These indicators when addressed together can maximize the performance of the design.

It is expected HVAC system retrofits would increase the overall energy performance in existing office buildings, since the high energy reduction can be achieved. However, the other indicators cost and carbon, in conventional projects are ignored or subjected individually which most often are not connected to energy.

Energy model calibration is vital in existing buildings to estimate an accurate baseline capacity for HVAC systems.

In existing buildings, before doing a HVAC retrofit it's vital to exhibit the heating and cooling demand correctly. This is important for plant and component selections. Correct sized plant and component selections as element of the system design have a linear relation with embodied carbon and an indirect relation with operational energy as an outcome of performance of the solutions.

In building energy modelling, heating and cooling loads and energy consumptions related to the systems at the design stage might differ from the actual building consumptions gathered from energy data metering. This can be the case even these models are calibrated with as-built inputs. In order to reduce this performance gap, the simulation should be updated with every change and calibrated with the final building user inputs and metered energy data.

In stage 1 analysis of the study, energy building model generated with the as-built information data named as baseline model is calibrated using the BMS energy data. In the given case study, cooling demand difference between baseline and the calibrated model is 30%. The calibration step also effects the pattern throughout the year which has an impact on the total operational energy consumption and OPEX.

EBM methodology is applicable for both existing and new buildings that has different functions.

The EBM proposes a mathematical model to analyze HVAC systems and plants. Even though the methodology proposed in the study focus on an existing building, the model is applicable for both existing and new buildings. The new building only requires the pre calculated load analysis hourly heating and cooling demand loads for the simulation year. Additionally, changing the building function related parameters, the mathematical model also allows calculation flexibility on other functional buildings.

HVAC modelling simulation time can be reduced following the EBM with staged approach.

In the stage 2 analysis, the EBM contributed on the development of calculation methodologies according to the type of building. Individual HVAC modelling focus reduced the simulation time of each iteration in the given case study. The parametric and mathematical modelling made it possible to reduce the calculation run time from 15 minutes to 6 seconds.

Non-dominated multi objective optimization can offer a wider range of solutions and add flexibility to real-life problems.

Based on the literature review, NSGA-ii optimizations one of the most commonly used algorithm in building performance testing problems. Being a multi objective algorithm, it’s used to optimize 3 conflicting cost functions in the study and allowed for the joint evaluation of these independent cost functions. Being a non-dominated algorithm, no other solution of the pareto front of 40 are better in all 3 objectives.

By providing 40 non-dominated solutions, study offers insights into the robustness and resilience of the optimal designs. This solution can propose decision-makers the differentiation of the solutions performance under different scenarios and necessities.

HVAC systems are intricate components of building design that affect various aspects including design, environment, finances, and thermal comfort. The choice of systems and related variables can affect these factors, and in existing buildings, this impact can be either comprehensive or limited to certain areas of the building.

Decisions can be made based on the project constraints and requirements.

In the explored range of potential solutions, the implemented measures yielded substantial benefits, with savings of up to 45% in operational energy, 35% in embodied carbon, and 48% in CAPEX.

When analyzing all three factors collectively, an average improvement of 30-35% in operational energy, 7-10% in embodied carbon, and 20-27% in CAPEX can be attained. To maximize these advantages, a thorough comprehension of the project's requirements, design, and the specific areas targeted for savings is crucial.

Terminal units with dedicated outdoor fresh air supply have a better overall energy performance and CAPEX results, however centralized air systems have better embodied carbon reduction results.

In the given trade-offs the DOAS system shows an overall 9% more energy efficiency and 21% cost reduction when compared to the AAHS system. On the other hand, the AAHS has a better overall embodied carbon performance with 19%.

As a control scenario, air supply temperature for both heating cooling has an impact on operational energy without effecting the embodied carbon and CAPEX.

Higher heating air supply temperatures lead to reduced flow rates. Reducing the heating air temperature from 35°C to 30°C, raising the cooling air flow temperature from 14°C to 18°C results in a 5% increase in energy consumption.

Airside supply temperatures show minimal influence on operational energy and no impact on embodied carbon and CAPEX when considered independently. Nevertheless, their effect on fan energy consumption enhances its overall significance.

Number of terminal units in DOAS systems is an important intervention for embodied carbon and CAPEX.

The quantity of indoor units within a DOAS system significantly influences the outcomes concerning embodied carbon and CAPEX. While larger terminal unit capacities lead to improved energy efficiency, they also introduce additional embodied carbon and CAPEX costs.

The study indicates that an increase in the number of indoor units has a minimal effect on operational energy consumption but has a more substantial impact of approximately 8-10% on embodied carbon and CAPEX. This factor also plays a crucial role in driving the design and controllability of thermal comfort.

Heat recovery in ventilation system is a significant contributor to reduce energy consumption in office buildings with neglectable embodied carbon and CAPEX increase.

Utilizing heat recovery in ventilation significantly enhances energy efficiency in office buildings. The effect of this heat recovery on operational energy varies between 17-26%, depending on the efficiency of the system. However, it also results in additional embodied carbon due to increased material usage and CAPEX costs.

Plant selections takes an important role in HVAC design.

Plant selection plays a vital role in designing HVAC systems for buildings, impacting operational energy, embodied carbon, and CAPEX. The plant capacity, fuel type, circulated water temperature, and plant efficiency are critical factors for achieving energy efficiency. Adjusting water temperatures, with lower temperatures for heating and higher temperatures for cooling, improves plant efficiency and reduces energy consumption without affecting embodied carbon and CAPEX.

Among the options, VRF stands out as the most efficient solution for operational energy consumption in heating and performs decently in cooling. It outperforms an NG Boiler operating at 70°C flow temperature by an impressive 49%. However, due to the amount of refrigerant used, has a poor embodied carbon performance.

ASHP, on the other hand, even has a higher CAPEX due to system complexity, it has a better overall performance against the all 3 cost functions.

ASHP in heating mode, operating at a flow temperature of 50 °C has an operational energy, 35% less than the electric boiler, 39% less than the natural gas boiler and 10% higher than the VRF system.

ASHP in cooling mode, operating at a flow temperature of 10 °C has an operational energy, 22% less than Air Cooled Chiller, 7% higher than the Water Cooled Chiller and 24% less than the VRF system.

Plants with heating and cooling capability together have a lower embodied carbon than individual units doing heating and cooling separately.

ASHP and VRF systems serve the heating and cooling together which enables a lower embodied carbon and investment cost.

OPEX and operational carbon emissions when analyzed over the lifespan of the systems and components have a significant impact over the CAPEX and embodied carbon.

In annual basis the study shows both CAPEX is 11-14 times greater than the OPEX and embodied carbon figures are 10-13 times greater than the operational carbon. However, over the lifespan of the systems and components, both OPEX and operational carbon exceed the CAPEX and embodied carbon figures. That's why these needs to be analyzed and considered for the life spun of the selected systems.

HVAC systems has a reputable impact on office building energy consumptions.

The baseline building energy use intensity is calculated as 164 kWh/m2.annum. When the average pareto solution HVAC system introduced to the other building energy consumptions, the proposed solution building energy use intensity is calculated as 143.78 kWh/m2.annum. This results an 12% reduction in total energy use intensity.

Buildings require long term carbon emission and cost projections to achieve their environmental and financial goals.

The climate emergency is now requiring urgent actions. Carbon emission reduction targets outlined in the guidelines and climate action declarations now point to operational energy and embodied carbon reductions as a part of a holistic solution.

In conclusion, this study underscores the importance of the combined focus to energy, carbon and cost in HVAC design. Setting lower consumption goals enables well-informed choices concerning energy-saving methods. By assessing embodied carbon during the selection process, sustainable construction practices can be promoted, aligning with environmental objectives. Solutions with lower CAPEX requirements may offer more financially feasible investment options. We can prioritize investment decisions by considering CAPEX alongside the project's potential and expected returns.

Study proves that each building has a different design, targets and requirements. There is no one perfect solutions fit for all building HVAC design. Buildings have different necessities in line with their location, orientation, architectural attributes, and function. All these parameters make the buildings unique. Results of different HVAC systems comparison and iteration through the parameters allow users to narrow down the options and support the decision-making process.

To build upon this research, several avenues for future investigation have been identified in the section 7.2 below.

7.2 Recommendations and Future Work

This work will benefit from discussing some of the limitations and constraints that should be addressed in future studies.

The location and the weather conditions are key inputs for building operational energy calculations. The methodology proposed is flexible and applicable for different climatic conditions and building types to calculate operational energy with changes to mathematical equations in line with the building HVAC system requirements.

However the building location is a key factor for embodied carbon and cost. The embodied carbon and cost libraries used in the EBM are created for a specific office building location in London. Also, these databases are created using reference HVAC systems for office buildings. In future studies, for different locations and functional types of buildings, HVAC systems and liberties related to these systems should be generated within this consideration.

The HVAC systems selected for the case study office building are limited by the current technology and system trends. Changes in energy efficiency, carbon and cost values may be seen with technological progress and updates in system selections.

The design of distribution systems such as ductwork and pipework affect all three functions investigated in the study. The effect of the design of these systems should also be a consideration for future work.

Mechanical ventilation is only evaluated under ventilation systems. The effect of natural and hybrid ventilation should be investigated.

ASHP system efficiencies are directly related to external air temperatures. The ASHP efficiencies included in the study were also calculated based on temperature values in the climate data used. The performance of the device should be investigated for different climates.

Embodied carbon is a calculation that is dependent on the manufacturer and location. The embodied carbon values of similar systems manufactured by companies other than those included in the study should be investigated.

There is a lack of data on the environmental impact of energy generation equipment, as evidenced by the limited availability of environmental product declarations (EPDs) and the limited amount of information on building services equipment in product databases.

Existing office operational scenarios are kept fixed only to test the impact of different HVAC system combinations. The scenarios such as temperature set points, fresh air rates and lighting scenarios are not considered as a part of the study.

Energy storage systems are not considered a part of the study. Energy storage in different forms is a key element to optimize the energy demand further and requires to be investigated further.

The implications of this study can be leveraged by designers and developers in practical applications and decision-making process of the HVAC systems design. I hope that this work inspires and stimulates further research, innovation, and collaboration in the energy efficiency and decarbonization studies.

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APPENDICES

A
OFFICE OPERATIONAL PROFILES

In appendix A the profiles that are used to generate the baseline model is given.

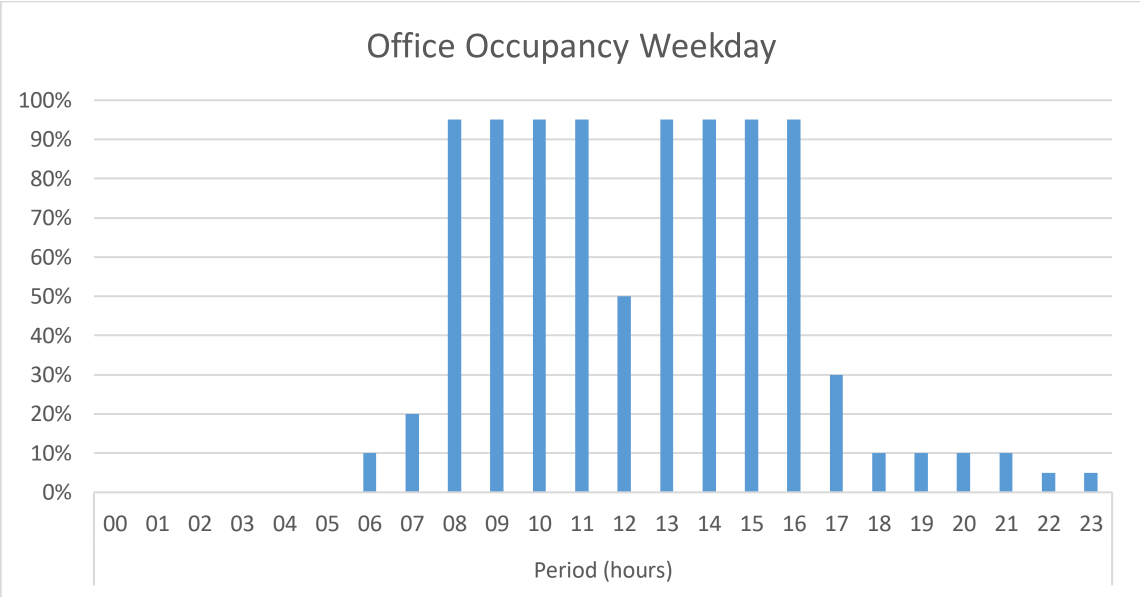

Figure A. 1 Office occupancy weekday profile

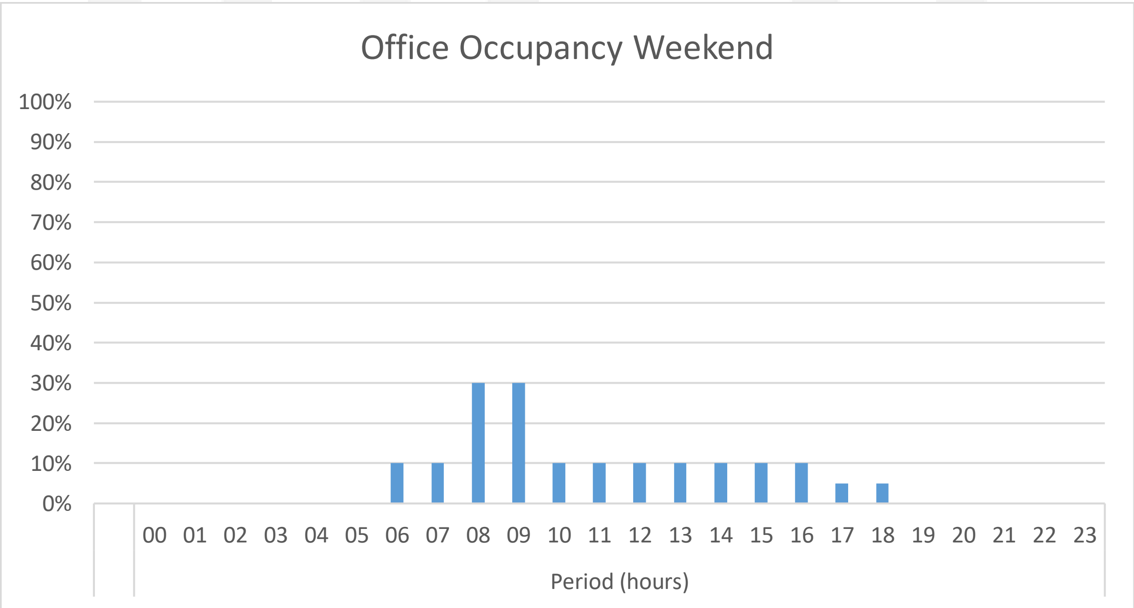

Figure A. 2 Office occupancy weekend profile

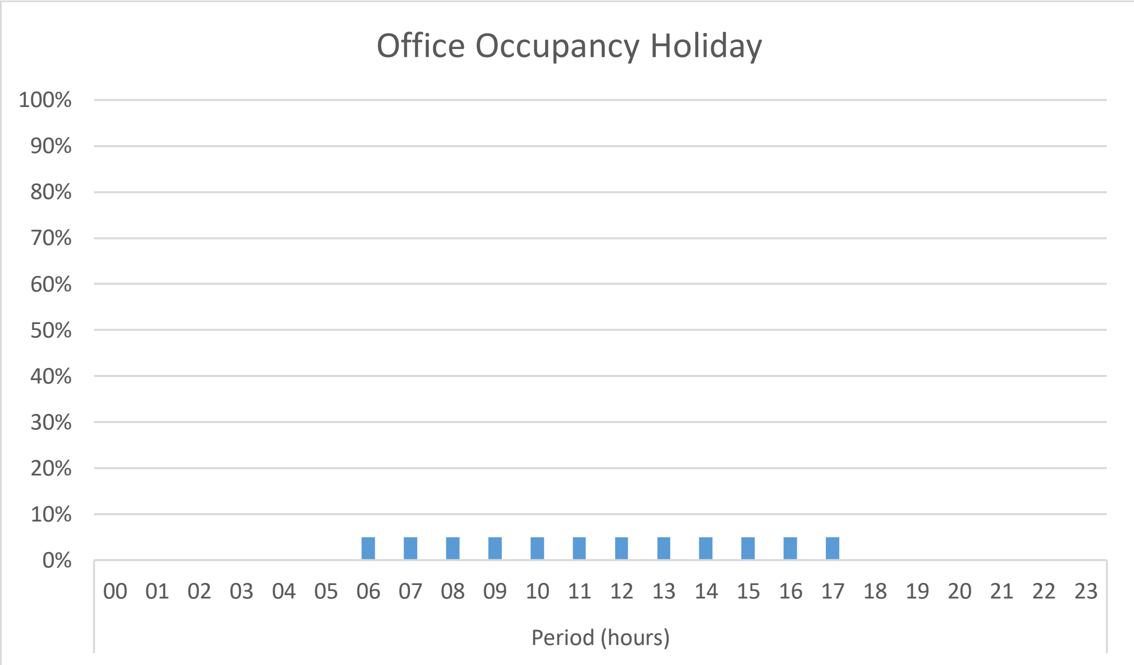

Figure A. 3 Office occupancy holiday profile

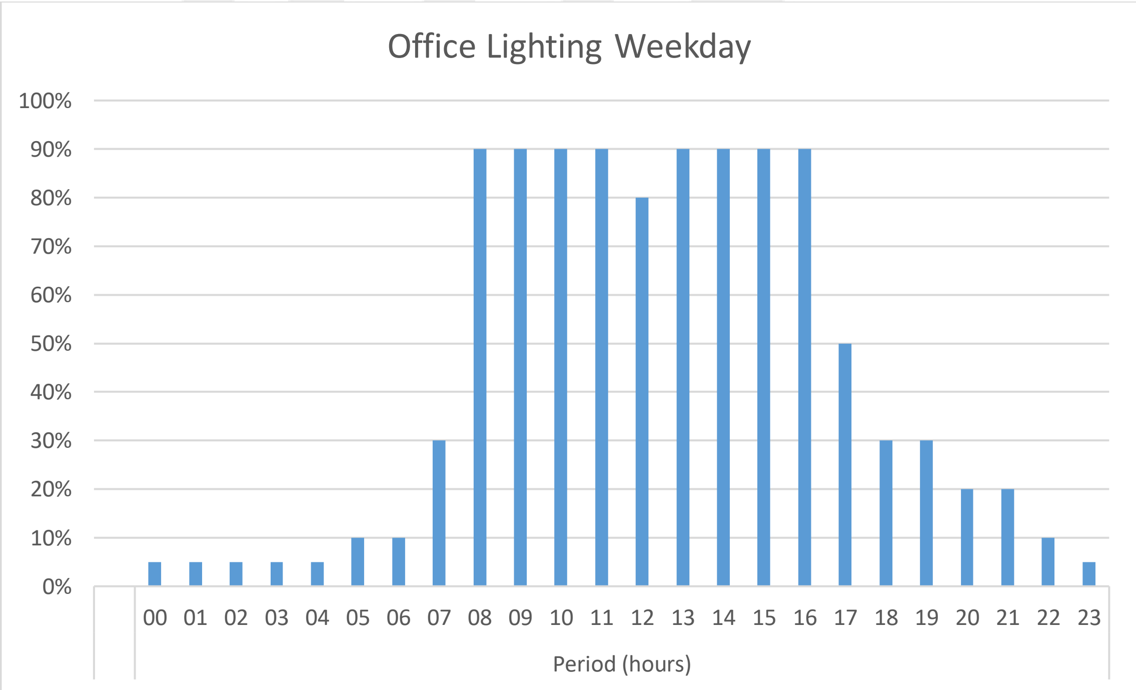

Figure A. 4 Office lighting weekday profile

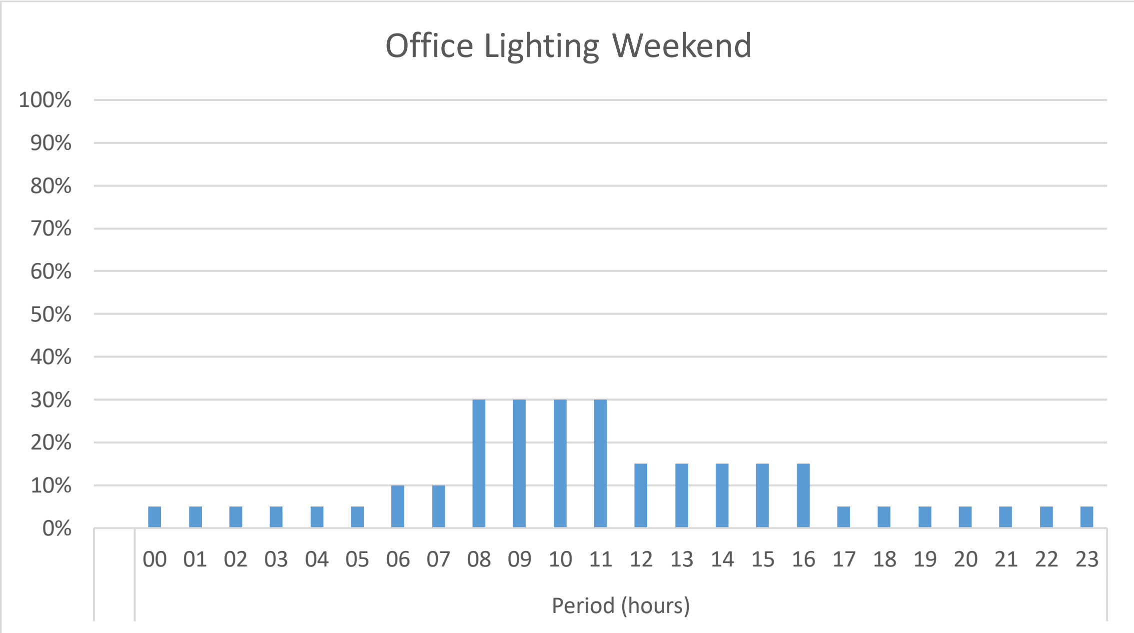

Figure A. 5 Office lighting weekend profile

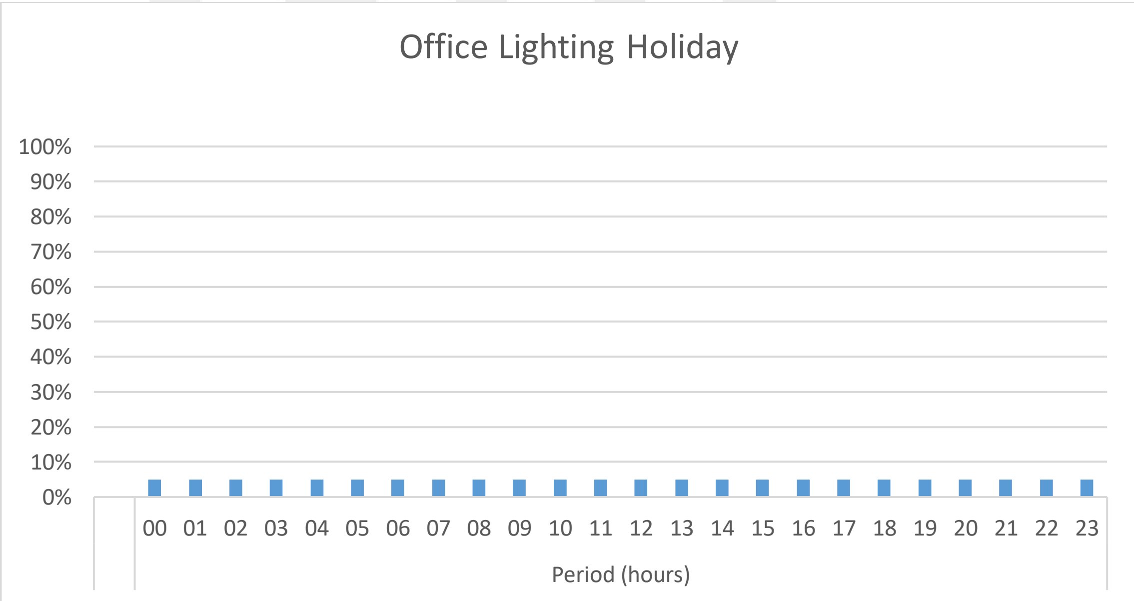

Figure A. 6 Office lighting holiday profile

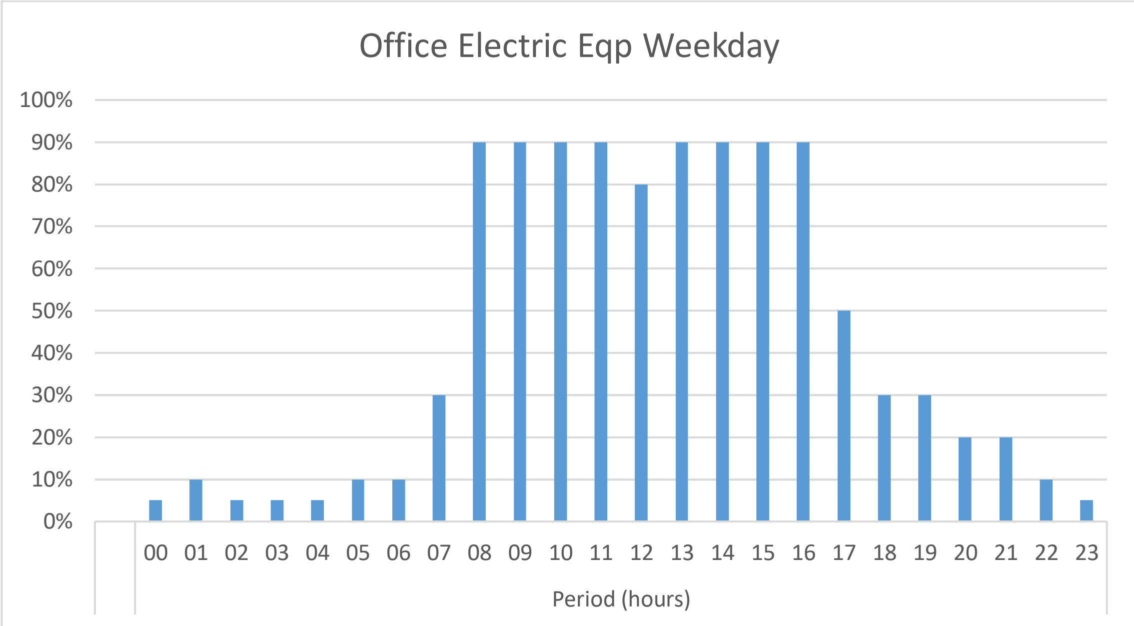

Figure A. 7 Office electric equipment weekday profile

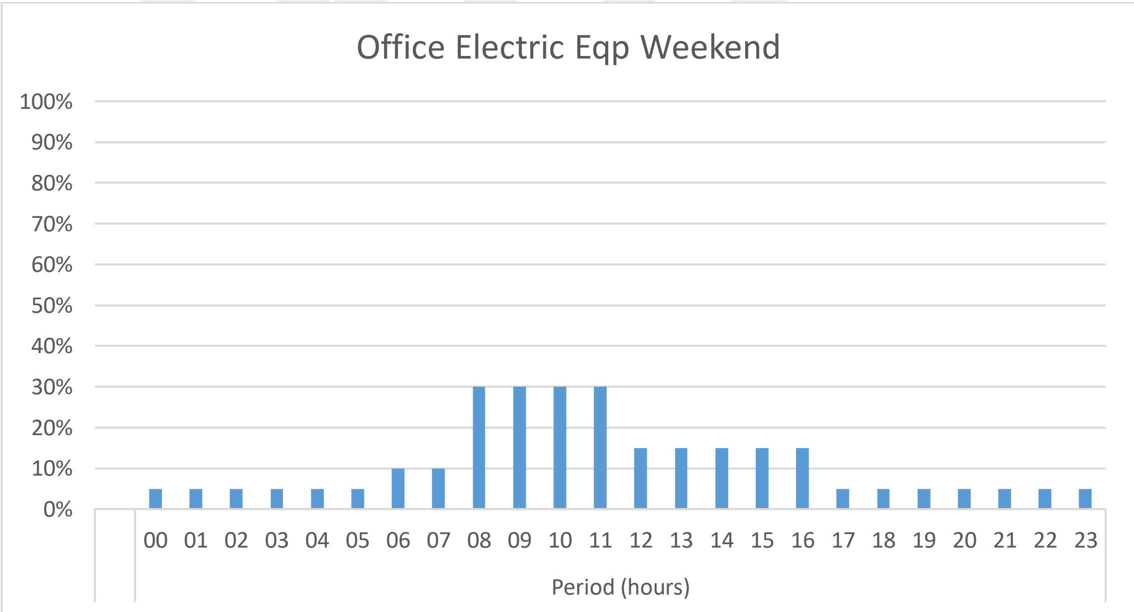

Figure A. 8 Office electric equipment weekend profile

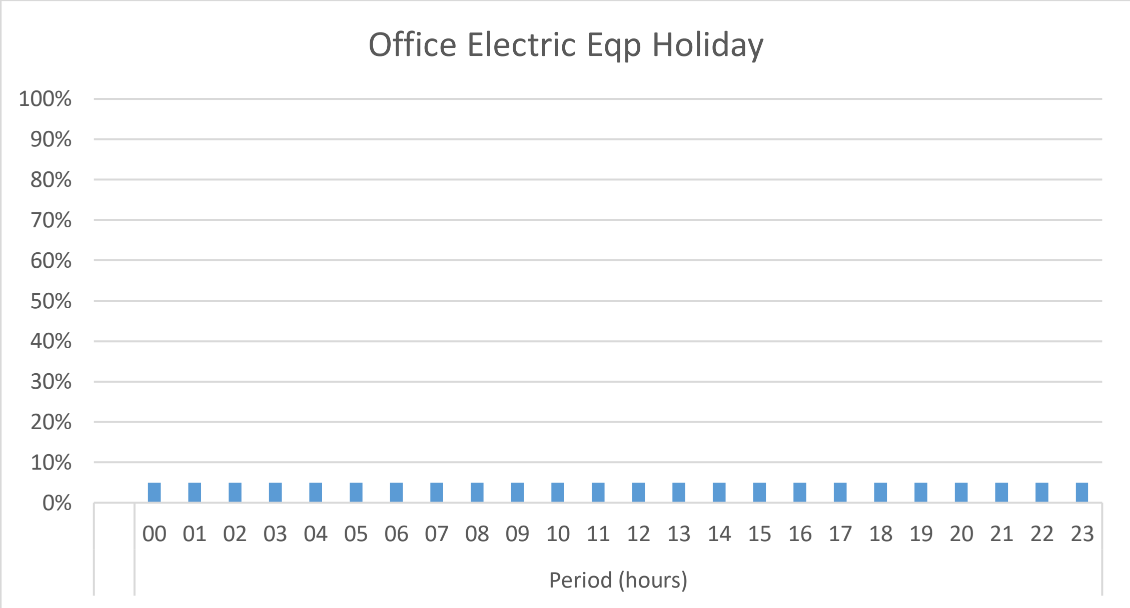

Figure A. 9 Office electric equipment holiday profile

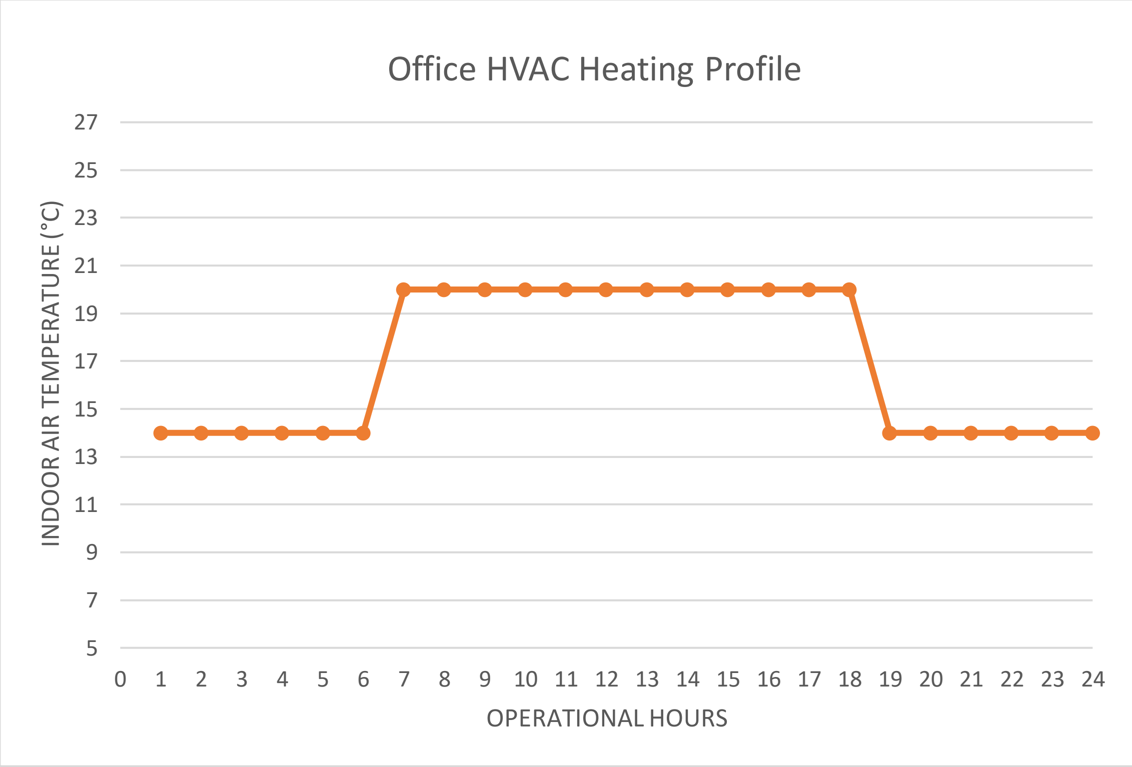

Figure A. 10 Office HVAC heating profile

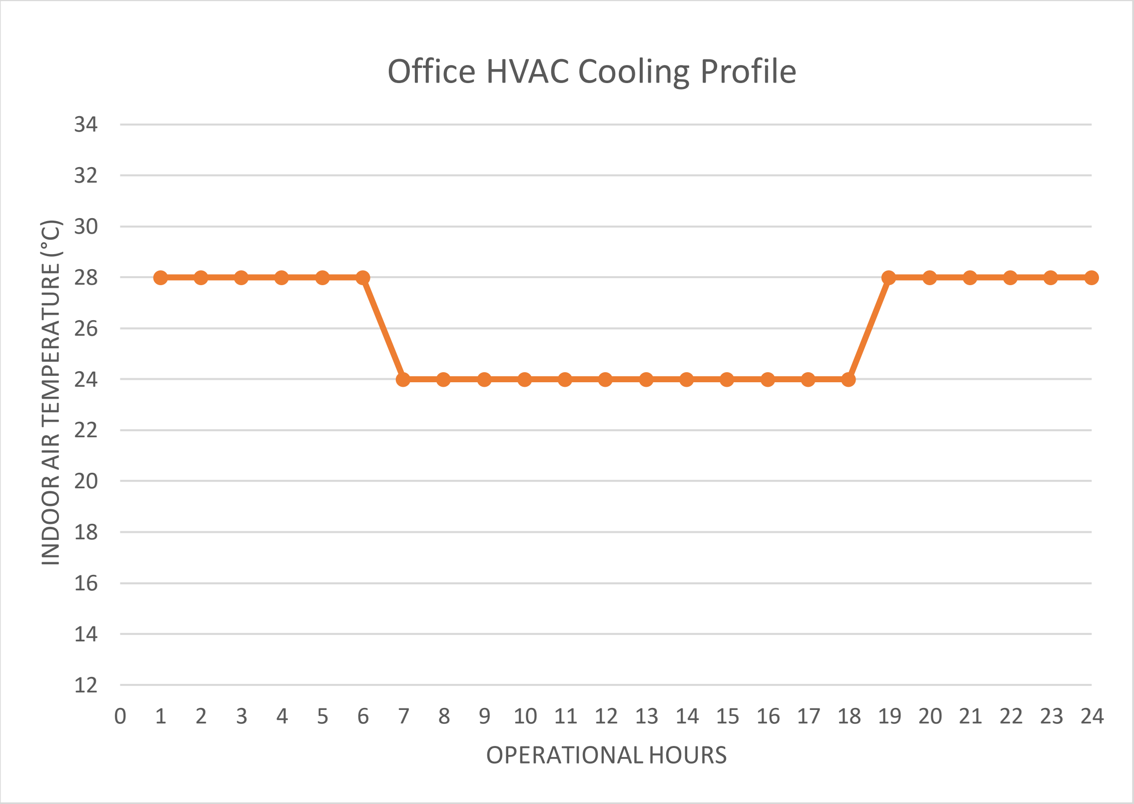

Figure A. 11 Office HVAC cooling profile

B
WEATHER PROFILES

Month	Average Dry-bulb temperature (°C)	Max Dry-bulb temperature (°C)	Min Dry-bulb temperature (°C)
January	6.0	14.4	-0.3
February	6.6	14.1	-0.8
March	7.9	20.2	-2.5
April	9.8	19.2	-1.2
May	14.5	24.6	6.2
June	17.4	30.1	6.7
July	19.2	31.5	11.1
August	19.2	28.1	11.3
September	16.3	24.7	7
October	13.5	20.5	4.1
November	8.6	16.9	0.3
December	7.1	15	-2.1

Month	Average Wet-bulb temperature (°C)	Max Wet-bulb temperature (°C)	Min Wet-bulb temperature (°C)
January	5.0	13.34	-0.87
February	5.3	11.98	-1.83
March	6.2	13.32	-3.28
April	7.7	16.11	-1.51
May	11.6	17.5	5.12
June	13.7	21.83	5.74
July	15.6	21.46	10.06
August	15.7	19.94	10.43
September	13.6	19.59	5.81
October	11.7	19.43	3.51
November	7.4	14.36	0.14
December	6.1	13.92	-2.3

Month	Average External Relative Humidity(%)	Max External Relative Humidity(%)	Min External Relative Humidity(%)
January	85.4	99	57
February	83.1	100	38
March	79.7	100	40

April	75.3	99	43
May	72.2	99	39
June	68.6	97	37
July	70.8	97	30
August	70.9	95	33
September	75.9	99	40
October	81.1	99	48
November	85.6	99	58
December	86.2	100	59

C
SYSTEM ENERGY EFFICIENCY

DOAS HVAC System AHU

Type	Flow Rate (l/s)	SFP (W/l/s)
Type 1	1389	2
Type 2	1389	1.8
Type 3	1389	1.6
Type 4	1389	1.4
Type 5	2778	2
Type 6	2778	1.8
Type 7	2778	1.6
Type 8	2778	1.4
Type 9	13889	2
Type 10	13889	1.8
Type 11	13889	1.6
Type 12	13889	1.4

DOAS HVAC System Indoor FCU

Type	Total Heating Capacity (kW)	Total Cooling Capacity (kW)	Sensible Cooling Capacity (kW)	SFP (W/l/s)
Type 1	2	2	1.5	0.18
Type 2	2.75	2.75	2	0.16
Type 3	3.5	3.5	3	0.14
Type 4	4.25	4.25	3.5	0.14
Type 5	5	5	4	0.12

All-Air HVAC System AHU

Type	Flow Rate (l/s)	SFP (W/l/s)
Type 1	1388	2
Type 2	1388	1.8
Type 3	1388	1.6
Type 4	1388	1.4
Type 5	2777	2
Type 6	2777	1.8
Type 7	2777	1.6
Type 8	2777	1.4
Type 9	13888	2

Type 10	13888	1.8
Type 11	13888	1.6
Type 12	13888	1.4

Heating and Cooling Circulation Pumps

Energy Consumption @ Flow is 20%	Energy Consumption @ Flow is 40%	Energy Consumption @ Flow is 60%	Energy Consumption @ Flow is 80%	Energy Consumption @ Flow is 100%
10	14	18	22	25

NG Boiler Efficiency

NG Boiler @ 70°C Supply Temperature					
Outdoor Air Temperature (°C)	**System Load (%)**				
	100	80	60	40	20
-15	0.86	0.84	0.82	0.8	0.7
-10	0.86	0.84	0.82	0.8	0.7
-5	0.86	0.84	0.82	0.8	0.7
0	0.86	0.84	0.82	0.8	0.7
5	0.86	0.84	0.82	0.8	0.7
10	0.86	0.84	0.82	0.8	0.7
15	0.86	0.84	0.82	0.8	0.7
20	0.86	0.84	0.82	0.8	0.7
25	0.86	0.84	0.82	0.8	0.7
30	0.86	0.84	0.82	0.8	0.7
35	0.86	0.84	0.82	0.8	0.7
40	0.86	0.84	0.82	0.8	0.7

NG Boiler @ 50°C Supply Temperature					
Outdoor Air Temperature (°C)	**System Load (%)**				
	100	80	60	40	20
-15	0.88	0.86	0.84	0.82	0.8
-10	0.88	0.86	0.84	0.82	0.8
-5	0.88	0.86	0.84	0.82	0.8
0	0.88	0.86	0.84	0.82	0.8
5	0.88	0.86	0.84	0.82	0.8
10	0.88	0.86	0.84	0.82	0.8
15	0.88	0.86	0.84	0.82	0.8
20	0.88	0.86	0.84	0.82	0.8
25	0.88	0.86	0.84	0.82	0.8

30	0.88	0.86	0.84	0.82	0.8
35	0.88	0.86	0.84	0.82	0.8
40	0.88	0.86	0.84	0.82	0.8

Direct Electric Boiler Efficiency

Electric Boiler @ 70°C and 50°C Supply Temperature					
Outdoor Air Temperature (°C)	**System Load (%)**				
	100	80	60	40	20
-15	1	1	1	1	1
-10	1	1	1	1	1
-5	1	1	1	1	1
0	1	1	1	1	1
5	1	1	1	1	1
10	1	1	1	1	1
15	1	1	1	1	1
20	1	1	1	1	1
25	1	1	1	1	1
30	1	1	1	1	1
35	1	1	1	1	1
40	1	1	1	1	1

Air Cooled Chiller Efficiency

Air Cooled Chiller @ 6°C Supply Temperature					
Outdoor Air Temperature (°C)	**System Load (%)**				
	100	80	60	40	20
-15	6.12	6.88	7.62	8.21	8.29
-10	6.12	6.88	7.62	8.21	8.29
-5	6.12	6.88	7.62	8.21	8.29
0	6.12	6.88	7.62	8.21	8.29
5	6.12	6.88	7.62	8.21	8.29
10	6.12	6.88	7.62	8.21	8.29
15	6.12	6.88	7.62	8.21	8.29
20	5.11	5.7	6.27	6.72	6.78
25	4.29	4.76	5.2	5.53	5.57
30	3.62	4	4.35	4.59	4.6
35	3.05	3.38	3.66	3.83	3.82
40	2.41	2.86	3.11	3.22	3.18

Air Cooled Chiller @ 10°C Supply Temperature					
Outdoor Air Temperature (°C)	**System Load (%)**				
	100	80	60	40	20
-15	7.23	8.07	8.81	9.31	9.21
-10	7.23	8.07	8.81	9.31	9.21
-5	7.23	8.07	8.81	9.31	9.21
0	7.23	8.07	8.81	9.31	9.21
5	7.23	8.07	8.81	9.31	9.21
10	7.23	8.07	8.81	9.31	9.21
15	7.23	8.07	8.81	9.31	9.21
20	5.94	6.59	7.17	7.56	7.5
25	4.94	5.44	5.89	6.19	6.15
30	4.15	4.55	4.89	5.1	5.08
35	3.51	3.83	4.09	4.24	4.2
40	2.95	3.24	3.46	3.55	3.49

Water Cooled Chiller Efficiency

Water Cooled Chiller @ 6°C Supply Temperature					
Outdoor Air Temperature (°C)	**System Load (%)**				
	100	80	60	40	20
-15	7.47	8.39	9.30	10.02	10.11
-10	7.47	8.39	9.30	10.02	10.11
-5	7.47	8.39	9.30	10.02	10.11
0	7.47	8.39	9.30	10.02	10.11
5	7.47	8.39	9.30	10.02	10.11
10	7.47	8.39	9.30	10.02	10.11
15	7.47	8.39	9.30	10.02	10.11
20	6.23	6.95	7.65	8.20	8.27
25	5.23	5.81	6.34	6.75	6.80
30	4.42	4.88	5.31	5.60	5.61
35	3.72	4.12	4.47	4.67	4.66
40	1.22	3.49	3.79	3.93	3.88

Water Cooled Chiller @ 10°C Supply Temperature					
Outdoor Air Temperature (°C)	**System Load (%)**				
	100	80	60	40	20
-15	8.82	9.85	10.75	11.36	11.24
-10	8.82	9.85	10.75	11.36	11.24
-5	8.82	9.85	10.75	11.36	11.24
0	8.82	9.85	10.75	11.36	11.24
5	8.82	9.85	10.75	11.36	11.24
10	8.82	9.85	10.75	11.36	11.24

15	8.82	9.85	10.75	11.36	11.24
20	7.25	8.04	8.75	9.22	9.15
25	6.03	6.64	7.19	7.55	7.50
30	5.06	5.55	5.97	6.22	6.20
35	4.28	4.67	4.99	5.17	5.12
40	3.60	3.95	4.22	4.33	4.26

ASHP Efficiency

ASHP Heating @ 70°C Supply Temperature					
Outdoor Air Temperature (°C)	**System Load (%)**				
	100	80	60	40	20
-15	1.7	1.7	1.6	1.8	1.6
-10	1.9	1.9	1.8	1.9	1.7
-5	2.1	2.1	2.0	2.1	1.9
0	2.4	2.3	2.3	2.3	1.9
5	2.6	2.5	2.5	2.4	2.0
10	2.8	2.8	2.6	2.5	2.1
15	3.1	2.9	2.7	2.6	2.1
20	3.3	3.1	2.9	2.7	2.2
25	3.5	3.3	3.0	2.8	2.3
30	3.8	3.5	3.1	2.9	2.3
35	4.0	3.7	3.2	3.0	2.4
40	4.2	3.9	3.3	3.1	2.5

ASHP Heating @ 50°C Supply Temperature					
Outdoor Air Temperature (°C)	**System Load (%)**				
	100	80	60	40	20
-15	1.8	1.7	1.7	1.9	1.8
-10	2.0	2.0	2.0	2.1	1.9
-5	2.3	2.3	2.2	2.3	2.0
0	2.6	2.5	2.5	2.5	2.2
5	2.9	2.8	2.7	2.6	2.2
10	3.1	3.0	2.9	2.8	2.3
15	3.4	3.3	3.1	2.9	2.4
20	3.7	3.5	3.2	2.9	2.4
25	3.9	3.6	3.3	3.0	2.4
30	4.1	3.8	3.4	3.0	2.4
35	4.2	3.9	3.5	3.0	2.3
40	4.3	3.9	3.5	2.9	2.3

ASHP @ 6°C Supply Temperature					
Outdoor Air Temperature (°C)	**System Load (%)**				
	100	80	60	40	20
-15	6.12	6.88	7.62	8.21	8.29
-10	6.12	6.88	7.62	8.21	8.29
-5	6.12	6.88	7.62	8.21	8.29
0	6.12	6.88	7.62	8.21	8.29
5	6.12	6.88	7.62	8.21	8.29
10	6.12	6.88	7.62	8.21	8.29
15	6.12	6.88	7.62	8.21	8.29
20	5.11	5.7	6.27	6.72	6.78
25	4.29	4.76	5.2	5.53	5.57
30	3.62	4	4.35	4.59	4.6
35	3.05	3.38	3.66	3.83	3.82
40	2.413333	2.86	3.11	3.22	3.18

ASHP @ 10°C Supply Temperature					
Outdoor Air Temperature (°C)	**System Load (%)**				
	100	80	60	40	20
-15	7.23	8.07	8.81	9.31	9.21
-10	7.23	8.07	8.81	9.31	9.21
-5	7.23	8.07	8.81	9.31	9.21
0	7.23	8.07	8.81	9.31	9.21
5	7.23	8.07	8.81	9.31	9.21
10	7.23	8.07	8.81	9.31	9.21
15	7.23	8.07	8.81	9.31	9.21
20	5.94	6.59	7.17	7.56	7.5
25	4.94	5.44	5.89	6.19	6.15
30	4.15	4.55	4.89	5.1	5.08
35	3.51	3.83	4.09	4.24	4.2
40	2.95	3.24	3.46	3.55	3.49

VRF Efficiency

VRF Heating					
Outdoor Air Temperature (°C)	**System Load (%)**				
	100	80	60	40	20
-15	4.2	4.2	4.2	4.2	4.2
-10	4.2	4.2	4.2	4.2	4.2
-5	4.2	4.2	4.2	4.2	4.2
0	4.2	4.2	4.2	4.2	4.2
5	4.2	4.2	4.2	4.2	4.2
10	4.2	4.2	4.2	4.2	4.2

15	4.2	4.2	4.2	4.2	4.2
20	4.2	4.2	4.2	4.2	4.2
25	4.2	4.2	4.2	4.2	4.2
30	4.2	4.2	4.2	4.2	4.2
35	4.2	4.2	4.2	4.2	4.2
40	4.2	4.2	4.2	4.2	4.2

VRF Cooling					
Outdoor Air Temperature (°C)	**System Load (%)**				
	100	80	60	40	20
-15	3.6	3.6	3.6	3.6	3.6
-10	3.6	3.6	3.6	3.6	3.6
-5	3.6	3.6	3.6	3.6	3.6
0	3.6	3.6	3.6	3.6	3.6
5	3.6	3.6	3.6	3.6	3.6
10	3.6	3.6	3.6	3.6	3.6
15	3.6	3.6	3.6	3.6	3.6
20	3.6	3.6	3.6	3.6	3.6
25	3.6	3.6	3.6	3.6	3.6
30	3.6	3.6	3.6	3.6	3.6
35	3.6	3.6	3.6	3.6	3.6
40	3.6	3.6	3.6	3.6	3.6

D
SYSTEM EMBODIED CARBON

DOAS HVAC System AHU

Type	Flow Rate (l/s)	Embodied Carbon (kgCO2)
Type 1	1389	7192
Type 2	1389	7192
Type 3	1389	7192
Type 4	1389	7192
Type 5	2778	10455
Type 6	2778	10455
Type 7	2778	10455
Type 8	2778	10455
Type 9	13889	31962
Type 10	13889	31962
Type 11	13889	31962
Type 12	13889	31962

DOAS HVAC System Indoor FCU

Total Heating Capacity (kW)	Total Cooling Capacity (kW)	Sensible Cooling Capacity (kW)	Embodied Carbon (kgCO2)
2.75	2.75	2	250
3.5	3.5	3	400
4.25	4.25	3.5	450

All-Air HVAC System AHU

Type	Flow Rate (l/s)	Embodied Carbon (kgCO2)
Type 1	1388	7192
Type 2	1388	7192
Type 3	1388	7192
Type 4	1388	7192
Type 5	2777	10455
Type 6	2777	10455
Type 7	2777	10455
Type 8	2777	10455
Type 9	13888	31962
Type 10	13888	31962
Type 11	13888	31962

Type 12	13888	31962

Heating and Cooling Circulation Pumps

Number of Pump	Embodied Carbon Each (kgCO2)
1	140

Plants

Plant Type	Embodied Carbon Each (kgCO2)
NG Boiler	7000
Electric Boiler	7000
ASHP	38000
Air Cooled Chiller	38000
Water Cooled Chiller	32000
VRF	118140

E
SYSTEM OPERATIONAL CARBON

BEIS Reference Guide

Year	Electricity Carbon Factor Projection ($kgCO_2e/kWh$)	Natural Gas Carbon Factor Projection ($kgCO_2e/kWh$)	District Heating Carbon Factor Projection ($kgCO_2e/kWh$)
2023	0.244	0.183	0.151
2024	0.227	0.183	0.151
2025	0.209	0.183	0.151
2026	0.190	0.183	0.151
2027	0.169	0.183	0.151
2028	0.147	0.183	0.151
2029	0.124	0.183	0.151
2030	0.098	0.183	0.151
2031	0.082	0.183	0.151
2032	0.068	0.183	0.151
2033	0.057	0.183	0.151
2034	0.047	0.183	0.151
2035	0.039	0.183	0.151
2036	0.033	0.183	0.151
2037	0.027	0.183	0.151
2038	0.023	0.183	0.151
2039	0.019	0.183	0.151
2040	0.016	0.183	0.151
2041	0.015	0.183	0.151
2042	0.014	0.183	0.151
2043	0.009	0.183	0.151
2044	0.008	0.183	0.151
2045	0.008	0.183	0.151
2046	0.008	0.183	0.151
2047	0.005	0.183	0.151
2048	0.005	0.183	0.151
2049	0.003	0.183	0.151
2050	0.002	0.183	0.151

F
OPEX

BEIS Reference Guide

Year	Electricity Unit Rate Projection (p/kWh)	Natural Gas Unit Rate Projection (p/kWh)	District Heating Unit Rate Projection (p/kWh)
2023	28.980	8.920	6.100
2024	23.030	6.400	4.384
2025	13.800	3.310	2.267
2026	13.210	3.020	2.068
2027	13.000	3.090	2.116
2028	12.680	3.120	2.137
2029	12.790	3.160	2.164
2030	12.730	3.190	2.185
2031	12.700	3.220	2.205
2032	12.580	3.260	2.233
2033	12.620	3.300	2.260
2034	13.010	3.340	2.288
2035	13.070	3.380	2.315
2036	13.100	3.380	2.315
2037	12.930	3.380	2.315
2038	13.030	3.390	2.322
2039	13.000	3.390	2.322
2040	13.300	3.390	2.322
2041	13.080	3.390	2.322
2042	13.070	3.390	2.322
2043	13.180	3.390	2.322
2044	13.310	3.400	2.329
2045	13.270	3.400	2.329
2046	13.320	3.400	2.329
2047	13.250	3.400	2.329
2048	13.130	3.400	2.329
2049	13.020	3.400	2.329
2050	13.020	3.410	2.336

G
CAPEX

DOAS HVAC System AHU

Type	Flow Rate (l/s)	CAPEX (£)
Type 1	1389	15000
Type 2	1389	17000
Type 3	1389	19000
Type 4	1389	21000
Type 5	2778	24000
Type 6	2778	26000
Type 7	2778	28000
Type 8	2778	32000
Type 9	13889	42000
Type 10	13889	45000
Type 11	13889	48000
Type 12	13889	50000

DOAS HVAC System Indoor FCU

Type	Total Heating Capacity (kW)	Total Cooling Capacity (kW)	Sensible Cooling Capacity (kW)	CAPEX (£)
Type 1	2	2	1.5	150
Type 2	2.75	2.75	2	200
Type 3	3.5	3.5	3	250

All-Air HVAC System AHU

Type	Flow Rate (l/s)	CAPEX (£)
Type 1	1388	15000
Type 2	1388	17000
Type 3	1388	19000
Type 4	1388	21000
Type 5	2777	24000
Type 6	2777	26000
Type 7	2777	28000
Type 8	2777	32000
Type 9	13888	42000
Type 10	13888	45000
Type 11	13888	48000

Type 12	13888	50000

Heating and Cooling Circulation Pumps

Number of Pump	CAPEX Each (£)
1	4500

Plants

Plant Type	CAPEX Each (£)
NG Boiler	48000
Electric Boiler	78000
ASHP	280000
Air Cooled Chiller	234000
Water Cooled Chiller	273000
VRF	390000

H

REGULARIZED METERING DATA

Date	HVAC- Heating Demand (kWh)	HVAC- Cooling Demand (kWh)	Chiller Energy Consumption (kWh)
01/01/2015	43,050.00	12,189.00	3,045.19
01/02/2015	34,727.00	12,650.00	4,014.62
01/03/2015	22,985.00	15,024.00	4,307.60
01/04/2015	22,042.00	21,939.00	7,540.86
01/05/2015	35,367.00	59,318.00	15,047.18
01/06/2015	34,514.00	24,417.00	12,396.67
01/07/2015	24,813.00	24,636.00	6,699.23
01/08/2015	26,405.00	14,349.00	4,955.26
01/09/2015	39,353.00	10,725.00	4,443.52
01/10/2015	39,522.00	6,526.00	1,590.92
01/11/2015	55,740.00	5,865.00	1,590.92
01/12/2015	48,743.00	53,998.00	1,506.51
01/01/2016	43,050.00	8,344.00	2,000.16
01/02/2016	39,960.00	9,352.00	2,740.48
01/03/2016	30,054.00	13,468.00	5,505.96
01/04/2016	28,861.00	8,744.00	7,757.56
01/05/2016	55,583.00	39,325.00	14,656.96
01/06/2016	50,483.00	37,412.00	15,157.00
01/07/2016	40,565.00	22,900.00	6,113.00
01/08/2016	31,416.00	12,538.00	9,534.00
01/09/2016	32,699.00	6,825.00	2,865.72
01/10/2016	45,449.00	6,526.00	2,450.18
01/11/2016	59,604.00	40,302.06	2,153.10
01/12/2016	41,730.00	6,785.00	1,872.00
01/01/2017	13,990.00	7,885.00	2,285.00
01/02/2017	39,960.00	38,206.00	2,566.00
01/03/2017	30,054.00	52,423.00	6,233.00
01/04/2017	28,861.00	52,423.00	20,203.15
01/05/2017	43,191.00	56,041.00	7,457.85
01/06/2017	41,525.00	54,745.00	11,742.90
01/07/2017	32,461.00	15,737.00	6,964.70
01/08/2017	40,587.00	20,465.00	8,094.10
01/09/2017	40,587.00	17,773.00	1,765.00
01/10/2017	40,587.00	17,773.00	1,281.00
01/11/2017	71,393.00	17,773.00	1,281.00

01/12/2017	44,729.00	8,548.00	1,238.00
01/01/2018	74,158.00	16,640.00	4,778.00
01/02/2018	20,526.00	16,808.00	4,778.00
01/03/2018	41,343.00	26,967.00	11,733.00
01/04/2018	21,435.00	15,798.00	8,308.00
01/05/2018	-	35.00	16,513.00
01/06/2018	41,525.00	54,745.00	16,626.00
01/07/2018	32,461.00	15,737.00	9,646.00
01/08/2018	31,266.00	3,054.00	8,344.00
01/09/2018	40,587.00	17,773.00	3,687.00
01/10/2018	-	-	3,271.00
01/11/2018	71,393.00	17,773.00	2,741.00
01/12/2018	315.00	1.00	4,048.00
01/01/2019	74,158.00	16,640.00	4,213.00
01/02/2019	29,338.00	2.00	5,125.00
01/03/2019	29,338.00	7.00	5,651.00
01/04/2019	59,797.00	34,928.20	9,604.00
01/05/2019	59,797.00	34,928.20	11,719.00
01/06/2019	84,164.00	26,719.00	26,842.00
01/07/2019	30,701.50	23,393.00	8,940.00
01/08/2019	30,701.50	16,246.00	7,519.00
01/09/2019	28,248.00	8,695.00	2,309.00
01/10/2019	67,669.00	13,034.00	528.00
01/11/2019	47,522.00	8,304.00	5,274.00
01/12/2019	49,109.00	11,607.00	3,278.00

Date	Airside HVAC Energy Consump. (kWh)	Landlord Lighting Energy Consump. (kWh)	Tenancy Lighting Energy Consump. (kWh)	Landlord Power Energy Consump. (kWh)	Tenancy Power Energy Consump. (kWh)
01/01/2015	28,728.92	6,885.61	19,406.30	3,564.98	14,511.56
01/02/2015	34,253.96	7,558.95	24,507.40	3,993.13	18,269.66
01/03/2015	27,065.66	6,031.95	20,720.31	3,726.38	16,623.18
01/04/2015	21,687.63	6,159.43	19,832.39	3,730.99	16,613.33
01/05/2015	23,463.22	6,772.26	23,944.03	4,091.84	18,550.00
01/06/2015	23,926.45	6,844.37	22,500.41	3,936.96	17,349.17
01/07/2015	22,437.04	6,533.93	22,233.54	4,048.74	18,080.78
01/08/2015	22,715.11	6,287.06	20,032.50	3,930.16	16,976.17
01/09/2015	24,926.06	6,393.59	22,211.28	4,165.23	18,137.65
01/10/2015	24,382.47	5,757.21	19,372.64	3,821.49	16,770.54

01/11/2015	22,765.02	5,495.41	18,302.38	3,826.15	15,292.90
01/12/2015	21,962.44	5,958.84	19,767.72	3,856.78	15,160.46
01/01/2016	16,017.60	5,733.73	17,974.40	3,742.37	15,151.62
01/02/2016	21,860.13	6,720.75	21,489.34	4,355.22	19,227.70
01/03/2016	21,990.56	5,909.85	18,915.10	3,879.04	17,151.17
01/04/2016	22,286.58	5,557.98	19,750.40	3,751.01	16,477.49
01/05/2016	26,568.05	6,258.10	21,429.63	4,271.91	18,668.12
01/06/2016	19,177.51	5,458.19	18,262.28	3,663.05	21,329.37
01/07/2016	23,952.00	4,369.00	14,417.00	3,032.00	15,050.00
01/08/2016	23,547.00	5,431.00	12,288.00	3,357.00	11,576.00
01/09/2016	21,754.26	5,545.98	12,349.98	3,361.86	9,937.60
01/10/2016	20,772.70	3,318.67	14,556.22	2,956.63	8,627.82
01/11/2016	20,216.03	8,316.51	15,554.80	3,224.51	9,278.05
01/12/2016	17,062.00	5,714.04	15,568.00	2,890.00	8,855.00
01/01/2017	13,121.00	5,204.26	12,342.00	2,333.00	7,158.00
01/02/2017	15,088.40	5,809.68	13,952.48	2,712.34	7,496.88
01/03/2017	20,963.99	5,614.84	18,780.53	2,743.26	11,604.12
01/04/2017	23,716.43	5,769.41	20,693.95	1,032.85	14,458.40
01/05/2017	23,926.27	6,224.47	17,574.04	2,852.84	14,821.60
01/06/2017	20,390.99	5,721.25	17,606.96	3,120.74	13,767.53
01/07/2017	19,551.96	5,694.77	17,416.06	2,882.53	13,842.57
01/08/2017	22,693.70	6,304.83	20,797.52	3,344.88	15,570.70
01/09/2017	1,785.76	6,593.19	21,025.50	2,289.00	5,759.57
01/10/2017	1,236.24	5,831.64	18,059.81	1,675.00	4,506.17
01/11/2017	20,776.74	6,107.44	20,231.67	4,032.83	14,041.81
01/12/2017	20,145.74	6,168.92	19,767.72	598.00	13,226.00
01/01/2018	16,322.26	5,733.73	17,974.40	3,276.00	24,201.62
01/02/2018	23,547.00	6,870.68	19,465.80	3,110.00	24,325.23
01/03/2018	21,351.00	5,482.00	9,609.00	3,397.00	24,096.74
01/04/2018	24,288.00	11,120.00	19,110.02	3,640.00	26,099.03
01/05/2018	22,090.00	4,776.00	20,196.36	3,137.00	24,454.10
01/06/2018	23,680.00	5,290.62	19,544.40	3,254.00	24,499.08
01/07/2018	21,728.00	5,160.00	20,698.31	3,575.00	25,201.18
01/08/2018	25,046.00	5,898.00	19,774.64	4,578.00	23,159.22
01/09/2018	19,899.00	4,295.00	20,689.79	4,364.00	26,071.93
01/10/2018	19,246.00	4,530.00	9,922.00	4,024.00	28,626.17
01/11/2018	20,963.00	4,663.00	8,557.00	4,311.00	27,810.14
01/12/2018	23,896.00	5,985.00	14,620.00	5,385.00	27,251.14
01/01/2019	19,547.00	4,720.00	19,692.22	4,051.00	15,194.39
01/02/2019	22,505.00	5,426.00	9,233.00	4,577.00	8,516.13
01/03/2019	20,821.00	4,848.71	19,393.53	4,067.49	17,350.61
01/04/2019	27,347.00	5,395.00	12,201.00	5,130.51	19,756.56
01/05/2019	22,555.00	5,206.00	20,473.62	3,993.00	29,285.31
01/06/2019	41,043.50	6,446.94	19,508.87	5,673.89	21,006.53
01/07/2019	19,527.50	4,475.90	17,347.61	3,981.11	20,300.38

01/08/2019	26,240.00	6,321.00	22,339.59	5,511.80	26,275.54
01/09/2019	13,755.00	3,761.00	14,028.26	3,358.20	17,021.98
01/10/2019	4,081.00	2,152.00	12,891.07	2,548.00	14,756.67
01/11/2019	42,205.00	9,588.00	9,850.66	7,809.00	11,530.64
01/12/2019	21,455.00	5,373.00	11,255.03	2,867.00	12,024.64

I
CALIBRATED HEATING AND COOLING DEMAND

Months	Total Heating Demand (kWh)	Total Cooling Demand (kWh)
January	28470	3089
February	23432	3989
March	21777	8452
April	7453	34086
May	1897	60200
June	413	83828
July	67	96921
August	53	95477
September	462	74628
October	3542	33173
November	15496	12245
December	23732	5654

J
PARETO FRONT OPTIMIZATION RESULTS

Run	Air System Selection	Heating Plant System	Cooling Plant System	HVAC Operational Energy Consumption (kWh)	HVAC Embodied Carbon (kgCO2)	HVAC CAPEX (£)	2023-2045 HVAC Operational Carbon Emission (kgCO2)	2023-2045 HVAC OPEX (£)
G199-01	AAHS	VRF Heating	Water Cooled C 10C	200,464	346,209	735,092	375,469	652,451
G199-02	DOAS	ASHP Heating 50C	ASHP Cooling 10C	289,443	174,239	477,045	542,127	942,051
G199-03	DOAS	ASHP Heating 50C	ASHP Cooling 10C	289,443	174,239	477,045	542,127	942,051
G199-04	AAHS	VRF Heating	Air Cooled C 10C	203,138	350,129	660,092	380,477	661,152
G199-05	AAHS	ASHP Heating 50C	ASHP Cooling 10C	245,435	234,069	352,092	459,700	798,818
G199-06	DOAS	VRF Heating	Water Cooled C 10C	219,246	286,379	860,100	410,647	713,579

G199-07	DOAS	ASHP Heating 50C	ASHP Cooling 10C	263,016	174,239	477,100	492,629	856,039
G199-08	DOAS	ASHP Heating 50C	Water Cooled C 10C	259,631	208,479	794,100	486,289	845,021
G199-09	DOAS	VRF Heating	Air Cooled C 10C	222,631	290,139	777,100	416,988	724,597
G199-10	AAHS	VRF Heating	Water Cooled C 10C	200,464	346,209	735,092	375,469	652,451
G199-11	AAHS	ASHP Heating 50C	ASHP Cooling 10C	245,435	234,069	352,092	459,700	798,818
G199-12	DOAS	ASHP Heating 50C	ASHP Cooling 10C	289,443	174,239	477,045	542,127	942,051
G199-13	AAHS	ASHP Heating 50C	ASHP Cooling 10C	245,435	234,069	352,092	459,700	798,818
G199-14	DOAS	ASHP Heating 50C	ASHP Cooling 10C	289,443	174,239	477,045	542,127	942,051
G199-15	DOAS	VRF Heating	Air Cooled C 10C	222,631	290,139	777,100	416,988	724,597
G199-16	AAHS	ASHP Heating 50C	Water Cooled C 10C	242,295	268,149	661,092	453,818	788,596

G199-17	AAHS	ASHP Heating 50C	ASHP Cooling 10C	245,435	234,069	352,092	459,700	798,818
G199-18	DOAS	VRF Heating	Water Cooled C 10C	238,774	286,379	860,045	447,224	777,138
G199-19	DOAS	VRF Heating	Water Cooled C 10C	219,246	286,379	860,100	410,647	713,579
G199-20	DOAS	VRF Heating	Water Cooled C 10C	238,774	286,379	860,045	447,224	777,138
G199-21	AAHS	ASHP Heating 50C	Water Cooled C 10C	242,295	268,149	661,092	453,818	788,596
G199-22	AAHS	VRF Heating	Water Cooled C 10C	200,464	346,209	735,092	375,469	652,451
G199-23	DOAS	ASHP Heating 50C	Water Cooled C 10C	259,631	208,479	794,100	486,289	845,021
G199-24	DOAS	VRF Heating	Water Cooled C 10C	219,246	286,379	860,100	410,647	713,579
G199-25	AAHS	ASHP Heating 50C	Water Cooled C 10C	242,295	268,149	661,092	453,818	788,596
G199-26	DOAS	ASHP Heating 50C	Water Cooled C 10C	259,631	208,479	794,100	486,289	845,021
G199-27	DOAS	VRF Heating	Air Cooled C 10C	242,181	290,139	777,045	453,604	788,225

G199-28	AAHS	VRF Heating	Water Cooled C 10C	200,464	346,209	735,092	375,469	652,451
G199-29	DOAS	VRF Heating	Water Cooled C 10C	238,774	286,379	860,045	447,224	777,138
G199-30	DOAS	ASHP Heating 50C	ASHP Cooling 10C	263,016	174,239	477,100	492,629	856,039
G199-31	DOAS	ASHP Heating 50C	Water Cooled C 10C	259,631	208,479	794,100	486,289	845,021
G199-32	DOAS	VRF Heating	Air Cooled C 10C	222,631	290,139	777,100	416,988	724,597
G199-33	AAHS	ASHP Heating 50C	ASHP Cooling 10C	245,435	234,069	352,092	459,700	798,818
G199-34	DOAS	ASHP Heating 50C	Water Cooled C 10C	259,631	208,479	794,100	486,289	845,021
G199-35	AAHS	VRF Heating	Air Cooled C 10C	203,138	350,129	660,092	380,477	661,152
G199-36	AAHS	VRF Heating	Air Cooled C 10C	203,138	350,129	660,092	380,477	661,152
G199-37	AAHS	VRF Heating	Water Cooled C 10C	200,464	346,209	735,092	375,469	652,451
G199-38	DOAS	VRF Heating	Air Cooled C 10C	242,181	290,139	777,045	453,604	788,225

G199-39	AAHS	ASHP Heating 50C	Water Cooled C 10C	242,295	268,149	661,092	453,818	788,596
G199-40	DOAS	VRF Heating	Air Cooled C 10C	242,181	290,139	777,045	453,604	788,225
G1-12	DOAS	VRF Heating	VRF Cooling	296,955	264,199	511,100	556,197	966,501
G9-23	DOAS	VRF Heating	VRF Cooling	310,593	249,899	499,045	581,741	1,010,887
G133-1	DOAS	VRF Heating	VRF Cooling	290,408	249,899	499,700	543,934	945,191
G158-5	DOAS	VRF Heating	VRF Cooling	310,032	249,899	499,045	580,690	1,009,062
G168-19	DOAS	VRF Heating	VRF Cooling	290,408	249,899	499,700	543,934	945,191

K
FORMULAS

HVAC System Intervention Operational Energy Consumption

$$\boldsymbol{OECHVAC} = \sum_{1}^{8760} (\boldsymbol{OECairside} + \boldsymbol{OECwaterside} + \boldsymbol{OECplants})$$

$$\boldsymbol{OECairside} = \sum_{1}^{8760} (\boldsymbol{OECtfan} + \boldsymbol{OECcfan})$$

$$\boldsymbol{OECwaterside} = \sum_{1}^{8760} (\boldsymbol{OEChpump} + \boldsymbol{OECcpump} + \boldsymbol{OECccpump})$$

$$\boldsymbol{OECplant} = \sum_{1}^{8760} (\boldsymbol{OEChplant} + \boldsymbol{OECcplant})$$

HVAC System Intervention Operational Carbon Emission

$$\boldsymbol{OCEHVAC} = \sum_{1}^{8760} \boldsymbol{OECelect} * \sum_{1}^{n+1} \boldsymbol{CERelect}(\boldsymbol{n}) + \sum_{1}^{8760} \boldsymbol{OECngas} * \sum_{1}^{n+1} \boldsymbol{CERngas}(\boldsymbol{n})$$

HVAC System Intervention Embodied Carbon Emission

$$\boldsymbol{ECHVAC} = \boldsymbol{ECairside} + \boldsymbol{ECwaterside} + \boldsymbol{ECplants}$$

$$\boldsymbol{ECairside} = \boldsymbol{ECAHUs} + \boldsymbol{ECterminal}$$

$$\boldsymbol{ECwaterside} = \boldsymbol{EChpump} + \boldsymbol{ECcpump}$$

$$\boldsymbol{ECplant} = \boldsymbol{EChplant} + \boldsymbol{ECcplant}$$

HVAC System Intervention CAPEX

$$\boldsymbol{CAPEXHVAC} = \boldsymbol{CAPEXairside} + \boldsymbol{CAPEXwaterside} + \boldsymbol{CAPEXplants}$$

$$\boldsymbol{CAPEXairside} = \boldsymbol{CAPEXAHUs} + \boldsymbol{CAPEXterminal}$$

$$\boldsymbol{CAPEXwaterside} = \boldsymbol{CAPEXhpump} + \boldsymbol{CAPEXcpump}$$

$$\boldsymbol{CAPEXplant = CAPEXhplant + CAPEXcplant}$$

HVAC System Intervention OPEX

$$\boldsymbol{OCEHVAC = \sum_{1}^{8760} OECelect * \sum_{1}^{n+1} CRelect(n) + \sum_{1}^{8760} CRngas * \sum_{1}^{n+1} CRngas(n)}$$

Calibration of the Metering Data

$$\mathbf{MBE} = \frac{\sum_{i=1}^{Np}(\mathbf{Mi - Si})}{\sum_{i=1}^{Np}(\mathbf{Mi})}$$

$$\mathbf{CV(RMSE)} = \frac{\sqrt{\sum_{i=1}^{Np}(\mathbf{Mi - Si})^2 / Np}}{Mp}$$

Mi: measured data

Si: Simulated data

Np: Entire number of values

Mp: Average of the measured data

Optimization

Minimize (*f*1(x), *f*2(x),…, *f*M(x))T,

Subject to

gj(x) ≥0, j=1,2,…,J,

hk(x) ≥0, k=1,2,…,K,

xi(L) ≥ 0, i=1,2,…,L

Crowding distance

$$CD_i = \frac{f^{i+1} - f^{i-1}}{f_{max} - f_{min}}$$

$$CD_i = Crowding\ Distance$$

Main loop of NSGA-II (pseudo-code)

Randomly initialize a parent population Po

Po=(F1,F2,….) = non dominated sort mode (Po)

For each Fi∈Po

Crowding distance assignment (Fi)

t=0

while(1)

Use selection, crossover and mutation to create new population Qt

Rt=Pt ∪ Qt (Elitism strategy)

F=(F1,F2,….) =non domination sort mode (Rt)

Let Pt+1=Ø,i=1

While (|Pt+1|+|Fi|<N)

Crowding distance assignment (Fi)

Pt+1= Pt ∪ Fi=i+1

End

Pt+1= Pt+1 ∪ Fi[1:(N-|Pt+1|)]

t=t+1

End

Return Fi

End

PUBLICATIONS FROM THE THESIS

Papers

1. B. Tanriverdi, G.Z. Gedik, “Importance of HVAC System Selection in Reducing the Energy Consumption of Building Retrofits–Case Study: Office Building in London”, Civil Engineering and Architecture Vol. 11(1), pp. 217 – 227, DOI: 10.13189/cea.2023.110118