

**UNIVERSIDAD POLITÉCNICA DE MADRID**

Escuela Técnica Superior de Edificación



**Simulation-Based Multi-Objective Optimization for  
Building Retrofits in Iran: Addressing Energy  
Consumption, Emissions, Comfort, and Indoor Air  
Quality Considering Climate Change**

**DOCTORAL THESIS**

Submitted for the degree of doctor by:

**Farshid Dehghan**

Civil Engineer

Madrid, 2025



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**Doctoral Degree in Technological Innovation in Building**

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# Abstract

Climate change presents significant challenges to energy efficiency and occupant comfort in residential buildings. This study introduces a simulation-based multi-objective optimization approach to architectural design, aimed at addressing these challenges and promoting environmental sustainability. Leveraging EnergyPlus for energy simulations and jEPlus for identifying objective functions and design parameters, the research utilized the NSGA-II algorithm via jEPlus + EA for multi-objective optimization. A Morris sensitivity analysis evaluated the influence of 25 design variables—including heating and cooling set points, air infiltration rates, insulation types, window selections, airflow rates, and HVAC systems—on essential objective functions. Focused on a residential building in Sari, Iran, the study examined various climate change scenarios to minimize five primary objectives: primary energy consumption, greenhouse gas emissions, indoor air quality, the predicted percentage of dissatisfied occupants, and visual discomfort hours. The weighted sum method was employed to identify optimal solutions from the Pareto front. The findings indicated that the proposed energy retrofit strategies could decrease primary energy consumption by up to 60%, reduce greenhouse gas emissions by 60%, lower predicted thermal dissatisfaction by 65%, and diminish visual discomfort hours by 83%, while also achieving indoor air quality levels consistent with ASHRAE recommended standards. However, the implementation of these energy-efficient solutions necessitates careful consideration of trade-offs in design decisions to effectively address the challenges posed by climate change.

## Resumen

El cambio climático representa desafíos significativos para la eficiencia energética y el confort de los ocupantes en edificios residenciales. Esta investigación propone un enfoque de optimización multiobjetivo basado en simulación para el diseño arquitectónico, con el objetivo de abordar estos desafíos y mejorar la sostenibilidad ambiental. Utilizando EnergyPlus para simulaciones energéticas y jEPlus para identificar funciones objetivo y parámetros de diseño, se empleó el algoritmo NSGA-II a través de jEPlus + EA para la optimización multiobjetivo. Un análisis de sensibilidad Morris evaluó el impacto de 25 variables de diseño, incluyendo puntos de consigna de calefacción y refrigeración, tasas de infiltración de aire, tipos de aislamiento, selección de ventanas, tasas de flujo de aire y sistemas HVAC, en funciones objetivo clave. Aplicado a un edificio residencial en Sari, Irán, el estudio analizó diversos escenarios de cambio climático para minimizar cinco objetivos principales: consumo de energía primaria, emisiones de gases de efecto invernadero, calidad del aire interior, porcentaje predicho de insatisfacción térmica y horas de incomodidad visual. Se utilizó el método de suma ponderada para seleccionar soluciones óptimas del frente de Pareto. Los resultados demostraron que las estrategias de rehabilitación energética recomendadas pueden reducir el consumo de energía primaria hasta en un 60%, las emisiones de gases de efecto invernadero en un 60%, la insatisfacción térmica predicha en un 65% y las horas de incomodidad visual en un 83%, al mismo tiempo que se alcanzan niveles de calidad del aire interior que cumplen con los estándares recomendados por ASHRAE. Sin embargo, la implementación de estas soluciones energéticamente eficientes requiere una consideración cuidadosa de las compensaciones en las decisiones de diseño al abordar los desafíos del cambio climático.

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## List of Publications Arising from This Thesis

1. Dehghan, Farshid and Porras-Amores, César and Khanmohammadi, Leila and Labib, Rania, Evaluating Machine Learning Models for Sustainable Building Design: Energy, Emissions, and Comfort Metrics. *Building and Environment*, 2025, Available at SSRN: <https://ssrn.com/abstract=5236941> or <http://dx.doi.org/10.2139/ssrn.5236941> (round 1 of review).
2. F. Dehghan and C. Porras Amores, "Simulation-Based Multi-Objective Optimization for Building Retrofits in Iran: Addressing Energy Consumption, Emissions, Comfort, and Indoor Air Quality Considering Climate Change", *Sustainability*, 2025, vol. 17, no. 5, 2056, doi: <https://doi.org/10.3390/su17052056>.
3. Dehghan. F., Porras-Amores. C., (2024), "Simulation-based multi-objective optimization and retrofit approach considering climate change to reduce primary energy consumption, greenhouse gases emissions, thermal and visual discomfort, and improve indoor air quality: A Case study in Iran", *IX International Conference on Technological Innovation in Building (IX Congreso Internacional de Innovación Tecnológica en Edificación)*, Universidad Politécnica de Madrid (Spain).
4. Dehghan. F., Porras-Amores. C., (2023), "Developing a simulation-based multi-objective optimization and retrofit approach to reduce energy consumption, greenhouse gases emissions, thermal and visual discomfort, and improve indoor air quality", *5<sup>th</sup> Building and Management International Conference (BIMIC), 5<sup>o</sup> Congreso Internacional De Gestión En Edificación*, Escuela Técnica Superior de Edificación (Universidad Politécnica de Madrid), Spain.
5. Dehghan. F., Porras-Amores. C., (2023), "Exploring Data-driven Energy Modeling and Simulation for Residential Buildings Retrofit and Optimization using the machine learning approach", *VIII International Conference on Technological Innovation in Building*, Escuela Técnica Superior de Edificación (Universidad Politécnica de Madrid), Spain.

## Abbreviations and Acronyms

|                     |                                                                            |
|---------------------|----------------------------------------------------------------------------|
| ASHRAE              | American Society of Heating, Refrigerating and Air- Conditioning Engineers |
| ACH                 | Air Changes per Hour                                                       |
| BEM                 | Building Energy Modeling                                                   |
| CLO                 | Clothing Unit                                                              |
| CO <sub>2</sub> -eq | Carbon Dioxide Equivalent                                                  |
| COP                 | Coefficient Of Performance                                                 |
| CV (RMSE)           | Coefficient of Variation of the Root-Mean-Square Error                     |
| DX                  | Direct Expansion                                                           |
| DGP                 | Daylight Glare Probability                                                 |
| DGI                 | Daylighting Glare Index                                                    |
| DOAS                | Dedicated Outdoor Air System                                               |
| EMS                 | Energy Management System                                                   |
| EPBD                | Energy Performance of Buildings Directive                                  |
| EER                 | Energy Efficiency Ratio                                                    |
| ERMs                | Energy Retrofit Measures                                                   |
| ENSIMS              | Energy Simulation Solutions                                                |
| GHG                 | Greenhouse Gas                                                             |
| GWP                 | Global Warming Potential                                                   |
| HVAC                | Heating, Ventilation, and Air Conditioning                                 |
| IAQ                 | Indoor Air Quality                                                         |
| IEA                 | International Energy Agency                                                |
| IPCC                | Intergovernmental Panel on Climate Change                                  |
| JEA                 | jEPlus Energy Analytics                                                    |
| Min                 | Minimum                                                                    |

|         |                                               |
|---------|-----------------------------------------------|
| NSGA-II | Non-dominated Sorting Genetic Algorithm II    |
| NMBE    | Normalized Mean Bias Error                    |
| O. K. B | Oberkante Fensterbank                         |
| PEC     | Primary Energy Consumption                    |
| PPD     | Predicted Percentage Dissatisfied             |
| PMV     | Predicted Mean Vote                           |
| PV      | Photovoltaic                                  |
| PTAC    | Packaged Terminal Air Conditioner             |
| PTHP    | Packaged Terminal Heat Pump                   |
| SHGC    | Solar Heat Gain Coefficient                   |
| SBMO    | Simulation-Based Multi-Objective Optimization |
| SDGs    | Sustainable Development Goal                  |
| UGR     | Unified Glare Rating                          |
| UNEP    | United Nations Environment Program            |
| VRF     | Variable Refrigerant Flow                     |
| VAV     | Variable Refrigerant Flow                     |
| XP      | Extruded Polystyrene                          |

# 1. Introduction

The 2030 Agenda for Sustainable Development, encapsulated in the 17 Sustainable Development Goals (SDGs), represents a global commitment to addressing pressing challenges such as climate change, energy efficiency, and environmental sustainability. Climate change, driven by rising greenhouse gas emissions, poses severe risks to ecosystems, economies, and human well-being.

The Intergovernmental Panel on Climate Change (IPCC) reports that global temperatures have already risen by approximately 1.1°C above pre-industrial levels as of 2023, necessitating urgent action to limit warming to 1.5°C. Among the key contributors to emissions, the building sector plays a pivotal role, accounting for approximately 39% of global energy-related carbon dioxide emissions and 40% of total energy consumption worldwide, according to the International Energy Agency [1].

In Asia, rapid urbanization and population growth have intensified energy demand in buildings, with the sector contributing over 30% of regional emissions in 2020 [2]. In Iran, the building sector is particularly significant, consuming around 35% of the nation's total energy and contributing to 25% of CO<sub>2</sub> emissions, driven largely by residential buildings with outdated designs and inefficient systems [3].

These figures underscore the urgent need for transformative strategies to enhance energy efficiency and reduce environmental impacts in the residential sector to align with SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). To address these challenges, building energy simulation has emerged as a powerful tool for advancing sustainability in the residential sector.

Simulation tools enable designers and engineers to model and analyze critical aspects of building performance, including energy consumption, thermal efficiency, and indoor environmental quality. By evaluating multiple design options, materials, and systems before construction or retrofitting, these tools facilitate the identification of optimal energy-efficient solutions, reducing energy demand and carbon footprints. Retrofitting existing residential buildings is a cornerstone

strategy for achieving these goals, particularly in regions like Iran, where a significant portion of the building stock predates modern energy standards.

Retrofitting involves upgrading insulation, HVAC systems, lighting, and integrating renewable energy technologies to enhance performance and minimize reliance on fossil fuels. When combined with simulation tools, retrofitting becomes a targeted process, allowing stakeholders to prioritize interventions that maximize energy savings and environmental benefits.

The integration of building energy simulation with retrofitting initiatives forms a robust framework for aligning the residential sector with the 2030 Agenda. By enabling data-driven decision-making, this approach supports the optimization of energy management, reduction of emissions, and enhancement of building sustainability.

In the context of Iran and broader global efforts, such strategies are essential for mitigating climate change impacts and fostering an environmentally responsible future in line with the SDGs.

## 2. State of the art

This chapter reviews existing research on Simulation-Based Multi-Objective Optimization considering building performance simulation and energy modeling, optimization of thermal and visual comfort, indoor air quality and pollutant reduction, and energy retrofitting and sustainability strategies.

After that, a detailed and scientific explanation of key environmental objective functions (energy consumption, CO<sub>2</sub> emissions, indoor air quality, thermal comfort, and visual comfort), and their role in optimizing building performance is reviewed.

### 2.1. Simulation-Based Multi-Objective Optimization

#### 2.1.1. Building Performance Simulation and Energy Modeling

Building Performance Simulation (BPS) and Building Energy Modeling (BEM) are critical tools for designing and retrofitting energy-efficient buildings. Pan et al. [4] highlights the pivotal role of BPS and BEM in developing energy-efficient designs, operations, and retrofits. Their study evaluates the research landscape, identifies emerging trends (e.g., advanced simulation tools like EnergyPlus), and provides recommendations for applying BEM across project phases. However, their focus is broad and does not specifically address humid subtropical climates.

Mostafazadeh et al. [5] introduce prNSGA-III, an enhanced NSGA-III algorithm using parallel computing and a results-saving archive, to optimize energy performance in residential buildings in Tehran. By integrating EnergyPlus with MATLAB, the study optimizes active, passive, water conservation, and renewable strategies, considering future climate change and energy price fluctuations. The results show significant reductions in energy use and life cycle costs, but the applicability to humid subtropical climates remains unexplored.

#### 2.1.2. Optimization of Thermal and Visual Comfort

Thermal and visual comfort are key environmental objective functions influencing occupant well-being and energy consumption. Naderi et al. [6] focus on optimizing architectural specifications and control parameters for smart shading systems, demonstrating significant potential for energy savings and improved occupant

comfort. However, the study does not specify applicability to humid climates, necessitating further investigation.

Ziaee and Vakilinezhad [7] investigate optimal light shelf properties for urban settings like Tehran and Sari. Their findings indicate that light shelves enhance visual comfort and reduce lighting energy use. This study is relevant to the humid subtropical climate of Sari, but it does not account for future climate change impacts.

Dokhanian et al. [8] evaluate shading strategies for an educational building in Sabzevar, identifying concrete overhang shading as the most effective solution. The study highlights the effectiveness of simple overhangs and light-shelf structures, but its focus on a hot-arid climate limits its applicability to humid regions.

### **2.1.3. Indoor Air Quality and Pollutant Reduction**

Indoor Air Quality (IAQ) is critical for occupant health and comfort. Baghoolizadeh et al. [9] investigate design factors affecting IAQ in the residential sector, applying optimization techniques to reduce CO<sub>2</sub> concentrations and pollutant levels while enhancing thermal comfort. The results show significant improvements, but the study does not specifically address humid subtropical climates.

Naderi et al. [10] assess design parameters of direct evaporative cooling systems across four Iranian climates, using EnergyPlus simulations to evaluate the impacts of cooling pad saturation efficiency, airflow rate, and thermostat set points on electricity and water consumption. While the study demonstrates energy-saving potential, it does not focus on IAQ in humid climates.

### **2.1.4. Energy Retrofitting and Sustainability Strategies**

Energy retrofitting is essential for reducing energy consumption and greenhouse gas emissions in existing buildings. Nateghi et al. [11] proposes a methodology for optimizing energy demands in multistory hotels, achieving significant energy savings and suggesting reinvestment of cost savings into renewable energy systems. However, the study focuses on non-residential buildings and does not address humid climates.

Tavakolan et al. [12] highlight challenges in energy retrofitting in Iran, where subsidized energy pricing hinders project feasibility. Their simulation-based multi-

objective optimization framework emphasizes the need for policy reforms to improve economic viability. This is relevant to the current study, as energy pricing policies pose similar barriers in the Caspian region.

Alimohamadi and Jahangir [13] integrate MATLAB and EnergyPlus with the NSGA-II algorithm to optimize energy consumption, thermal comfort, and net present value in residential buildings. The study accounts for energy price inflation, revealing that many optimal solutions are unprofitable under current pricing. While relevant, it does not specifically address humid subtropical climates.

Karimi et al. [14] introduce an innovative optimization framework combining Bayesian optimization, XGBoost, and multi-objective genetic algorithms to enhance non-residential building performance, focusing on total energy (TE), indoor overheating degree (IOD), and predicted percentage dissatisfied (PPD). The framework highlights the importance of building envelopes and HVAC management in response to climate change but does not cover humid climates.

Karimi et al. [15] analyze a decade of research (2010–2020) on urban heat island mitigation, based on 91 studies. The findings emphasize the role of urban parks, trees, and green roofs in reducing urban heat, relevant to humid subtropical climates. However, the study does not focus on building retrofitting in these regions.

### 2.1.5. Analysis of Relationships and Trends

The reviewed studies demonstrate significant advancements in energy simulation tools (e.g., EnergyPlus) and optimization algorithms (e.g., NSGA-II, prNSGA-III) for improving building performance. Key relationships include:

- **Thematic Focus:** Studies like [4] and [5] emphasize comprehensive energy modeling and multi-objective optimization, while others ([9], [10]) focus on specific aspects like IAQ or evaporative cooling.
- **Climatic Focus:** Most studies target hot-arid or temperate climates, with limited attention to humid subtropical regions like the Caspian Sea area.
- **Practical Application:** Studies [12] and [13] highlight Iran's energy pricing challenges, which align with barriers to retrofitting in the Caspian region.

Key trends include increased use of advanced simulation tools, a focus on multi-objective optimization, and growing attention to climate change adaptation.

However, the lack of focus on humid subtropical climates and future climate scenarios is a common limitation.

### 2.1.6. Knowledge Gaps

The literature review identifies the following gaps:

1. **Limited Focus on Humid Subtropical Climates:** Most studies address hot-arid or temperate climates, with minimal research on the Caspian region's high humidity and moderate temperatures.
2. **Lack of Integrated Strategies:** Many studies focus on single strategies (e.g., shading or evaporative cooling) rather than integrating active, passive, and renewable approaches.
3. **Future Climate Change Impacts:** Except for [5] and [14], few studies analyze the effects of future climate scenarios on building design and retrofitting.
4. **Policy Challenges:** Studies [12] and [13] note economic barriers due to subsidized energy prices in Iran, but practical solutions for humid regions are lacking.
5. **Residential Sector Focus:** Studies like [11] and [14] target non-residential buildings, while residential buildings in humid climates require specific attention.

### 2.1.7. Conclusions and Justification for the Current Study

This study introduces a comprehensive framework for energy retrofit projects tailored to buildings in Iran, with a focus on the humid subtropical climate of the Caspian Sea region. Unlike prior research (see Table 2-1), which primarily explored limited energy efficiency measures and climatic impacts, this work integrates active, passive, and renewable energy strategies to optimize energy performance, occupant comfort, and indoor air quality while addressing the multifaceted effects of climate change. Despite the pressing need for climate adaptation, there is a significant research gap regarding its implications for residential buildings in these distinctive climatic zones. This study seeks to bridge this gap by investigating how future climate scenarios shape effective building design and retrofit strategies in humid subtropical regions.

Table 2-1: The number of studies conducted on multi-objective optimization in the building sector

| Authors                    | Objective Functions                                                                           | Design Variables                                                                              | Application           | Geo. Regions  | Ref. |
|----------------------------|-----------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|-----------------------|---------------|------|
| Mostafazadeh et al. (2023) | Discomfort hours, environmental performance, life cycle cost                                  | Envelope insulations, HVAC systems, window properties, PV solar cells, domestic faucets       | Residential buildings | Iran          | [5]  |
| Tavakloan et.al (2022)     | Primary energy consumption, net present value, discounted payback period (NSGA-II)            | Envelope insulations, HVAC systems, window properties, PV solar cells                         | Residential buildings | Iran          | [12] |
| Naderi et al. (2020)       | Energy consumption, thermal and visual discomfort                                             | Shading control strategy, temperature set-point, solar irradiance set-points, load set-points | Office buildings      | Iran          | [6]  |
| Mauro et al. (2015)        | LCC, energy consumption (sensitivity analysis)                                                | Envelope characteristics (wall, roof, and window), HVAC systems, renewable energy             | Office buildings      | South Italy   | [16] |
| Duah et al. (2016)         | Heating and cooling energy consumption, thermal comfort (sensitivity analysis)                | Envelope characteristics (wall, roof, and window), HVAC systems                               | Residential buildings | United States | [17] |
| Lin et.al (2022)           | Energy Consumption, Thermal comfort (ANN + Whale Optimization Algorithm)                      | Air condition and mechanical ventilation (ACMV) characteristics                               | Residential buildings | Taiwan        | [18] |
| Chegari et.al (2021)       | Annual weighted average discomfort degree hours, annual thermal energy demand (ANN + NSGA-II) | Building envelope, ACH, glazing                                                               | Residential buildings | Morocco       | [19] |
| Jung et.al (2021)          | Building energy demand, life cycle cost, life cycle assessment (ANN + NSGA-II)                | Building envelope, ACH, WWR, number of occupants, window properties                           | Residential buildings | Korea         | [20] |
| Wu (2021)                  | Energy consumption, thermal comfort (NSGA-II)                                                 | Primary airflow rate, chilled water flow rate                                                 | Sample room           | Singapore     | [21] |
| Bre et al. (2020)          | Energy demand, thermal comfort (ANN + NSGA-II)                                                | Building azimuth, building envelopes, air mass flow, window properties                        | Residential buildings | Argentina     | [22] |
| Ebrahimi-Moghadam et.al    | Total energy, predicted percentage of dissatisfied (NSGA-II)                                  | Shelf properties                                                                              | Residential buildings | Mashhad, Iran | [23] |

|                       |                                                                                                                           |                                                                                                                                                                                                                  |                       |                               |      |
|-----------------------|---------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|-------------------------------|------|
| (2020)                |                                                                                                                           |                                                                                                                                                                                                                  |                       |                               |      |
| Yao et al.<br>(2018)  | Energy demand, thermal comfort (parametric analysis)                                                                      | Building azimuth, wall properties, WWR, window properties, ACH                                                                                                                                                   | Residential buildings | Chongqing, Shanghai, Changsha | [24] |
| Gou et.al<br>(2018)   | Building energy demand, comfort time Ratio (ANN + NSGA-II)                                                                | Building orientation, window properties, building envelope, wall insulations                                                                                                                                     | Residential buildings | Shanghai                      | [25] |
| Li et.al<br>(2017)    | Life cycle costing, carbon dioxide emissions, the amount of thermal discomfort throughout the year<br>(C++ + NSGA-II)     | Building envelope, building azimuth, WWR                                                                                                                                                                         | Residential buildings | Nanjing                       | [26] |
| Bre et al.<br>(2017)  | Energy demand, thermal comfort<br>(GA + Morris screening method for sensitivity analysis)                                 | Building azimuth, building envelopes, window and door properties                                                                                                                                                 | Residential buildings | Argentine                     | [27] |
| Wang et al.<br>(2024) | Building energy consumption, thermal comfort (support vector regression non-dominated genetic algorithm-II (SVR-NSGA-II)) | Parameters of the building envelope are as follows: the exterior wall U-value, roof U-value, exterior wall U-value, solar heat gain coefficient value (SHGC), and south, north, east, west window-to-wall ratios | Office buildings      | Chongqing                     | [28] |

## 2.2. Environmental objective functions

Environmental objective functions in the context of building design and performance optimization are mathematical or analytical constructs used to evaluate and optimize the environmental sustainability and occupant well-being of built environments. These functions integrate multiple performance metrics to achieve a balance between minimizing adverse environmental impacts, enhancing energy efficiency, and ensuring occupant comfort. They serve as critical tools in sustainable design, urban planning, and building performance evaluation, aligning with global goals such as carbon neutrality, resource conservation, and improved indoor environmental quality (IEQ). Below are a detailed and scientific explanation of key environmental objective functions (energy consumption, CO<sub>2</sub>

emissions, indoor air quality, thermal comfort, and visual comfort), and their role in optimizing building performance.

### 2.2.1. Energy consumption

The proposed framework for evaluating the environmental impacts of building energy retrofits adopts primary energy consumption (PEC) as a key metric, in line with the recast Energy Performance of Buildings Directive (EPBD). PEC is calculated by converting net electricity and natural gas demands into primary energy values using locally relevant primary energy factors (PEFs). These factors, which account for energy losses during conversion and distribution, are typically defined by local regulations or energy efficiency standards. Monthly energy demand data are obtained through dynamic simulations using EnergyPlus software (V24.1.0), which models building energy performance under diverse conditions. A key feature of the framework is the integration of rooftop photovoltaic (PV) panels as a retrofit measure, with the energy they generate deducted from total consumption, thereby lowering the net demand on the electrical grid [29, 30]. This integrated approach emphasizes the critical role of incorporating renewable energy sources to strengthen the sustainability evaluation of building retrofits. To convert site energy to source energy in EnergyPlus, specific conversion factors are applied to account for energy losses during production, transmission, and delivery. In Iran, these conversion factors depend on the efficiency of the national energy infrastructure. Globally adopted conversion factors, which can be tailored for Iran, are outlined Table 2-2:

Table 2-2: Site-to-Source Conversion Factors for Building Energy Simulations

| Energy Source | Site-to-Source Conversion Factor | Reference |
|---------------|----------------------------------|-----------|
| Electricity   | 3.15                             | [31, 32]  |
| Natural Gas   | 1.05                             | [31, 32]  |

These factors can be adjusted based on the specific efficiencies of Iran's energy infrastructure.

### 2.2.2. Greenhouse gas emissions

Greenhouse gases (GHGs) are atmospheric gases that absorb and retain heat, significantly influencing Earth's temperature via the greenhouse effect.

Comprehending GHGs and their emissions is essential for tackling climate change and its related risks. By reducing GHG emissions, we can alleviate climate impacts and promote a more sustainable future [33]. CO<sub>2</sub>-eq, or carbon dioxide equivalent, is a standardized metric used to quantify the global warming potential (GWP) of different greenhouse gases (GHGs) relative to CO<sub>2</sub> over a specified period, typically 100 years. It indicates the equivalent amount of CO<sub>2</sub> that would produce the same warming effect. CO<sub>2</sub>-eq enables organizations and individuals to assess and report their total carbon footprint, facilitating a clearer understanding of their role in climate change. In Figure 2-1, the proportion of greenhouse gas emissions is presented as a percentage.

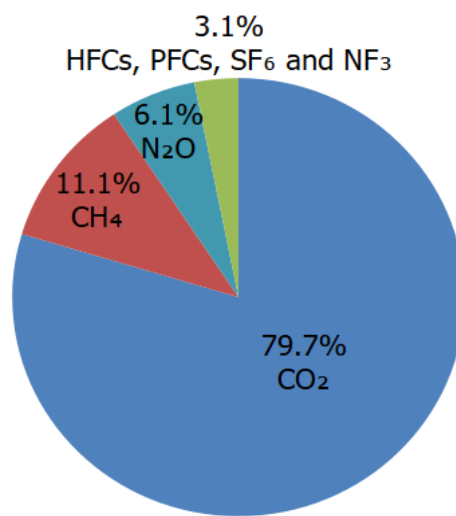


Figure 2-1: Greenhouse gas emissions [34]

### Climate Change Impacts

Increasing concentrations of GHGs from human activities enhance the greenhouse effect, leading to global warming and climate change. Some of the impacts include the following:

- Rising temperatures: increased average temperatures and more frequent heatwaves.
- Severe weather events: more frequent and intense hurricanes, droughts, and floods.
- Melting ice and rising sea levels: Arctic and Antarctic ice melt contributes to rising sea levels, threatening coastal areas.
- Ecosystem disruption: changing habitats affecting biodiversity, with some species struggling to adapt to rapid changes.

## Emission Factors

Within the framework of climate change and environmental policy, understanding greenhouse gas emission factors is vital for developing effective mitigation strategies. In Iran, the building sector significantly contributes to emissions of carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O). The precise quantification of these emission factors is critical for assessing the sector's overall emissions, guiding policy formulation, and advancing sustainability initiatives. Emission factors are key to estimating greenhouse gas emissions from various fuel types, electricity production, and specific activities. In Iran, typical emission factors can be obtained from national inventories and studies on sectoral emissions, as outlined Table 2-3:

Table 2-3: CO<sub>2</sub> Emission Factors for Electricity Generation and Natural Gas in Iran for Building Energy Analysis

| Energy Source          | Emission Factor                  | Reference |
|------------------------|----------------------------------|-----------|
| Electricity Generation | 565 g CO <sub>2</sub> per kWh    | [35, 36]  |
| Natural gas            | 181.07 g CO <sub>2</sub> per kWh | [35, 36]  |

Iran's emissions primarily come from the following sectors:

- Household energy: residential areas significantly contribute to CO<sub>2</sub> emissions, with estimates suggesting that households accounted for approximately 23.4% of total CO<sub>2</sub> emissions in the country [37]. This is connected to energy consumption patterns, where fossil fuels predominately supply energy.
- Industrial sector: this sector is also a major contributor, responsible for around 24.1% of CO<sub>2</sub> emissions [37].
- Transportation: accounts for about 21.2% of CO<sub>2</sub> emissions, highlighting the impact of vehicle fuel consumption [37].

The calculation of carbon dioxide equivalent is as follows:

$$CO_2e = Energy\ Consumption \times Emission\ Factor \quad (1)$$

To calculate CO<sub>2</sub> equivalent emissions (CO<sub>2</sub>-eq) in Iran, one needs to utilize specific emission factors that define the greenhouse gas emissions associated with various sources and activities. These factors help in converting the emissions of different

greenhouse gases into a common unit, allowing for an aggregation of their impacts. In Iran, the emission factors for methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) associated with electricity and natural gas consumption are significant for assessing greenhouse gas emissions and are as shown in Table 2-4:

Table 2-4: Greenhouse Gas Emission Factors for Electricity Generation and Natural Gas Consumption in Building Energy Analysis

| Energy Source           | Greenhouse Gas                   | Emission Factor (g/MJ) | Reference |
|-------------------------|----------------------------------|------------------------|-----------|
| Electricity Generation  | Methane (CH <sub>4</sub> )       | 1.4                    | [35, 36]  |
|                         | Nitrous Oxide (N <sub>2</sub> O) | 0.03                   | [35, 36]  |
| Natural Gas Consumption | Methane (CH <sub>4</sub> )       | 4.73                   | [35, 36]  |
|                         | Nitrous Oxide (N <sub>2</sub> O) | 0.094                  | [35, 36]  |

The emission factors indicate a higher methane emission associated with natural gas compared to electricity. In summary, these values illustrate the importance of transitioning to cleaner energy sources to mitigate greenhouse gas emissions in Iran.

### Global Warming Potentials

The GWP is a key metric developed by the Intergovernmental Panel on Climate Change (IPCC) that quantifies the warming impact of greenhouse gases compared to CO<sub>2</sub> over a specified time horizon, commonly 100 years. When calculating CO<sub>2</sub>e, it is essential to also consider the global warming potential (GWP) of other gases.

Methane (CH<sub>4</sub>), with a GWP of 28 (over 100 years), has a significant impact when converted to CO<sub>2</sub>e, which is crucial in comprehensive emissions accounting.

$$CO_2e_{CH_4} = \text{Mass of } CH_4 \text{ (Metric tonnes)} \times \text{GWP of } CH_4 \text{ (28)} \quad (2)$$

Nitrous oxide (N<sub>2</sub>O): The GWP for N<sub>2</sub>O is typically around 298 for a 100-year time horizon. This means that one unit of N<sub>2</sub>O is equivalent to 298 units of CO<sub>2</sub> in terms of its potential impact on warming over the next century.

$$CO_2e_{N_2O} = \text{Mass of } N_2O \text{ (Metric tonnes)} \times \text{GWP of } N_2O \text{ (298)} \quad (3)$$

$$\text{Total } CO_2e = CO_2e_{\text{Electricity}} + CO_2e_{\text{Natural Gas}} + CO_2e_{CH_4} + CO_2e_{N_2O} \quad (4)$$

### 2.2.3. Indoor air quality

The indoor air quality (IAQ) objective function focuses on quantifying and optimizing factors that influence air quality within indoor environments. Key considerations for IAQ include:

- Pollutant levels: monitoring concentrations of CO<sub>2</sub> and other harmful substances is crucial for ensuring occupant health and productivity.
- Ventilation rates: adequate ventilation is essential to dilute indoor pollutants and maintain air quality.
- Humidity control: keeping relative humidity within an optimal range (30–60%) to prevent Mold growth and enhance comfort [38].

By utilizing this objective function, we aim to create healthier indoor environments that promote occupant well-being.

### 2.2.4. Thermal comfort

This approach is suitable for environments where occupants perform activities with metabolic rates ranging from 1.0 to 2.0 met and wear clothing providing thermal insulation of 1.5 Clo or less. The ASHRAE thermal sensation scale, which quantifies individuals' temperature perceptions, is defined as follows: +3 (hot), +2 (warm), +1 (slightly warm), 0 (neutral), -1 (slightly cool), -2 (cool), and -3 (cold). The predicted mean vote (PMV) model applies heat balance principles to link six critical factors affecting thermal comfort with the average responses on this scale. The predicted percentage dissatisfied (PPD) index is correlated with the PMV, as illustrated in Figure 2-2.

$$PMV = f(I_{cl}, M, t_a, t_{mrt}, P_a, v) \quad (5)$$

$$PPD = 100 - 95 \exp(-0.03353PMV^4 - 0.2179PMV^2) \quad (6)$$

This index is derived from the premise that participants who rate their comfort as +2, +3, -2, or -3 are considered dissatisfied, and it simplifies the PPD to be symmetrical around the neutral PMV point. Table 3-4 specifies the recommended ranges for PPD and PMV for typical settings. The comfort zone is defined as the range of combinations of the six thermal comfort factors where the PMV remains within the recommended limits outlined in Table 2-5. The PMV model is calculated based on the relevant air temperature and mean radiant temperature, as well as considering the metabolic rate, clothing insulation, air speed, and humidity. If the

PMV value produced by the model falls within the suggested range, it indicates that the environmental conditions are within the comfort zone [39].

Table 2-5: A suitable thermal environment for overall comfort [39]

| PPD | PMV Range                        |
|-----|----------------------------------|
| <10 | $-0.5 < \text{PMV Range} < +0.5$ |

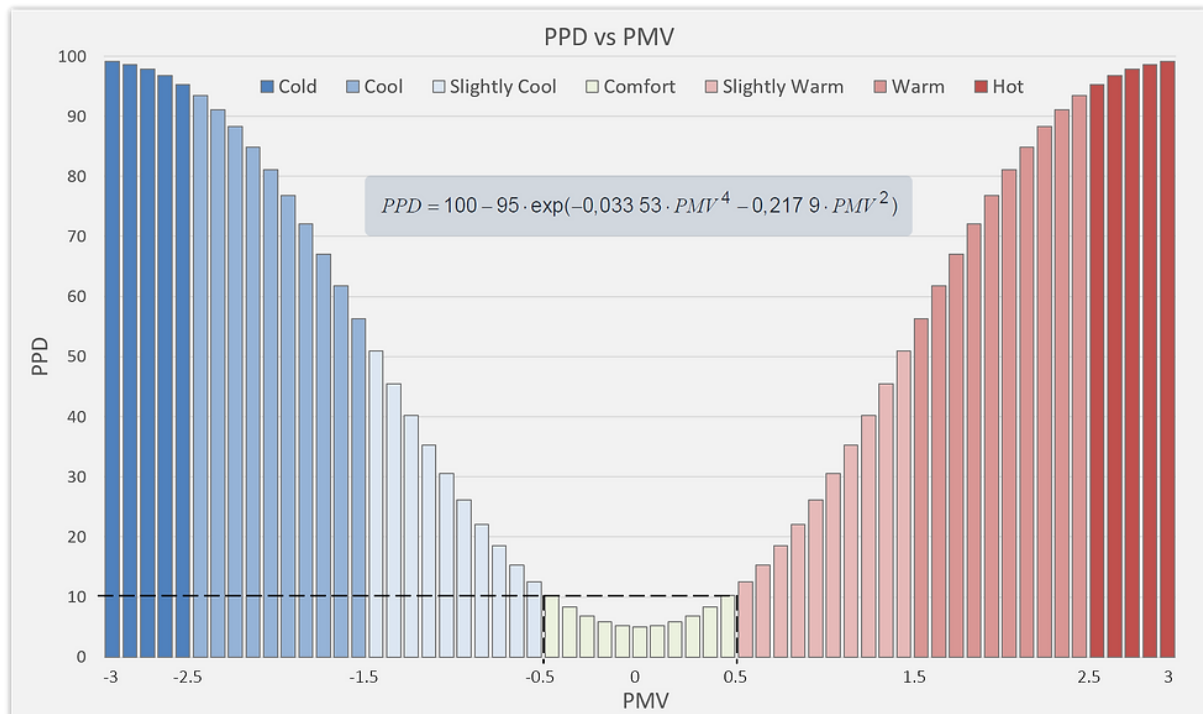
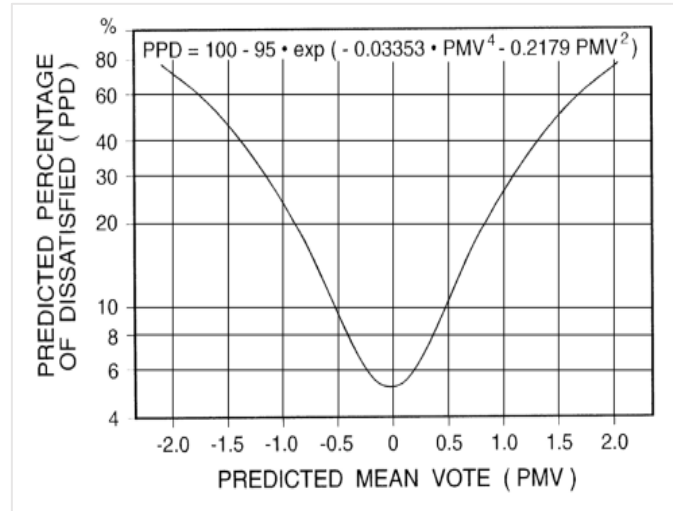


Figure 2-2: The predicted percentage of dissatisfied individuals (PPD) based on the predicted mean vote (PMV) [39]

### 2.2.5. Visual comfort

Visual comfort is essential for occupant well-being and productivity in built environments, with glare posing a significant challenge among its influencing factors. EnergyPlus, a sophisticated building energy simulation tool, offers robust functionality for evaluating glare and other visual comfort metrics. A critical output is the Daylighting Reference Point 1 Glare Index Setpoint Exceeded Time, which enables the assessment of visual comfort in daylight-lit spaces. By analyzing this exceedance time, designers and researchers can identify periods of excessive glare, guiding decisions such as optimizing window sizes, implementing shading solutions, or adjusting spatial layouts. The glare index quantifies glare at a designated reference point, typically based on metrics like the Unified Glare Rating (UGR), Daylight Glare Probability (DGP), or Daylighting Glare Index (DGI). EnergyPlus computes glare index values using luminance levels at the reference point, factoring in variables such as window placement, shading systems, and surface reflectance. As noted in Table 2-6, the setpoint represents a predefined threshold for acceptable glare levels, aligned with established standards like DGI and UGR. The Exceed Time indicates the duration during which the glare index exceeds this threshold, offering valuable insights for ensuring compliance with visual comfort standards and informing architectural enhancements. By incorporating glare assessment capabilities, EnergyPlus supports a holistic evaluation of visual comfort, fostering healthier and more productive indoor environments.

$$DGI = 10 \log_{10} \left[ 0.478 \sum_{i=1}^n \left( \frac{L_{si}^{1.6} \Omega_{si}^{0.8}}{L_b + 0.07 \Omega_{si} L_{win} P_i^{1.6}} \right) \right] \quad (7)$$

where  $L_{si}$ ,  $L_b$ , and  $L_{win}$  are the luminance of the glare source, the background, and the window in “cd/m<sup>2</sup>”, respectively. In addition,  $\Omega_{si}$  is the solid angle subtended by the glare source from the occupants’ point of view, modified by Guth’s position index, i.e.,  $P_i$ .  $n$  is the number of glare sources [40]. For residential and office buildings, the maximum allowable threshold for DGI is 22 [40].

Table 2-6: Glare regions and their related glare index [41]

| Zone            | Region             | DGI | UGR |
|-----------------|--------------------|-----|-----|
| Discomfort zone | intolerable        | >28 | >28 |
|                 | just intolerable   | 28  | 28  |
|                 | uncomfortable      | 26  | 25  |
|                 | just uncomfortable | 24  | 22  |
| Comfort zone    | acceptable         | 22  | 19  |

|  |                  |    |    |
|--|------------------|----|----|
|  | just acceptable  | 20 | 16 |
|  | noticeable       | 18 | 13 |
|  | just perceptible | 16 | 10 |

### 3. Objective

The main objective of this doctoral research is to develop and validate a simulation-based multi-objective optimization (SBMO) framework for energy retrofitting in residential buildings in humid subtropical climates, with a specific focus on reducing primary energy consumption, greenhouse gas emissions, and visual and thermal discomfort, while improving indoor air quality under current and future climate change scenarios.

To achieve the main objective, the following secondary objectives have been defined:

- To characterize the baseline energy performance of a representative residential building located in Sari, Iran, including envelope properties, HVAC systems, occupancy patterns, and climatic conditions.
- To identify and quantify the most influential design parameters through a global sensitivity analysis (Morris method), including heating/cooling setpoints, infiltration rates, insulation, glazing, HVAC types, and renewable energy systems.
- To implement and calibrate dynamic building simulations using EnergyPlus and jEPlus for accurately modeling energy consumption, indoor air quality (IAQ), and comfort indicators.
- To design a comprehensive set of Energy Retrofit Measures (ERMs) integrating passive, active, and renewable strategies adapted to the humid subtropical context.
- To optimize the ERM s using the NSGA-II evolutionary algorithm, generating Pareto-optimal solutions for multiple environmental and comfort-related objectives.
- To assess the impact of future climate change (2050 and 2080 projections under the A2 scenario) on building energy performance and retrofit effectiveness.
- To select the most suitable retrofit strategies through a weighted decision-making approach that considers trade-offs between objectives and stakeholder preferences.

## 4. Methodology

The proposed methodology is structured into four distinct phases, detailed in the subsequent sections and depicted in Figure 4-1:

- Phase 1: This phase focuses on creating an initial building model using data from thorough audits. Energy simulations are then conducted to calibrate the baseline model accurately.
- Phase 2: Here, objective functions are established, and parametric energy retrofit measures (ERMs) are incorporated into the model to assess potential improvements in performance.
- Phase 3: The NSGA-II algorithm is utilized to iteratively optimize ERM combinations, generating a set of Pareto-optimal solutions that effectively balance multiple objectives.
- Phase 4: A multi-criteria decision-making process, employing the weighted sum method, is applied to select the final retrofit strategies, customized to align with stakeholder priorities.

The research process involves the following steps in more detail:

**Building architecture modeling:** Architectural modeling is performed using SketchUp, leveraging the existing building plan and architectural drawings to generate a precise digital representation of the building.

**Collecting data:** Data collection is vital for evaluating a building's energy performance and designing effective retrofit projects. Each building possesses distinct characteristics that affect its energy use, making accurate data acquisition critical for informed analysis and actionable recommendations. The collected data can be classified into the following categories: building layout and general information, occupancy details, construction specifications, lighting systems, and mechanical and electrical system characteristics

**Building energy simulation:** EnergyPlus is used to perform detailed building energy simulations. These simulations capture the energy performance of the building under various conditions, creating a baseline EnergyPlus model of the building studied.

**Calibration of building energy model:** Calibrating building energy models is a vital process to ensure that simulated energy consumption aligns closely with actual usage, thereby improving the accuracy and reliability of energy performance

evaluations. This process entails comparing simulation outputs with real-world energy consumption data, typically obtained from energy bills, and refining the model to minimize discrepancies. If differences are identified, the model is iteratively adjusted until it achieves an acceptable level of accuracy, effectively mirroring actual conditions. While calibration thresholds may vary, a Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) below 15% and a Normalized Mean Bias Error (NMBE) within  $-5\%$  to  $+5\%$  are generally regarded as best practice [42].

**Analyzing Model Weaknesses and Energy Inefficiencies:** The energy performance data is evaluated to pinpoint components contributing to substantial energy waste, identifying key areas for optimization. These insights guide the definition of decision variables in subsequent steps.

**Parametric study:** a comprehensive parametric study is conducted using EnergyPlus to gain insight into how various factors influence building energy performance, facilitating informed decisions for design or retrofitting projects.

**Energy retrofit measures (ERMs):** This section presents a range of energy retrofit measures (ERMs) aimed at improving building performance. The options for each decision variable are proposed based on considerations such as market availability, stakeholder needs, climatic conditions, and building-specific characteristics. A comprehensive array of ERMs, including passive, active, and renewable strategies, is evaluated to achieve three primary goals: minimizing primary energy consumption, enhancing environmental performance through reduced carbon emissions, and improving occupant comfort. The key ERMs explored in this study are outlined below:

- Building envelope: enhancements in thermal insulation for floor and roof, and replacement of exterior door and windows (passive measures),
- Controlling infiltration: improving window/door airtightness (passive measures),
- Building physics: optimizing north window-to-wall ratio, installing overhangs and fins (passive measures),
- Daylighting controls: implementing stepped, continuous, continuous-off lighting controls (passive measures),
- Window shading control: applying shading control strategies (passive measures),

- Intelligent control systems: utilizing an energy management system (EMS) EnergyPlus to improve indoor air quality (active measures),
- HVAC systems: adjusting heating and cooling setpoint and replacing existing systems (active measures),
- Renewable energy sources: installing photovoltaic (PV) panels (renewable measures).

**Scenario development:** The methodology investigates two scenarios concerning future climate change. The first scenario evaluates the case study under current climate conditions, while the second examines the potential effects of climate change. For each scenario, a simulation-based multi-objective optimization (SBMO) framework is applied, as varying weather files impact the solutions along the Pareto front.

- **Scenario 1—Current Climate Conditions:** This scenario employs present-day weather data for building performance simulations. It uses baseline data reflecting current climate parameters, such as temperature, precipitation, and seasonal variations, derived from existing environmental conditions and practices.
- **Scenario 2—climate change projections:** In this scenario, the CCWorldWeatherGen software V1.9, developed by Jentsch et al. [43], is utilized to generate EnergyPlus Weather (EPW) and Typical Meteorological Year Data (TMY2) weather files for the A2 emission scenario (medium-high). This approach estimates future energy consumption and greenhouse gas emissions for the years 2050 and 2080, based on the HadCM3 (Hadley Centre Coupled Model version 3) [44].

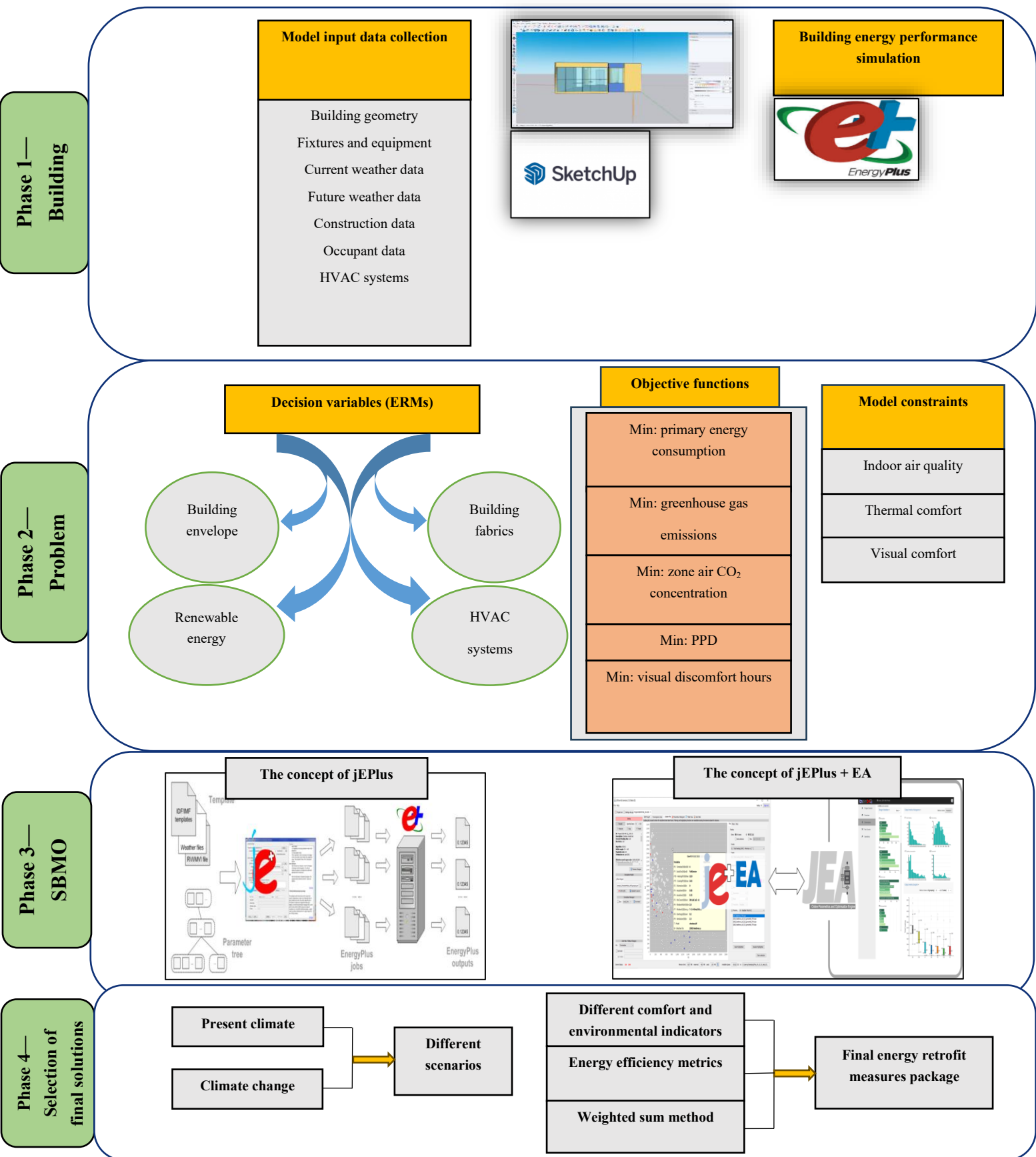
**Objective functions and decision-making:** jEPlus is used to determine the objective functions and decision-making parameters for the optimization. These functions represent the performance metrics to be minimized, and the decision-making parameters define the design variables to be optimized.

**Sensitivity Analysis:** A Morris sensitivity analysis, implemented using jEPlus + EA, is performed to evaluate the impact of input variables on the objective functions. This process identifies the most influential design variables, guiding subsequent optimization efforts.

**Multi-objective optimization:** The NSGA-II evolutionary algorithm, coupled with jEPlus + EA, is utilized for multi-objective optimization. NSGA-II iteratively

refines a population of candidate solutions through genetic operators—selection, crossover, and mutation—to explore the design space and identify optimal or near-optimal solutions.

**Evaluation and selection:** The optimization process generates a set of Pareto solutions, representing trade-offs between the multiple objectives. The weighted sum method is used to select the final solution from the Pareto front, considering the specific preferences or priorities of the decision-maker. The weighted sum method is a simple and commonly used approach in multi-objective optimization to select the final solution from a set of Pareto optimal solutions.



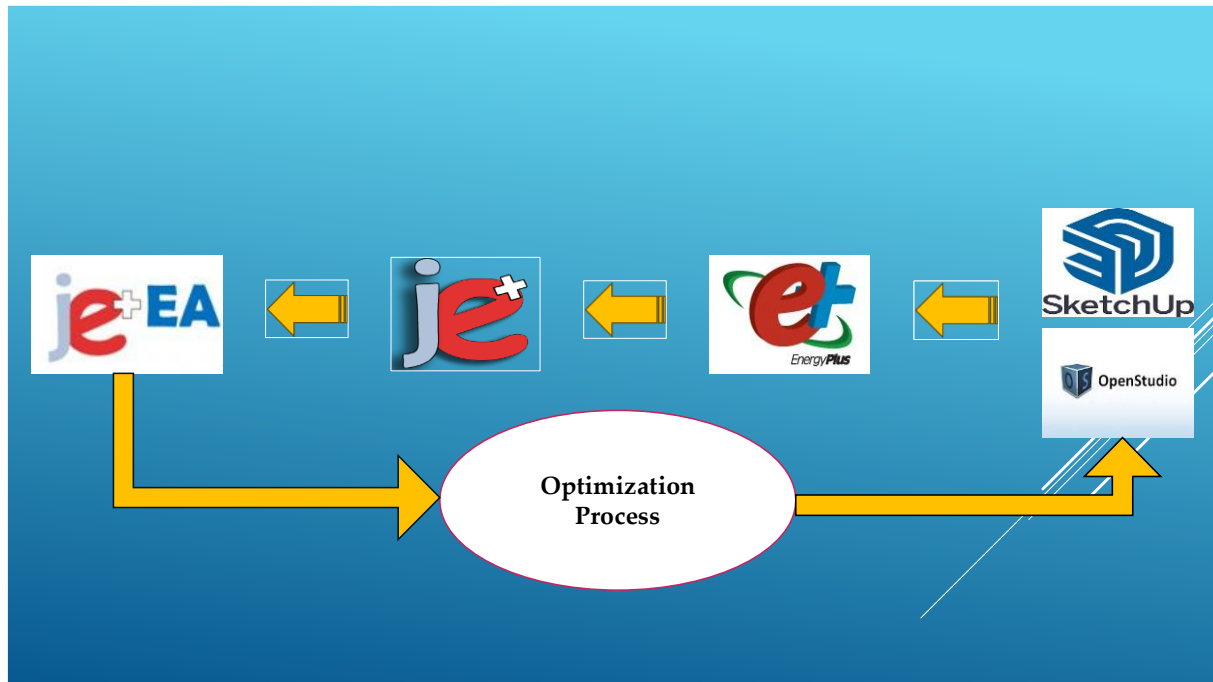


Figure 4-1: Methodology framework

The approach integrates detailed architectural modeling, energy simulation, sensitivity analysis, and optimization techniques to support sustainable building design and decision-making. Understanding both scenarios can ultimately aid in engaging various stakeholders, from governments to local communities, in taking collaborative action toward climate-resilient futures.

#### 4.1. Characteristics of the Case study building

The optimization of objective functions is being implemented for a typical residential unit located on the last floor of a five-story reinforced concrete apartment building constructed in 2017 in Sari, Iran. The building exhibits a deviation of 5.2 degrees from the true north. This region has a humid subtropical climate characterized by mild conditions without a dry season and hot summers. The results of this study may serve as a useful guideline for buildings with similar functionalities, climatic conditions, construction technologies, and HVAC systems.

This building is adjacent to neighbouring units to the east and south while being exposed to external environmental factors to the north and west. Heat transfer occurs between this building and the adjacent units during the spring and summer months, with recorded indoor temperatures of 26 °C and 24 °C, respectively. In contrast, during the fall and winter seasons, temperatures of 26 °C and 28 °C indicate ongoing thermal interaction with the adjacent units.

To understand the building's features, occupancy types, and energy usage trends, data were gathered through surveys, building inspections, and energy bills. The occupancy pattern for this residential unit, which accommodates three individuals, is as follows: From Saturday to Wednesday, the unit is fully occupied until 6:30 AM, after which it remains unoccupied until 3:00 PM. Between 3:00 PM and 5:00 PM, 60% of the residents are present, and full occupancy resumes until midnight. On Thursday, there is full occupancy until 6:30 AM, followed by a period of unoccupancy until 2:00 PM, after which full occupancy again occurs until midnight.

Finally, all residents are fully present throughout the day on Fridays and holidays. This schedule illustrates a combination of full occupancy and designated periods of absence. The exterior walls consist of clay blocks with a thickness of 35 cm, while the interior walls are 28 cm thick, finished with 1.6 cm of gypsum board. The windows are fitted with double-glazing glass, characterized by a U-value of 2.670 W/m<sup>2</sup>K, a solar heat gain coefficient (SHGC) of 0.703, and a visible transmittance of 0.781. The main characteristics of the building and its exterior fenestration are summarized in Table 4-1. Additionally, Figure 4-2 illustrates the monthly temperature range in Sari.

Table 4-1: Characterization of exterior fenestration

| SUB-SURFACES             | Construction      | Glass Area [m <sup>2</sup> ] | Frame Area [m <sup>2</sup> ] | Divider Area [m <sup>2</sup> ] | Glass U-Factor [W/m <sup>2</sup> -K] | Glass SHGC | Glass Visible Trans. | Frame Conductance [W/m <sup>2</sup> -K] | Divider Conductance [W/m <sup>2</sup> -K] |
|--------------------------|-------------------|------------------------------|------------------------------|--------------------------------|--------------------------------------|------------|----------------------|-----------------------------------------|-------------------------------------------|
| SUB SURFACE 4-Hall       | DBLCLR6MM/13MMAIR | 0.52                         | 0.32                         | 1.21                           | 2.670                                | 0.703      | 0.781                | 4.000                                   | 4.000                                     |
| SUB SURFACE 1-Hall       | DBLCLR6MM/13MMAIR | 8.90                         | 0.69                         | 1.58                           | 2.670                                | 0.703      | 0.781                | 4.000                                   | 4.000                                     |
| SUB SURFACE 2-Kitchen    | DBLCLR6MM/13MMAIR | 1.21                         | 0.24                         | 0.000                          | 2.670                                | 0.703      | 0.781                | 1.800                                   | 0.000                                     |
| SUB SURFACE 10-Bedroom 1 | DBLCLR6MM/13MMAIR | 3.09                         | 0.38                         | 0.000                          | 2.670                                | 0.703      | 0.781                | 1.800                                   | 0.000                                     |
| SUB SURFACE 11-Bedroom 2 | DBLCLR6MM/13MMAIR | 3.21                         | 0.38                         | 0.000                          | 2.670                                | 0.703      | 0.781                | 1.800                                   | 0.000                                     |

Infiltration refers to the unintended flow of outdoor air into a thermal zone and is primarily caused by the opening and closing of exterior doors, cracks around

windows, and minor gaps in building elements. Per the information provided by Table 4-2, in this building, the infiltration rate measures 1.9 air changes per hour (Ach) as determined through blower door testing for the thermal zones, including the hall, kitchen, and bedrooms.

Air infiltration significantly contributes to energy loss, making building sealing a critical component of energy efficiency. The effectiveness of sealing measures is influenced by the number and size of air leakage paths, and improving airtightness is considered a decision variable in the optimization process that aims to reduce the infiltration rate through the application of air barrier strips. Ventilation in the building is facilitated through two distinct systems: a mechanical intake ventilation system in the toilet, which operates at a fan pressure rise of 70 Pa with a total efficiency of 0.9, and natural ventilation in the bathroom with a flow rate of 0.00944 m<sup>3</sup>/s per person.

Additionally, there are two operable windows—one in the hall with an opening area of 0.7 m<sup>2</sup> and another in the kitchen with an opening area of 0.9 m<sup>2</sup>—alongside two glass doors in the bedrooms, each with an opening area of 1 m<sup>2</sup>. These openings are utilized for natural ventilation and thermal comfort during seasonal transition days when the mechanical ventilation system is offline. Cross-zone mixing occurs between adjacent zones, facilitating equal air exchange among pairs (Hall and Bedroom 1, Hall and Bedroom 2, Hall and Kitchen, Hall and Toilet, Hall and Bathroom). This cross-mixing significantly affects the energy balance within both zones.

The heating system consists of hot water radiators supplied by a natural gas boiler that operates with an efficiency of 85%. The building's cooling system comprises a split air conditioner, which has an Energy Efficiency Ratio (EER) of 3.13 and a Coefficient of Performance (COP) of 3.53. Energy for the building is sourced primarily from natural gas and grid electricity. The cooling system, lighting fixtures, and electrical appliances, including a refrigerator and television, draw electricity, while natural gas is utilized for space heating via hot water radiators, domestic hot water (DHW) supply, and cooking.

The calculation of carbon emissions associated with gas heating and electrical cooling is summarized in Table 4-3.

Table 4-2: Characterization of the baseline building

| Location | Coordinates | U-Value (W/m <sup>2</sup> K) |
|----------|-------------|------------------------------|
|----------|-------------|------------------------------|

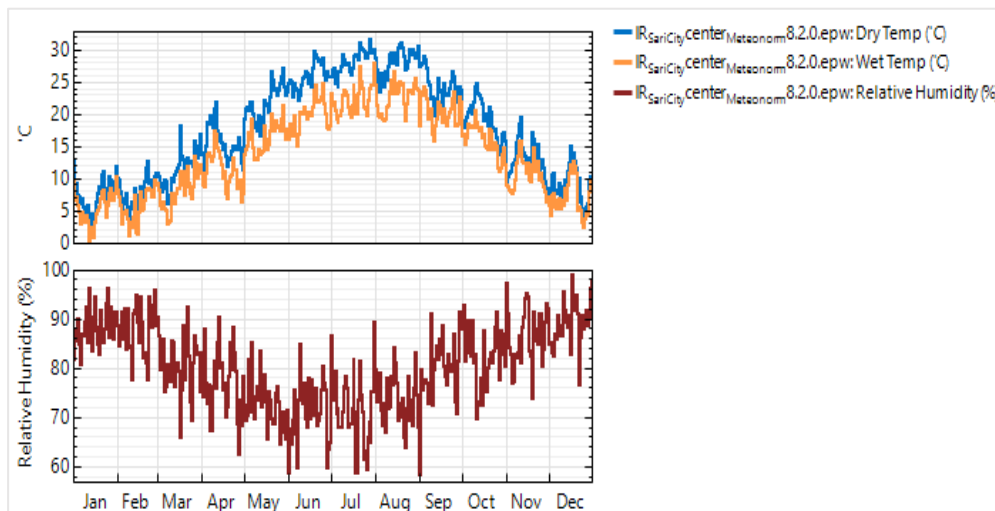
|            |                      | Floor Area (m <sup>2</sup> ) | External Walls                                             | Roof | Double-Glazing Windows | Heating and Cooling Systems                                                    | Lighting System                  | Air Infiltration Rate |
|------------|----------------------|------------------------------|------------------------------------------------------------|------|------------------------|--------------------------------------------------------------------------------|----------------------------------|-----------------------|
| Sari, Iran | {N 36°3'}, {E 53°2'} | 79.35                        | 0.52 (Façade), 0.50, 0.51, 0.53 (Kitchen), 0.49 (Bathroom) | 0.44 | 2.67                   | Natural gas boiler ( $\eta = 0.85$ )<br>Duct Split (EER = 3.13 and COP = 3.53) | Light Emitting Diode (LEDs) Lamp | 1.9 Ac/h              |

Heating degree days (baseline 18 °C): 1382.00, cooling degree days (baseline 10 °C): 3017.00; heating setpoint: 20 °C, cooling setpoint: 28 °C; setback temperature for heating: 18 °C, setback temperature for cooling: 29 °C; mean outdoor annual relative humidity: 79.91%; maximum dry-bulb temperature: 36.8 °C occurs on Jul 29, minimum dry-bulb temperature: -2.1 °C occurs on 15 February; climate: humid subtropical (mild without dry season, hot summer, lat. 20–35°N); ASHRAE climate zone: 3A, ASHRAE description: warm-humid, elevation (m) above sea level: 69; source: Meteonorm 8.2.0.

Table 4-3: Emissions intensity from electricity and natural gas generation in Iran

| Existing Fuel Resource Name       | Units | Electricity | Natural Gas |
|-----------------------------------|-------|-------------|-------------|
| Source Energy Factor              | J/J   | 3.15        | 1.05        |
| CO <sub>2</sub> emissions factor  | g/MJ  | 156.94      | 50.3        |
| CH <sub>4</sub> emissions factor  | g/MJ  | 1.4         | 4.73        |
| N <sub>2</sub> O emissions factor | g/MJ  | 0.03        | 0.094       |

Figure 4-2 presents the monthly ranges of dry-bulb and wet-bulb temperatures, as well as relative humidity in Sari, Iran. This data highlights the city's climatic variations throughout the year. These fluctuations in temperature and humidity can significantly affect both the local ecosystem and daily life.



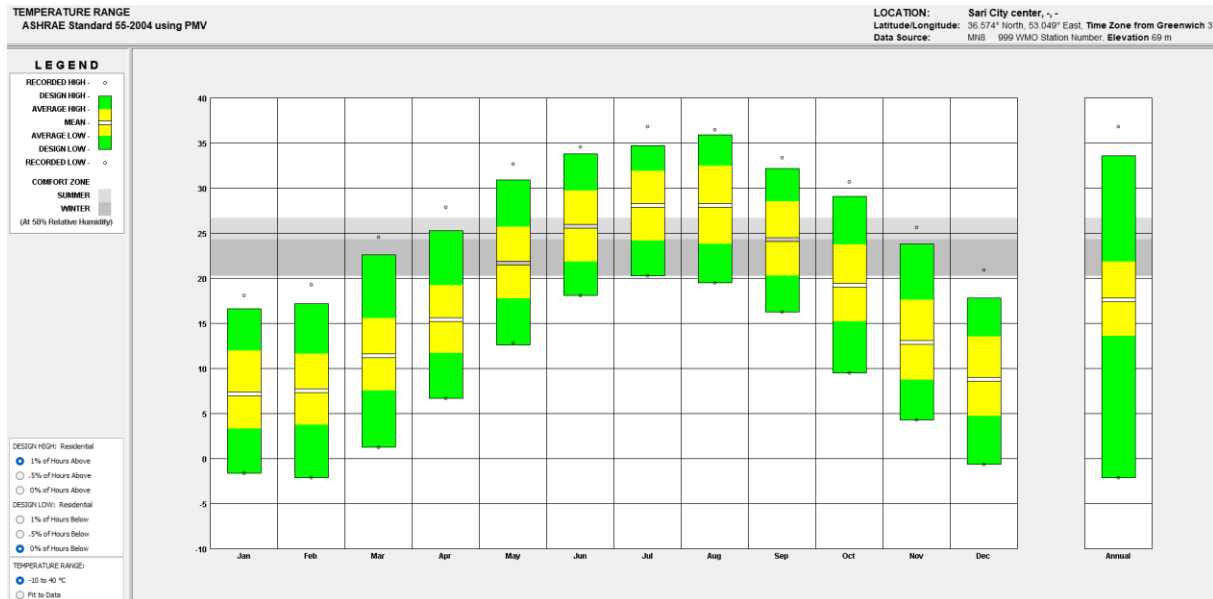


Figure 4-2: Monthly ranges of dry-bulb, wet-bulb temperatures, and relative humidity in Sari, Iran

Table 4-4 offers a comprehensive overview of the baseline performance data, which is essential for understanding energy consumption patterns and their associated environmental impacts. This table highlights key metrics related to energy usage, specifically focusing on both electricity and natural gas consumption, as well as the resulting carbon dioxide (CO<sub>2</sub>) emissions. By analyzing this data, stakeholders can gain valuable insights into the operational efficiency of the system and identify opportunities for enhancing sustainability. Furthermore, the information regarding CO<sub>2</sub> concentrations and the predicted percentage of dissatisfied occupants underscores the importance of assessing indoor air quality and thermal comfort.

Table 4-4: Baseline performance data

| Net Source Energy (Primary Energy Consumption) [kWh] |                          | CO <sub>2</sub> Equivalent [kg] | Zone Air CO <sub>2</sub> Concentration [ppm] | PPD [%] | Daylighting Reference Point Glare Index Setpoint Exceeded Time [hr] |
|------------------------------------------------------|--------------------------|---------------------------------|----------------------------------------------|---------|---------------------------------------------------------------------|
| Electricity (Site) [kWh]                             | Natural Gas (Site) [kWh] |                                 |                                              |         |                                                                     |
| 3814.23                                              | 19,711.67                |                                 |                                              |         |                                                                     |
| 32,712.09                                            |                          | 17,771.39                       | 718.10                                       | 27.40   | 215.95                                                              |

Table 4-5 outlines the details of a residential unit featuring six thermal zones. It specifies key information, including the area, regularly occupied area, unconditioned area, and typical hours of operation per week.

Table 4-5: Space usage type

| Thermal Zones                | Space Area Regularly Occupied Area | Unconditioned Area | Typical Hours/Week in Operation |        |
|------------------------------|------------------------------------|--------------------|---------------------------------|--------|
|                              | [m²]                               | [m²]               | [hr/week]                       |        |
| Thermal Zone 1—<br>Toilet    | 1.82                               | 1.82               | 0.00                            | 120.04 |
| Thermal Zone 2—<br>Hall      | 48.04                              | 48.04              | 0.00                            | 120.04 |
| Thermal Zone 3—<br>Kitchen   | 6.04                               | 6.04               | 0.00                            | 120.04 |
| Thermal Zone 4—<br>Bathroom  | 3.10                               | 3.10               | 0.00                            | 120.04 |
| Thermal Zone 5—<br>Bedroom 1 | 11.38                              | 11.38              | 0.00                            | 120.04 |
| Thermal Zone 6—<br>Bedroom 2 | 8.98                               | 8.98               | 0.00                            | 120.04 |
| Totals                       | 79.35                              | 79.35              | 0.00                            | -      |

According to the diagram presented in Figure 4-3, several key factors are contributing significantly to energy loss in the existing building, with specific heat removal values highlighted. The window heat removal accounts for a substantial loss of  $-2740.8$  kWh, indicating a considerable amount of thermal energy being exchanged through glazing systems. Additionally, interzone air transfer contributes to heat loss with a value of  $-490.79$  kWh, reflecting the inefficiencies in air movement between different thermal zones. Infiltration is another critical area, showing a significant heat removal of  $-17,830.7$  kWh, which emphasizes the impact of uncontrolled air leaks that allow outside air to enter the conditioned spaces, thereby disrupting thermal comfort and increasing energy demand. Furthermore, opaque surface conduction and other forms of heat transfer contribute an additional  $-2841.78$  kWh to the overall energy loss. Collectively, these values highlight the areas with the highest energy losses, suggesting that targeted energy retrofit measures in these domains are essential for minimizing energy waste, enhancing the building's overall energy efficiency, and promoting sustainable building practices. Addressing these factors could lead to significant reductions in energy consumption and operational costs, while simultaneously improving indoor comfort levels.

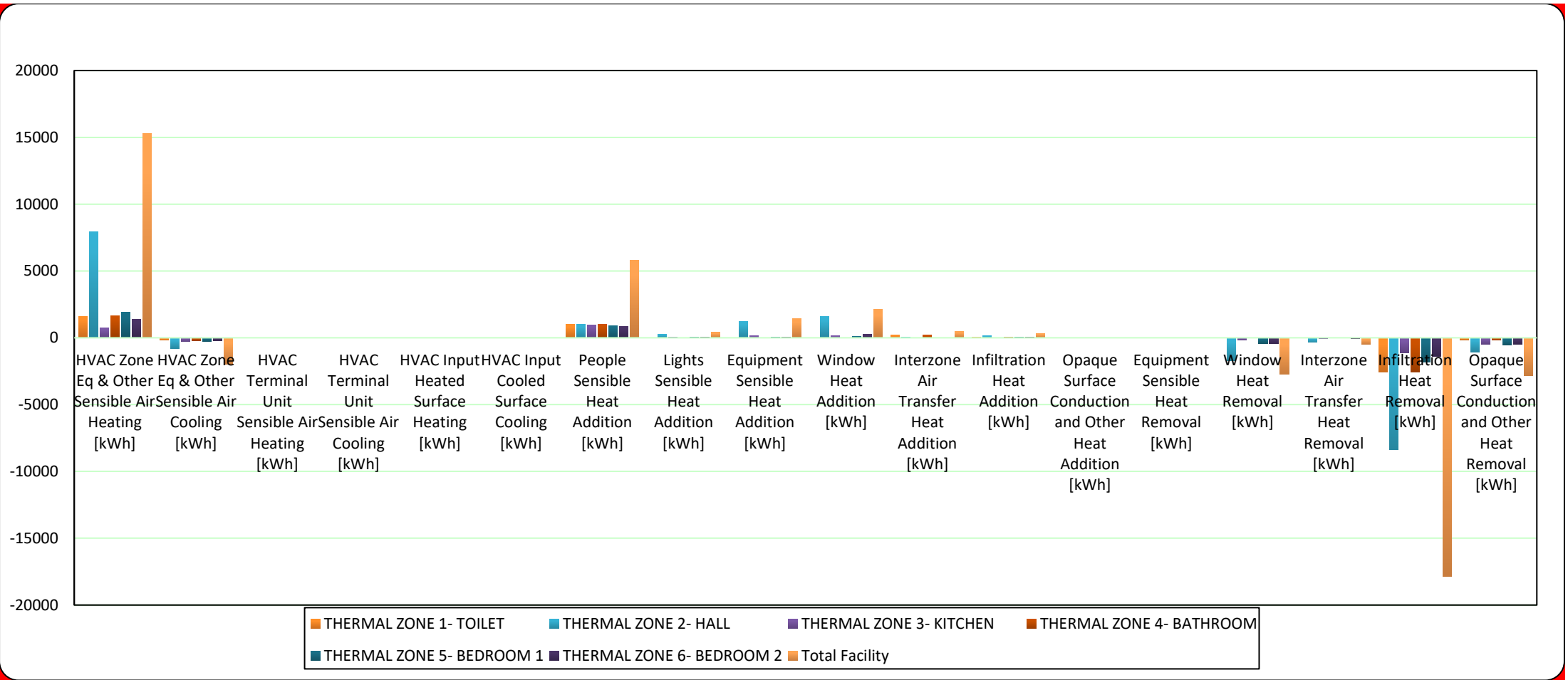


Figure 4-3: Identifying weaknesses of the model by annual building sensible heat gain components

## 4.2. Characteristics of the HVAC of the case study building

The PTAC system serves an integral function within various building designs, particularly in environments where localized heating and cooling are crucial. The incorporation of both a DX cooling coil and a diverse range of heating options (electric, gas, or water-based) optimizes the climate control capabilities of the unit, enhancing comfort and energy efficiency in indoor settings. Moreover, the outdoor air mixer implemented in this configuration is pivotal for integrating fresh outdoor air into the conditioned space, thereby improving indoor air quality (IAQ). Such systems are particularly beneficial in densely populated environments where cross-contamination of air can be a concern. The balance achieved between cooling and heating loads, guided by precise controls, facilitates an energy-efficient operation, conforming to modern environmental standards and expectations for reduced carbon footprints, essential in the pursuit of sustainable building practices [45]. The design scheme aligns with the contemporary directives for energy performance in buildings, addressing both the thermal comfort of occupants and the operational costs for facility managers. As emphasized in the guidelines established by the European Union, a focus on energy efficiency, particularly in HVAC systems, is paramount as we move towards achieving energy-neutral buildings in the context of future urban development. Figure 4-4 schematic: the operational diagram representing a packaged terminal air conditioner with its associated components, depicting the integration of the outdoor air mixer and heating/cooling coils.

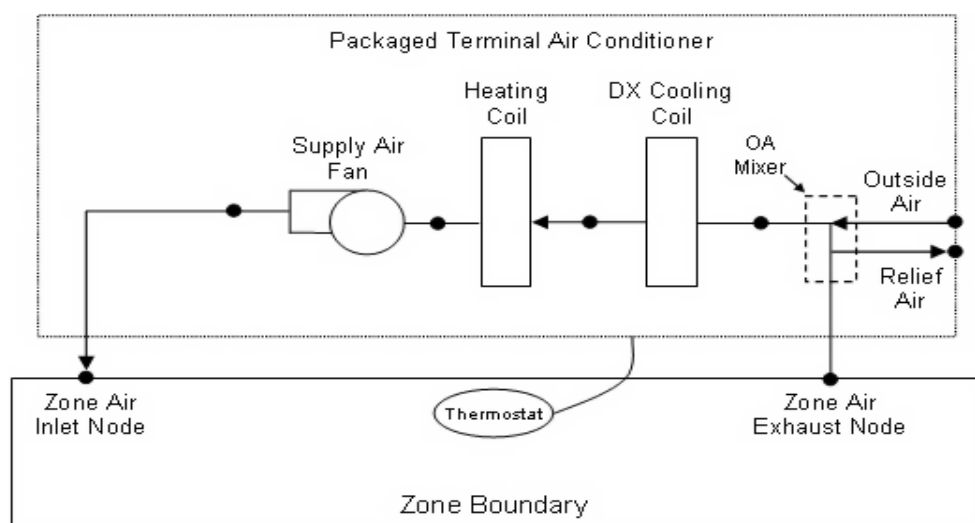


Figure 4-4: Schematic of a packaged terminal air conditioner featuring a draw-through fan placement [40]

### 4.3. Psychrometric chart

The weather data for a typical year in Sari have been imported into Climate Consultant 6.0 for analysis. Figure 4-5 presents a psychrometric chart that offers a detailed overview of the thermal environment throughout the year, facilitating informed decisions regarding building design and HVAC system operation. The chart indicates that the blue box represents the hours during which the climate is comfortable without any interventions, comprising only 5.5% of the year. This highlights the necessity for the building to implement measures to enhance occupant comfort. Given Sari's classification as a humid subtropical region, it must account for both heating and cooling requirements across different seasons. As illustrated in Figure 4-5, the demand for active heating constitutes 26.8%, while active cooling accounts for 19.7%. Consequently, to achieve energy efficiency through passive design, maximizing solar energy utilization and improving the properties of the building's outer envelope are essential strategies. This facilitates analysis of how weather affects indoor conditions and highlights potential strategies for optimizing comfort and energy efficiency. The figure allows stakeholders to visualize the relationship between temperature and humidity, essential for assessing indoor air quality, comfort levels, and system control strategies.

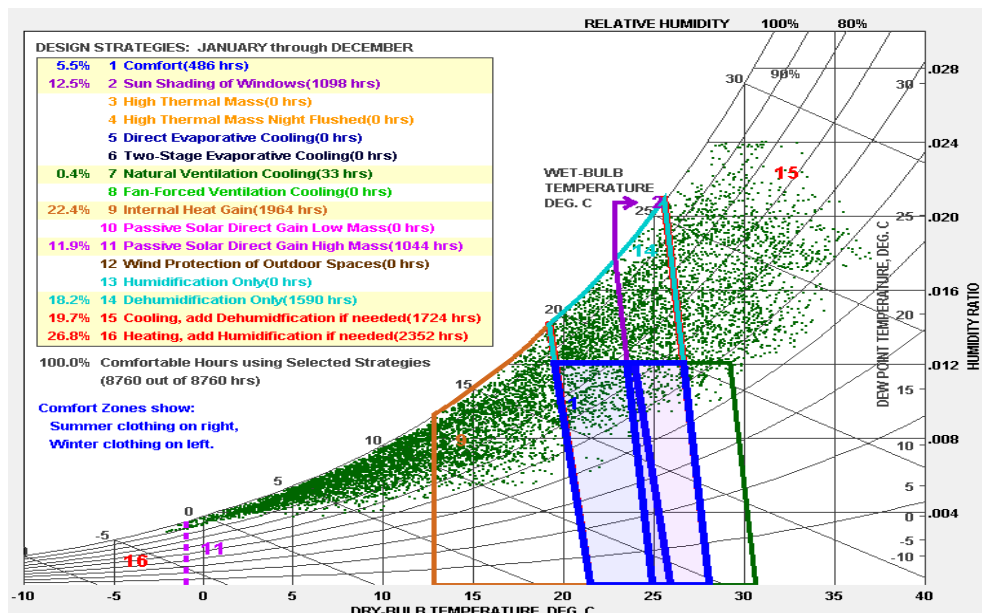


Figure 4-5: Psychrometric chart: ASHRAE standard 55-2004 using PMV

#### **4.4. Parametric study with EnergyPlus**

In this parametric study, the primary objective is to minimize two critical performance functions: indoor air quality (IAQ) and thermal comfort. This optimization will be conducted using EnergyPlus, which incorporates various control mechanisms such as thermostat settings for maintaining thermal comfort, humidistats for humidity regulation, and an energy management system (EMS) for overall operational efficiency. Both IAQ and thermal comfort will be managed to ensure they remain within predefined acceptable ranges essential for occupant health and comfort. Furthermore, optimization techniques will be applied within the jEPlus + EA framework to minimize three other main objective functions, culminating in the goal of simultaneously optimizing all five target functions. To facilitate this comprehensive multi-objective optimization process, systematic modifications will be implemented in the EnergyPlus input file based on the parameters detailed in Table 4-6, thereby adequately preparing the simulation model for the application of a genetic metaheuristic algorithm. This algorithm, known for its adaptability in solving complex multi-dimensional optimization problems, will explore potential solutions and their performance relative to the defined objectives, ultimately identifying configurations that balance energy efficiency with enhanced indoor environmental quality.

Table 4-6: Parametric study with EnergyPlus before optimization by jEPlus + EA

| Design Variables for Parametric Study     | Initial Value                                                  | Parametric Value                                                                                                                                                                                                                                                                                         |
|-------------------------------------------|----------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Window shading<br>Control strategies      | On if schedule allows                                          | On night if low outdoor temperature and on day if cooling (dominant effect on cooling and heating load)                                                                                                                                                                                                  |
| Air velocity                              | 0.05 (fall and winter), 0.2 (spring and summer)                | 0.1 (fall and winter), 0.5 (spring and summer)                                                                                                                                                                                                                                                           |
| Coil cooling DX                           | Single speed                                                   | Variable speed                                                                                                                                                                                                                                                                                           |
| Split air conditioner system              | Existing split air conditioner system (COP = 3.53, EER = 3.13) | Split air conditioner system + inverter (COP = 4.3, EER = 3.81)                                                                                                                                                                                                                                          |
| Headered pumps                            | Single speed                                                   | Variable speed                                                                                                                                                                                                                                                                                           |
| Boiler type and efficiency                | Hot water boiler ( $\eta = 0.85$ )                             | Condensing hot water boiler ( $\eta = 0.95$ )                                                                                                                                                                                                                                                            |
| Boiler flow mode                          | Constant flow                                                  | Leaving setpoint modulated                                                                                                                                                                                                                                                                               |
| Zone control: thermostat: thermal comfort | $-1.2 < \text{PMV range} < +1.2$<br>$20\% < \text{PPD} < 30\%$ | $-0.5 < \text{PMV range} < +0.5$<br>$\text{PPD} < 10\%$                                                                                                                                                                                                                                                  |
| Indoor air quality                        | PPM < 800                                                      | PPM < 700 (The standard level of indoor air quality; ASHRAE recommends CO <sub>2</sub> levels not exceeding 700 ppm above outdoor levels (ASHRAE-62.1 [46]) by energy management system (EMS) and zone cross-mixing EnergyPlus                                                                           |
|                                           | -<br>(Zone mean annual air relative humidity = 52.49%)<br>-    | Zone control: humidistat<br>(Zone mean annual air relative humidity = 47.04%)<br>Zone predicted moisture load to humidifying setpoint moisture transfer rate =<br>-0.00331,<br>[kgWater/s]<br>Zone predicted moisture load to dehumidifying setpoint moisture transfer rate =<br>0.001928<br>[kgWater/s] |
| Solar panel                               | -                                                              | Polycrystalline<br>Area = 10, 15, 20, 25 m <sup>2</sup>                                                                                                                                                                                                                                                  |

According to Table 4-7, the operational procedure of the energy management system (EMS) in this case is designed to regulate indoor air quality by managing carbon dioxide (CO<sub>2</sub>) concentrations in thermal zones. The protocol is initiated when occupants are present in these zones, ensuring that the system is responsive to actual occupancy and corresponding air quality needs. The procedure outlines a

tiered response based on CO<sub>2</sub> concentration levels. When the CO<sub>2</sub> concentration exceeds 600 parts per million (ppm) but remains below 800 ppm, the EMS will open 25% of the total area of windows and glass door openings. This partial opening allows for the introduction of fresh air into space, effectively diluting the accumulated CO<sub>2</sub> and thereby improving indoor air quality without excessive energy consumption. If the concentration rises further, exceeding 800 ppm but remaining under 1000 ppm, the EMS response escalates; it will open 50% of the area of the openings. This increased ventilation rate addresses the heightened levels of CO<sub>2</sub> more aggressively, ensuring that air quality remains within healthier thresholds for occupants. In scenarios where CO<sub>2</sub> concentrations surpass 1000 ppm, a critical threshold indicating significant air quality degradation, the EMS will fully open all window and glass door openings. This full ventilation strategy is implemented to quickly reduce CO<sub>2</sub> levels and improve air quality, safeguarding occupant health and comfort. The overarching goal of this operational procedure is to maintain optimal indoor air quality through proactive management of CO<sub>2</sub> levels, thereby improving occupant well-being and productivity. By utilizing the EnergyPlus energy management system, this approach not only enhances the comfort levels within the building but also demonstrates energy efficiency by modulating ventilation based on real-time conditions, optimizing both energy consumption and air quality simultaneously. This responsive system underscores the importance of integrating sustainable practices in building management, promoting healthier indoor environments while adhering to energy conservation principles.

Table 4-7: Indoor air quality with energy management system (EMS) EnergyPlus

| Ventilation Profile                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Indoor air quality with energy management system (EMS) EnergyPlus<br>IF Occupancy Sensor > 0 && ((CO <sub>2</sub> Sensor_Hall>=600ppm && CO <sub>2</sub><br>Sensor_Hall < 800ppm)    (CO <sub>2</sub> Sensor_Kitchen>=600ppm && CO <sub>2</sub><br>Sensor_Kitchen < 800ppm)    (CO <sub>2</sub> Sensor_Bedroom1>=600ppm && CO <sub>2</sub><br>Sensor_Bedroom1 < 800ppm)    (CO <sub>2</sub> Sensor_Bedroom2>=600ppm && CO <sub>2</sub><br>Sensor_Bedroom2 < 800ppm)),<br>SET A1=0.25 opening area,<br>ELSEIF Occupancy Sensor > 0 && ((CO <sub>2</sub> Sensor_Hall>=800ppm && CO <sub>2</sub><br>Sensor_Hall < 1000ppm)    (CO <sub>2</sub> Sensor_Kitchen>=800ppm && CO <sub>2</sub><br>Sensor_Kitchen<1000ppm)    (CO <sub>2</sub> Sensor_Bedroom1>=800ppm && CO <sub>2</sub><br>Sensor_Bedroom1<1000ppm)    (CO <sub>2</sub> Sensor_Bedroom2>=800ppm && CO <sub>2</sub><br>Sensor_Bedroom2<1000ppm)),<br>SET A1=0.5 opening area,<br>ELSEIF Occupancy Sensor > 0 && ((CO <sub>2</sub> Sensor_Hall>=1000ppm)    (CO <sub>2</sub><br>Sensor_Kitchen >=1000ppm)    (CO <sub>2</sub> Sensor_Bedroom1>=1000ppm)    (CO <sub>2</sub><br>Sensor_Bedroom2>=1000ppm)),<br>SET A1=1 opening area,<br>ELSE,<br>SET A1=0 opening area,<br>ENDIF; |

Table 4-8 summarizes the outcomes of the parametric study conducted using EnergyPlus before optimization with jEPlus + EA. The study successfully met the objectives of maintaining predicted percentage dissatisfied (PPD) and indoor air quality at acceptable levels. Notably, the PPD for thermal comfort remains below 10%, reflecting a high degree of occupant satisfaction within the space. Additionally, CO<sub>2</sub> concentrations are kept below 700 ppm, ensuring a healthy indoor environment. These findings highlight the efficacy of the implemented design strategies and system performance in enhancing occupant well-being and comfort.

Table 4-8: Results of parametric study with EnergyPlus before optimization by jEPlus + EA

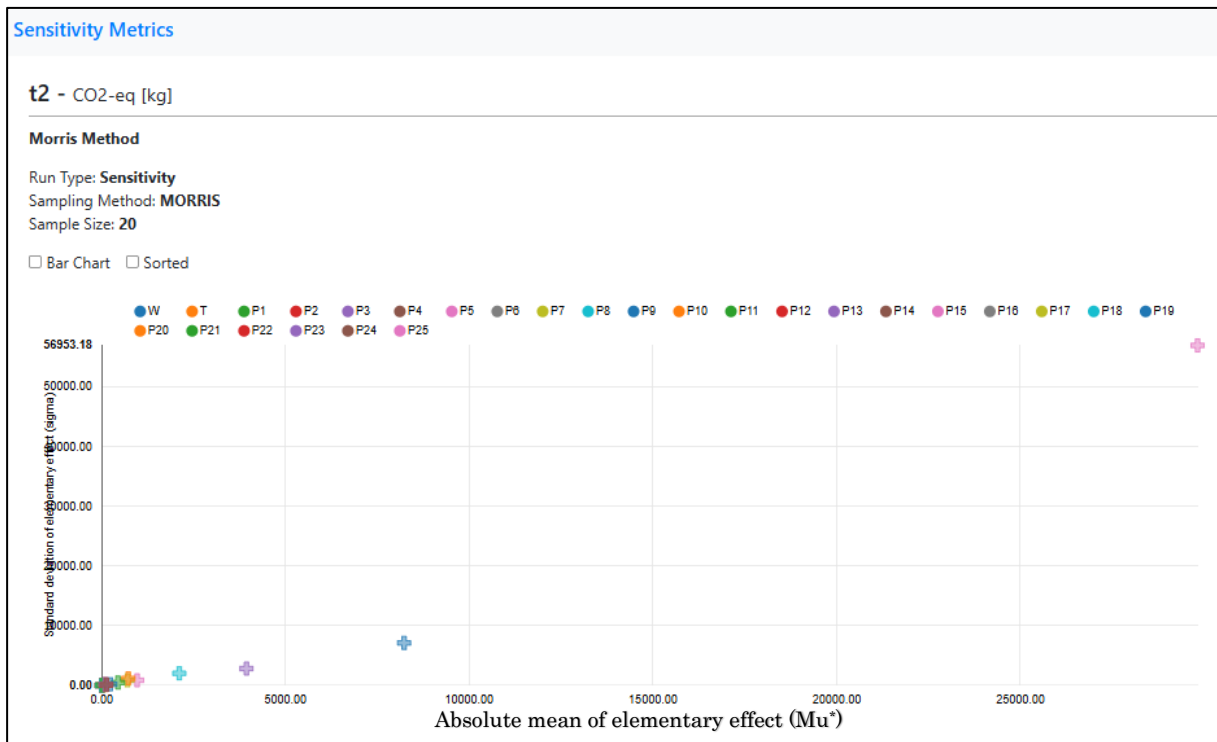
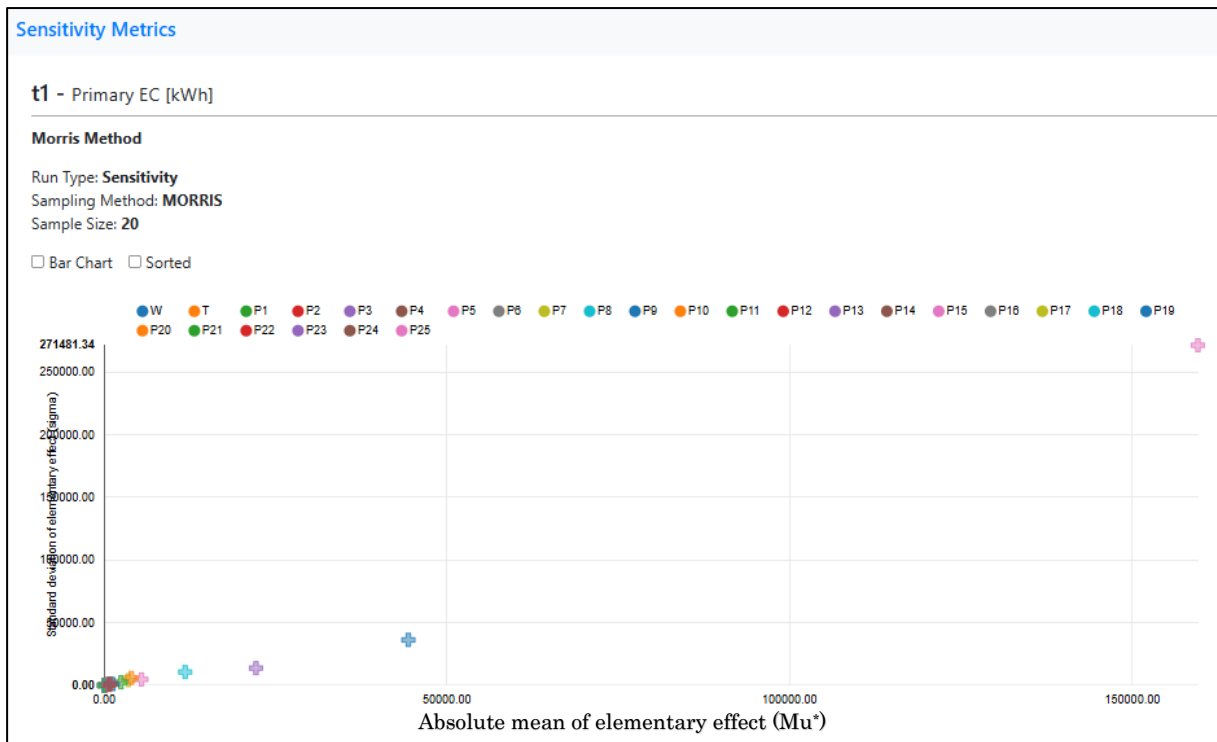
| Net Source Energy<br>(Primary Energy<br>Consumption) [kWh] |                             | CO <sub>2</sub> Equivalent<br>[kg] | Zone Air CO <sub>2</sub><br>Concentration<br>[ppm] | PPD [%] | Daylighting Reference Point<br>Glare Index Setpoint<br>Exceeded Time [hr] |
|------------------------------------------------------------|-----------------------------|------------------------------------|----------------------------------------------------|---------|---------------------------------------------------------------------------|
| Electricity<br>(Site) [kWh]                                | Natural Gas<br>(Site) [kWh] |                                    |                                                    |         |                                                                           |
| 3996.14                                                    | 27,815.39                   |                                    |                                                    |         |                                                                           |
| 24,974.56                                                  |                             | 23,147.30                          | 650.14                                             | 9.77    | 347.19                                                                    |

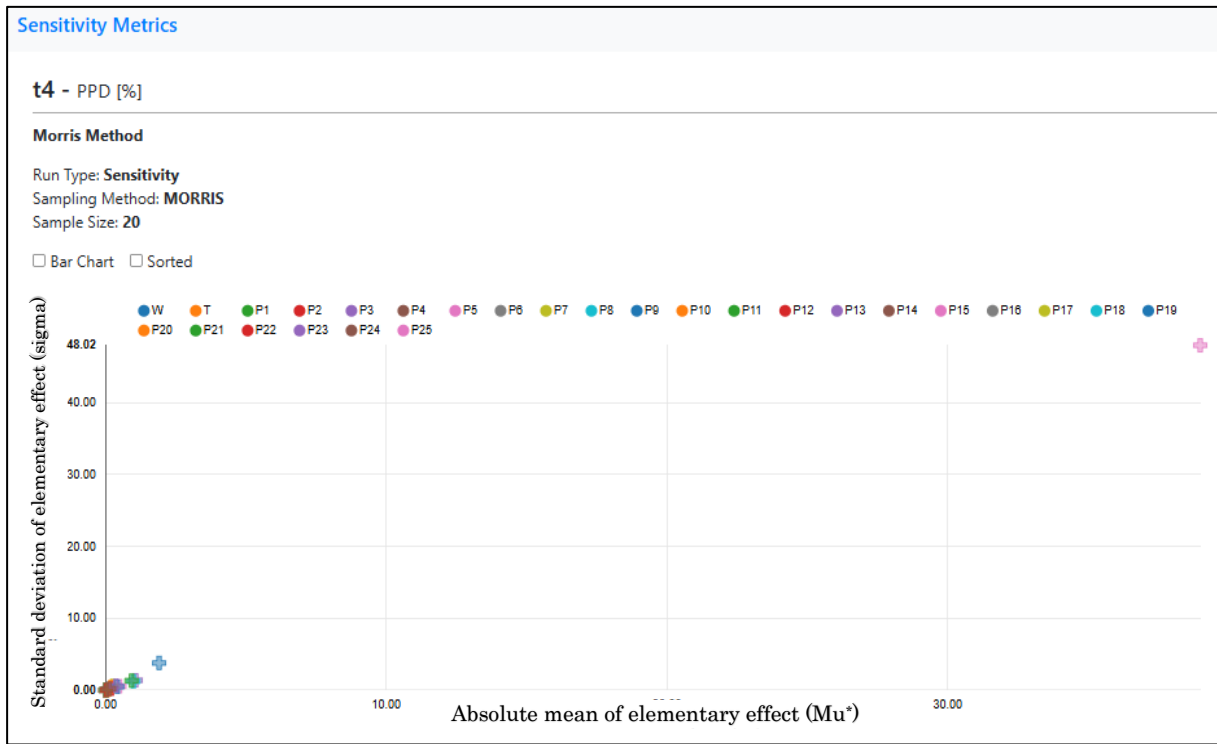
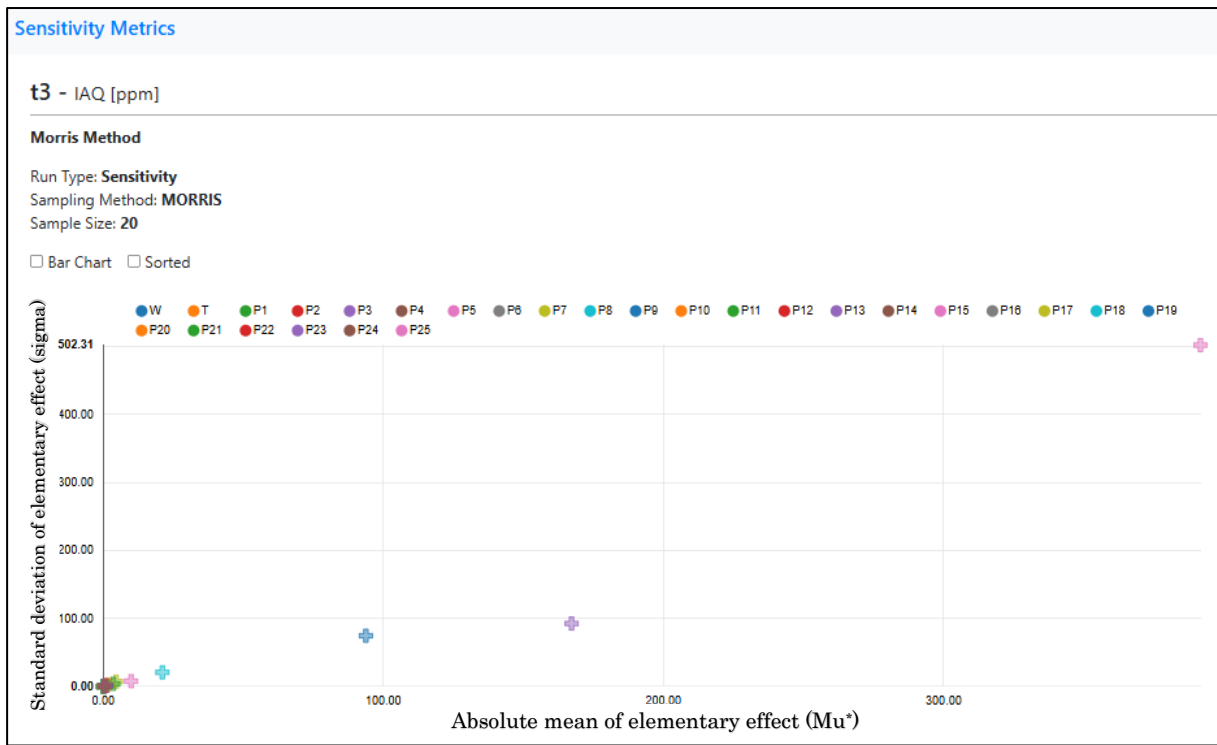
## 4.5. Sensitivity analysis

Sensitivity analysis serves as a pivotal analytical approach for assessing the extent to which variations in independent input variables affect a designated dependent output variable, all within the framework of predefined assumptions. Among the diverse methodologies available, the Morris method is widely regarded for its efficiency and robustness, particularly when applied to complex models characterized by numerous input parameters. This global sensitivity analysis technique operates by computing elementary effects for each input factor, yielding two fundamental metrics: the mean of absolute elementary effects ( $\mu^*$ ), which quantifies the overall influence of an input variable on the model's output, and the standard deviation ( $\sigma$ ), which captures the variability in these effects, thereby shedding light on non-linear dynamics and interactions between variables. By leveraging these metrics, the Morris method provides a nuanced understanding of how model outputs respond to perturbations in input parameters, making it an invaluable tool for identifying critical factors in computationally demanding models while maintaining a balance between accuracy and efficiency [47, 48].

As illustrated in Figure 4-6, the sensitivity analysis conducted using the Morris method pinpointed ten key design variables that exert the most substantial influence on the objective functions. These variables include HVAC system characteristics, heating and cooling setpoints, airflow rate, air infiltration rate, air velocity, roof and floor insulation properties, and the construction specifications of windows oriented towards north/west and south directions. The high  $\mu^*$  values associated with variables such as HVAC systems and temperature setpoints underscore their dominant role in driving the model's outcomes, suggesting that even small adjustments in these parameters can lead to significant changes in performance metrics. Meanwhile, elevated  $\sigma$  values for factors like air infiltration and window construction indicate the presence of non-linear effects or strong interactions with other variables, necessitating careful consideration in the design process.

These findings empower engineers and designers to prioritize optimization efforts on these influential parameters, enabling more informed decision-making to enhance building performance while effectively managing computational resources.





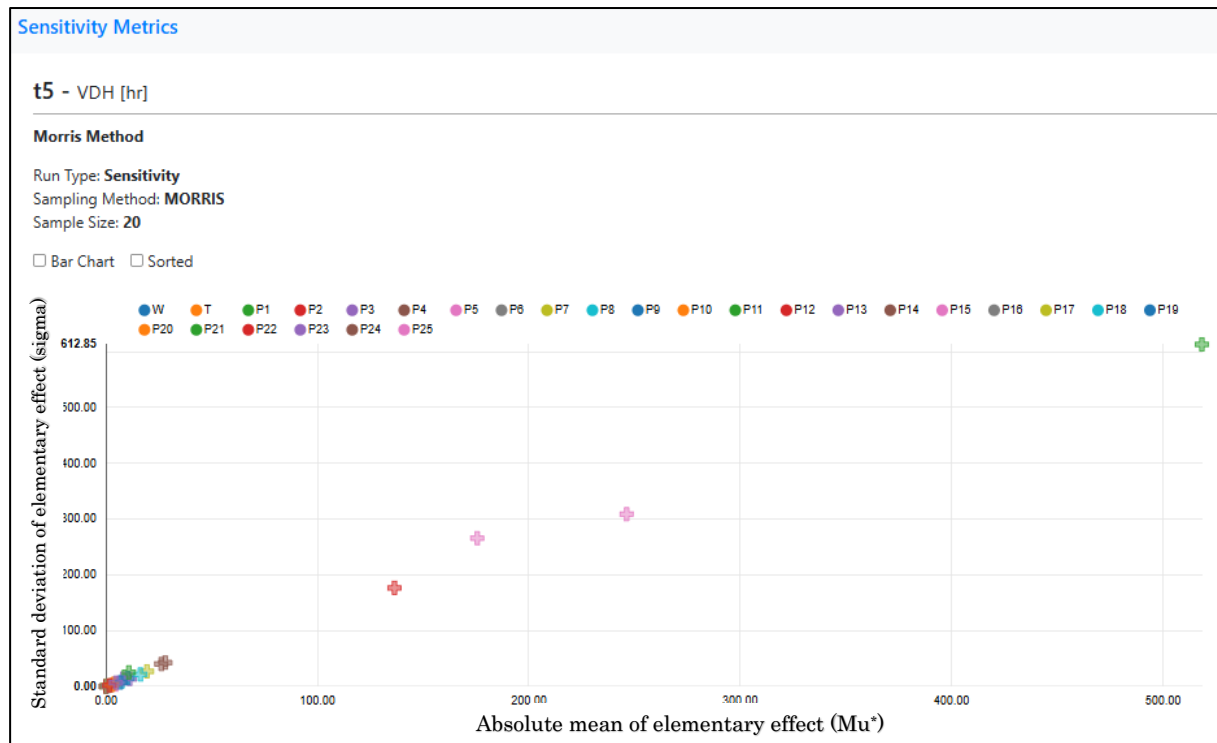


Figure 4-6: Sensitivity analysis using the Morris method

## 4.6. Characteristics of design variables

Table 4-9 and Table 4-10 summarizes the properties of solar panels and their electricity production. Table 4-9 provides an overview of the details of the photovoltaic (PV) panels investigated. The panels, with areas of 10, 15, 20, and 25 m<sup>2</sup>, are input into the software for parametric analysis. A tilt angle of 36.64° is used to optimize sunlight exposure, and the panels exhibit an efficiency of 13.2%, indicating the proportion of solar energy converted into usable electricity. These polycrystalline panels are installed on a roof, specifically south oriented, to maximize solar gain. The study aims to select the configuration that yields the highest electricity production, ensuring optimal energy output for the given parameters. According to Table 4-10 the photovoltaic system generates a total of 5448.481 kWh of electricity, representing 143.05% of the expected output. After accounting for power conversion losses, the total on-site electricity produced is 5339.511 kWh, which meets 140.19% of the energy demand.

Table 4-9: Details of PV panels investigated

| Area (m <sup>2</sup> ) | Tilt Angle (°C) | Efficiency (%) | Type            | Location             |
|------------------------|-----------------|----------------|-----------------|----------------------|
| 10, 15, 20, 25         | 36.64           | 13.2           | Polycrystalline | Roof, south oriented |

Table 4-10: Electric Loads Satisfied

| Solar Panel Properties                     | Electricity [kWh] | Percent electricity [%] |
|--------------------------------------------|-------------------|-------------------------|
| Photovoltaic Power                         | 5448.481          | 143.05                  |
| Power Conversion                           | -108.97           | -2.9                    |
| Total On-Site Electric Sources             | 5339.511          | 140.19                  |
| Electricity Coming from Utility            | 2711.379          | 71.19                   |
| Surplus Electricity Going to Utility       | 4242.166          | 111.38                  |
| Net Electricity from Utility               | -1530.79          | -40.2                   |
| Total On-Site and Utility Electric Sources | 3808.725          | 100.00                  |
| Total Electricity End Uses                 | 3808.725          | 100.00                  |

The study identifies and evaluates a total of 25 design variables, as presented in Table 4-11. Among these variables, several key factors play a critical role in influencing the energy performance and overall efficiency of the building. These factors include the heating and cooling setpoints, which determine the indoor temperature and directly affect energy consumption; the air infiltration rate, which measures the uncontrolled exchange of outside air with indoor air and impacts heating and cooling loads; and the types and thicknesses of thermal insulation used in both the floor and roof, which are crucial for minimizing heat loss or gain. Additionally, the construction of windows is significant, as it influences thermal performance and light infiltration. Other important variables include the air flow rate, essential for maintaining indoor air quality and comfort, and the type of HVAC (heating, ventilation, and air conditioning) system employed, which affects energy use, operational efficiency, and occupant satisfaction. By systematically analyzing these design variables, the study aims to identify optimal strategies for improving building energy efficiency. This design variables includes content from two chapters (Chapter 25 and Chapter 30) of the ASHRAE 2005 Handbook of Fundamentals [49].

Table 4-11: Characteristics of design variables for investigated energy retrofit measures (ERMs)

| Design Variables          | Units | Ranges            | Initial Values |
|---------------------------|-------|-------------------|----------------|
| P1: Heating Setpoint      | °C    | Double [18, 28]   | 20             |
| P2: Cooling Setpoint      | °C    | Double [28, 32]   | 28             |
| P3: Air Infiltration Rate | 1/hr  | Double [0.1, 1.9] | 1.9            |

|                                        |                   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                                           |
|----------------------------------------|-------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------|
| P4: Clothing Level for Spring          | Clo               | Double {0.61, 0.67, 0.72, 0.74}                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0.72                                      |
| P5: Clothing Level for Summer          | Clo               | Double {0.36, 0.54, 0.57}                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 0.54                                      |
| P6: Clothing Level for Fall            | Clo               | Double {0.89, 0.96, 1.01}                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 0.89                                      |
| P7: Clothing Level for Winter          | Clo               | Double {1.10, 1.14, 1.30, 1.37}                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 1.10                                      |
| P8: Air Velocity                       | m/s               | Double [0.1, 0.5]                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | 0.05 (Fall, winter), 0.2 (spring, summer) |
| P9: Air Flow Rate                      | m <sup>3</sup> /s | Double {0.00944, 0.01888, 0.02832, 0.03776, 0.0472, 0.05664, 0.06608, 0.07552, 0.08496, 0.0944}                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0.00944                                   |
| P10: Roof Insulation                   | -                 | Discrete {ExistingRoof, RoofwithVegetation, RoofwithInsulationCellularGlass25mm, RoofwithInsulationCellularGlass50mm, RoofwithInsulationCellularGlass75mm, RoofwithInsulationGlassfiber25mm, RoofwithInsulationGlassfiber50mm, RoofwithInsulationGlassfiber75mm, RoofwithInsulationExpandedrubber(rigid)25mm, RoofwithInsulationXPS25mm, RoofwithInsulationXPS50mm, RoofwithInsulationXPS75mm, RoofwithInsulationBatt89mm, RoofwithInsulationBatt154mm, RoofwithInsulationBatt244mm, RoofwithInsulationBoard25mm, RoofwithInsulationBoard50mm, RoofwithInsulationBoard75mm, RoofwithInsulationExpandedPerlite25mm} | ExistingRoof                              |
| P11: Window Construction (North, West) | -                 | Discrete {DblClr6mm/13mmAir, DblBronze6mm/13mmAir, DblGreen6mm/13mmAir, DblGrey6mm/13mmAir, DblBlue6mm/13mmAir, DblRef-A-LTint6mm/13mmAir, DblRef-A-MTint6mm/13mmAir, DblRef-A-HTint6mm/13mmAir, DblLoE(e2 = 0.1)Tint6mm/13mmAir, DblLoESpecSelTint6mm/13mmAir, DblElecAbsBleached6mm/13mmAir, DblElecAbsColored6mm/13mmAir, DblElecRefBleached6mm/13mmAir, DblElecRefColored6mm/13mmAir, DblLoEElecAbsBleached6mm/13mmAir, DblLoEElecAbsColored6mm/13mmAir, DblLoEElecRefBleached6mm/13mmAir, DblLoEElecRefColored6mm/13mmAir, TrpLoEFilm(33)Bronze6mm/13mmAir,                                                   | DblClr6mm/13mmAir                         |

|                                                                                                                                       |    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                |
|---------------------------------------------------------------------------------------------------------------------------------------|----|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------|
| TrpLoEFilm(44)Bronze6mm/13mmAir,TrpLoEFilm(55)Bronze6mm/13mmAir,TrpLoEFilm(66)Bronze6mm/13mmAir, QuadrupleLoEFilms(88)3mm/8mmKrypton} |    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                |
| P12: Window Height (O.K.B)                                                                                                            | m  | Double [0.20, 1.40] and {0.17}                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | 0.17                           |
| P13: Overhang Depth                                                                                                                   | m  | Double [0.1, 0.5] and {0.01}                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 0.01                           |
| P14: Tilt Angle Overhang                                                                                                              | °C | Integer {30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 105, 110, 115, 120}                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | 90                             |
| P15: Window Material Shade                                                                                                            | -  | Discrete {HIGHREFLECT-LOWTRANSSHADE, MEDIUMREFLECT-MEDIUMTRANSSHADE, MEDIUMREFLECT-LOWTRANSSHADE, LOWREFLECT-HIGHTRANSSHADE, LOWREFLECT-MEDIUMTRANSSHADE, LOWREFLECT-LOWTRANSSHADE}                                                                                                                                                                                                                                                                                                                                                                                                                              | MEDIUMREFLECT-MEDIUMTRANSSHADE |
| P16: Lighting Control Type                                                                                                            | -  | Discrete {Continuous, Stepped, ContinuousOff}                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Stepped                        |
| P17: Fin Depth 1 (Left Depth)                                                                                                         | m  | Double [0.1, 0.5] and {0.01}                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 0.01                           |
| P18: Tilt Angle Fin                                                                                                                   | °C | Integer [30, 120]                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 90                             |
| P19: Solar Absorptance                                                                                                                | -  | Double {0.9, 0.91, 0.94, 0.89, 0.86, 0.85, 0.84, 0.82, 0.8, 0.79, 0.77, 0.71, 0.69, 0.59, 0.57, 0.54, 0.53, 0.51, 0.45, 0.4, 0.3}                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 0.7                            |
| P20: Exterior Door                                                                                                                    | -  | Discrete {G0413mmwood, G0525mmwood, G0650mmwood, G07100mmwood}                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | G0650mmwood                    |
| P21: Fin Depth 2 (Right Depth)                                                                                                        | m  | Double [0.1, 0.5] and {0.01}                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 0.01                           |
| P22: Window Material Gas                                                                                                              | -  | Discrete {AIR13MM, ARGON13MM, KRYPTON13MM, XENON13MM}                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | AIR13MM                        |
| P23: Floor Insulation                                                                                                                 | -  | Discrete {ExistingFloor, FloorwithInsulationCellularglass25mm, FloorwithInsulationCellularglass50mm, FloorwithInsulationCellularglass75mm, FloorwithInsulationGlassfiber25mm, FloorwithInsulationGlassfiber50mm, FloorwithInsulationGlassfiber75mm, FloorwithInsulationExpandedrubber(rigid)25mm, FloorwithInsulationXPS25mm, FloorwithInsulationXPS50mm, FloorwithInsulationXPS75mm, FloorwithInsulationBatt89mm, FloorwithInsulationBatt154mm, FloorwithInsulationBatt244mm, FloorwithInsulationBoard25mm, FloorwithInsulationBoard50mm, FloorwithInsulationBoard75mm, FloorwithInsulationExpandedPerlite25mm} | ExistingFloor                  |

|                                  |   |                                                                                                                                                                                                                                                |                   |
|----------------------------------|---|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------|
| P24: Window Construction (South) | - | Discrete {DblClr6mm/13mmAir, DblClrLowIron5mm/13mmAir, DblLoE(e2 = 0.2)Clr6mm/13mmAir, DblLoE(e2 = 0.1)Clr6mm/13mmAir, DblLoESpecSelClr6mm/13mmAir, DblElecAbsBleached6mm/13mmAir, TrpLoEFilm(55)Clr6mm/13mmAir, TrpLoEFilm(66)Clr6mm/13mmAir} | DblClr6mm/13mmAir |
| P25: HVAC Systems                | - | Discrete {ConstantVolumeChillerBoiler, DualDuct, FanCoil, FanCoil-DOAS, PackagedVAV, PTAC, PTAC-DOAS, PTHP, PTHP-DOAS, UnitaryHeatPump:AirToAir, VAVWater-CooledChillers, VAVAir-CooledChillers, VRF, VRF-DOAS, WaterToAirHeatPump}            | PTAC              |

Table 4-12 outlines the construction layers for both the existing floor and roof of a building, detailing the materials used in each layer. The outermost layer of the existing floor consists of F16 acoustic tiles, while the roof features bituminous waterproofing. Beneath the outer layers, the existing floor has a 30mm cement mortar layer, compared to a thicker 50mm cement mortar layer in the roof construction. The floor includes M11 lightweight concrete (100mm) while the roof utilizes a denser M12 lightweight concrete (150mm). Both structures incorporate a ceiling unolith with 50mm of expanded polystyrene insulation, contributing to thermal performance. Additionally, they feature air space resistance, represented by F05, and both the floor and roof share a block joist for structural support. The innermost layer in both cases consists of a 16mm gypsum board (G01), providing a finished surface.

Table 4-12: Construction Layer related to Existing Floor, Roof, and Wall

| Construction           | Existing Floor                                            | Existing Roof                                             | Existing Interior Wall        |
|------------------------|-----------------------------------------------------------|-----------------------------------------------------------|-------------------------------|
| <b>Outside Layer 1</b> | F16 Acoustic tile                                         | Bituminous waterproofing                                  | G01 16mm gypsum board         |
| <b>2</b>               | Cement mortar 30mm                                        | Cement mortar 50mm                                        | Clay block                    |
| <b>3</b>               | M11 100mm lightweight concrete                            | M12 150mm lightweight concrete                            | F04 Wall air space resistance |
| <b>4</b>               | Ceiling unolith (Insulation 50mm)<br>Expanded polystyrene | Ceiling unolith (Insulation 50mm)<br>Expanded polystyrene | Clay block                    |
| <b>5</b>               | F05 Ceiling air space resistance                          | F05 Ceiling air space resistance                          | G01 16mm gypsum board         |

|                       |                       |                       |   |
|-----------------------|-----------------------|-----------------------|---|
| <b>6</b>              | Block Joist           | Block Joist           | - |
| <b>Inside Layer 7</b> | G01 16mm gypsum board | G01 16mm gypsum board | - |

| Construction           | Existing Exterior Wall 1 (façade)                   | Existing Exterior Wall 2                            | Existing Exterior Wall 3                            | Existing Exterior Wall 4 (Kitchen)                  | Existing Exterior Wall 5 (Bathroom)                 |
|------------------------|-----------------------------------------------------|-----------------------------------------------------|-----------------------------------------------------|-----------------------------------------------------|-----------------------------------------------------|
| <b>Outside Layer 1</b> | Fire brick facade                                   | Bituminous waterproofing                            | G01 16mm gypsum board                               | Gypsum plaster: Lightweight aggregate - 16mm        | Bituminous waterproofing                            |
| <b>2</b>               | Cement mortar 30mm                                  | Clay block                                          | Clay block                                          | Clay block                                          | Clay block                                          |
| <b>3</b>               | Clay block                                          | Wall unilith (Insualtion 50mm) Expanded polystyrene | Wall unilith (Insualtion 50mm) Expanded polystyrene | Wall unilith (Insualtion 50mm) Expanded polystyrene | Wall unilith (Insualtion 50mm) Expanded polystyrene |
| <b>4</b>               | Wall unilith (Insualtion 50mm) Expanded polystyrene | F04 Wall air space resistance                       | F04 Wall air space resistance                       | F04 Wall air space resistance                       | F04 Wall air space resistance                       |
| <b>5</b>               | F04 Wall air space resistance                       | Clay block                                          | Clay block                                          | Clay block                                          | Clay block                                          |
| <b>6</b>               | Clay block                                          | G01 16mm gypsum board                               | G01 16mm gypsum board                               | Cement mortar 30mm                                  | Cement mortar 30mm                                  |
| <b>Inside Layer 7</b>  | G01 16mm gypsum board                               | -                                                   | -                                                   | Wall Tiles                                          | Wall Tiles                                          |

Figures 4-7 through 4-12 in the case study illustrate various aspects of the baseline building model, providing a comprehensive visualization of its design and performance. Figures 4-7 and 4-8 shows the overall case study building, highlighting its architectural features and layout. Figure 4-9 presents a detailed rendering by thermal zones, which is critical for understanding temperature distribution and comfort levels within space. Figure 4-10 focuses on construction types, illustrating different materials used in the building, which impact energy efficiency and sustainability. Figure 4-11 depicts the boundary conditions, essential for assessing the thermal interactions between the building and its environment. Finally, Figure 4-12 illustrates the integration of solar panels, emphasizing the building's commitment to renewable energy and enhancing its

overall energy performance. Together, these figures provide valuable insights that support the analysis and findings presented in this research.

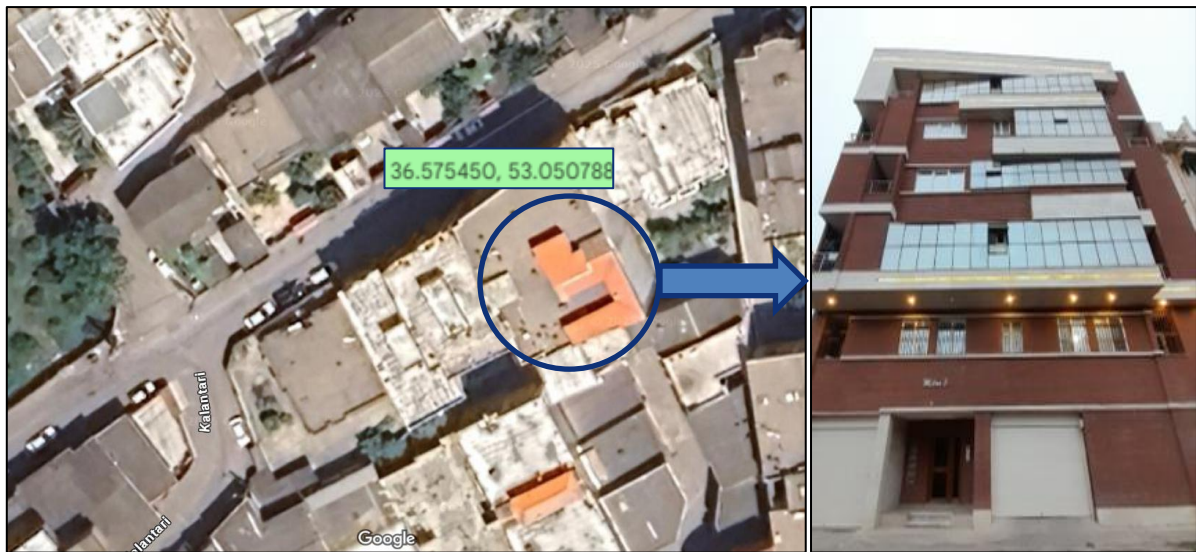
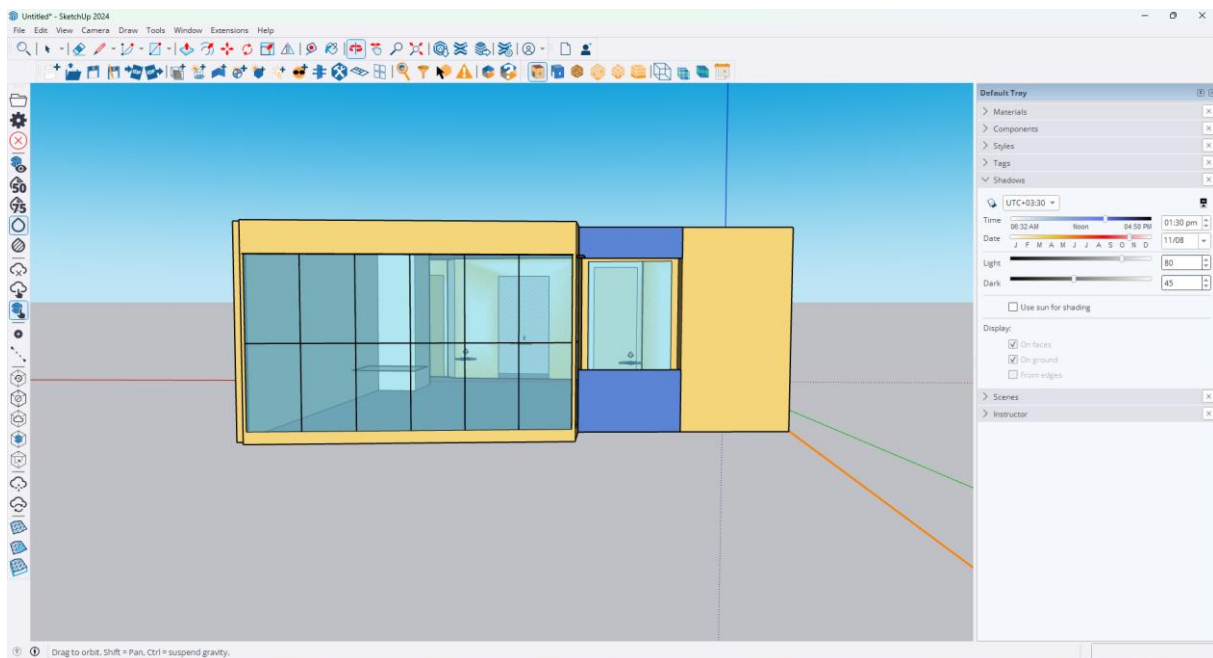


Figure 4-7: Case study building



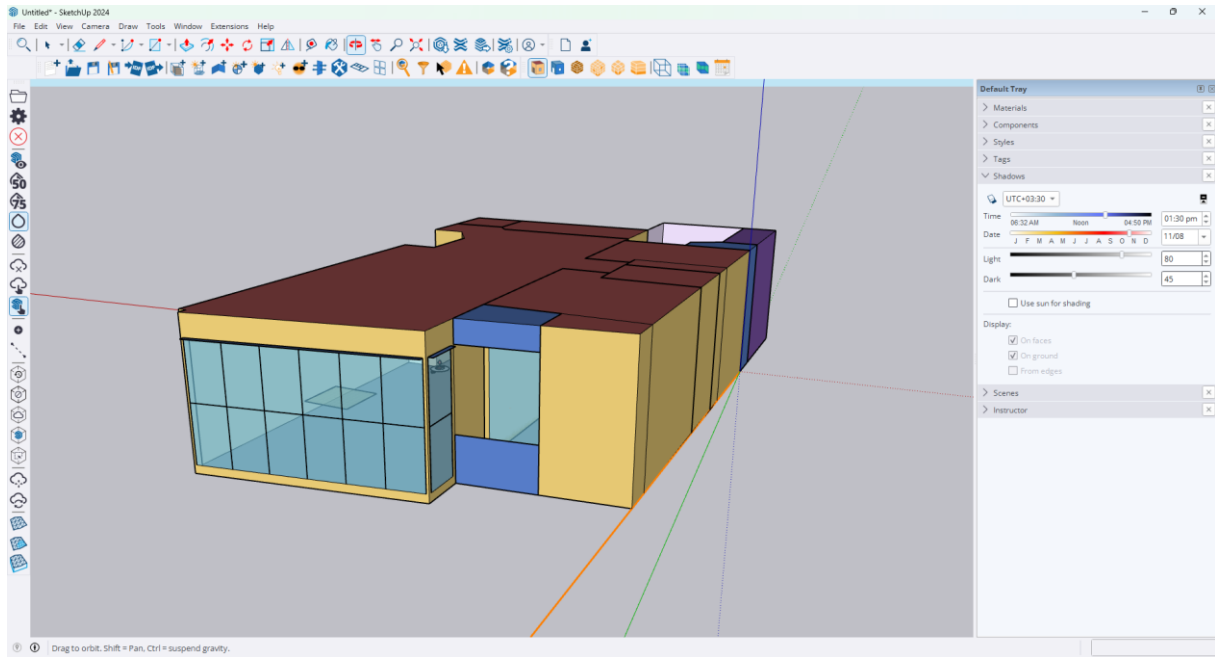


Figure 4-8: Baseline building model

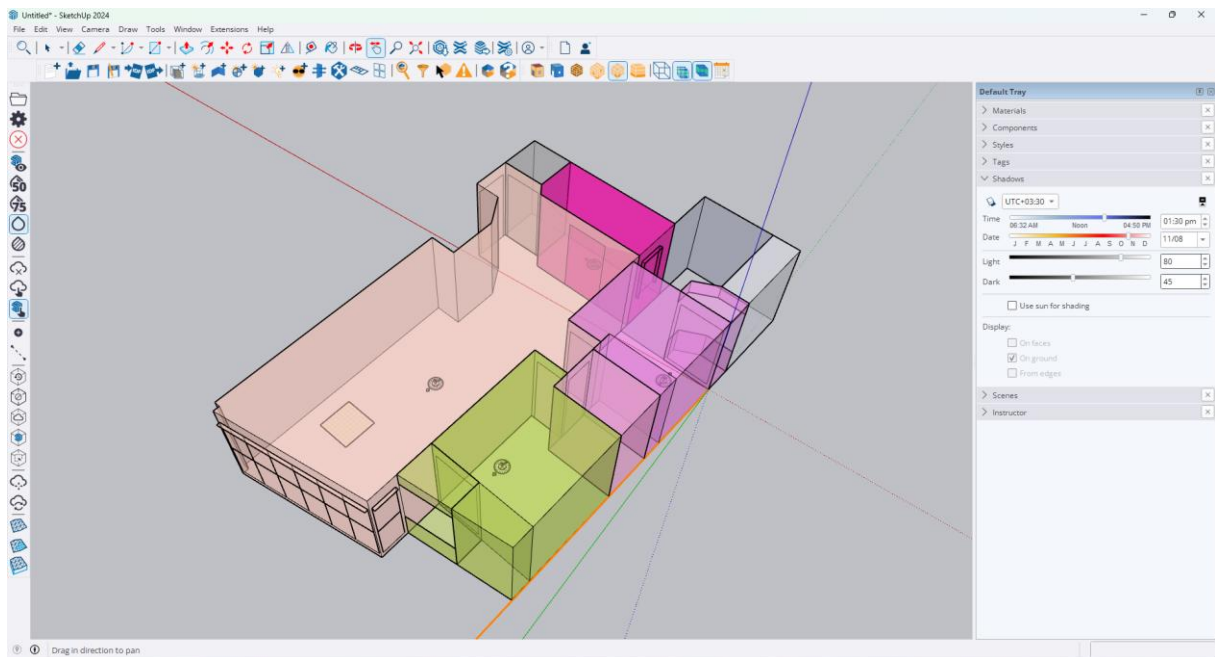


Figure 4-9: Rendering by thermal zones

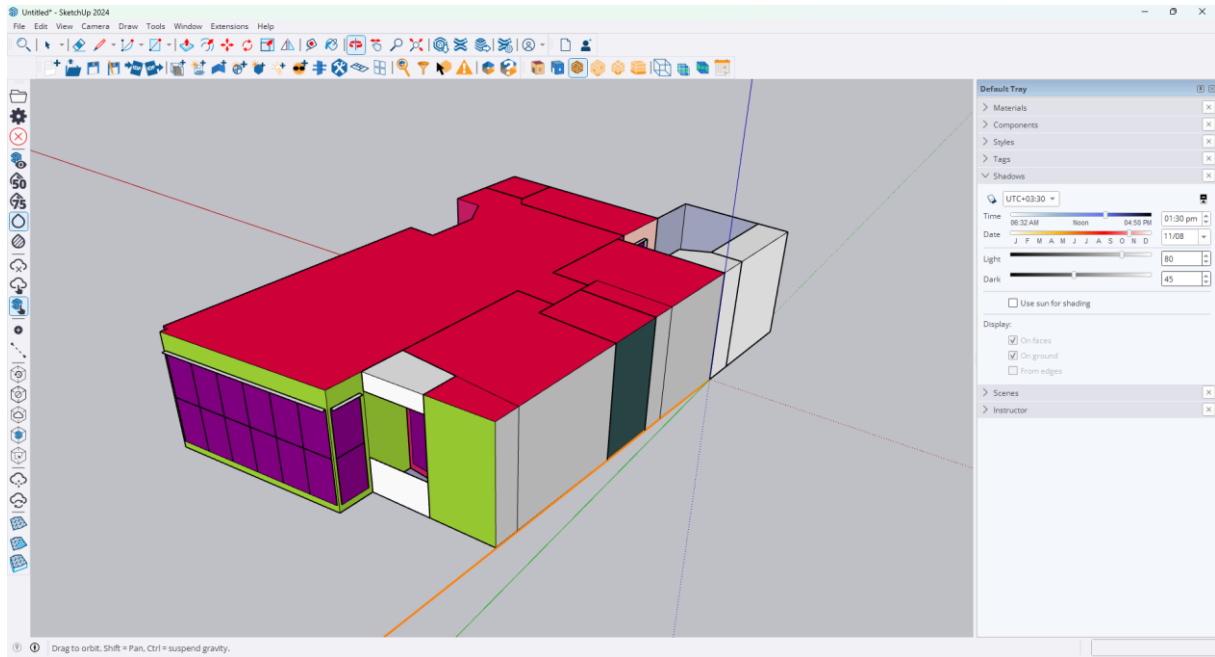


Figure 4-10: Rendering by construction

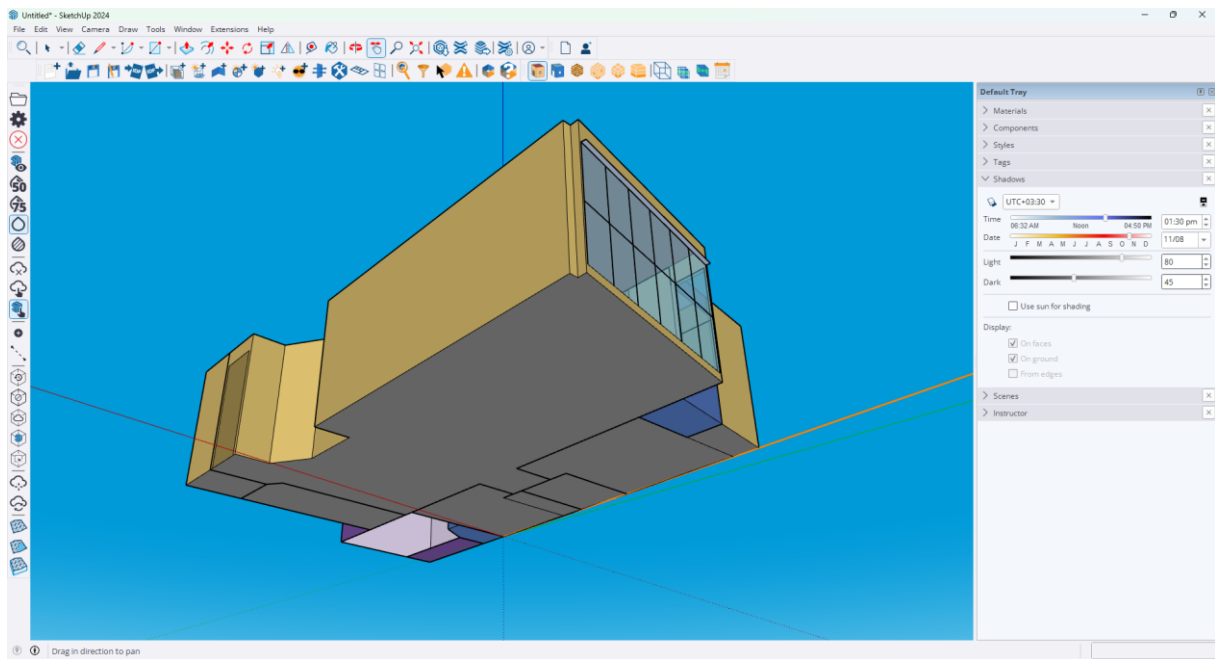


Figure 4-11: Rendering by boundary conditions

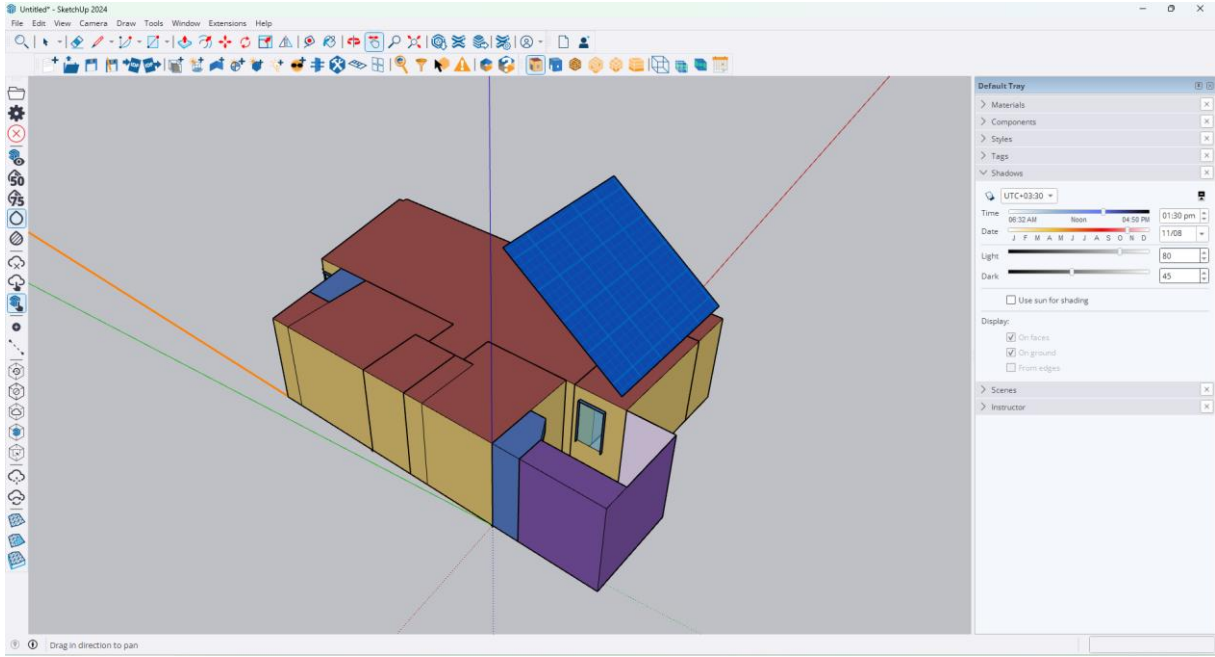


Figure 4-12: Solar panel

## 4.7. Simulation of energy-related measures using NSGA-II

The analysis of Energy-Related Measures (ERMs) reveals that the total number of available combinations is approximately  $1.41 \times 10^{24}$ , highlighting an extensive search space for potential solutions. Given that each EnergyPlus simulation takes about three minutes to complete, simulating all possible combinations of ERMs would be impractical due to the immense computational time required.

Optimization through NSGA-II: to address this challenge, the Non-dominated Sorting Genetic Algorithm II (NSGA-II) is employed, which significantly reduces the computation time involved in exploring the solution space.

- Crossover Rate: 100%
- Mutation Rate: 20%
- Tournament Size: 5
- Maximum Generations: 100

These parameters contribute to a balance between computational efficiency and reliable results in the optimization process [28, 50].

Computational Framework: the NSGA-II process was limited to a maximum of 100 generations, serving as the stopping criterion. Utilizing parallel computing capabilities on an Intel Xeon® processor (2.80 GHz, 12 MB cache, and 12 cores),

the total elapsed computational time for the optimization was approximately 7 hours and 20 minutes.

This setup illustrates the model's capacity to intelligently explore the solution space while efficiently managing computational resources. By leveraging the NSGA-II and parallel processing, the study effectively navigates the vast array of ERM combinations, enabling the identification of optimal energy strategies within a feasible timeframe. This approach demonstrates the power of advanced computational techniques in tackling complex optimization problems in energy management.

## 5. Results

### 5.1. Model validation/ calibration

The analysis of average annual electricity and natural gas consumption from 2021 to 2023 shows that consumption levels were 3814.23 kWh for electricity and 19,711.67 kWh for natural gas, as obtained from building utility bills. Table 5-1 and Figures 5-1 and 5-2 provide a comparison between the energy simulation results and the actual consumption data. These results indicate a strong correlation between the actual and simulated consumption results, as both sets of values fall within the acceptable calibration thresholds set forth by ASHRAE. The calibration results affirm the reliability of the energy simulations, demonstrating that they closely match the actual building performance. This strong correlation enhances the credibility of the modeling process and supports its use for making informed decisions regarding energy management and potential retrofit strategies.

Table 5-1: Calibration and Validation of Energy Consumption Simulation Results (2021-2023)

| Section                                                                                          | Details                                                                                                                                                                                                                                                                                      |
|--------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Analysis of Consumption (2021-2023)                                                              | <ul style="list-style-type: none"> <li>- Electricity: 3814.23 kWh</li> <li>- Natural Gas: 19,711.67 kWh</li> <li>- Source: Building utility bills</li> <li>- Comparison: Figures 5-1 and 5-2</li> </ul>                                                                                      |
| Calibration Criteria (ASHRAE Guideline 14-2014 [42], and ASHRAE Handbook Fundamentals 2021 [51]) | <ul style="list-style-type: none"> <li>- Monthly Data: <ul style="list-style-type: none"> <li>- NMBE: &lt; 5%</li> <li>- CV(RMSE): &lt; 15%</li> </ul> </li> <li>- Hourly Data: <ul style="list-style-type: none"> <li>- NMBE: &lt; 10%</li> <li>- CV(RMSE): &lt; 30%</li> </ul> </li> </ul> |
| Understanding NMBE and CV(RMSE)                                                                  | <ul style="list-style-type: none"> <li>- NMBE: Signed error relative to the mean (percentage bias)</li> </ul>                                                                                                                                                                                |

|            |                                                                                                                                                                                                                                                                                     |
|------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|            | <ul style="list-style-type: none"> <li>- Positive (NMBE &gt; 0): Underestimation</li> <li>- Negative (NMBE &lt; 0): Overestimation</li> <li>- CV(RMSE): Accuracy measure, percentage error of squared errors divided by actual mean</li> </ul>                                      |
| Findings   | <ul style="list-style-type: none"> <li>- Electricity: <ul style="list-style-type: none"> <li>- NMBE: -0.97%</li> <li>- CV(RMSE): 12.90%</li> </ul> </li> <li>- Natural Gas: <ul style="list-style-type: none"> <li>- NMBE: 0.35%</li> <li>- CV(RMSE): 14.50%</li> </ul> </li> </ul> |
| Conclusion | <ul style="list-style-type: none"> <li>- Results within ASHRAE thresholds indicate strong correlation between actual and simulated consumption</li> <li>- Calibration affirms reliability of energy simulations for informed energy management and retrofit decisions</li> </ul>    |

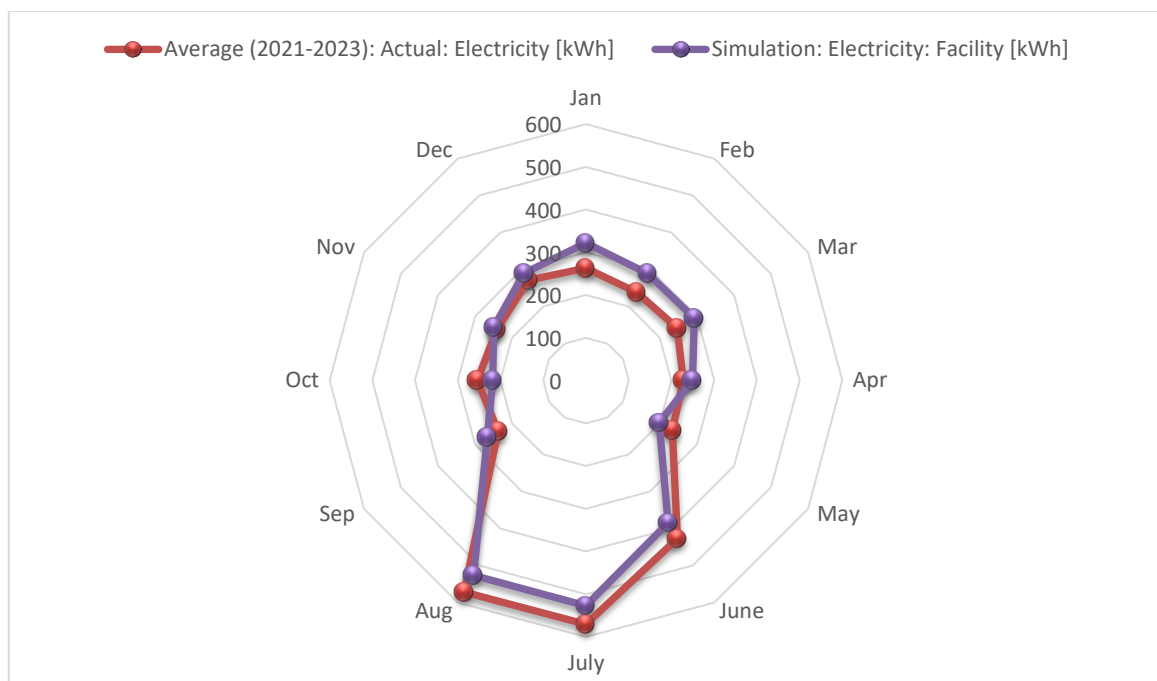


Figure 5-1: Comparison of actual building electricity consumption with simulated results

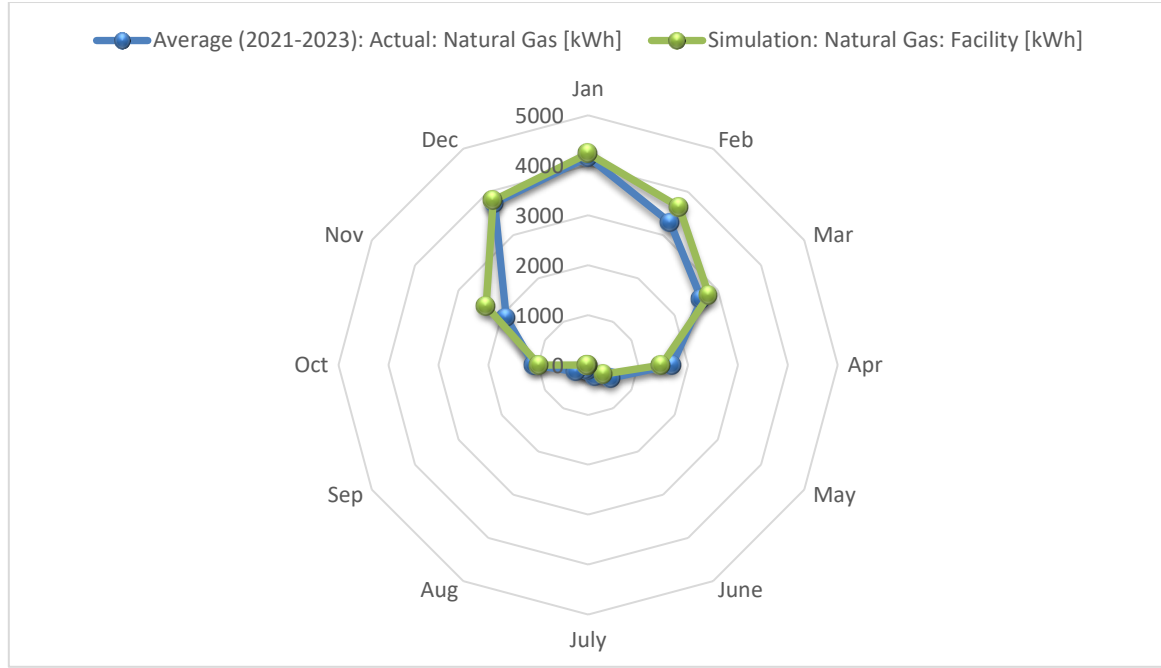


Figure 5-2: Comparison of actual building natural gas consumption with simulated results

$$NMBE = \frac{\sum(V_{actual} - V_{modeled})}{(N-1) \times \text{Mean}(V_{actual})} \times 100\% \quad (8)$$

$$CV(RMSE) = \frac{\sqrt{\frac{\sum(V_{actual} - V_{modeled})^2}{N-1}}}{\text{Mean}(V_{actual})} \times 100\% \quad (9)$$

where  $V_{actual}$ = parameter's measured or metered value for each time step (e.g., month),  $V_{modeled}$ = parameter's estimated or modeled value for each time step, and  $N$ = number of time steps being analyzed during period of evaluation.

## 5.2. Software tools and workspaces for building energy modeling, parametric study, and optimization

Figure 5-3 displays a screenshot of SketchUp 2024, a 3D modeling software, showcasing a building model in X-Ray mode. The model to be a simplified representation of a building with multiple rooms, featuring transparent walls and a glass facade on one side, allowing a clear view of the internal structure. The X-Ray mode, indicated by the semi-transparent rendering, helps visualize the building's interior layout, including walls, doors, and windows, while maintaining the outline of the external structure. The model is used for energy simulation purposes, as it aligns with the context of the study involving tools like EnergyPlus

for building performance analysis. The date and time settings in the "Shadows" panel on the right suggest that the model can be used to evaluate daylighting and shadow effects, which are critical for assessing energy efficiency and thermal comfort in building design.

The left sidebar contains various tools for modeling and editing, such as drawing, push/pull, and measurement tools, typical of SketchUp's interface for creating and modifying 3D geometry. The right panel includes options for managing components, materials, styles, tags, and shadows, with the "Shadows" settings active, indicating the ability to simulate solar positioning and shading effects. The "Display" options allow toggling features like shadows and transparency, which are useful for visualizing different aspects of the building model during analysis. This model, with its clear depiction of structural elements and transparent rendering, serves as the baseline geometry for energy simulations in EnergyPlus, enabling the evaluation of design variables such as window placement, wall insulation, and HVAC configurations, which are critical for the multi-objective optimization and sensitivity analysis discussed in the study.

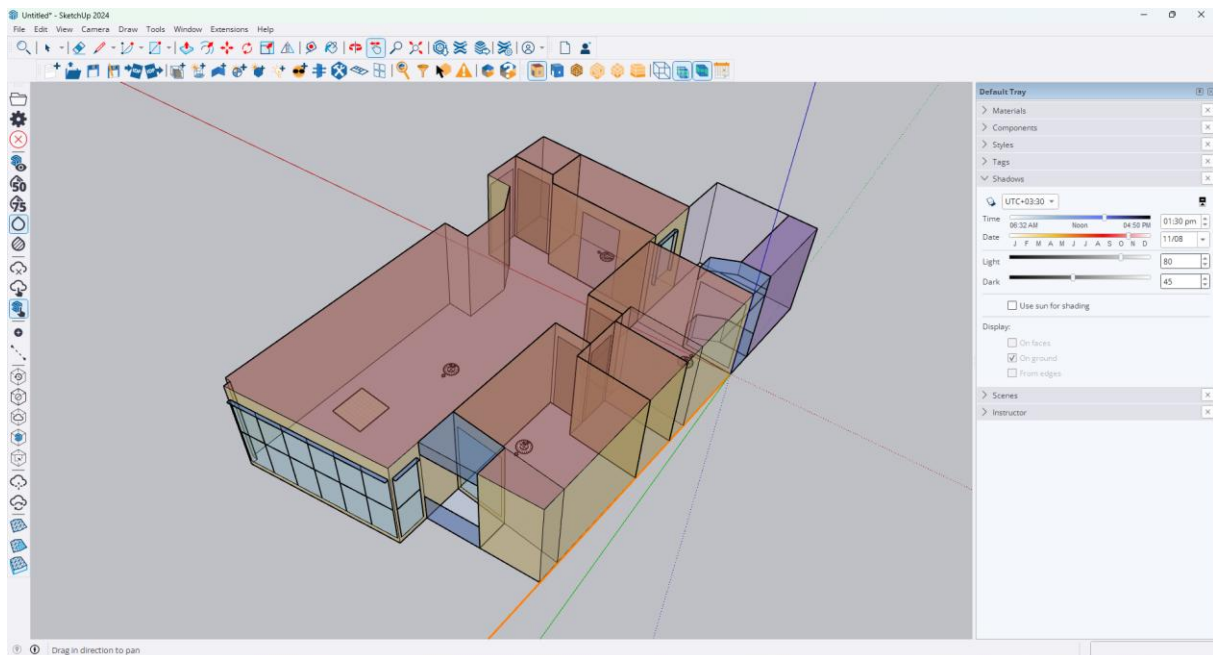


Figure 5-3: Baseline Model Visualized in X-Ray Mode

Figure 5-4 shows a screenshot of SketchUp 2024, a 3D modeling software, displaying a building model in a standard rendering mode with shadows enabled. The model depicts a multi-room building with a glass facade on one side and a distinct roof structure, like the baseline model used in the study for energy simulations. The walls and roof are rendered in different colors, to differentiate various zones or

materials, with the glass facade allowing visibility into the interior layout. Shadows are cast on the ground and building surfaces, indicating the sun's position, as configured in the "Shadows" panel on the right, set to November, at 8:00 AM (UTC+03:30, matching Iran's time zone). This setup facilitates the analysis of solar gain, daylighting, and shading effects, which are essential for evaluating the building's energy performance and thermal comfort in the context of the multi-objective optimization study.

The left sidebar contains SketchUp's modeling tools, including options for drawing, extruding, and measuring, used to create and modify the 3D geometry. The right panel includes settings for components, materials, styles, tags, and shadows, with the "Shadows" tab active, allowing users to adjust the time, date, and light intensity for shadow simulations. The "Display" options enable toggling shadows and other visual features, aiding in the detailed examination of the model's interaction with sunlight. This model, developed in SketchUp, provides the geometric foundation for energy simulations in EnergyPlus, where design variables such as window placement, roof insulation, and HVAC configurations are analyzed for their impact on energy efficiency and occupant comfort, aligning with the study's focus on sensitivity analysis and optimization using tools like jEPlus and EnSimS.

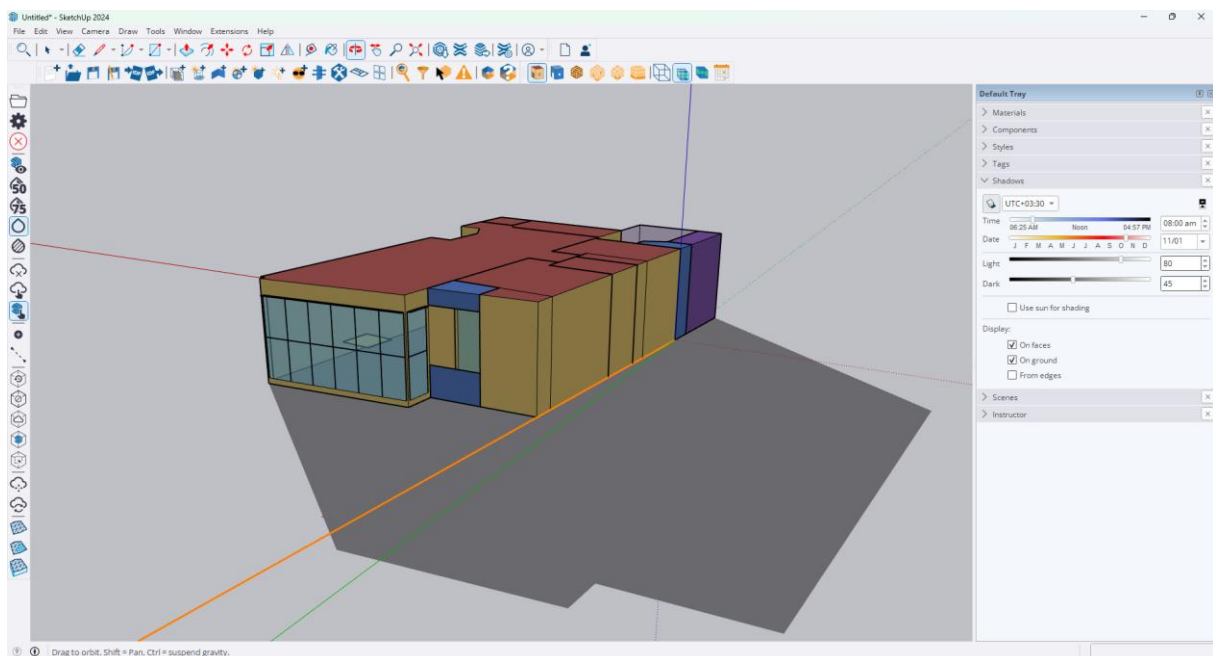


Figure 5-4: Baseline Model Visualized with show shadows

Figure 5-5 shows a screenshot of the EnergyPlus software interface, specifically the IDF Editor, which is used for creating and editing input data files (.idf) for building

energy simulations. The left panel lists various categories of objects that can be defined in an EnergyPlus model, such as "Building," "Zone," "Construction," "Material," "WindowMaterial," and "Schedule," among others. These categories represent the components and parameters required to define a building's geometry, materials, HVAC systems, and operational schedules for energy simulation. The highlighted object, "Output: Variable," suggests that the user is configuring the output variables to be reported after the simulation, such as energy consumption, temperature, or comfort metrics, which are crucial for analyzing the building's performance in the context of the multi-objective optimization study mentioned in the thesis.

The right panel provides a detailed view of the selected object, "Output: Variable," with fields for specifying the variable name, reporting frequency, and other settings, although the fields are currently empty in this view. The top section includes a description of the selected field, explaining its purpose and providing guidance on how to specify the variable (e.g., "Enter a unique name"). The EnergyPlus version displayed at the bottom (EnergyPlus 24.1.0) indicates the software version used for simulations. This interface is essential for setting up the baseline model for the study, allowing the user to define the building's characteristics and simulation parameters, which are then used in tools like jEPlus for parametric analysis and optimization. The IDF Editor's role in this workflow is to prepare the input file that EnergyPlus uses to simulate the building's energy performance, providing the foundation for subsequent sensitivity and optimization analyses.



parametric studies by linking adjustable parameters with EnergyPlus simulations, making it a powerful tool for optimizing building energy performance and conducting sensitivity analyses.

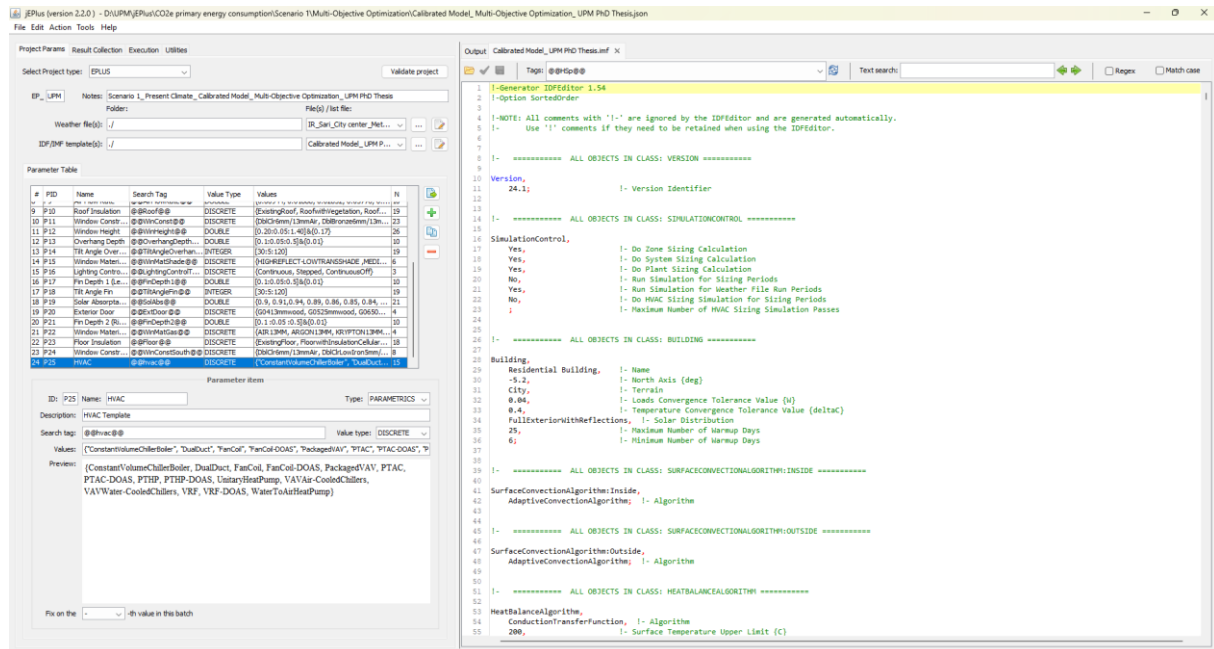


Figure 5-6: jEPlus Software Space: Parameter Configuration and IDF Editing for Building Energy Simulations

Figure 5-7 shows a screenshot of the jEPlus+EA software interface (version 2.0 beta), a tool designed for parametric analysis, optimization, and sensitivity studies, often integrated with EnergyPlus for building energy simulations. The interface is structured to manage and execute optimization projects efficiently. At the top, the project details are displayed, including the project name, scenario, and description, indicating that this project focuses on a multi-objective optimization study, related to building energy performance. The navigation bar provides options for managing projects, such as creating new projects, opening existing ones, and accessing optimization settings.

The main workspace is divided into several tabs and panels. The "Optimisation" tab is currently active, showing the optimization problem definition on the left side. This section lists various parameters (labeled P1 to P25) that are being optimized, such as heating and cooling setpoints, insulation properties, window characteristics, and HVAC settings. Each parameter is associated with a range or set of values (discrete or continuous) that the optimization algorithm will explore. On the right side, the "Variable Definition" panel allows users to define or modify parameters, with fields for parameter name, display caption, value type (weather

file), and search string (specifying a weather file location "IR\_Sari\_City center\_Meteonorm 8.2.0.epw"). This setup enables users to configure the optimization process by defining the variables and constraints, facilitating the exploration of design alternatives to achieve optimal building performance. The interface also includes a status bar at the bottom, indicating server activity, memory usage, and project status, which helps users monitor the computational process during optimization runs.

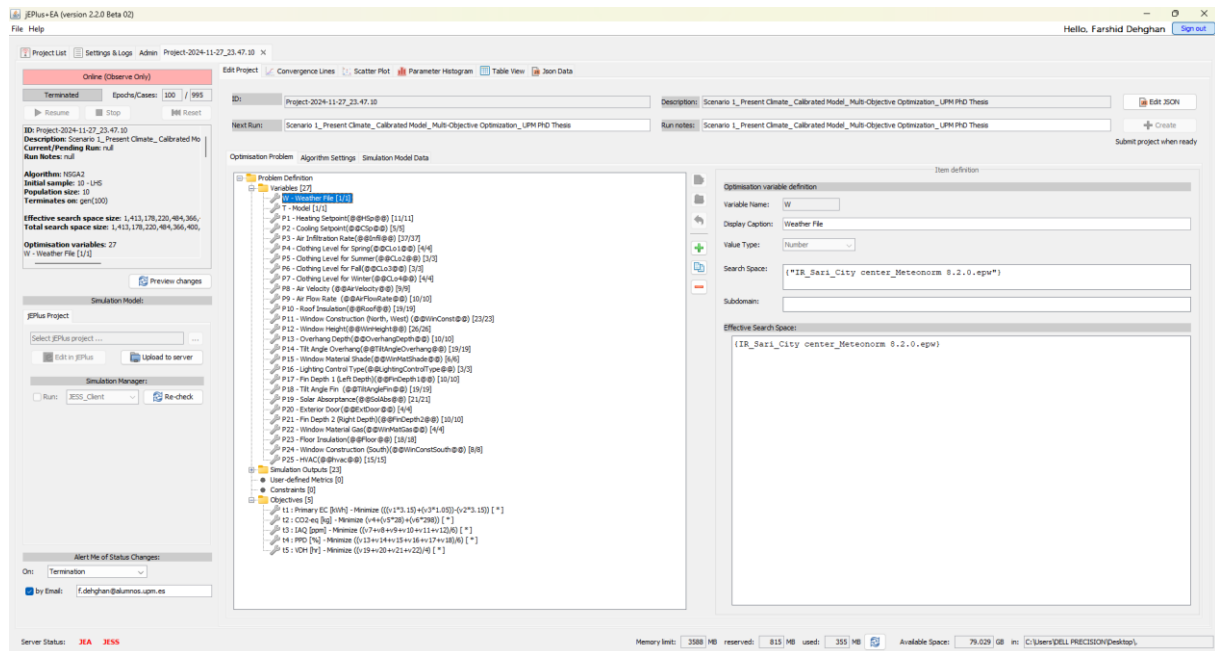


Figure 5-7: jEPlus + EA Software Space: Configuration of Parameters for Multi-Objective Optimization

Figure 5-8 presents a screenshot of the jEPlus+EA software interface (version 2.0 beta), specifically within the "Plot" tab, showcasing the outcomes of optimization study focused on building energy performance. The primary visualization is a scatter plot depicting the results of multi-objective optimization analysis. The x-axis, labeled "t1," represents the annual primary energy consumption (measured in kWh) as one objective function, while the y-axis, labeled "t3," corresponds to another objective, indoor air quality (IAQ, measured in ppm). Each point on the scatter plot signifies a distinct simulation scenario, with the spread of points highlighting the trade-offs between the two competing objectives. A notable concentration of points near lower values of t1 and higher values of t3 indicates that many scenarios achieve reduced energy consumption (improved t1) at the cost of increased IAQ levels (worsened t3), effectively delineating the Pareto front—a hallmark of multi-objective optimization where further improvement in one objective leads to a compromise in the other. This visualization underscores the inherent conflicts between minimizing energy use and maintaining acceptable indoor air quality, providing valuable insights for decision-making in building design optimization.

On the left side, the project navigation panel lists various sections, including "Optimisation," "Simulation," and "Results," indicating that this plot is part of the results analysis phase. The right panel provides options for customizing the plot, such as selecting data series ("All," "Best," "Feasible") and highlighting specific points (e.g., "Highlight select" is checked, with some points marked in pink). The "Run" section shows settings for the optimization process, including the number of generations (3) and population size (3), suggesting a genetic algorithm was used for the optimization. The scatter plot's spread, and the highlighted points allow users to identify optimal design solutions that balance the competing objectives, aiding in decision-making for building design or energy efficiency improvements. The status bar at the bottom indicates server activity and memory usage, ensuring users can monitor the computational resources during analysis.

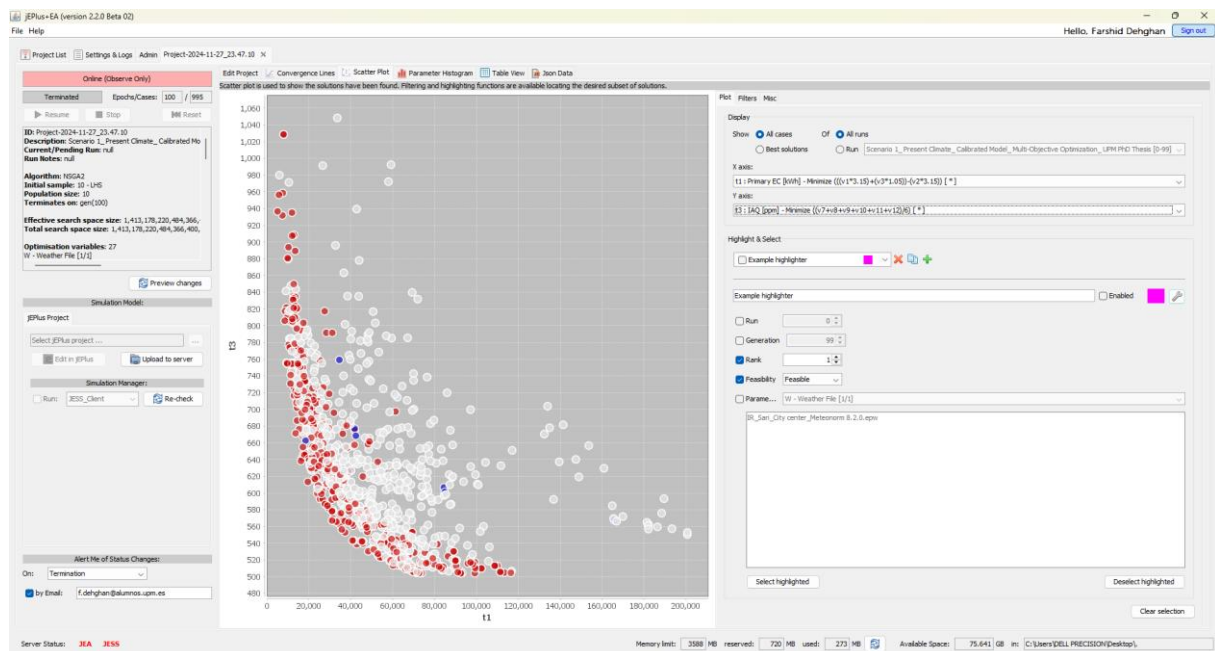


Figure 5-8: jEPlus + EA Software Space: Scatter Plot of Multi-Objective Optimization for Energy and IAQ

Figure 5-9 showcases a screenshot of the jEPlus+EA software interface (version 2.0 beta) within the "Plot" tab, highlighting the results of the multi-objective optimization study, centered on building energy performance. The core visualization is a scatter plot that illustrates the trade-offs between two objective functions: "t1" on the x-axis and "t4" on the y-axis. The x-axis (t1) quantifies annual energy consumption (in kWh), while the y-axis (t4) represents the percentage of people dissatisfied (PPD), a metric of thermal comfort. Each dot on the scatter plot corresponds to a distinct simulation scenario, with the distribution of points reflecting the spectrum of achievable outcomes. A noticeable clustering of points at

lower t1 values alongside a broader range of t4 values delineates a Pareto front, characteristic of multi-objective optimization. This front indicates that reducing energy consumption (improving t1) often compromises thermal comfort (increasing PPD), highlighting the inherent trade-offs between these objectives. This visualization provides critical insights into balancing energy efficiency and occupant comfort in building design optimization.

The left panel lists the project structure, including sections like "Optimisation," "Simulation," and "Results," indicating that this plot is part of the post-optimization analysis. On the right, the plotting options allow users to filter the data, with categories such as "All," "Best," and "Feasible" solutions, and a "Highlight select" feature (enabled, with some points marked in pink) to emphasize specific scenarios. The "Run" settings reveal that the optimization was performed using a genetic algorithm, with parameters set to 3 generations and a population size of 3, indicating a small-scale optimization run, for testing purposes. This scatter plot enables users to visualize the trade-offs between competing objectives, identify optimal design solutions, and make informed decisions for improving building performance, such as balancing energy efficiency with occupant comfort. The status bar at the bottom provides real-time feedback on server status and memory usage, ensuring efficient management of computational resources during the analysis.

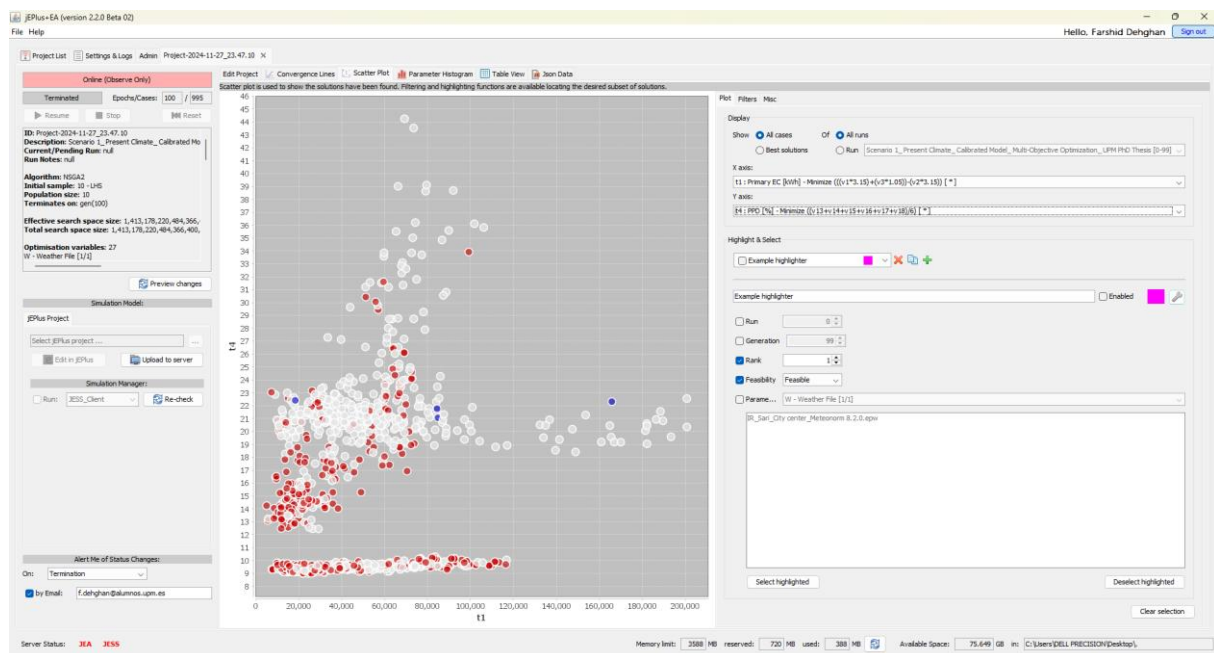


Figure 5-9: jEPlus + EA Software Space: Scatter Plot of Multi-Objective Optimization for Energy and Comfort

Figure 5-10 shows a screenshot of the jEPlus+EA software interface (version 2.0 beta), with the "Progress" tab active, illustrating the progress of a multi-objective optimization process, related to building energy performance. The central visualization consists of a series of stacked area charts, each representing the distribution of solutions across generations of the optimization run. The x-axis denotes the generation number (from 0 to 100), while the y-axis represents the count of solutions. The charts are divided into different functions or metrics, such as energy consumption, cost, or thermal comfort, with each chart corresponding to a specific output variable. The shaded areas within each chart indicate the number of solutions falling within specific ranges of the objective values, with colors (blue, pink) representing different value bins. For instance, the top chart shows a gradual increase in the number of solutions with better performance (higher values) as the generations progress, suggesting that the optimization algorithm is converging toward improved solutions over time.

On the left side, the project navigation panel lists sections like "Optimisation," "Simulation," and "Results," indicating that this progress visualization is part of the optimization workflow. The right panel provides options to customize the display, such as selecting the state of solutions ("Show state freq") and choosing specific output charts to visualize. The "Progress above" dropdown allows users to filter solutions based on their performance relative to a threshold. These charts help users monitor the evolution of the optimization process, providing insights into how the population of solutions improves across generations and whether the algorithm is effectively exploring the design space. The status bar at the bottom displays server activity and memory usage, ensuring users can track the computational resources utilized during the optimization run. This progress visualization is crucial for understanding the convergence behavior of the optimization algorithm and making informed decisions about continuing or adjusting the process.

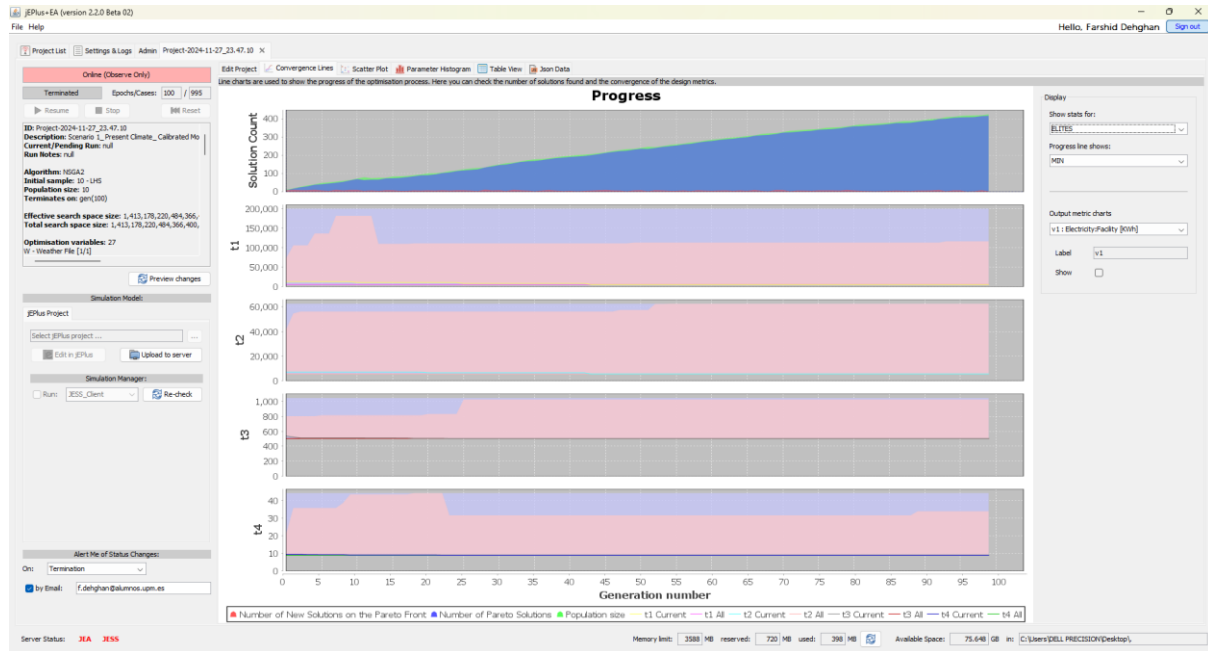


Figure 5-10: jEPlus + EA Software Space: Progress of Multi-Objective Optimization Across Generations

Figure 5-11 displays a screenshot of the jEPlus+EA software interface (version 2.0 beta), with the "Results" tab active, presenting the outcomes of a parametric or optimization study, focused on building energy performance. The main section features a series of histograms, each corresponding to a specific parameter or variable involved in the study, such as weather files, heating and cooling setpoints, clothing levels, air infiltration rates, airflow rates, surface construction types, and window properties (e.g., height and construction for north-facing windows). Each histogram shows the distribution of values for that parameter across all simulation runs, with the x-axis representing the parameter values (e.g., temperature in °C for setpoints, or clo-values for clothing) and the y-axis indicating the frequency or number of occurrences. The histograms are color-coded, with red bars representing the distribution of all solutions and gray bars showing the distribution of a selected subset (e.g., "best" or "feasible" solutions), allowing users to compare how optimal solutions differ from the overall population in terms of parameter values.

On the left side, the project navigation panel lists sections like "Optimisation," "Simulation," and "Results," confirming that this view is part of the post-simulation analysis. The right panel, labeled "Parameter value distribution of all," provides additional details, including a dropdown to switch between different solution sets ("All run," "Best generation," "Best solutions only") and a bar chart summarizing the number of solutions (1 to 5 categories). This setup enables users to analyze the range and frequency of parameter values used in the simulations,

offering insights into which parameter settings are most common or effective for achieving optimal outcomes. For example, the histogram for heating setpoints (P2) shows a concentration of values around 20–22°C, indicating that these temperatures were frequently selected in the simulations. This analysis is crucial for understanding the impact of each parameter on the objective functions and for identifying optimal design configurations in building energy studies. The status bar at the bottom provides server and memory usage details, ensuring efficient resource management during the analysis.

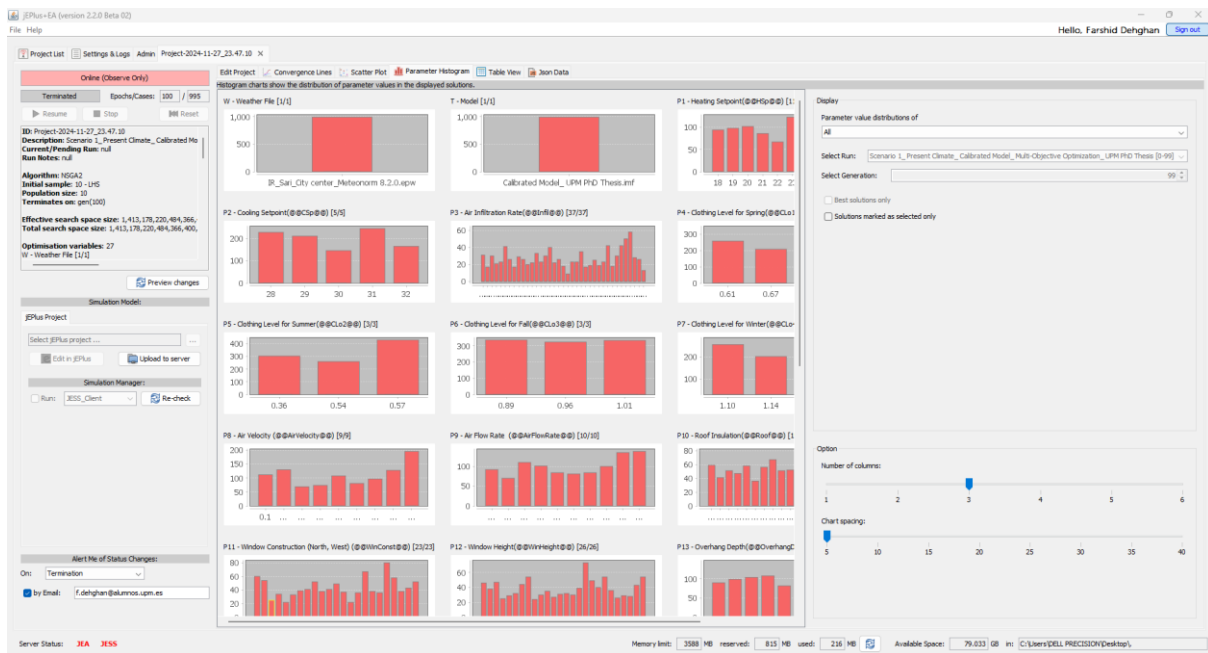


Figure 5-11: jEPlus + EA Software Space: Histogram Visualization of Parameter Distributions for Building Performance

Figures 5-12 and 5-13 shows a screenshot of the EnSimS web-based platform, specifically displaying a scatter plot from the multi-objective optimization study as part of a project titled "Scenario 1: Present Climate, Calibrated Model, Multi-Objective Optimization, UPM PhD Thesis." The scatter plot visualizes the results of the optimization, with the x-axis labeled "t1: Primary EC (kWh)" (representing primary energy consumption) and the y-axis labeled "t3: IAQ (ppm)" (possibly indicating weighted average discomfort hours or a similar thermal comfort metric). Each point on the plot represents a simulation scenario, color-coded to indicate different categories: "Best" (purple), "Feasible" (red), "Infeasible" (gray), and "Marked" (green), with a total of 100 runs, 995 solutions, and 100 iterations. The dense clustering of points near lower values of t1 and higher values of t3 highlights the trade-off between minimizing energy consumption and maintaining IAQ, a

common outcome in multi-objective optimization, with the Pareto front visible as the boundary of feasible solutions.

The right panel provides detailed controls for customizing the visualization. The "Display" section allows users to toggle between 2D and 3D chart styles, select the dataset to show (run-0 in this case), and choose which data to display (feasible or best solutions). The "Options" section enables users to specify the axes, with t1 (Primary EC) on the x-axis and t3 (IAQ) on the y-axis, and to categorize points by various parameters like cooling setpoints, window properties, or HVAC types (P25: HVAC systems). A histogram on the right side of the plot shows the distribution of the selected parameter (P25), with a color gradient indicating the frequency of values, helping users understand the range of parameter settings in the solutions. The "Markers" section allows for further customization, such as highlighting specific populations. This interface provides a comprehensive tool for analyzing optimization results, enabling users to explore trade-offs, identify optimal design solutions, and assess the impact of design parameters on building performance metrics like energy efficiency and occupant comfort.

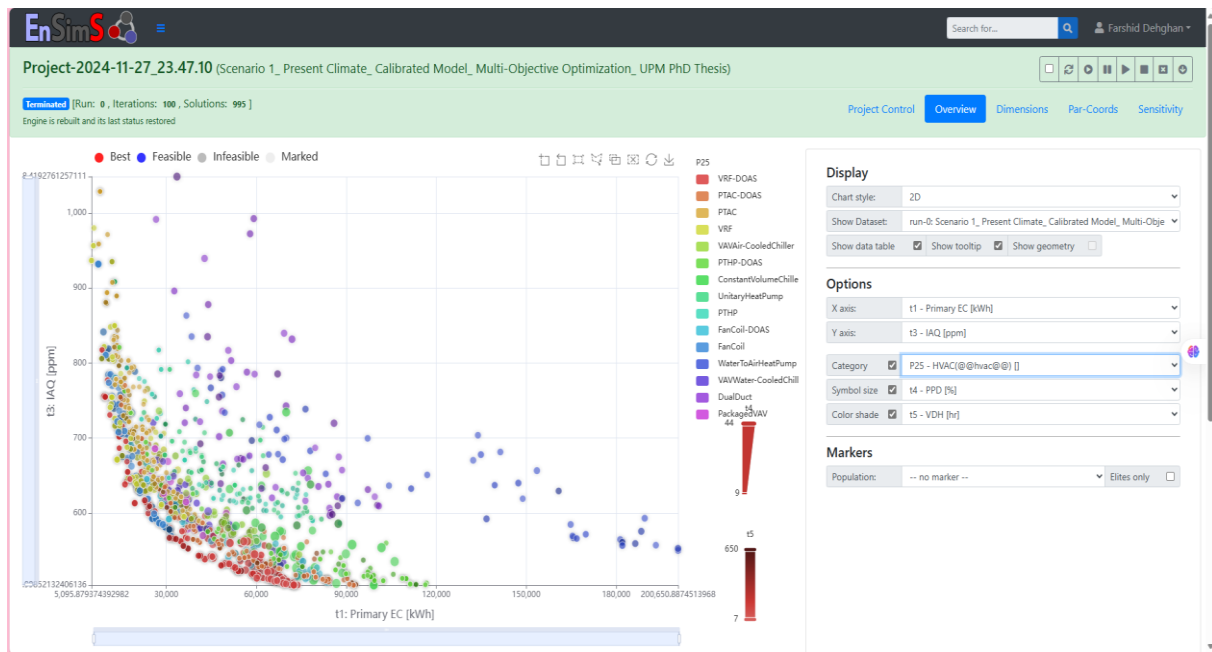


Figure 5-12: EnSimS Web Platform: Scatter Plot of Multi-Objective Optimization for Energy and IAQ in Scenario 1

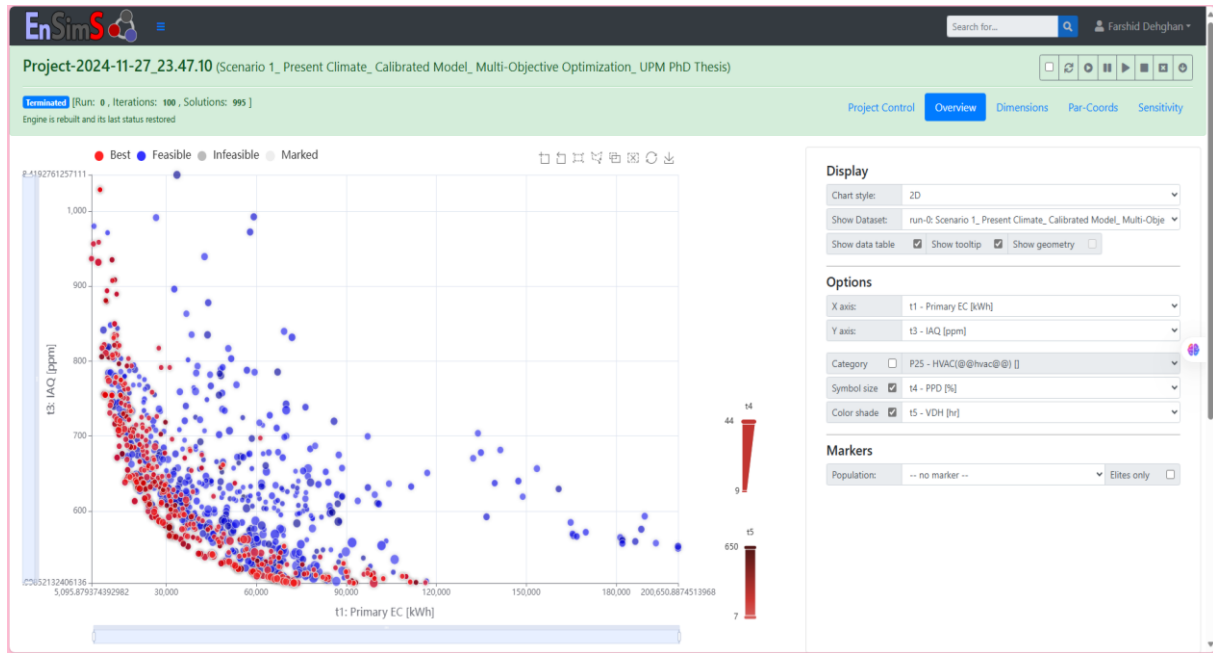


Figure 5-13: EnSimS Web Platform: Scatter Plot of Multi-Objective Optimization for Energy and IAQ in Scenario 1

Figure 5-14 captures a screenshot of the EnSimS web-based platform, displaying a scatter plot from a multi-objective optimization study within the project titled "Scenario 1: Present Climate, Calibrated Model, Multi-Objective Optimization, UPM PhD Thesis." The scatter plot illustrates the optimization results, with the x-axis labeled "t1: Primary EC (kWh)" (representing primary energy consumption) and the y-axis labeled "t4: PPD" (likely indicating ventilation-related discomfort hours or a similar metric). Each point on the plot represents a simulation scenario, color-coded to distinguish between categories: "Best" (purple), "Feasible" (red), "Infeasible" (blue), and "Marked" (green), with a total of 590 runs, 598 feasible solutions, and 995 iterations. The distribution of points, with a dense concentration near lower t1 values and a wider range of t4 values, highlights the trade-off between minimizing energy consumption and maintaining acceptable ventilation or comfort levels, forming a Pareto front that showcases optimal solutions balancing these objectives.

The right panel offers detailed customization options for the visualization. The "Display" section allows users to switch between 2D and 3D chart styles, select the dataset (run-6 in this case), and choose which solutions to display (feasible or best). The "Options" section enables axis selection, with t1 (Primary EC) on the x-axis and t4 (PPD) on the y-axis, and categorization by parameters such as cooling setpoints or window properties (P25: HVAC systems). A histogram on the right of the scatter plot shows the distribution of the selected parameter (P25), with a color

gradient indicating frequency, providing insight into the range of values tested for that parameter across solutions. The "Markers" section allows for further customization, such as highlighting specific populations. This interface facilitates a comprehensive analysis of optimization outcomes, helping users explore trade-offs, identify optimal design configurations, and evaluate the influence of design parameters on building performance metrics like energy efficiency and ventilation-related comfort.



Figure 5-14: EnSimS Web Platform: Scatter Plot of Multi-Objective Optimization for Energy and Comfort in Scenario 1

Figure 5-15 showcases a screenshot of the EnSimS web-based platform, presenting a 3D scatter plot from a multi-objective optimization study within the project titled "Scenario 1: Present Climate, Calibrated Model, Multi-Objective Optimization, UPM PhD Thesis." The 3D scatter plot visualizes the optimization results across three dimensions: the x-axis represents "t1: Primary EC (kWh)" (primary energy consumption), the y-axis shows "t2: CO<sub>2</sub>-eq (kg)" (carbon dioxide equivalent emissions), and the z-axis indicates "t3: IAQ (ppm)" (indoor air quality, likely measured as CO<sub>2</sub> concentration in parts per million). Each point in the plot corresponds to a simulation scenario, color-coded to differentiate between categories: "Best" (purple), "Feasible" (red), "Infeasible" (blue), and "Marked" (green), with a total of 590 runs, 598 feasible solutions, and 995 iterations. The spread of points illustrates the trade-offs among the three objectives, with a dense concentration of feasible solutions at lower values of energy consumption and CO<sub>2</sub>

emissions but varying IAQ levels, highlighting the challenge of balancing energy efficiency, environmental impact, and indoor air quality in building design.

The right panel provides customization options for the visualization. The "Display" section indicates that the chart style is set to 3D, with the dataset selected as "run-0," and users can choose to show specific solution types (e.g., feasible or best). The "Options" section allows users to define the axes, with t1 (Primary EC), t2 (CO<sub>2</sub>-eq), and t3 (IAQ) selected for the x, y, and z axes, respectively, and to categorize points by parameters such as heating setpoints (P1: HeatingSetpoint). The "Category" dropdown enables further analysis by color-coding points based on other parameters, with a color gradient indicating the range of values. The "Markers" section offers additional customization, such as highlighting specific populations. This 3D visualization tool enables users to explore the complex relationships between multiple objectives, identify optimal design solutions that balance energy use, emissions, and indoor air quality, and assess the impact of design parameters on overall building performance.

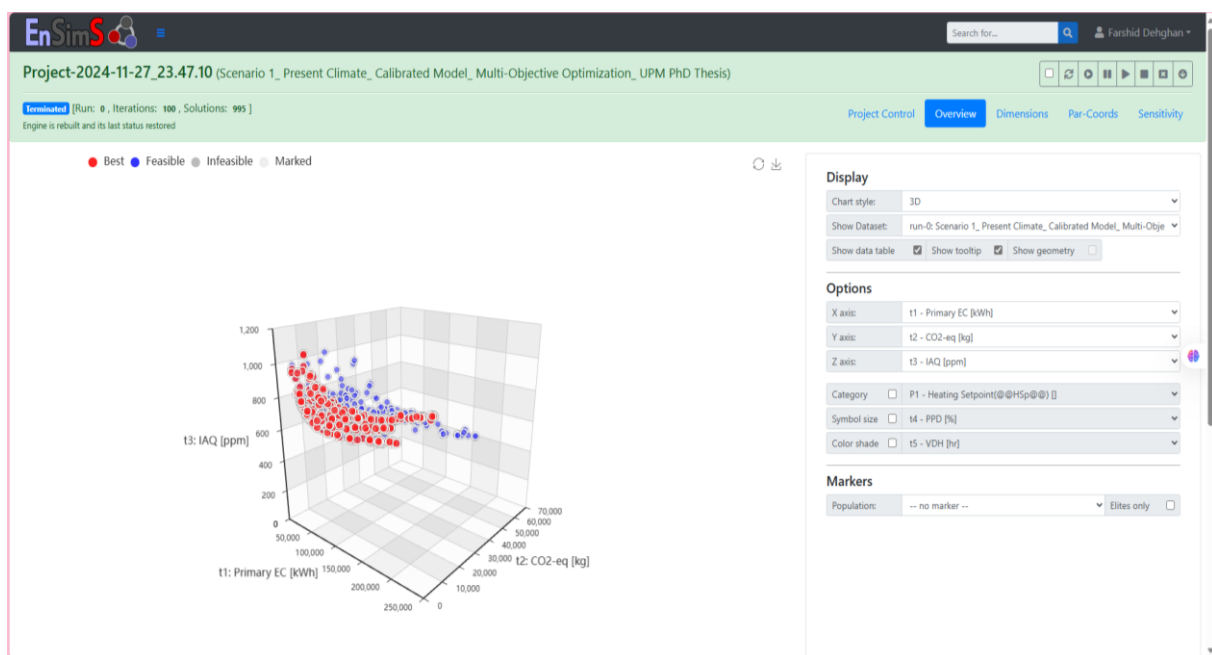


Figure 5-15: EnSimS Web Platform: 3D Scatter Plot of Multi-Objective Optimization for Energy, Emissions, and IAQ in Scenario 1

Figure 5-16 displays a screenshot of the EnSimS web-based platform, specifically within the "Dimensions" tab, as part of a project titled "Scenario 1: Present Climate, Calibrated Model, Multi-Objective Optimization, UPM PhD Thesis." The interface is divided into several sections to analyze the results of a multi-objective optimization study. On the left, the "Design records" section lists key design

variables and their selected values for the simulations, including the weather file (IR\_Sari\_City center\_Meteonorm 8.2.0.epw), the model (calibrated for the thesis), and various parameters such as heating setpoints (P1: ranging from 18 to 24°C). These variables, labeled P1 to P25, correspond to the design factors previously identified as significant, such as HVAC settings, insulation properties, and window constructions, which influence the objective functions.

The right side of the interface features two sets of visualizations: "Output metrics histograms" and "Output metrics boxplot." The histograms display the distribution of five output metrics across all simulation runs: "t1: Primary EC (kWh)" (primary energy consumption), "t2: CO<sub>2</sub>-eq (kg)" (carbon dioxide equivalent emissions), "t3: IAQ (ppm)" (indoor air quality), "t4: PPD (%)" (percentage of people dissatisfied, a thermal comfort metric), and "t5: VDH (hr)" (visual discomfort hours). For instance, the histogram for Primary EC shows a skewed distribution with most values clustered between 40,000 and 60,000 kWh, indicating that many solutions achieve relatively low energy consumption. Similarly, the PPD histogram shows a wide range of values, with a peak around 10–15%, reflecting variability in thermal comfort outcomes. The boxplot below summarizes the same metrics, showing the median, quartiles, and outliers for each output, providing a concise overview of the spread and central tendency of the results. These visualizations help users understand the range and distribution of performance metrics, assess the trade-offs between objectives, and identify solutions that best balance energy efficiency, environmental impact, indoor air quality, and occupant comfort.

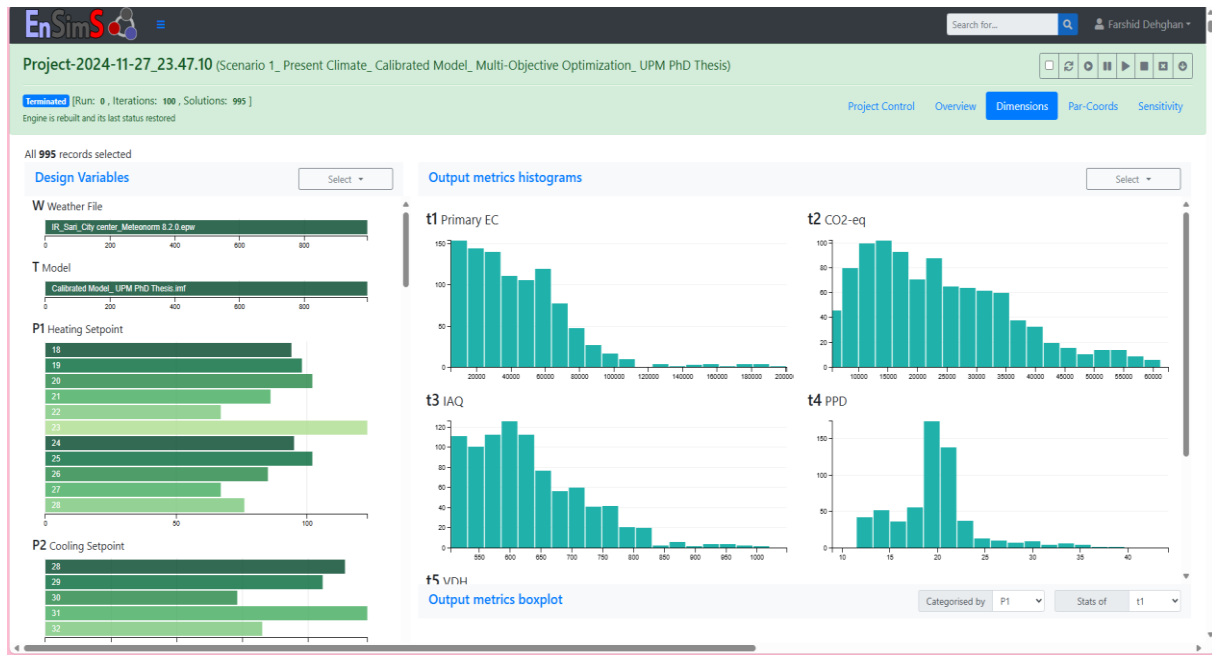


Figure 5-16: EnSimS Web Platform: Histogram and Boxplot Visualization of Multi-Objective Optimization Metrics in Scenario 1

JEA Web is the portal for managing parametric, optimisation and sensitivity analysis project. The JEA (jEPlus Energy Analytics) Web Portal serves as a sophisticated online platform designed for comprehensive management, execution, and analysis of parametric, optimization, and sensitivity analysis projects, particularly within the domain of energy modeling and building performance simulation. Developed as part of the ENSIMS Web Service ecosystem by Energy Simulation Solutions Limited, this portal integrates advanced computational tools to facilitate detailed investigations into the performance of building energy systems. It provides a robust framework for users to define, simulate, and evaluate a wide range of design parameters, optimizing energy efficiency and environmental impact metrics under varying conditions.

The portal supports parametric analysis by enabling users to systematically vary input parameters—such as building geometry, material properties, HVAC settings, and climatic conditions—across multiple scenarios, generating extensive datasets for comparative analysis. This capability is critical for understanding how different design choices influence energy consumption, indoor air quality (IAQ), and carbon emissions. Optimization functionalities leverage advanced algorithms, such as the Non-dominated Sorting Genetic Algorithm II (NSGA-II), to identify optimal trade-offs among multiple objectives (e.g., minimizing energy use while maximizing thermal comfort), even in complex, multi-dimensional solution spaces. Sensitivity analysis, a key feature of the JEA Web Portal, quantifies the impact of

uncertainties or variations in input parameters on model outputs, employing techniques such as variance-based methods or Monte Carlo simulations. This allows researchers and engineers to pinpoint the most influential factors affecting system performance, enhancing the robustness and reliability of the optimization process.

Accessible via a RESTful API, the JEA Web Portal offers a scalable and user-friendly interface, supporting full project data management, including exploration histories and detailed solution datasets in JSON format. It incorporates parallel computing capabilities to handle computationally intensive tasks efficiently, making it suitable for large-scale parametric studies and real-time analytics. This platform is particularly valuable in academic and industrial contexts, such as the optimization of building designs under Scenario 1 (present climate conditions) as outlined in my thesis, providing a data-driven foundation for developing sustainable energy strategies within feasible computational constraints.

### 5.3. Evaluation and selection

The optimization process generates a wide array of outcomes, with each point along the Pareto front representing an optimal trade-off solution among energy consumption, CO<sub>2</sub> emissions, indoor air quality (IAQ), and comfort. To determine the most appropriate solution from the set of Pareto front points, this study adopts the weighted sum method as a structured decision-making framework, enabling a systematic evaluation of the competing objectives based on their prioritized importance.

The weighted sum method involves assigning specific weights to each objective criterion, reflecting their relative significance in the decision-making process as determined by stakeholder priorities or project goals. These weights are then used to compute a composite score for each solution, facilitating the comparison and ranking of alternatives. The overall score for each solution is derived using the following equation:

$$f_{ws}(x) = \sum_{i=1}^5 a_i \frac{f_i(x) - f_i(x)^{min}}{f_i(x)^{max} - f_i(x)^{min}} \quad (10)$$

The use of the weighted sum method allows for a structured decision-making process that considers the varied priorities of stakeholders. By selecting the most suitable solution from the Pareto front points, this study aims to guide the

implementation of effective and sustainable HVAC retrofits while balancing energy efficiency, emissions, and user satisfaction.

## 5.4. Scenarios

Two scenarios are examined concerning future climate change. The first scenario assesses the case study under current climate conditions, while the second scenario considers the potential impacts of climate change.

According to Figure 5-17 To assess the long-term energy performance and greenhouse gas emissions of the studied residential unit (79.35 m<sup>2</sup>, Sari, Iran, ASHRAE Zone 3A), future-oriented weather data were generated using CCWorldWeatherGen version 1.9, a robust tool developed by Jentsch et al. [43]. This software leverages the Hadley Centre Coupled Model version 3 (HadCM3), a well-established global climate model, to produce EnergyPlus Weather (EPW) and Typical Meteorological Year 2 (TMY2) files tailored to the A2 emission scenario (medium-high). The A2 scenario, as defined by the Intergovernmental Panel on Climate Change (IPCC), assumes heterogeneous global development with moderate technological advancements and high population growth, leading to elevated greenhouse gas emissions by the late 21st century.

According to Figure 5-17, the generated weather files enabled the simulation of building energy consumption and associated carbon emissions for two future time horizons: 2050 and 2080. These projections are critical for evaluating the resilience of sustainable building designs under climate change impacts, such as rising temperatures and shifting precipitation patterns in ASHRAE Zone 3A. The HadCM3 model provides high-resolution climate projections, incorporating variables such as temperature, humidity, solar radiation, and wind speed, which are essential inputs for EnergyPlus simulations conducted in this study. By integrating these weather files with the design scenarios, the study quantifies the impact of climate-driven changes on energy demand, CO<sub>2</sub> emissions, and occupant comfort metrics (e.g., IAQ, PPD, VDH), aligning with the multi-objective optimization framework.

To ensure methodological rigor, the weather data generation process followed established protocols, with the A2 scenario selected to reflect a plausible yet challenging future for sustainable building design in Iran. The use of CCWorldWeatherGen enhances the reproducibility of the simulations, as the software is publicly available and widely validated in building performance

studies. Limitations of this approach, such as uncertainties in long-term climate projections and the reliance on a single emission scenario, are acknowledged in the discussion (Section 5.3) and will be addressed in future work through sensitivity analyses with alternative scenarios (e.g., A1B, B1) or ensemble climate models.

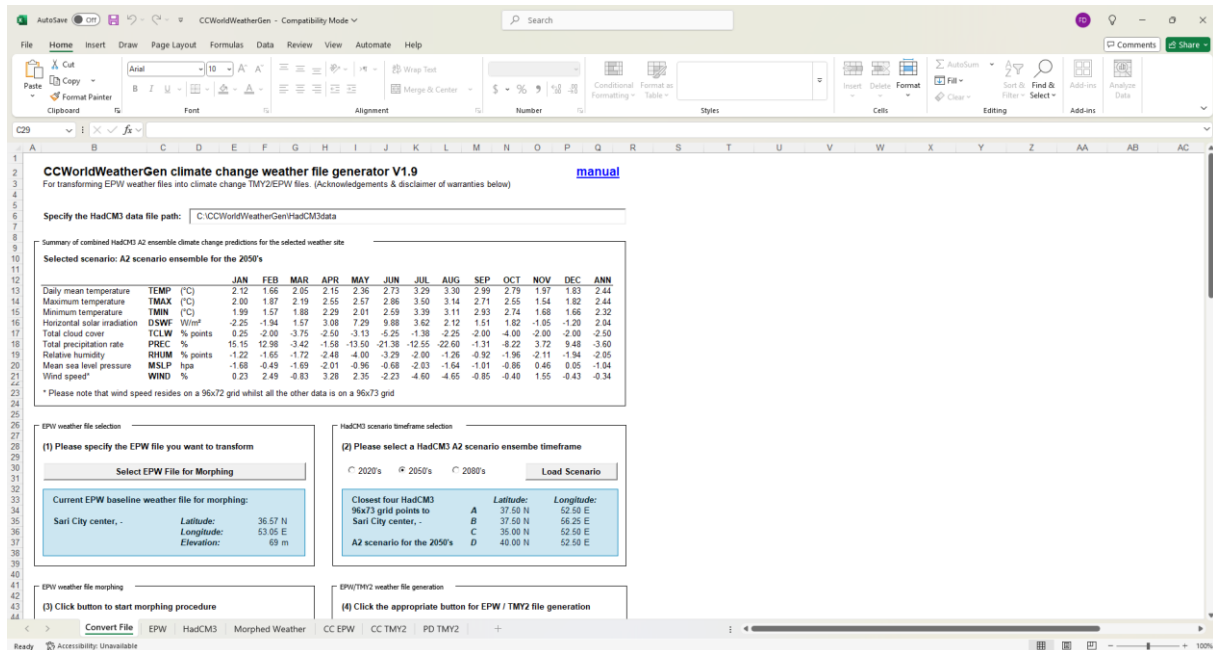


Figure 5-17: CCWorldWeatherGen climate change weather file generator V1.9 software space

### 5.4.1. Scenario 1: present climate condition

In this scenario, the building performance is assessed under current climate conditions using data from the Meteoronorm 8.2.0.epw file for Sari City. The analysis explores various configurations of building materials, insulation types, and mechanical systems to evaluate their impacts on energy efficiency, CO<sub>2</sub> equivalent emissions, indoor environmental quality, and thermal comfort.

Figure 5-18 presents the Pareto front for Scenario 1 under present climate conditions, offering a detailed visualization of the intricate interplay among Indoor Air Quality (IAQ), Primary Energy Consumption (EC), and CO<sub>2</sub> Emissions through a 3D scatter plot. The plot uses red and blue points to represent different simulation solutions, with red points highlighting the most optimal combinations that effectively balance these three critical factors. A clear trade-off emerges from the analysis: higher IAQ levels are generally associated with increased energy consumption and CO<sub>2</sub> emissions, underscoring the challenge of enhancing air quality without significantly elevating energy use and environmental impact.

However, the flattening of the Pareto curve indicates diminishing returns beyond a certain threshold of IAQ improvement, where further enhancements result in only marginal gains in performance relative to the substantial increases in energy and emissions, suggesting that excessive focus on IAQ may not be cost-effective or sustainable.

This analysis has significant implications for stakeholders aiming to achieve sustainable building performance while ensuring occupant well-being. It highlights the importance of adopting a balanced approach that carefully navigates the trade-offs between IAQ, energy efficiency, and emissions. By identifying optimal configurations and technologies along the Pareto front, stakeholders can implement retrofit strategies that deliver meaningful improvements in indoor environmental quality without disproportionately compromising energy performance or increasing CO<sub>2</sub> emissions. This strategic balance is crucial for meeting sustainability goals, reducing environmental impact, and enhancing occupant comfort, thereby supporting informed decision-making in building design and energy management.

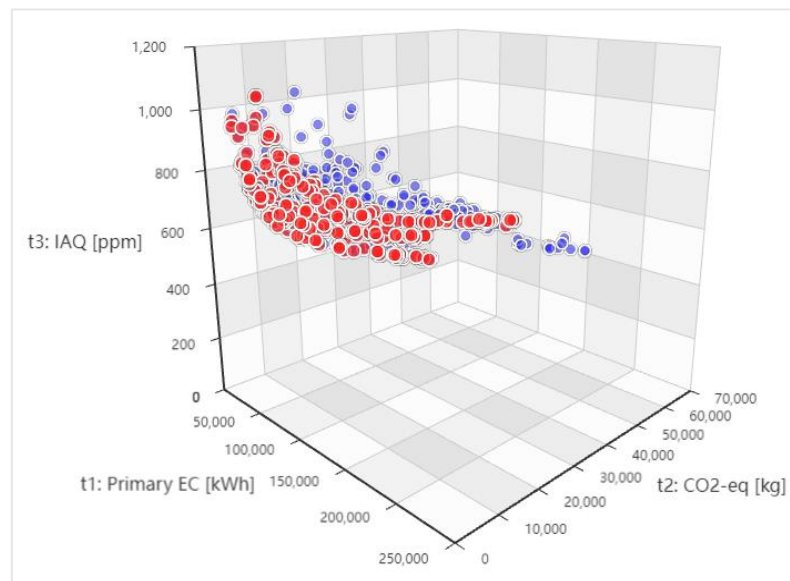


Figure 5-18: Pareto front of Scenario 1—present climate condition

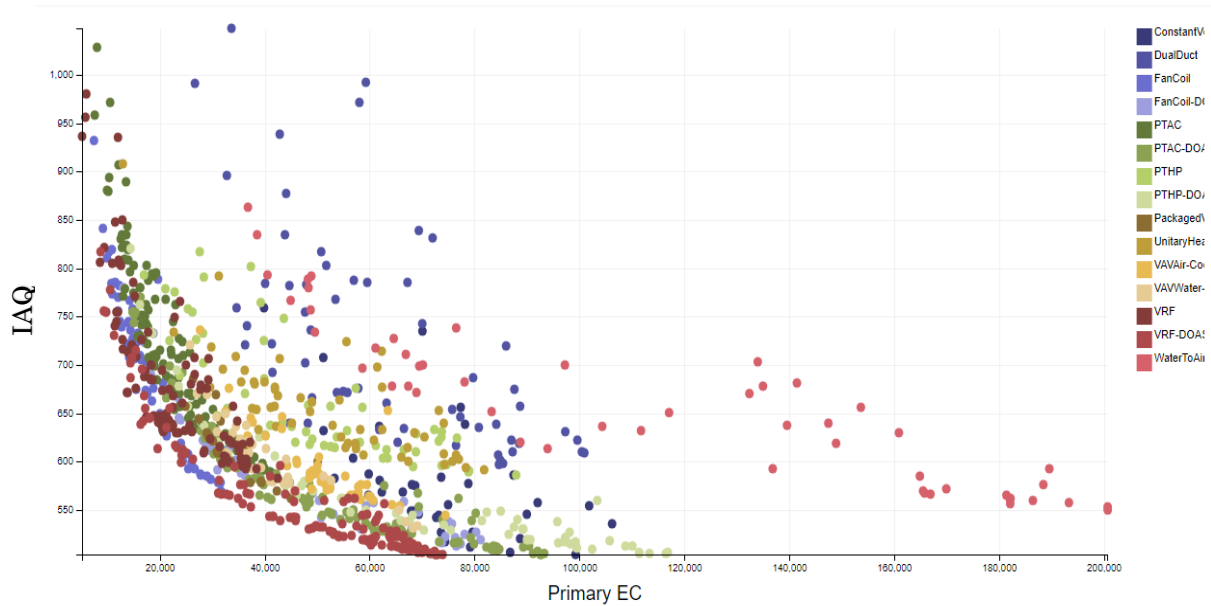


Figure 5-19: Scatter with categories of primary energy consumption and IAQ

According to Figure 5-19, the analysis of HVAC systems focuses on the relationship between primary energy consumption (EC) and indoor air quality (IAQ), as represented in the scatter plot.

- X-Axis: The horizontal axis represents primary energy consumption, ranging from approximately 20,000 kWh to 200,000 kWh.
- Y-Axis: The vertical axis measures indoor air quality in parts per million (ppm), expected to vary from below 500 ppm to around 1000 ppm or higher, with the optimal IAQ range indicated as being between 500 and 700 ppm.

The analysis highlights the critical role of HVAC system design in achieving a delicate balance between energy consumption and optimal Indoor Air Quality (IAQ) performance, a key determinant of occupant satisfaction and building efficiency. Systems that successfully maintain IAQ within the recommended range of 500–700 ppm significantly enhance user comfort, as evidenced by improved occupant feedback and compliance with health standards. Conversely, HVAC systems that consume excessive energy without delivering acceptable IAQ levels—potentially exceeding 700 ppm—demonstrate inefficiencies that may lead to user dissatisfaction and necessitate redesign or optimization. A deeper understanding of the energy-IAQ relationship is pivotal for informing market trends and guiding manufacturers toward developing advanced technologies that integrate energy efficiency with superior air quality. This synergy is essential for addressing the

dual challenges of sustainability and occupant well-being, particularly in the context of evolving building performance expectations.

The scatter plot analysis reveals a strong correlation between primary energy consumption and IAQ, underscoring that maintaining IAQ levels between 500 and 700 ppm is crucial for optimal system performance. HVAC configurations such as Fan Coil, Packaged Terminal Heat Pump (PTHP), PTHP with Dedicated Outdoor Air System (DOAS), Variable Refrigerant Flow (VRF), and VRF-DOAS demonstrate superior performance by achieving this IAQ range while minimizing energy use, thus offering a benchmark for efficient design. For stakeholders, the recommendation is to prioritize these technologies, focusing on solutions that reduce operational energy costs while ensuring high IAQ to meet stringent health and environmental standards. By investing in HVAC systems that optimize both energy efficiency and air quality, stakeholders can significantly enhance overall building performance, ensuring compliance with regulatory expectations and fostering sustainable, occupant-centric environments that align with current global sustainability goals.

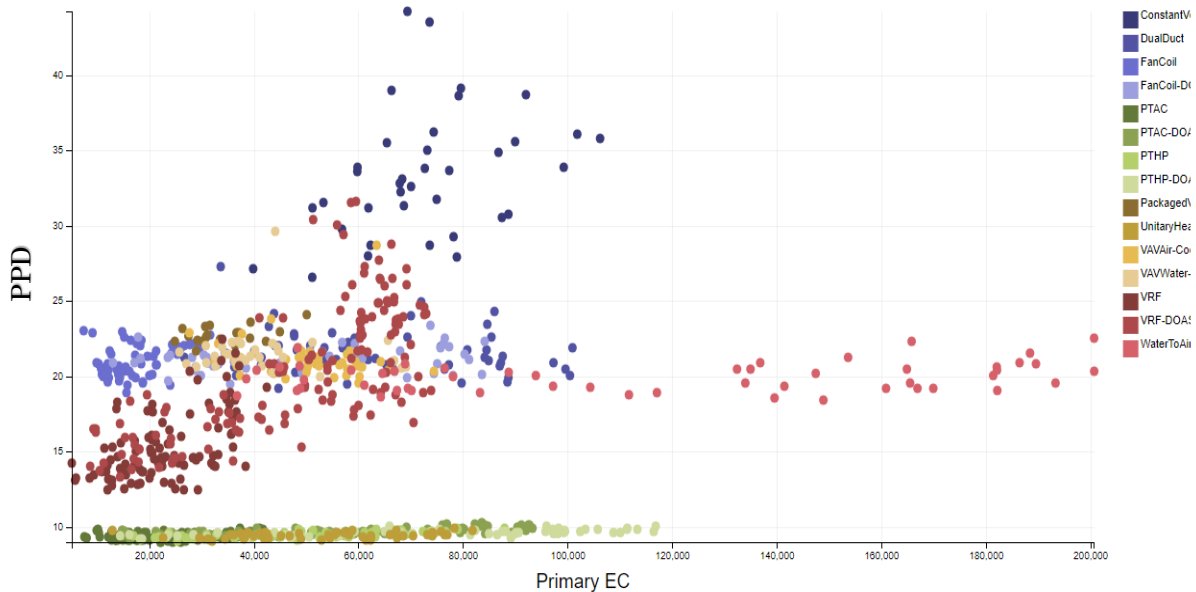


Figure 5-20: Scatter with categories of primary energy consumption and PPD

Based on Figure 5-20, the scatter plot provides an insightful analysis of various HVAC systems regarding their primary energy consumption (EC) and the predicted percentage of dissatisfaction (PPD) among users.

- X-Axis: Represents primary energy consumption of the HVAC systems, ranging roughly from 20,000 to 200,000 kWh.

- Y-Axis: Indicates the predicted percentage of dissatisfaction among users due to system performance, where higher values reflect greater predicted dissatisfaction.

The plot illustrates the relationship between primary energy consumption (in kWh) and predicted dissatisfaction percentages across different HVAC systems. Color coding distinguishes between system types, highlighting performance trends. Notably, systems such as Packaged Terminal Air Conditioner (PTAC), Unitary Heat Pump, and Packaged Terminal Heat Pump with Dedicated Outdoor Air System (PTHP-DOAS) show up in the lower energy consumption range while corresponding to low dissatisfaction rates, indicating satisfactory user performance. This analysis reveals that increased energy consumption does not inherently guarantee greater user satisfaction. Therefore, it's crucial for stakeholders to prioritize systems that efficiently utilize energy while also maintaining low levels of predicted dissatisfaction. Understanding these dissatisfaction levels enables more informed selections of HVAC systems that align better with user needs. Moreover, focusing on high-energy consumption systems that exhibit high predicted dissatisfaction may uncover opportunities for redesign or technological advancements. This insight underscores the notion that higher energy consumption is not synonymous with lower dissatisfaction, emphasizing the necessity of achieving a balance between performance and energy efficiency. Future research should aim to identify specific characteristics of HVAC systems that effectively reduce predicted dissatisfaction, enhancing design and operational strategies. Understanding these attributes could lead to improved user satisfaction and more sustainable HVAC solutions.

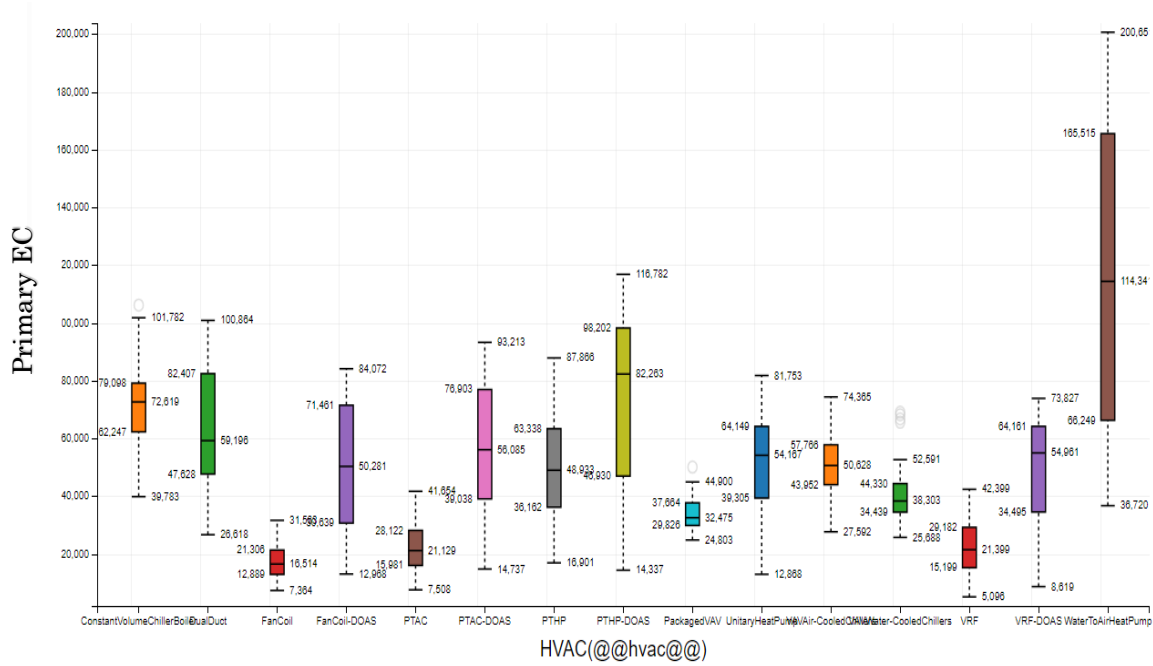


Figure 5-21: Output metrics boxplot of HVAC systems

Referring to Figure 5-21, the boxplot effectively illustrates the primary energy consumption associated with different HVAC systems. The variations in energy usage highlight the importance of selecting systems that meet energy consumption objectives, efficiency benchmarks, and overall operational costs. Systems such as Variable Refrigerant Flow (VRF), Fan Coil, Packaged Terminal Heat Pump (PTHP), and Packaged Terminal Air Conditioner (PTAC) demonstrate comparatively lower energy consumption, generally ranging from approximately 15,000 to 25,000 kWh. These options may be regarded as more efficient choices in terms of energy use and emissions, making them especially suitable for environmentally conscious projects. This analysis underscores the need for decision-makers to prioritize HVAC systems that not only align with energy efficiency standards but also contribute positively to sustainability goals, fostering an eco-friendlier approach to building management.

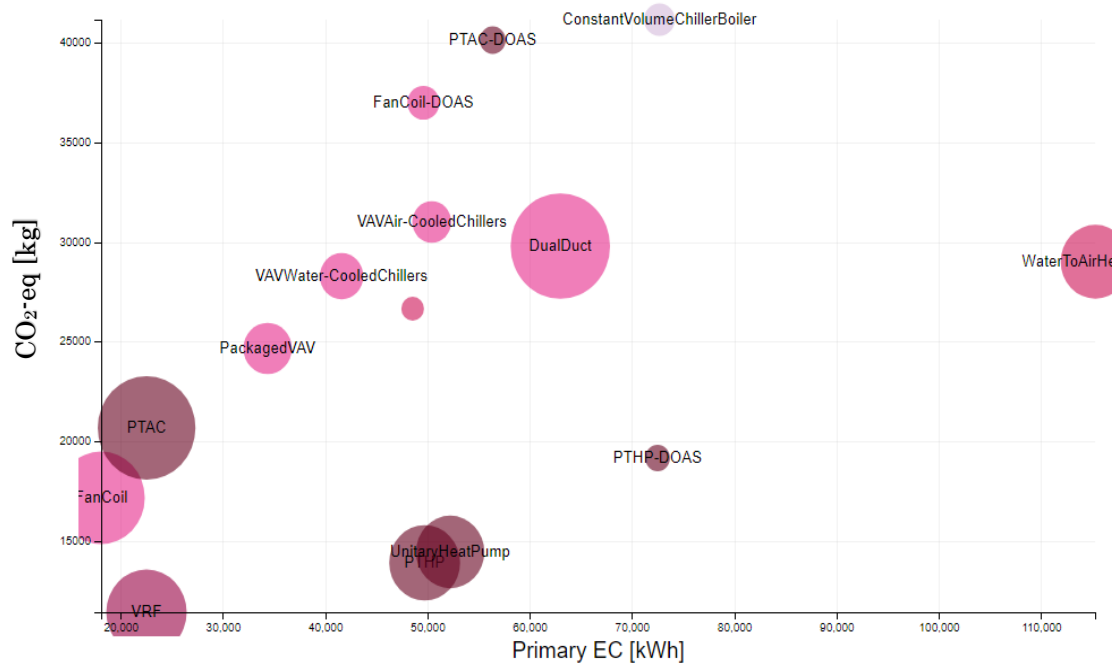


Figure 5-22: Bubble chart of HVAC systems

Figure 5-22 presents a bubble chart that offers a comprehensive view of how various HVAC systems perform concerning their energy consumption and associated CO<sub>2</sub> emissions. This visualization helps identify systems that strike the best balance between these two factors, guiding decisions toward more efficient and environmentally friendly HVAC solutions. The analysis reveals that systems like Variable Refrigerant Flow (VRF), Fan Coil, and Packaged Terminal Air Conditioner (PTAC) exhibit lower energy consumption, typically ranging from 15,000 to 25,000 kWh, along with lower CO<sub>2</sub> emissions. These systems can be considered more efficient choices for both energy use and emissions, making them potentially more favorable for implementation in eco-conscious projects. Further analysis could delve into the economic aspects and operational efficiencies associated with these systems, helping stakeholders evaluate their overall viability not only from an environmental standpoint but also in terms of cost-effectiveness and long-term benefits. This approach would support informed decision-making in the selection of HVAC systems that align with sustainability goals.

Figure 5-23 presents a comprehensive visualization through parallel coordinates, illustrating the intricate relationships among various parameters (P1 to P25) and performance metrics.

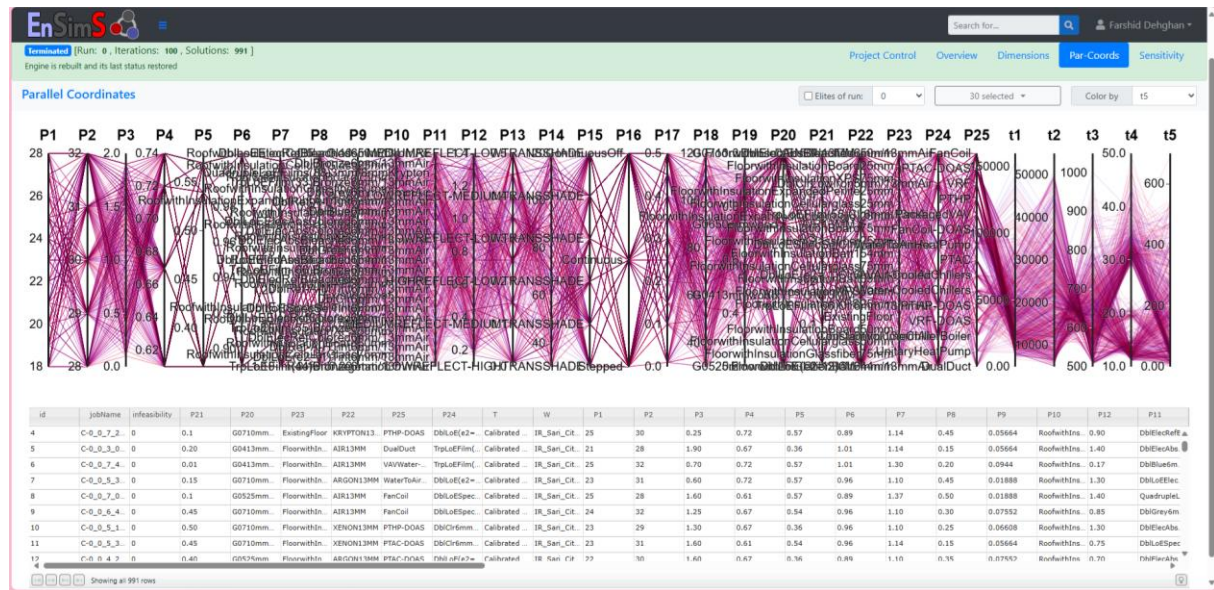


Figure 5-23: All parallel coordinates

Figure 5-24 showcases the selected energy retrofit measures (ERMs) for optimal solutions under Scenario 1, which reflects current climate conditions. The parallel coordinates visualization highlights how each ERM interacts with key performance indicators represented on the axes from P1 to P25. The purple lines in the plot indicate the best solutions among the available options, revealing significant fluctuations and demonstrating the varying effectiveness of each ERM. This visualization helps to identify which measures excel in specific performance metrics and underscores the complexities involved in implementing effective energy retrofits. By analyzing these interactions, stakeholders can make informed decisions about which ERMs to prioritize for enhancing overall building performance while addressing energy efficiency and sustainability goals.

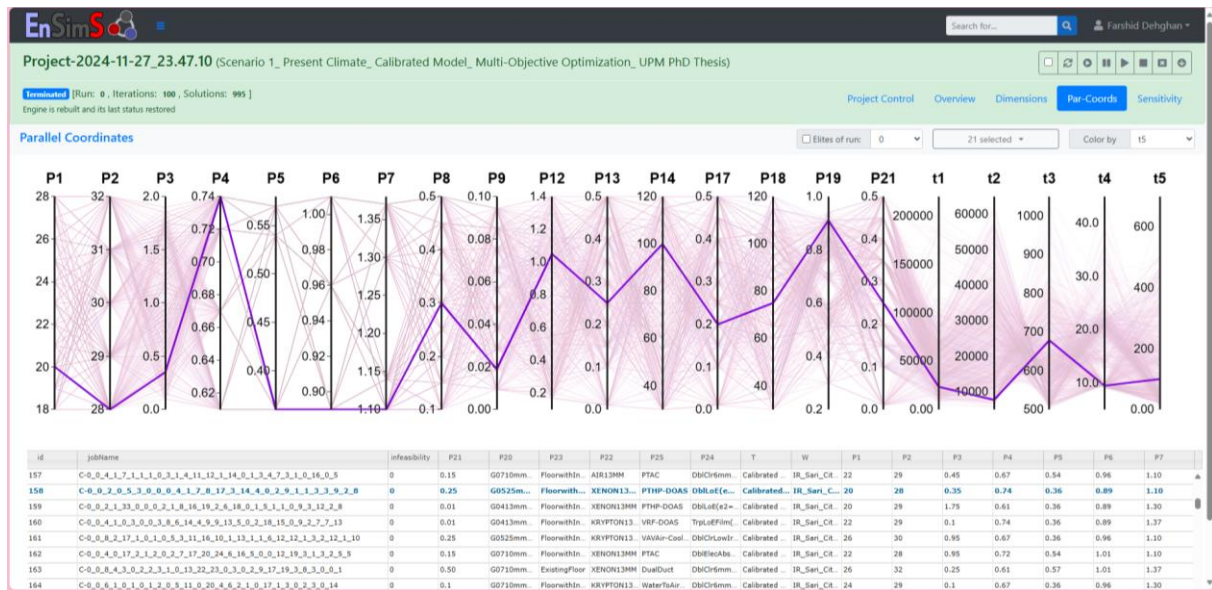


Figure 5-24: Selected ERM for optimal solutions of Scenario 1—present climate

Figure 5-25 depicts the distribution of HVAC systems in the Pareto front for the first scenario. The pie chart reveals that the Variable Refrigerant Flow with Dedicated Outdoor Air System (VRF-DOAS) dominates with 24%, followed closely by both Packaged Terminal Air Conditioner (PTAC) and PTAC-DOAS, each comprising 19%. Other notable systems include Packaged Terminal Heat Pump with Dedicated Outdoor Air System (PTHP-DOAS) at 12% and VRF at 14%. In contrast, systems such as Constant Volume Chiller Boiler, Unitary Heat Pump, and Packaged VAV show minimal representation, with proportions of 0%, 3%, and 1%, respectively. This distribution highlights a clear preference for versatile and efficient systems, emphasizing their critical role in achieving energy efficiency and sustainability objectives in the current climate conditions. The dominance of VRF-DOAS reflects its effectiveness in optimizing indoor climate control while minimizing energy consumption, indicating a trend towards adopting technologies that balance performance and sustainability in HVAC design. This preference is essential for guiding future investment and development in efficient HVAC solutions.

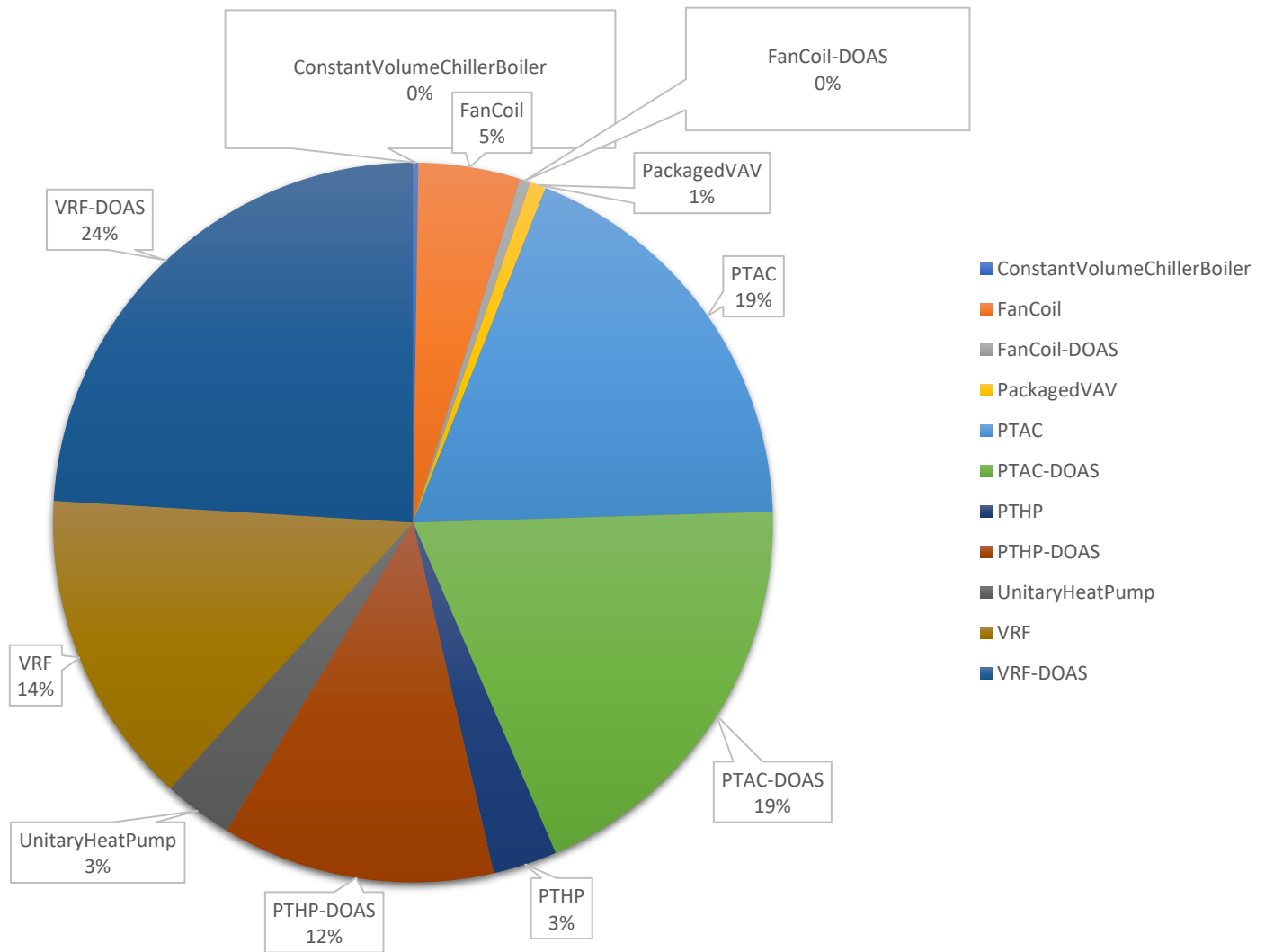


Figure 5-25: The distribution of HVAC systems in the Pareto front in the Scenario 1—present climate

## 5.4.2. Scenario 2: considering climate change for the mid and late century (2050 and 2080)

### 5.4.2.1. Scenario 2: considering climate change (2050)

In this scenario, the building performance is evaluated under projected climate conditions for the year 2050, considering anticipated changes in temperature, humidity, and other environmental factors resulting from climate change. The primary goal of this analysis is to understand how these changes will impact energy consumption, indoor air quality, thermal comfort, and overall building performance. To achieve this, updated meteorological data, such as those from the Meteonorm 8.2.0.epw file, is utilized. This data incorporates expected increases in average temperatures and variations in precipitation patterns, which are critical

for accurately simulating future energy demands and assessing thermal comfort levels within the building. By leveraging this comprehensive set of data, the analysis aims to provide insights into how emerging climate realities will influence the efficacy of HVAC systems and overall sustainability efforts in building designs. This detailed evaluation not only helps in understanding current vulnerabilities but also aids in developing adaptive strategies that enhance resilience to future climate conditions, ultimately contributing to improved energy efficiency and occupant comfort. Increased cooling loads: As temperatures rise, the demand for cooling is expected to increase significantly. Simulations indicate that buildings may require up to 20–30% more energy for cooling compared to present conditions. This necessitates a re-evaluation of HVAC systems to ensure they can handle the increased loads efficiently. The second scenario highlights the significant challenges posed by climate change on building performance by 2050. It emphasizes the need for proactive measures in design and retrofitting to ensure energy efficiency and occupant comfort in a changing climate. By focusing on advanced materials, innovative HVAC solutions, and effective shading strategies, buildings can be better equipped to handle the impacts of climate change while promoting sustainability and resilience. Further research and simulation will be essential to refine these strategies and adapt to future conditions effectively.

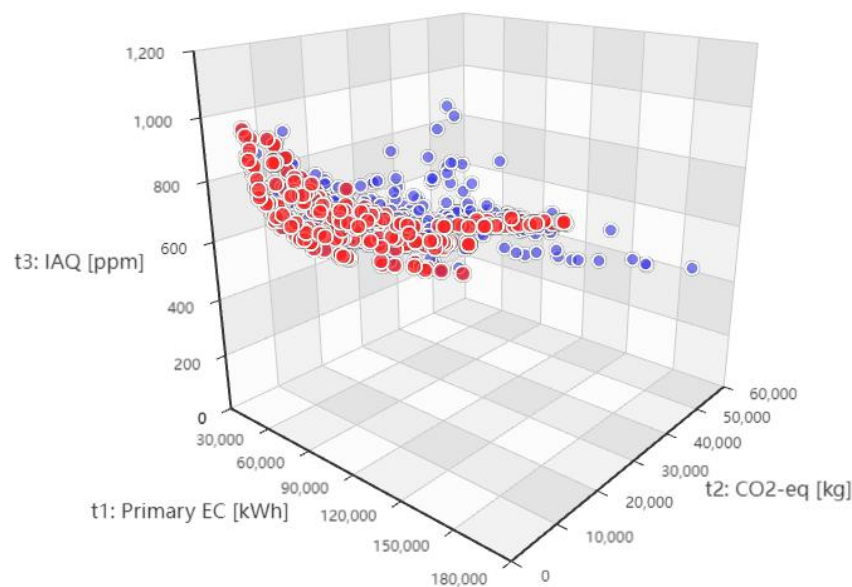


Figure 5-26: Pareto front of Scenario 2—climate change (2050)

Figure 5-26 presents the Pareto front for Scenario 2, reflecting the impact of the analysis of climate change in 2050 is visually represented in a 3D plot that illustrates the balance between indoor air quality (IAQ), primary energy

consumption (EC), and CO<sub>2</sub> emissions. The red points in the plot indicate optimal solutions, clearly demonstrating a trade-off: as improvements in IAQ are achieved, both energy consumption and CO<sub>2</sub> emissions tend to increase. As the number of selected solutions moves towards the upper left area of the graph, it becomes evident that achieving high indoor air quality may require higher energy use, complicating sustainability efforts. The distribution of the points reveals a shift in performance metrics due to climate change, highlighting the urgent need for innovative strategies that enhance energy efficiency while still maintaining satisfactory indoor conditions. This analysis underscores the challenges of navigating environmental impacts while optimizing HVAC systems in future scenarios. It signals the importance of developing solutions that can address air quality needs without disproportionately increasing energy demand and emissions, thereby supporting broader sustainability goals in the face of changing climate conditions.

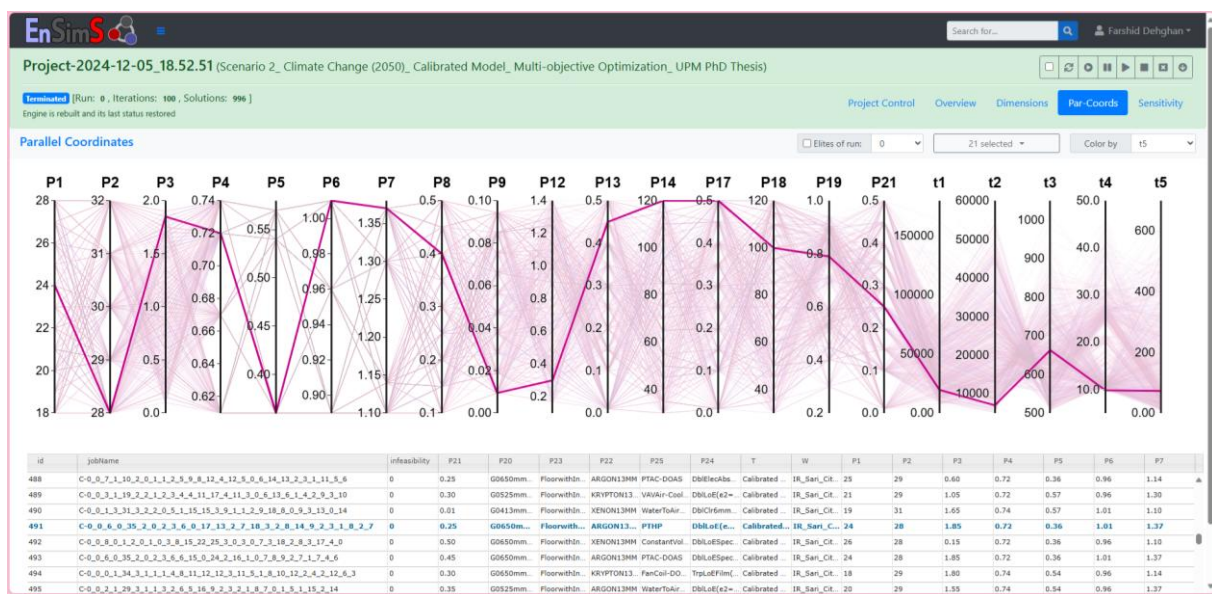


Figure 5-27: Selected ERM for optimal solutions of Scenario 2—climate change (2050)

Figure 5-27 illustrates the selected energy retrofit measures (ERMs) for optimal solutions in Scenario 2, which focuses on the effects of climate change in 2050. The parallel coordinates plot highlights how each ERM correlates with key performance indicators, represented from P1 to P25. The magenta lines signify the best performing solutions, revealing significant variations across different measures. Specific ERM, such as Packaged Terminal Air Conditioner (PTAC) and Variable Refrigerant Flow with Dedicated Outdoor Air System (VRF-DOAS), demonstrate marked effectiveness in achieving desired outcomes, while

others contribute less optimally. The clustering of lines indicates that certain combinations of ERM's yield better performance regarding energy consumption and indoor air quality, underscoring the complexities involved in retrofitting for climate resilience. This analysis emphasizes the importance of selecting optimal ERM's to address the challenges posed by climate change while enhancing energy efficiency and environmental sustainability. By carefully evaluating the interactions between different measures and their overall impact, stakeholders can make informed decisions that align with both environmental goals and user comfort.

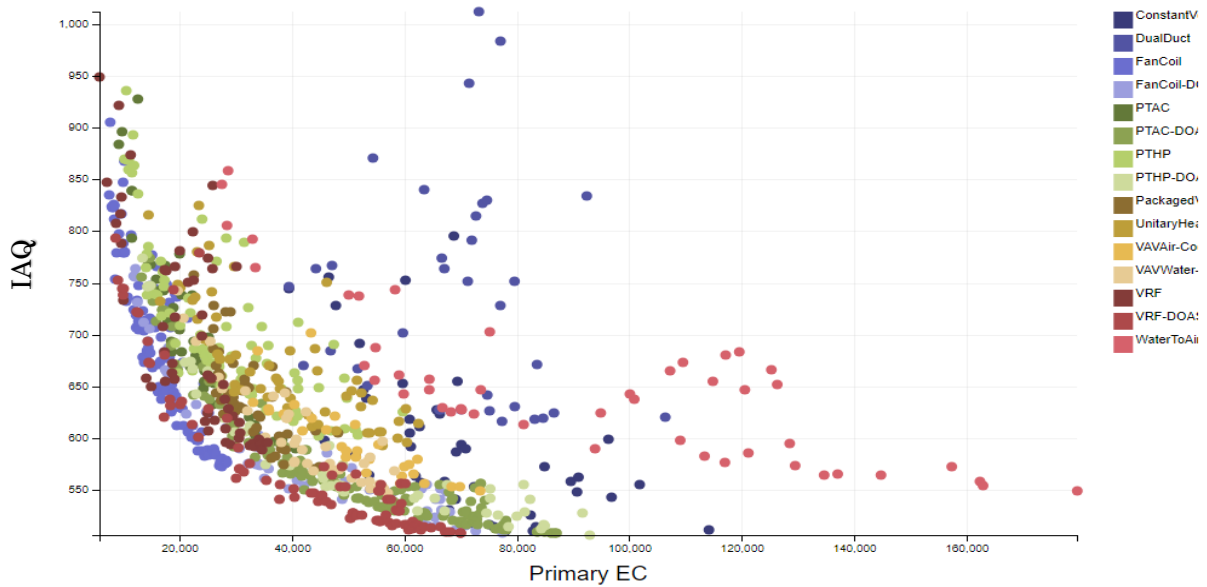


Figure 5-28: Scatter with categories of primary energy consumption and IAQ

As indicated by Figure 5-28, the X-axis represents primary energy consumption, ranging from approximately 20,000 kWh to 200,000 kWh. The Y-axis measures indoor air quality (IAQ), expected to range from below 500 ppm to around 1,000 ppm or higher, with an optimal IAQ range of 500 to 700 ppm. This analysis emphasizes the critical need for HVAC systems that effectively balance energy consumption with optimal IAQ performance. Systems that maintain IAQ within the ideal range enhance user satisfaction, while those with high energy consumption and poor IAQ may require redesign or optimization. Understanding the relationship between energy consumption and IAQ is vital for guiding market trends and helping manufacturers prioritize both efficiency and air quality. The scatter plot reveals a clear correlation between primary energy consumption and IAQ, underscoring that maintaining IAQ levels between 500 and 700 ppm is essential for optimal performance. Systems such as Fan Coil, Fan Coil-

DOAS, Packaged Terminal Air Conditioner (PTAC), PTAC-DOAS, Variable Refrigerant Flow (VRF), and VRF-DOAS effectively achieve this balance while exhibiting lower energy consumption. Stakeholders should prioritize technologies that reduce energy costs while ensuring high indoor air quality, ultimately leading to greater user satisfaction and adherence to health standards. This focus on efficiency and air quality can drive the future development of HVAC systems in alignment with user needs and environmental goals.

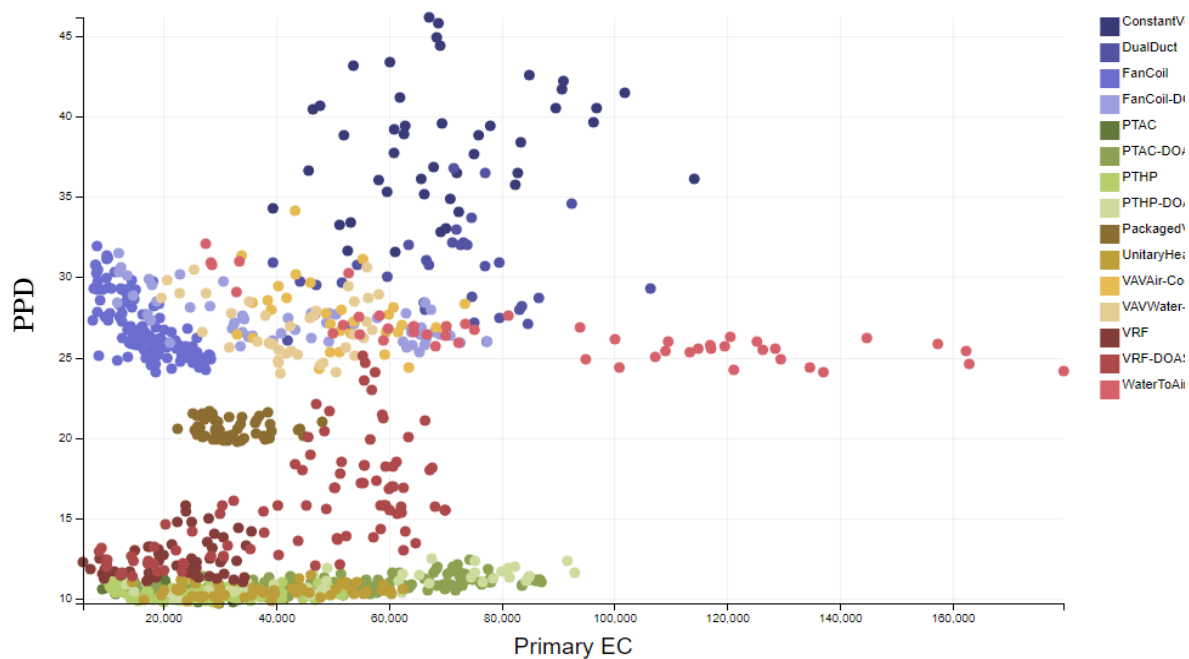


Figure 5-29: Scatter with categories of primary energy consumption and PPD

As illustrated in Figure 5-29, the X-axis represents the primary energy consumption (EC) of HVAC systems, ranging from approximately 20,000 to 200,000 kWh. The Y-axis indicates the predicted percentage of user dissatisfaction (PPD) due to system performance, where higher values reflect greater dissatisfaction. The scatter plot demonstrates the relationship between primary energy consumption in kilowatt-hours and the predicted percentage of dissatisfaction across various HVAC systems, using color coding to distinguish different system types and highlight performance trends. Notably, systems such as Packaged Terminal Air Conditioner (PTAC), PTAC-DOAS, Packaged Terminal Heat Pump (PTHP), PTHP-DOAS, Unitary Heat Pump, and Variable Refrigerant Flow (VRF) fall within the lower energy consumption range while corresponding to low dissatisfaction rates, indicating satisfactory user performance. This plot illustrates that increased energy consumption does not guarantee greater user satisfaction, underscoring the necessity to prioritize systems that utilize energy

efficiently while maintaining low predicted dissatisfaction. By understanding these dissatisfaction levels, stakeholders can make informed choices about HVAC systems that better align with user needs. Additionally, examining high-energy consumption systems that also exhibit high predicted dissatisfaction can reveal opportunities for redesigning or technological advancements. This analysis highlights that higher energy consumption does not necessarily equate to lower dissatisfaction, emphasizing the importance of balancing performance and energy efficiency. Future research should focus on identifying specific characteristics of systems that effectively minimize predicted dissatisfaction, thereby enhancing design and operational strategies in HVAC solutions.

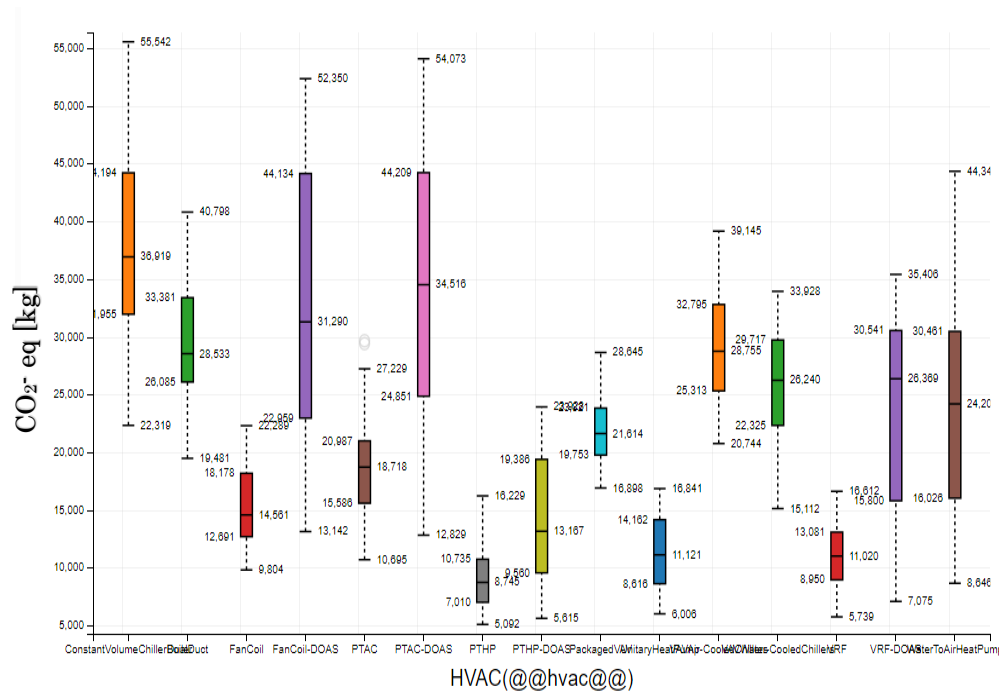


Figure 5-30: Output metrics boxplot of HVAC systems

In accordance with Figure 5-30, the boxplot effectively illustrates the CO<sub>2</sub>-equivalent emissions associated with different HVAC systems. Systems such as Packaged Terminal Heat Pump (PTHP), Unitary Heat Pump, Variable Refrigerant Flow (VRF), and Packaged Terminal Air Conditioner (PTAC) exhibit relatively lower CO<sub>2</sub>-equivalent emissions, ranging from approximately 5,000 to 15,000 kg. These options can be regarded as more efficient choices in terms of energy use and emissions, making them particularly suitable for environmentally conscious projects. This analysis emphasizes the importance of selecting HVAC systems that minimize environmental impact while maintaining functionality and performance.

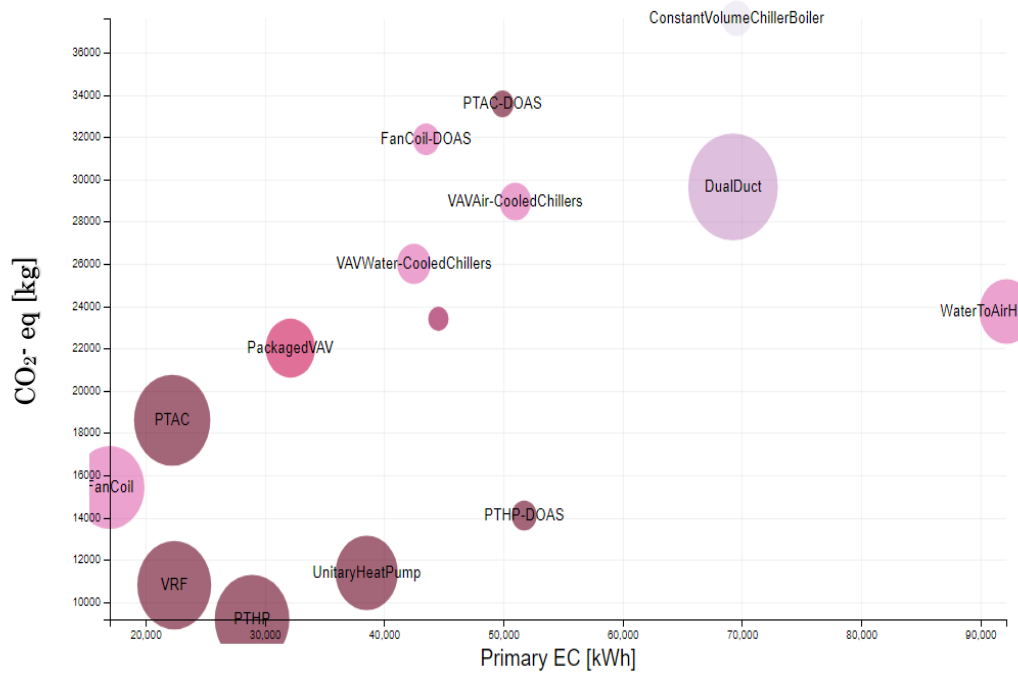


Figure 5-31: Bubble chart of HVAC systems related to Scenario 2 (2050)

Figure 5-31 presents a bubble chart that offers a comprehensive overview of the performance of various HVAC systems in terms of energy consumption and associated CO<sub>2</sub> emissions. By identifying systems that achieve the best balance between these two factors, we can make more informed decisions regarding efficient and environmentally friendly HVAC solutions. Further analysis could delve into the economic aspects and operational efficiencies associated with these systems. Systems such as Variable Refrigerant Flow (VRF), Fan Coil, Packaged Terminal Heat Pump (PTHP), and Packaged Terminal Air Conditioner (PTAC) demonstrate lower energy consumption, typically ranging from 10,000 to 30,000 kWh, along with correspondingly lower CO<sub>2</sub> emissions. These systems are seen as more efficient choices for energy use and emissions, making them particularly favorable for implementation in eco-conscious projects. This focus on efficient HVAC solutions supports sustainability efforts while also addressing operational and environmental concerns.

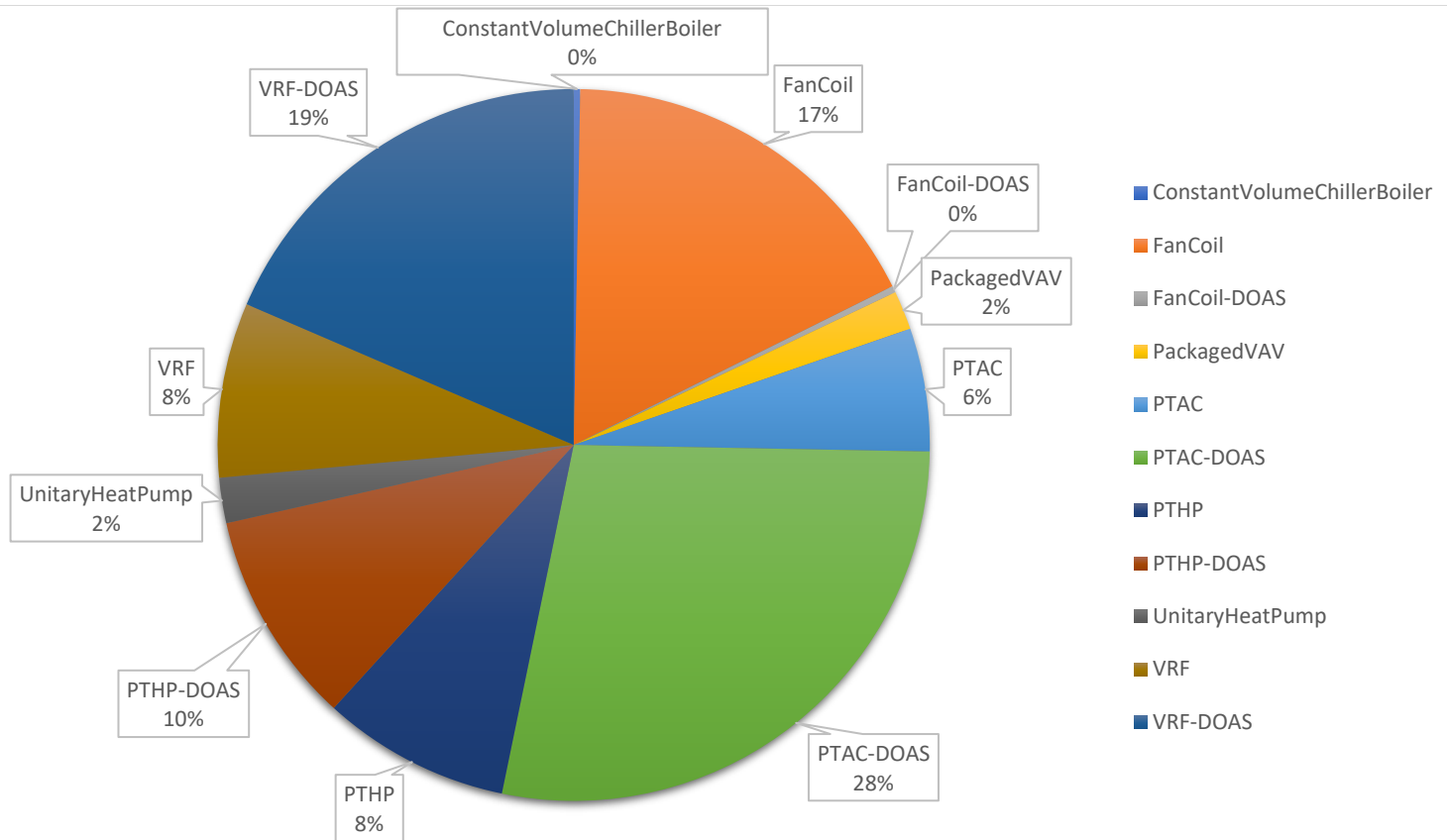


Figure 5-32: The distribution of HVAC systems in the Pareto front in the second scenario (2050)

Figure 5-32 illustrates the distribution of HVAC systems present in the Pareto front for the second scenario, targeting the year 2050. The pie chart clearly shows the relative contributions of various HVAC technologies, with PTAC-DOAS representing the largest segment at 28%. Other notable systems include VRF-DOAS at 19% and PTHP-DOAS at 10%. In contrast, systems like Fan Coil, Unitary Heat Pump, and Packaged VAV contribute minimally, each with percentages below 10%. This distribution highlights a strong preference for systems that effectively balance performance and energy efficiency, indicating a strategic direction toward optimized HVAC solutions tailored to future climate conditions. The dominance of PTAC-DOAS underscores its critical role in achieving sustainability goals while addressing indoor climate needs, making it a key player in the transition to more efficient and environmentally friendly building systems.

#### 5.4.2.2. Scenario 2: considering climate change (2080)

In this section, we evaluate building performance under projected climate conditions for the year 2080. This scenario builds upon the findings from the 2050 analysis and incorporates additional anticipated changes in climate variables, including temperature, humidity, and extreme weather events. By considering these evolving climate factors, we aim to assess how buildings may perform in terms of energy efficiency, indoor air quality, and overall resilience. This approach not only highlights potential challenges that may arise due to more severe climate impacts but also guides the development of adaptive strategies and solutions to enhance building performance and sustainability in the face of changing environmental conditions.

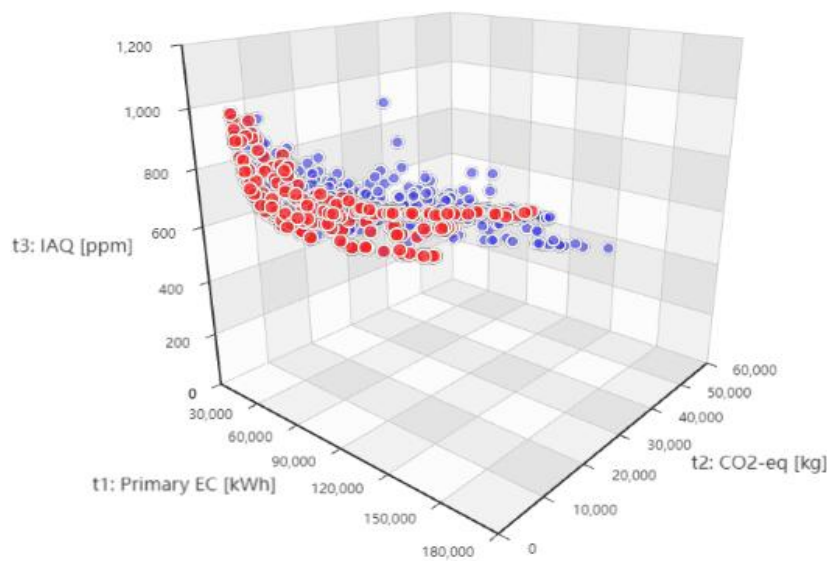


Figure 5-33: Pareto front of Scenario 2—climate change (2080)

As detailed in Figure 5-33, the Pareto front for Scenario 2, which focuses on climate change in 2080, is depicted in the provided 3D plot illustrating the trade-offs between indoor air quality (IAQ), primary energy consumption (EC), and CO<sub>2</sub> emissions. The red points on the graph represent solutions that optimize these parameters, revealing an inverse relationship between energy consumption and CO<sub>2</sub> emissions while maintaining acceptable levels of IAQ. As the graph progresses, it becomes clear that enhanced energy efficiency can result in lower emissions without significantly compromising air quality. This analysis underscores the importance of identifying optimal energy retrofit measures that balance these critical factors, ensuring both environmental sustainability and compliance with health standards. By focusing on these trade-offs, stakeholders can make informed decisions that promote both energy conservation and occupant well-being.



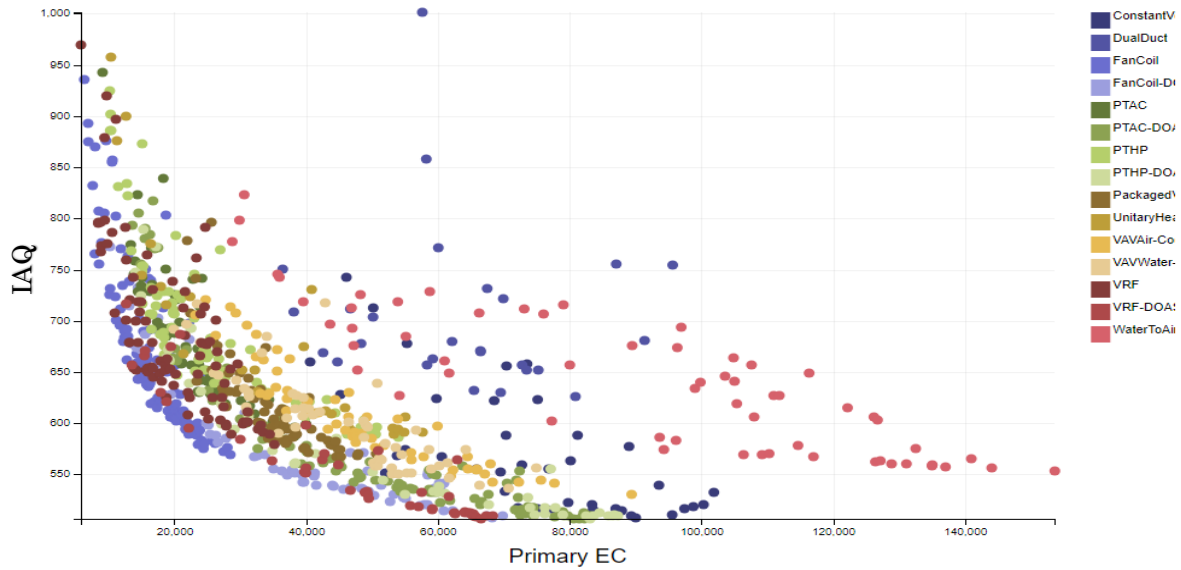


Figure 5-35: Scatter with categories of primary energy consumption and IAQ

As illustrated in Figure 5-35, the X-axis represents primary energy consumption, ranging from approximately 20,000 kWh to 200,000 kWh. The Y-axis measures indoor air quality (IAQ), expected to vary from below 500 ppm to around 1000 ppm or higher, with an optimal range of 500 to 700 ppm. This analysis highlights the importance of selecting or designing HVAC systems that effectively balance energy consumption with optimal IAQ performance. Systems that maintain IAQ within the ideal range enhance user satisfaction, while those with high energy consumption that fail to achieve good IAQ may require redesign or optimization to address performance issues and mitigate user dissatisfaction. Understanding the relationship between energy consumption and IAQ is crucial for informing market trends and guiding manufacturers in developing technologies that prioritize both efficiency and air quality. The scatter plot demonstrates a clear correlation between primary energy consumption and IAQ, underscoring the necessity of maintaining IAQ levels between 500 and 700 ppm for optimal performance. Systems such as Fan Coil, Fan Coil-DOAS, Variable Refrigerant Flow (VRF), and VRF-DOAS effectively achieve this balance while consuming less energy. Stakeholders should concentrate on technologies that reduce energy costs while ensuring high indoor air quality, ultimately leading to increased user satisfaction and compliance with health standards.

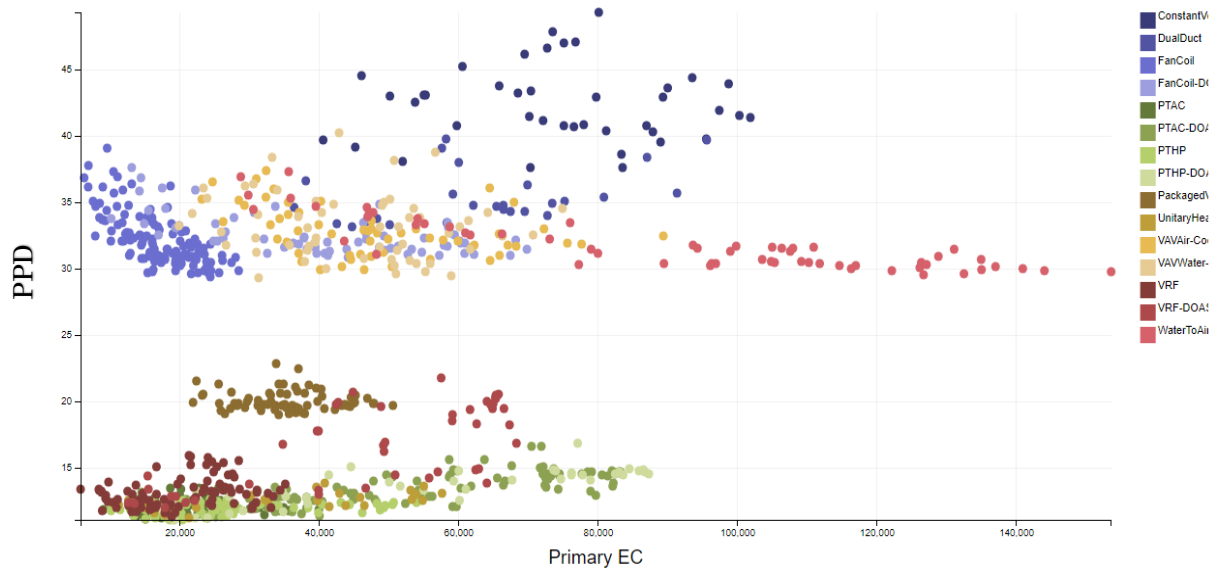


Figure 5-36: Scatter with categories of primary energy consumption and PPD

In reference to Figure 5-36, the X-axis represents the primary energy consumption of HVAC systems, ranging from approximately 20,000 to 200,000 kWh. The Y-axis indicates the predicted percentage of user dissatisfaction due to system performance, where higher values signify greater dissatisfaction. The scatter plot illustrates the relationship between primary energy consumption (EC) in kilowatt-hours and the predicted percentage of dissatisfaction (PPD) across various HVAC systems, with color coding to highlight different system types and performance trends. Notable systems such as Packaged Terminal Air Conditioner (PTAC), Packaged Terminal Heat Pump (PTHP), Variable Refrigerant Flow (VRF), and VRF-DOAS fall within the lower energy consumption range and correspond to low dissatisfaction rates, indicating satisfactory user performance. The plot reveals that increased energy consumption does not necessarily lead to greater user satisfaction, underscoring the need to prioritize systems that efficiently utilize energy while maintaining low dissatisfaction levels. Understanding these dissatisfaction levels enables stakeholders to make informed decisions regarding HVAC system selections that align better with user needs. Additionally, examining high-energy consumption systems with high predicted dissatisfaction may uncover opportunities for redesigning or advancing technology. This analysis emphasizes that higher energy consumption does not equate to lower dissatisfaction, highlighting the importance of balancing performance and energy efficiency. Future research should focus on identifying specific characteristics of systems that effectively reduce predicted dissatisfaction to enhance design and operational strategies in HVAC solutions.



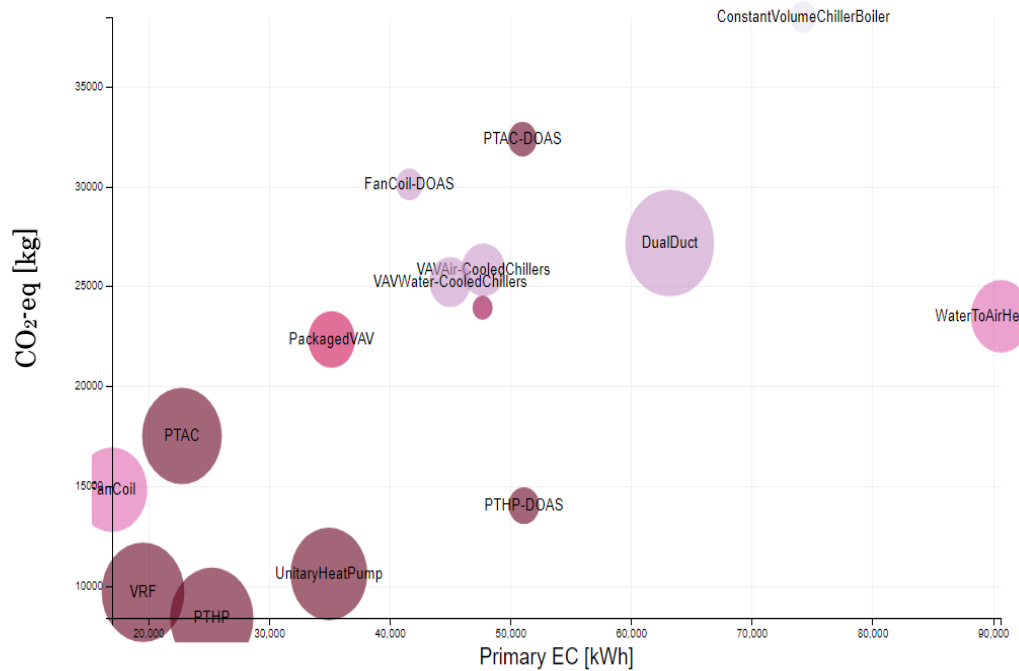


Figure 5-38: Bubble chart of HVAC systems related to Scenario 2 (2080)

In accordance with Figure 5-38, the presented bubble chart visually compares selected HVAC systems based on their energy consumption and CO<sub>2</sub> equivalent emissions, highlighting their environmental impact. The analysis reveals that five systems—Packaged Terminal Air Conditioners (PTACs), Fan Coil Units (FanCoils), Variable Refrigerant Flow (VRF) systems, Packaged Terminal Heat Pumps (PTHPs), and Unitary Heat Pumps—exhibit significantly lower energy use and carbon dioxide emissions compared to other systems. This analysis emphasizes the critical importance of selecting energy-efficient HVAC systems as a strategy for reducing carbon footprints and promoting sustainability. By prioritizing the deployment of PTACs, FanCoils, VRFs, PTHPs, and Unitary Heat Pumps, policymakers and industry stakeholders can make informed decisions that support global climate goals.

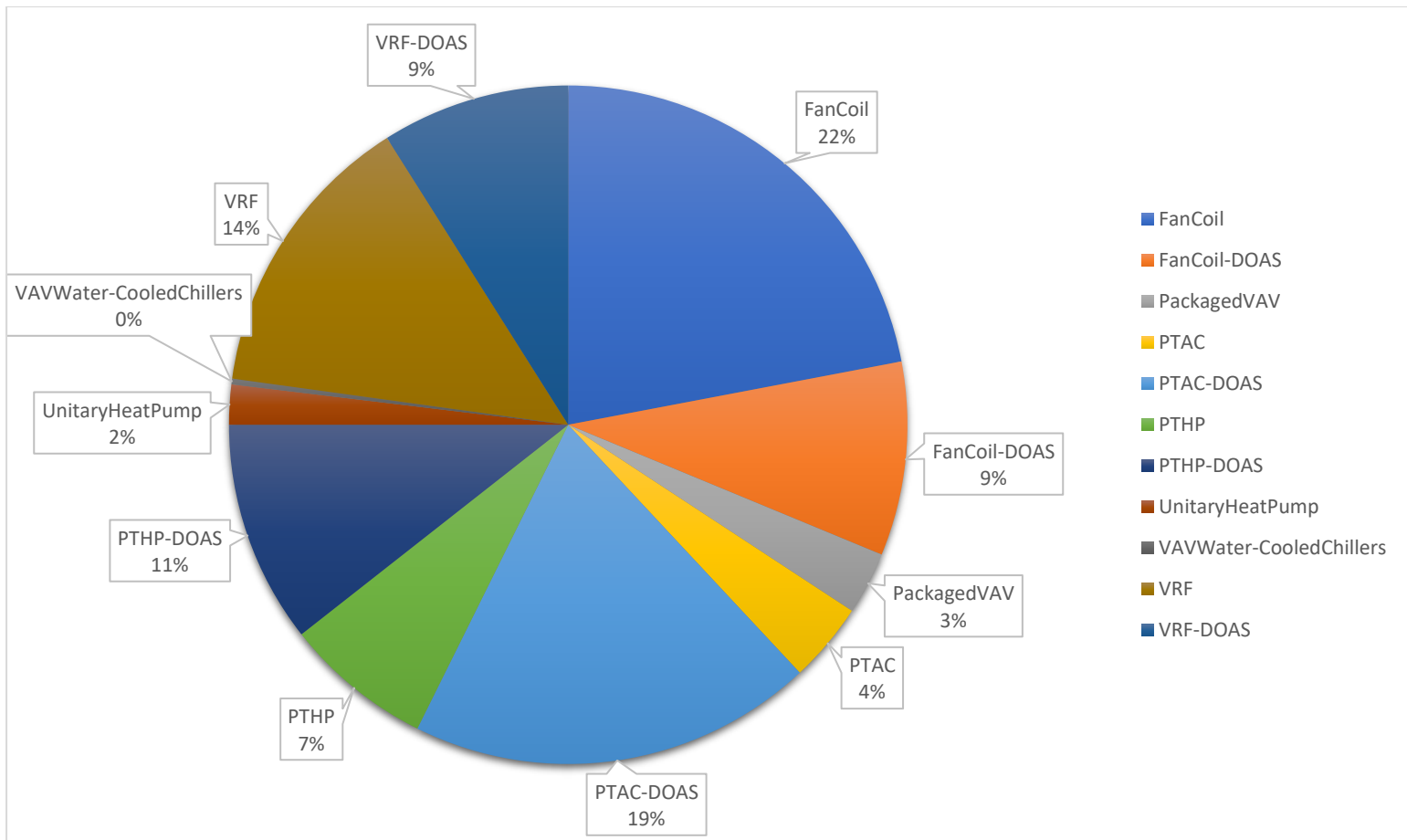


Figure 5-39: The distribution of HVAC systems in the Pareto front in the second scenario (2080)

The data illustrated in the pie chart in Figure 5-39 highlights the market share of various HVAC systems within the dataset. The Fan Coil system leads with the largest market share at 22%, demonstrating its effectiveness and efficiency in heating and cooling applications, which contributes to its popularity in the HVAC sector. Following closely, the PTAC-DOAS system, accounting for 19%, signifies a growing trend toward systems that integrate outdoor air, thereby enhancing indoor air quality. Variable Refrigerant Flow (VRF) systems make up 14% of the market, reflecting their energy-efficient operation and versatility in different environments. In the moderate representation category, both PTHP-DOAS (11%) and Fan Coil-DOAS (9%) suggest a tendency to combine technologies for optimal HVAC performance. The Packaged Terminal Heat Pump (PTHP) holds a notable 7% share, emphasizing its utility in specific applications. Conversely, systems like VRF-DAS (9%), Unitary Heat Pump (2%), PTAC (4%), and Packaged VAV (3%) show lower prevalence, indicating they may be less common in certain applications or regions. Notably, the absence of VAV Water-Cooled Chillers (0%)

suggests either a lack of implementation in the projects studied or a potential shift toward more efficient alternatives.

Analysis of Table 5-2 focuses on key parameters such as heating and cooling setpoints, clothing levels, insulation types, window constructions, and HVAC systems as follows:

- The heating setpoint is adjusted from 20 °C in the current climate to 24 °C in the 2050 scenario, reflecting a necessary increase to maintain thermal comfort as external temperatures rise. In the 2080 scenario, the heating setpoint is slightly reduced to 22 °C, indicating a potential adaptation to changing climate conditions. Conversely, the cooling setpoint remains constant at 28 °C for the 2050 scenario but increases to 30 °C in the 2080 scenario. This trend highlights the anticipated rise in cooling demand due to higher ambient temperatures, indicating a need for adjustments in cooling strategies and energy consumption to maintain comfortable indoor conditions.
- Air infiltration rates exhibit a significant increase from 0.35 ACH (air changes per hour) in the present climate to 1.85 ACH in the 2050 scenario, before stabilizing at 1.55 ACH in the 2080 scenario. This increase may be attributed to the anticipated deterioration of building envelopes under more extreme weather conditions, leading to higher energy losses and increased heating and cooling loads. The implications of this trend highlight the importance of enhancing building airtightness and implementing effective air sealing strategies to mitigate energy loss.
- The suggested clothing levels for spring are as follows: 0.74 Clo for sweatpants and a long-sleeve sweatshirt, 0.72 Clo for long-sleeve coveralls and a t-shirt, and 0.67 Clo for a knee-length skirt, long-sleeve shirt, and full slip, corresponding to Scenario 1, Scenario 2 (2050), and Scenario 2 (2080), respectively. For summer, the recommendations include 0.36 Clo for walking shorts and a short-sleeve shirt in both Scenario 1 and Scenario 2 (2050), and 0.57 Clo for trousers and a short-sleeve shirt in Scenario 2 (2080). In the fall, suggested clothing levels are 0.89 Clo for overalls, a long-sleeve shirt, and a t-shirt and 1.01 Clo for two long-sleeve sweaters and a t-shirt, corresponding to Scenario 1, Scenario 2 (2050), and Scenario 2 (2080), respectively. For winter, the recommendations are 1.10 Clo for a knee-length skirt, long-sleeve shirt, half-slip, and long-sleeve sweater in Scenario

1 and Scenario 2 (2080), and 1.37 Clo for insulated coveralls and long-sleeve thermal underwear tops and bottoms in Scenario 2 (2050).

- Insulation strategies evolve significantly across scenarios. Roof insulation transitions from glass fiber (75 mm) in the present climate to board insulation (75 mm) in 2050, and finally to XPS insulation (25 mm) in 2080. This progression indicates a growing recognition of the need for enhanced thermal resistance in response to rising temperatures. Similarly, window constructions vary, with the north and west-facing windows transitioning from double low-emissivity (LoE) glass to more advanced glazing systems, such as triple low-emissivity (LoE) film (33) bronze 6 mm in the 2080 scenario. These changes reflect an adaptive strategy to minimize solar heat gain and improve energy efficiency.
- In Scenario 1, the overhead lights are set to Continuous Lighting Control, which allows them to gradually and linearly dim from maximum electric power and light output to a minimum level as daylight illuminance increases; the lights remain at the minimum output even with further increases in daylight. In Scenario 2, set to continuous-off, the lights behave similarly but switch off completely when they reach the minimum dimming point, rather than remaining illuminated.
- The solar absorptance values for the external walls and roof in both scenarios are as follows: 0.91 for classic bronze, 0.79 for slate gray (redwood, teal), and 0.57 for rawhide. These values play a significant role in energy efficiency. Surfaces with high solar absorptance contribute to increased heat gain inside buildings, which can affect cooling loads, while surfaces with lower absorptance help maintain cooler indoor temperatures by reflecting more sunlight. Therefore, based on the analysis obtained for both scenarios, it is recommended to use materials with solar absorptance values above 0.5.
- The HVAC systems also adapt to changing climate conditions. The current climate utilizes a packaged terminal heat pump with dedicated outdoor air systems (PTHP-DOAS), while the 2050 scenario shifts to a standard PTHP system. The variable refrigerant flow (VRF) system in the 2080 scenario suggests a strategic move to enhance indoor air quality and energy efficiency as external temperatures rise and ventilation needs increase.

Table 5-2: Optimal ERM's for Scenario 1—current climate conditions, Scenario 2—climate change (2050), and Scenario 2—climate change (2080)

| Design Variables                  | Scenario 1—Current Climate       | Scenario 2—Climate Change (2050) | Scenario 2—Climate Change (2080)  |
|-----------------------------------|----------------------------------|----------------------------------|-----------------------------------|
| Heating Setpoint                  | 20                               | 24                               | 22                                |
| Cooling Setpoint                  | 28                               | 28                               | 30                                |
| Air Infiltration Rate             | 0.35                             | 1.85                             | 1.55                              |
| Clothing Level for Spring         | 0.74                             | 0.72                             | 0.67                              |
| Clothing Level for Summer         | 0.36                             | 0.36                             | 0.57                              |
| Clothing Level for Fall           | 0.89                             | 1.01                             | 1.01                              |
| Clothing Level for Winter         | 1.1                              | 1.37                             | 1.1                               |
| Air Velocity                      | 0.3                              | 0.4                              | 0.4                               |
| Air Flow Rate                     | 0.01888                          | 0.00944                          | 0.00944                           |
| Roof Insulation                   | RoofwithInsulationGlassfiber75mm | RoofwithInsulationBoard75mm      | RoofwithInsulationXPS25mm         |
| Floor Insulation                  | FloorwithInsulationXPS50mm       | FloorwithInsulationXPS25mm       | FloorwithInsulationGlassfiber50mm |
| Window Construction (North, West) | DblLoE(e2 = 0.1)Tint6mm          | DblElecRefColored6mm             | TrpLoEFilm(33)Bronze6mm           |
| Window Construction (South)       | DblLoE(e2 = 0.2)Clr6mm           | DblLoE(e2 = 0.2)Clr6mm           | TrpLoEFilm(55)Clr6mm              |
| Window Material Gas               | XENON13MM                        | ARGON13MM                        | XENON13MM                         |
| Window Height (O.K.B)             | 1.05                             | 0.3                              | 0.5                               |
| Overhang Depth                    | 0.25                             | 0.45                             | 0.2                               |
| Tilt Angle Overhang               | 100                              | 120                              | 70                                |
| Fin Depth 1 (Left Depth)          | 0.2                              | 0.5                              | 0.15                              |
| Fin Depth 2 (Right Depth)         | 0.25                             | 0.25                             | 0.5                               |
| Tilt Angle Fin                    | 75                               | 100                              | 105                               |
| Window Material Shade             | LOWREFLECT-MEDIUMTRANSSHade      | LOWREFLECT-HIGHTRANSSHade        | LOWREFLECT-MEDIUMTRANSSHade       |
| Lighting Control Type             | Continuous                       | ContinuousOff                    | ContinuousOff                     |
| Solar Absorptance                 | 0.91                             | 0.79                             | 0.57                              |
| Exterior Door                     | G0525mmwood                      | G0650mmwood                      | G0525mmwood                       |
| HVAC Systems                      | PTHP-DOAS                        | PTHP                             | VRF                               |

Table 5-3 presents the optimal solutions derived from the multi-objective optimization process, along with the corresponding values for the objective

functions. These results highlight the most effective strategies for achieving energy efficiency, reducing carbon footprint, improving indoor environmental quality, and achieving thermal and visual comfort in building retrofits.

Table 5-3: Results of optimal solutions and objective function values

| Different Scenarios                 | Net Source Energy<br>(Primary Energy<br>Consumption) [kWh] | CO <sub>2</sub><br>Equivalent<br>[kg] | Zone air CO <sub>2</sub><br>Concentration<br>[ppm] | PPD<br>[%] | Daylighting<br>Reference Point<br>Glare Index<br>Setpoint Exceeded<br>Time [hr] |
|-------------------------------------|------------------------------------------------------------|---------------------------------------|----------------------------------------------------|------------|---------------------------------------------------------------------------------|
| Scenario 1—current<br>climate       | 23,504.84                                                  | 7707.92                               | 678.37                                             | 9.47       | 99.73                                                                           |
| Scenario 2—climate<br>change (2050) | 19,659.19                                                  | 7010.57                               | 662.92                                             | 9.81       | 72.77                                                                           |
| Scenario 2—climate<br>change (2080) | 13,066.08                                                  | 8301.65                               | 678.71                                             | 11.71      | 35.02                                                                           |

As shown in Figure 5-40, baseline energy consumption is represented on the far left. It serves as a reference point for evaluating the performance of the scenarios. The analysis of Figure 5-40 reveals that the implementation of energy performance strategies in both scenarios has led to improved energy efficiency compared to baseline measurements. It highlights the importance of considering both site and source energy in evaluating overall performance and sustainability.

Annual Building Performance – Site and Source Energy – Total Energy [kWh] – Side by side Bar

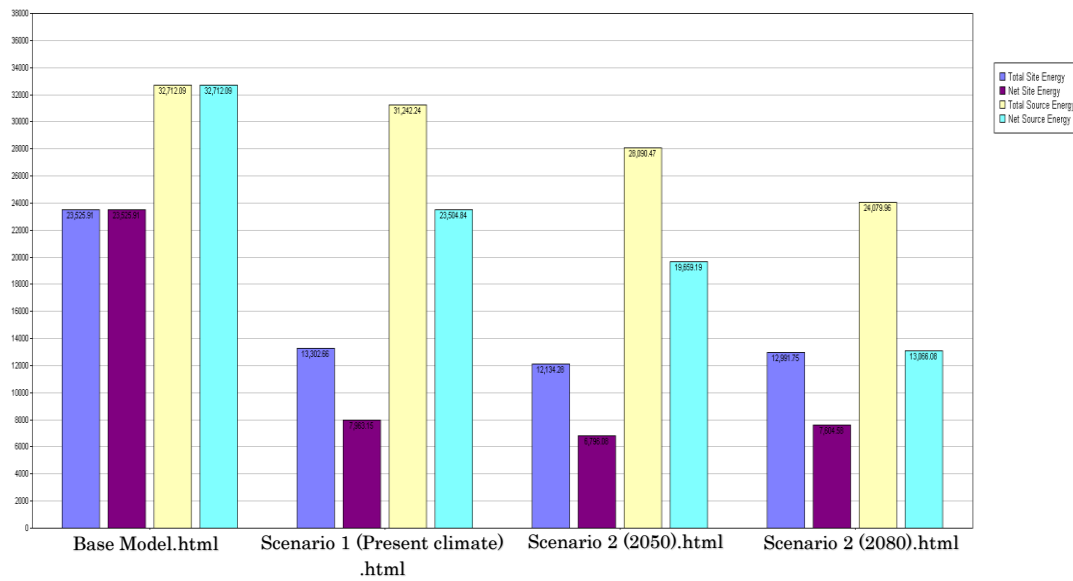


Figure 5-40: EP-Compare: comparison of total site energy, net site energy, total source energy, and net source energy across both scenarios relative to baseline values

As shown in Figure 5-41, in the base model, the primary energy consumption is 32,712.09 kWh. After optimization, the primary energy consumption levels are as follows: 23,504.84 kWh for Scenario 1 (present climate), 19,659.19 kWh for Scenario 2 (2050, climate change), and 13,066.08 kWh for Scenario 2 (2080, climate change).

Annual Building Utility Performance Summary – Site and Source Energy – Total Energy [kWh] – Simple Bar

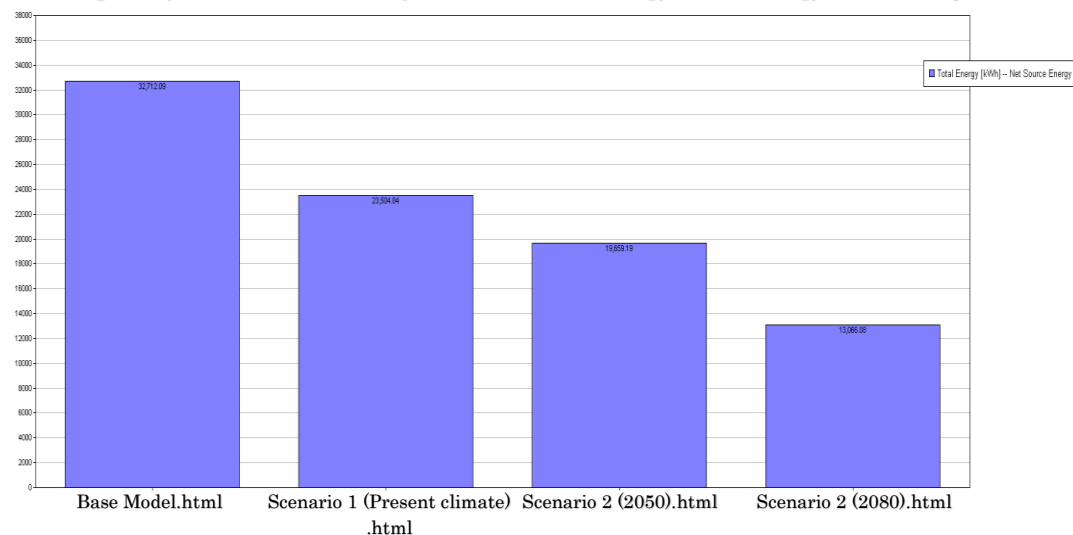


Figure 5-41: Total energy [kWh]-net source energy (primary energy consumption)

As shown in Figure 5-42, in the base model, the primary energy consumption per total building area is 412.24 kWh/m<sup>2</sup>. After optimization, the primary energy consumption levels are as follows: 296.21 kWh/m<sup>2</sup> for Scenario 1 (present climate),

247.75 kWh/m<sup>2</sup> for Scenario 2 (2050, climate change), and 164.66 kWh/m<sup>2</sup> for Scenario 2 (2080, climate change).

Annual Building Utility Performance – Site and Source Energy – Net Source Energy – Energy Per Total Building Area [kWh/m<sup>2</sup>] – Simple Bar

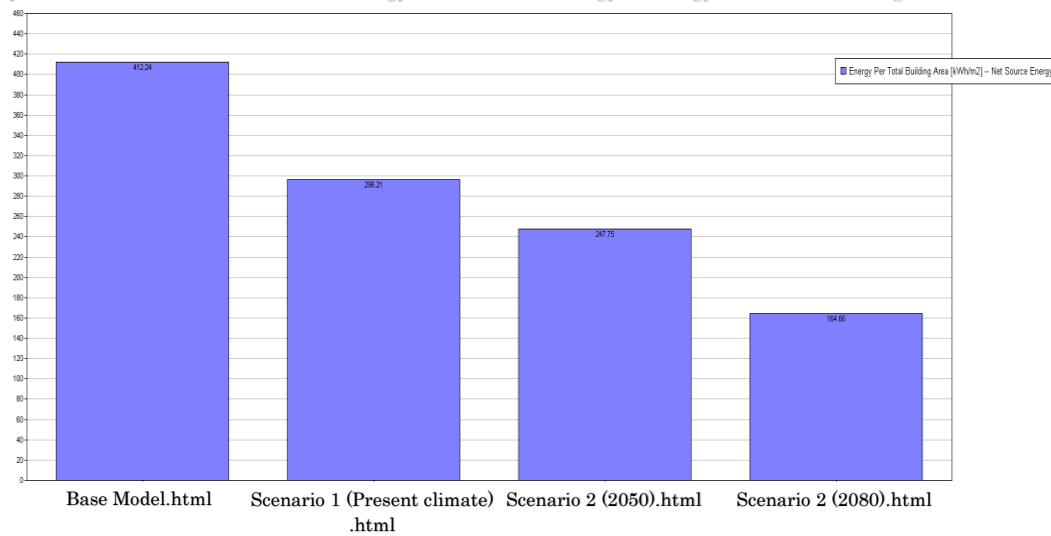


Figure 5-42: Energy Use Intensity (EUI)-energy per total building area [kWh/m<sup>2</sup>]

## 6. Conclusions

This research introduces a simulation-based framework designed to optimize the environmental aspects of building energy retrofits in response to climate change, with a focus on occupant comfort and health outcomes. The efficiency of the Non-dominated Sorting Genetic Algorithm II (NSGA-II) optimization algorithm is significantly enhanced through the implementation of a parallel computing architecture, which facilitates simultaneous simulations across multi-core processors. This methodology incorporates a results-saving archive to minimize redundancy and reduce computational demands, leading to a substantial decrease in processing time. By considering both environmental impacts and social factors, this framework promotes the advancement of more sustainable and resilient building practices. The optimization process integrates EnergyPlus, a comprehensive building energy simulation engine, with NSGA-II, executed within the jEPlus + EA environment. The framework evaluates a blend of active, passive, and renewable strategies aimed at maximizing environmental performance, improving indoor air quality, and reducing hours of thermal and visual discomfort. This approach is applied to a residential case study in Sari, Iran, where it assesses two scenarios related to future climate change.

The results yield the following conclusions for the investigated case study:

- The proposed energy retrofit measures (ERMs) have the potential to significantly improve building performance relative to baseline conditions. These measures can reduce primary energy consumption by up to 60% and decrease CO<sub>2</sub>-equivalent emissions by as much as 60%. Furthermore, optimal implementation of these solutions can lead to a 65% reduction in predicted thermal dissatisfaction and an 83% reduction in visual discomfort hours, achieving indoor air quality levels that meet ASHRAE recommended standards.
- Climate change significantly impacts building performance by changing external thermal loads, which in turn affects heating and cooling requirements. Rising outdoor temperatures greatly increase cooling demand during the summer months while simultaneously reducing heating demand during the winter. Since heating demand accounts for a considerable segment of the total energy consumption in the case study building, global warming results in decreased primary energy consumption and lower CO<sub>2</sub>-equivalent emissions.

- In parametric studies utilizing the parametric group within EnergyPlus, among the 24 window shading control strategies available, the strategy labeled “OnNightIfLowOutdoorTempAndOnDayIfCooling” emerges as the most effective in terms of its significant impact on cooling and heating loads. This strategy operates by activating shading at night when the outdoor air temperature falls below a predetermined setpoint. Additionally, if the cooling rate of the zone was non-zero during the preceding time step, shading is also implemented during the day. The application of shading both at night and during the day is contingent upon a specified schedule, if applicable.
- The EnergyPlus energy management system (EMS) was effectively utilized to maintain carbon dioxide concentrations within the six thermal zones between 600 and 700 ppm. This specified range aligns with the recommendations set forth by the ANSI/ASHRAE Standard 62.1, which emphasizes the importance of adequate indoor air quality for occupant health and comfort. Maintaining carbon dioxide levels within this range is crucial, as elevated concentration can lead to discomfort, reduced cognitive function, and other adverse health effects. The successful management of indoor air quality through the strategic implementation of the EMS demonstrates the potential for advanced building management systems to facilitate compliance with recognized environmental standards, thereby enhancing the overall performance and sustainability of the indoor environment. This approach not only ensures regulatory compliance but also contributes to the well-being of occupants by providing a healthier and more comfortable living or working space.
- The analysis of clothing levels reveals a decrease in thermal comfort adaptation over time. For spring, clothing levels decrease from 0.74 in the present climate to 0.72 in 2050 and further to 0.67 in 2080. Similar trends are observed in summer and fall, with clothing levels in summer remaining constant at 0.36 before increasing to 0.57 in 2080. This suggests a potential shift in occupant behavior in response to changing climatic conditions, which may affect indoor thermal comfort and energy consumption patterns.
- For both scenarios analyzed, the implementation of energy-efficient measures is strongly recommended. These measures include the installation of extruded polystyrene (XPS) and fiberglass thermal insulation with a thickness ranging from 25 to 75 mm for the flooring, as well as the

application of fiberglass, board, and XPS insulation with similar thickness specifications for the roofs. This approach is anticipated to significantly enhance the thermal performance of the building envelope, leading to improved energy efficiency and reduced overall energy consumption. For south-facing windows, it is recommended to use double low-emissivity clear glass ( $e_2 = 0.1$  to  $0.2$ ) for both Scenario 1 and Scenario 2 (2050), and triple low-emissivity film (55) clear 6mm for Scenario 2 (2080), with 13mm spaces filled with xenon for Scenario 1 and argon and xenon for Scenario 2. For north- and west-facing windows, double low-emissivity tinted glass ( $e_2 = 0.1$ ) is advisable for Scenario 1, while Scenario 2 (2050) should feature double electrochromic reflective colored 6mm glass, and Scenario 2 (2080) should use triple low-emissivity film (33) bronze 6mm, with 13mm spaces filled with xenon for Scenario 1 and argon and xenon for Scenario 2.

- For HVAC systems, it is recommended to install Packaged Terminal Heat Pumps (PTHPs) with inverter technology ( $COP = 4.3$ ,  $EER = 3.81$ ) alongside a dedicated outdoor air system (supply fan total efficiency =  $0.9$ ) and variable refrigerant flow (VRF) system (gross rated cooling  $COP = 4.3$  and gross rated heating  $COP = 4.6$ ). Additionally, the installation of  $25 \text{ m}^2$  of photovoltaic panels is suggested. Temperature controls should be set at  $28^\circ\text{C}$  and  $30^\circ\text{C}$  for cooling, and  $20^\circ\text{C}$ ,  $24^\circ\text{C}$ , and  $22^\circ\text{C}$  for heating. However, if economic considerations are a primary concern, renovating the windows and HVAC systems may not be advisable.
- The north-windows-to-wall ratio for both scenarios are  $41.34\%$  for Scenario 1,  $60.72\%$  for Scenario 2 in 2050, and  $55.55\%$  for Scenario 2 in 2080. The fluctuating percentages over the timeframes suggest an adaptive approach to building design, responding to evolving climate conditions and energy efficiency standards.
- In all optimal solutions for both scenarios, the installation of photovoltaic (PV) panels is consistently chosen. This trend is primarily due to Iran's favorable climatic conditions, characterized by high solar radiation, along with the government's commitment to purchasing generated solar electricity at rates higher than those of grid electricity.

The findings underscore the urgent necessity for collaborative action among a diverse array of stakeholders, including governments, architects, local communities, and researchers, to foster a collective commitment to climate-

resilient futures. Engaging these groups can facilitate the adoption of innovative design practices and retrofitting solutions that not only mitigate environmental impacts but also enhance residents' quality of life. This research lays a solid foundation for future studies and initiatives aimed at creating sustainable, energy-efficient, and comfortable living spaces capable of adapting to the evolving challenges posed by climate change. In Iran, the prevailing building technology often relies on outdated and inefficient systems, resulting in high energy consumption. Improvements in building design and energy efficiency present significant opportunities for emission reductions; however, the uptake of renewable energy sources remains limited. Additionally, rapid population growth and urbanization in major Iranian cities exacerbate energy demand, leading to increased emissions as residential and commercial buildings place additional strain on the existing energy grid.

The proposed approach, characterized by a robust metaheuristic algorithm and parallel processing capabilities, offers advanced computational methods to tackle complex building energy performance optimization challenges. Future studies will apply this framework to a variety of case studies encompassing diverse construction technologies, functionalities, and climatic conditions. This comprehensive analysis aims to establish nationwide guidelines for energy retrofit projects to achieve environmentally sustainable buildings. Moreover, the adaptability of the proposed model will support the design of nearly zero-energy and zero-carbon buildings that are resilient to climate change, a goal that is particularly vital given the high rate of new construction in developing countries in the Middle East compared to their developed counterparts. Implementing this method at the district level will provide valuable insights for policymakers in planning energy retrofits for neighborhoods.

## 7. Future research

While this study successfully demonstrated the efficacy of a simulation-based multi-objective optimization framework for enhancing energy efficiency and occupant comfort in residential buildings under climate change scenarios, several avenues remain for further exploration to address existing limitations and extend the research's impact. The following directions outline potential pathways for advancing this work, focusing on methodological enhancements, technological integrations, and broader applications.

1. **Integration of Advanced Control Strategies:** The current study relied on static design parameters and set points for optimization. Future research could incorporate dynamic control strategies, such as Model Predictive Control (MPC) and Reinforcement Learning (RL), to enable real-time adaptation of building systems (e.g., HVAC, lighting) to occupant behavior, weather variations, and grid demands. By coupling these control algorithms with the NSGA-II framework, buildings could achieve greater energy efficiency and demand response capabilities, particularly in smart grid contexts.
2. **Incorporation of IoT and Real-Time Data:** While this study utilized simulated data via EnergyPlus, integrating Internet of Things (IoT) technologies for real-time data collection (e.g., occupancy patterns, indoor environmental quality, and energy consumption) could enhance the accuracy and applicability of the optimization framework. Future work could explore IoT-enabled sensor networks to validate simulation results against in-situ measurements and develop hybrid models that combine simulated and real-world data for more robust optimization.
3. **Expansion to Machine Learning-Driven Predictive Models:** The NSGA-II algorithm effectively identified optimal solutions, but its computational complexity can be a limitation for large-scale applications. Future research could leverage machine learning (ML) techniques, such as deep neural networks or ensemble methods (e.g., Random Forest, XGBoost), to develop predictive surrogate models that approximate EnergyPlus simulations. These models could reduce computational time while maintaining accuracy, enabling optimization for larger building portfolios or urban-scale retrofits.
4. **Life Cycle Assessment (LCA) and Cost-Benefit Analysis:** The current study focused on energy, emissions, comfort, and air quality metrics but did not

account for the life cycle environmental impacts or economic feasibility of retrofit strategies. Future work could integrate Life Cycle Assessment (LCA) to evaluate the embodied carbon of materials (e.g., insulation, windows) and a cost-benefit analysis to assess the economic viability of proposed retrofits. This would provide a more holistic framework for decision-making, balancing sustainability with affordability.

5. **Scalability to Diverse Climates and Building Typologies:** The case study was conducted for a residential building in Sari, Iran, under specific climate change scenarios. To enhance generalizability, future research could extend the framework to diverse climates (e.g., arid, or polar) and building typologies (e.g., commercial, institutional, or high-rise). This would involve adapting the Morris sensitivity analysis and NSGA-II parameters to account for regional variations in climate, construction practices, and occupant preferences.
6. **Human-Centric Design and Occupant Behavior Modeling:** While occupant comfort was a key objective, the study assumed standardized occupant behavior. Future work could develop agent-based models or data-driven occupant behavior models to capture dynamic interactions between occupants and building systems. By integrating these models into the optimization framework, researchers could better address personalized comfort preferences and their impact on energy performance.
7. **Policy and Industry Applications:** The proposed retrofit strategies offer significant potential for reducing energy consumption and emissions, but their adoption depends on supportive policies and industry uptake. Future research could focus on translating the optimization framework into practical guidelines for policymakers, architects, and engineers. This could involve developing user-friendly decision-support tools or collaborating with industry partners to pilot retrofit strategies in real-world buildings.
8. **Resilience to Extreme Climate Events:** The study addressed long-term climate change scenarios but did not explicitly consider extreme weather events (e.g., heatwaves, storms). Future work could incorporate resilience metrics into the optimization framework, evaluating how design strategies perform under acute climate stressors. This would ensure that buildings remain functional and comfortable during unexpected disruptions.

9. **Open-Source Data and Framework Accessibility:** To foster collaboration and reproducibility, future research could focus on creating an open-source repository of the optimization framework, including EnergyPlus models, jEPlus configurations, and NSGA-II scripts. This would enable other researchers to build upon the methodology, adapt it to new contexts, and validate findings across different case studies.

By pursuing these directions, future research can build upon the foundation established in this study, advancing the field of sustainable building design and contributing to global efforts to mitigate climate change impacts. These efforts will require interdisciplinary collaboration, leveraging advancements in data science, control systems, and building technologies to create resilient, energy-efficient, and occupant-friendly built environments.

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## Annexes

**Data Availability Statement:** The following research data and supporting reported results can be downloaded at: [ENSIMS Web Tools](#).