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Energy Planning and Optimization Model for Campus Buildings: A Case Study of Erciyes University

Atabek MOVLYANOV [1]*, Beyza AKYOL [2] Saltuk Buğra SELÇUKLU [3]

ORCID 1: 0000-0001-6676-5231
ORCID 2: 0000-0002-5933-5724
ORCID 3: 0000-0002-9295-3866

[1] *Erciyes University, Graduate School of Natural and Applied Sciences, Energy Systems Engineering Department, 38039, Kayseri, Türkiye.*

[2-3] *Erciyes University, Engineering Faculty, Energy Systems Engineering Department, 38039, Kayseri, Türkiye.*

***** e-mail**: atabekmovlyanov@gmail.com*

Abstract

This study addresses energy consumption and climate change challenges in university campus buildings, focusing on Erciyes University. The research develops a multi-objective optimization model using GAMS software and NEOS Server to enhance campus energy efficiency. The model evaluates various energy-saving measures and their investment costs. Findings indicate that building envelope insulation can reduce heating energy consumption by 35%, while efficient hot water systems and energy-saving technologies can achieve savings up to 75.5%. Model calculations using SCIP and LINDO solvers demonstrate high accuracy, with results differing by only 0.2%. This research provides valuable guidance for university decision-makers in implementing targeted interventions for significant primary energy savings.

Keywords: *Campus building, energy efficiency, multi-objective optimization.*

Kampüs Binaları için Enerji Planlama ve Optimizasyon Modeli: Erciyes Üniversitesi Örneği

Öz

Bu çalışma, üniversite kampüs binalarında artan enerji tüketimi ve iklim değişikliği gibi önemli sorunları, Erciyes Üniversitesi örneğinde ele almıştır. Araştırmada, GAMS yazılımı ve NEOS Server kullanılarak kampüs enerji verimliliğini artırmak için çok amaçlı bir optimizasyon modeli geliştirilmiştir. Model, çeşitli enerji tasarrufu önlemlerini ve yatırım maliyetlerini değerlendirmektedir. Bulgular, bina kabuğu yalıtımının ısıtma enerji tüketimini %35, verimli sıcak su sistemleri ve enerji tasarrufu teknolojilerinin ise tasarrufları %75,5'e kadar artırabileceğini göstermektedir. SCIP ve LINDO çözücüleri ile yapılan model hesaplamaları, %0,2'lik farkla yüksek doğruluk göstermektedir. Bu araştırma, üniversite karar vericilerine önemli enerji tasarrufları sağlayacak müdahaleler konusunda değerli bir rehber sunmaktadır.

Anahtar kelimeler: *Üniversite kampüs binaları, enerji verimliliği, çok amaçlı optimizasyon.*

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1. Introduction

The rise in primary energy consumption and climate change are critical challenges of our time. Many governments are actively pursuing policies to reduce primary energy consumption through enhanced energy efficiency (EE) and integrating renewable energy sources (RES). These strategies are crucial for addressing climate change, ensuring energy security, and promoting sustainable economic growth (Karmellos et al., 2015). The increasing population and industrial activity in Türkiye have indeed created a pressing need to harness EE and RES. The building sector's significant share of total final energy consumption underscores the need for effective policies aimed at improving energy efficiency. There are a total of 208 universities in Türkiye, each of which has multiple campus buildings (Figure 1). Universities function similarly to small towns, with their diverse populations and a wide range of activities and services. While they bring many benefits such as economic growth, cultural enrichment, and innovation they also have negative impacts on both the natural and social environments (Gültekin et al., 2024; Rüşen et al., 2018). Their efforts not only enhance their immediate environments but also contribute to global sustainability goals, making them key institutions in the transition toward a more sustainable future. Designing sustainable university campuses requires a holistic and long-term approach to process management. Universities have very dense populations of both staff and students, as well as energy-intensive structures such as buildings. It is important to create alternatives to the use of consumable resources in buildings where educational activities are carried out, to stimulate more efficient use of expended energy and materials, to prevent all types of waste, and to implement environmentally friendly building designs (Rüşen et al., 2018). In educational buildings, energy efficiency measures targeting heating, cooling, ventilation, and lighting systems have great potential to save energy, improve efficiency, and deliver environmental benefits (Ascione et al., 2017; Bellia et al., 2018; Guerrieri et al., 2019; Han et al., 2015). In the studies reviewed, insulation of building envelopes, installation of cogeneration heating systems, increasing the efficiency of lighting systems, strengthening and insulating the roof with a photovoltaic installation, replacing windows, using biomass or heat pumps in heating systems, optimizing air conditioning settings, installing heat recovery systems were identified as significant energy efficiency measures.

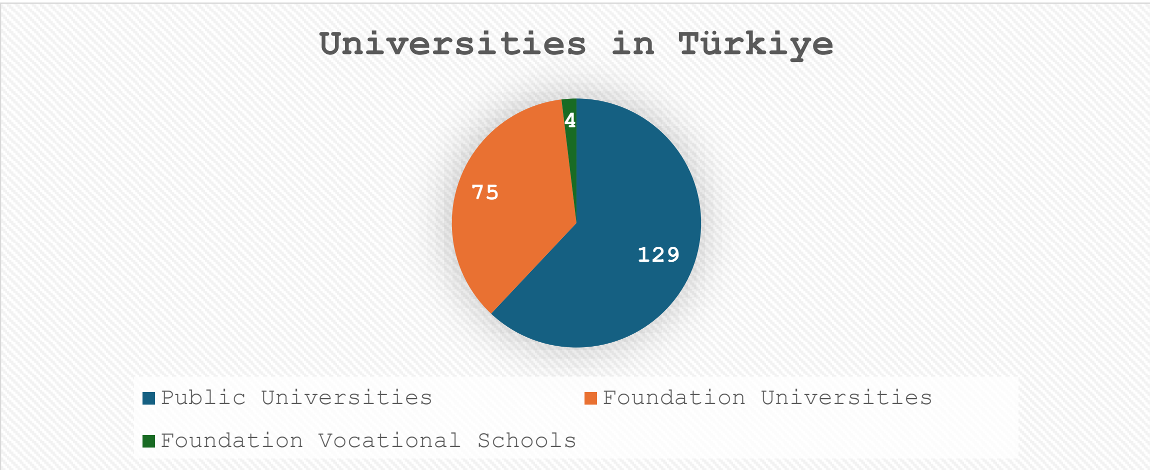

Figure 1. Number of universities in Türkiye (YÖK, 2024)

Diakaki et al. (2010) developed a multi-objective decision-making model for improving the energy efficiency of buildings. The decision criteria were focused on reducing primary energy consumption, minimizing the initial investment cost (including the cost of construction, acquisition, and installation), and lowering CO_2 emissions. The successful application of the model to a case study underscores its viability and potential for future advancements. In another study, Diakaki and Grigoroudis (2021) demonstrated the effectiveness of interactive mathematical modeling for improving energy efficiency. The paper proposes a mathematical programming approach to identify and incorporate decision-maker preferences into a decision-making model through utility assessment using the UTASTAR multi-criteria decision aid method. The study results indicate that the proposed approach effectively assists decision analysts in recommending energy measures that align closely with the decision maker's preferences, without requiring precise definitions of those preferences in advance. This flexibility allows for a more adaptive and responsive decision-making process. Karmellos et al. (2015) focused on evaluating energy efficiency measures in the residential and small commercial sectors. Their work aims to develop a methodology and a software tool to optimally prioritize these measures, enhancing decision-making and implementation strategies. A software tool has been developed using MATLAB allowing decision-makers to effectively utilize it for energy efficiency assessments. Bayata and Temiz (2017) developed a methodology and two distinct software tools using MATLAB to address multi-objective optimization problems related to building energy efficiency. The first tool, the Building Energy Consumption Calculation Program, is designed to calculate a building's annual energy consumption following Turkish standards for thermal insulation requirements. It also assesses initial investment costs and CO_2 emissions. The second tool, the Building Energy Optimization Program, is a multi-objective optimization tool that employs NSGA-II to minimize various objectives related to building energy efficiency. Hashempour et al. (2020) conducted a comprehensive literature review focusing on the energy performance optimization of existing buildings. Their analysis highlighted various strategies and technologies aimed at improving energy efficiency, addressing factors such as retrofitting, renewable energy integration, and smart building technologies. Penna et al. (2015) explored the relationship between the initial characteristics of residential buildings and the development of optimal retrofit solutions. Their research focused on achieving either maximum economic performance or minimizing energy consumption to promote nearly zero-energy building (nZEB) behavior, while also addressing thermal comfort levels. Shi and Chen (2024) introduced optimization method for building energy-saving renovations that integrates automated machine learning with the NSGA-III algorithm. Their approach aims to efficiently and accurately identify the most effective renovation schemes, contributing to enhanced energy efficiency in buildings. Vardopoulos et al. (2024) explored how smart building technologies can enhance energy efficiency and occupant comfort, demonstrating their potential to promote sustainable architectural practices. Benaddi et al. (2023) investigated the integration of innovative thermal management techniques in building design, highlighting their effectiveness in reducing energy consumption and improving indoor climate conditions. Abdou et al. (2021) analyzed the effects of renewable energy integration in building systems, demonstrating its potential to enhance energy efficiency and reduce carbon footprints in urban environments.

2. Material and Method

The optimization of energy efficiency in buildings, particularly in complex environments like university campuses, is a critical challenge. In our study, we leverage the Karmellos et al. (2015) model to target energy efficiency improvements specifically for university campus buildings. This model is renowned for its multi-objective decision optimization capabilities, which facilitate the evaluation of trade-offs between various objectives in the context of energy efficiency improvements. Multi-objective decision optimization is crucial here as it helps identify optimal solutions by evaluating a set of trade-offs in the objective function space. Their model addresses the challenge of finding the best trade-offs among multiple objectives, even when the solution space is vast and complex. We refined the Diakaki et al. (2010) model by incorporating improvements proposed by Karmellos et al. (2015) to better suit our specific application. The enhancements proposed by Karmellos et al. (2015) provide a more detailed and context-sensitive approach to energy efficiency optimization. By incorporating these improvements, our model better aligns with the unique needs of university campus buildings, offering a more precise and effective optimization solution.

In this study, we utilized the General Algebraic Modeling System (GAMS) as our modeling language to formulate the optimization problem. To solve the optimization model, we employed the NEOS Server (Czyzyk et al., 1998). Within the NEOS Server environment, we used two specific solvers for our Mixed Integer Nonlinear Programming (MINLP) model, namely, *SCIP and LINDO* solvers. The SCIP solver is well-suited for tackling complex integer programming problems with nonlinear constraints. It is known for its efficiency in solving large-scale and challenging optimization problems. The LINDO solver is specialized in handling nonlinear dynamic optimization problems, including those with mixed-integer constraints. It provides additional tools for dealing with specific types of nonlinearities in the optimization model.

2.1. Decision Variables

In the optimization model for improving energy efficiency in university campus buildings, we have identified four key decision variables. Here's a detailed breakdown of each variable and its role within the model:

Building Shells. This variable represents the selection and configuration of the building envelope components, such as doors, windows, walls, roofs, and ceilings. The building shell affects thermal insulation, energy loss, and overall energy consumption for heating and cooling. Optimizing this variable helps in enhancing energy efficiency by improving thermal performance and reducing the demand for energy-intensive climate control. In the optimization model, building shells are categorized into two distinct types: single-layer and multiple-layer constructions. Each type influences energy efficiency and cost in different ways. Single-layer construction refers to building components that consist of a single uniform material or component. This category includes doors and windows. Choices related to the type of doors can vary in terms of material, insulation properties, and energy performance. Similarly, selecting the type of windows involves considerations such as glazing options, frame materials, and insulation performance, all of which impact energy efficiency and overall building performance. Multiple-layer construction involves building components made up of two or more distinct layers of materials. This category includes walls, ceilings, and floors. The choice of composition of walls, ceilings, and floors, including materials and the number of layers, influence thermal resistance and insulation.

Building Heating and Domestic Hot Water (DHW) Systems. This variable encompasses the choice and optimization of heating systems (e.g., boilers, heat pumps) and systems for domestic hot water supply. Effective management and optimization of heating and DHW systems are crucial for minimizing energy consumption. This variable affects the operational efficiency and the energy required to maintain comfortable temperatures and provide hot water, influencing both energy use and operational costs. In optimizing building heating and Domestic Hot Water (DHW) supply systems, it's crucial to carefully categorize and select from the various system types to ensure an effective and efficient combination. (Table 1).

Table 1. Building Heating and DHW Systems Category (Authors)

	Electrical Systems	**Non-Electrical Systems**
Heating Only Systems	Utilize electric heaters or heat pumps solely for space heating	Includes systems like gas boilers or oil heaters systems for heating
Heating - DHW Systems	Use electric-powered systems for both space heating and DHW (e.g., electric boilers with integrated storage tanks)	Combine heating and DHW with non-electrical sources (e.g., gas or oil boilers with an integrated DHW tank)
DHW Only Systems	Employ electric water heaters or heat pump water heaters solely for DHW	Includes systems like gas water heaters or solar water heating systems without space heating components

Solar collector systems that use solar energy to pre-heat water or provide both heating and DHW, can also be integrated into existing systems or used as standalone solutions.

Building Lighting Systems. This variable deals with the selection and configuration of lighting systems within the building. Efficient lighting systems reduce electricity consumption and improve energy efficiency. In optimizing lighting systems, the decision variables represent the different types or categories of these systems. Each category impacts energy consumption and cost.

Electrical Appliances in Building. This variable includes the selection and usage patterns of various electrical appliances and equipment within the building, such as computers and laptops. Electrical appliances significantly contribute to the building's total energy consumption. In optimizing electrical appliances, the decision variables represent the different types or categories of these systems. Each category impacts energy consumption and cost.

The model formulations are presented in equations A1 through A62:

Door type summation constraint:

$$x_d^{DOOR} = \begin{cases} 1, if\ door\ type\ d\ is\ selected \\ 0, else \end{cases} \tag{A1}$$

$$\sum_{d=1}^{D} x_d^{DOOR} = 1$$

d: Available number of door type, x_d^{DOOR}: Decision variable where $d = 1, \dots, D$

Window type summation constraint:

$$x_z^{WIN} = \begin{cases} 1, if\ window\ type\ z\ is\ selected \\ 0, else \end{cases} \tag{A2}$$

$$\sum_{z=1}^{Z} x_z^{WIN} = 1$$

z: Available number of window type, x_z^{WIN}: Decision variable where $z = 1, \dots, Z$

Wall structure type summation constraint:

$$x_w^{WALL} = \begin{cases} 1, if\ wall\ type\ w\ is\ selected \\ 0, else \end{cases} \tag{A3}$$

$$\sum_{w=1}^{W} x_w^{WALL} = 1$$

w: Available number of known wall layer, x_w^{WALL}: Decision variable where $w = 1, \dots, W$

Wall structures material type summation constraint:

$$x_{wp}^{mWALL} = \begin{cases} 1, if\ alternative\ material\ p \\ \quad is\ selected\ of\ wall\ type\ w \\ 0, else \end{cases} \tag{A4}$$

$\sum_{p=1}^{P_w} x_{wp}^{mWALL} = x_w^{WALL}\ \forall\ (\ w = 1, \dots, W\ )$

p: Available number of unknown wall layer, x_{wp}^{mWALL}: Decision variable where $p = 1, \dots, P_w$

Ceiling structure type summation constraint:

$$x_r^{CEIL} = \begin{cases} 1, if\ ceil\ type\ r\ is\ selected \\ 0, else \end{cases} \tag{A5}$$

$$\sum_{r=1}^{R} x_r^{CEIL} = 1$$

r: Available number of known ceiling layer, x_r^{CEIL}: Decision variable where $r = 1, \dots, R$

Ceiling structures material type summation constraint:

$$x_{ra}^{mCEIL} = \begin{cases} 1, if\ alternative\ material\ a \\ is\ selected\ of\ ceil\ type\ r \\ 0, else \end{cases} \tag{A6}$$

$$\sum_{a=1}^{A_r} x_{ra}^{mCEIL} = x_r^{CEIL}\ \forall\ (r = 1, \dots, R)$$

a: Available number of unknown ceiling layer, x_{ra}^{mCEIL}: Decision variable where $a = 1, \dots, A_r$

Floor structure type summation constraint:

$$x_h^{FLO} = \begin{cases} 1, if\ floor\ type\ h\ is\ selected \\ 0, else \end{cases} \tag{A7}$$

$$\sum_{h=1}^{H} x_h^{FLO} = 1$$

h: Available number of known floor layer, x_h^{FLO}: Decision variable where $h = 1, \dots, H$

Floor structures material type summation constraint:

$$x_{hg}^{mFLO} = \begin{cases} 1, if\ alternative\ material\ g \\ is\ selected\ of\ ceil\ type\ h \\ 0, else \end{cases} \tag{A8}$$

$$\sum_{g=1}^{G_h} x_{hg}^{mFLO} = x_h^{FLO}\ \forall\ (h = 1, \dots, H)$$

g: Available number of unknown floor layer, x_{hg}^{mFLO}: Decision variable where $g = 1, \dots, G_h$

Heating system summation constraint:

$$\sum_{ehsi=1}^{EHSI} \sum_{ehsj=1}^{EHSJ_{ehsi}} x_{ehsi,ehsj}^{EHS} + \sum_{nehsi=1}^{NEHSI} \sum_{nehsj=1}^{NEHSJ_{nehsi}} x_{nehsi,nehsj}^{NEHS} + \sum_{ehwsi=1}^{EHWSI} \sum_{ehwsj=1}^{EHWSJ_{ehwsi}} x_{ehwsi,ehwsj}^{EHWS} + \sum_{nehwsi=1}^{NEHWSI} \sum_{nehwsj=1}^{NEHWSJ_{nehwsi}} x_{nehwsi,nehwsj}^{NEHWS} = 1 \tag{A9}$$

$$x_{ehsi,ehsj}^{EHS} = \begin{cases} 1, if\ available\ types\ of\ electrical\ heating\ systems\ ehsj \\ of\ available\ categories\ ehsi\ is\ selected \\ 0, else \end{cases}$$

$$x_{nehsi,nehsj}^{NEHS} = \begin{cases} 1, if\ available\ types\ of\ non-electrical\ heating\ systems\ nehsj \\ of\ available\ categories\ nehsi\ is\ selected \\ 0, else \end{cases}$$

$$x_{ehwsi,ehwsj}^{EHWS} = \begin{cases} 1, if\ available\ types\ of\ electrical\ heating-DHW\ systems\ ehwsj \\ of\ available\ categories\ ehwsi\ is\ selected \\ 0, else \end{cases}$$

$$x_{nehwsi,nehwsj}^{NEHWS} = \begin{cases} 1, if\ available\ types\ of\ non-electrical\ heating-DHW\ systems\ nehwsj \\ of\ available\ categories\ nehwsi\ is\ selected \\ 0, else \end{cases}$$

$x_{ehsi,ehsj}^{EHS}$: Decision variable of available types of electrical heating systems $ehsj$ of available categories $ehsi$

$x_{nehsi,nehsj}^{NEHS}$: Decision variable of available types of non - electrical heating systems $nehsj$ of available categories $nehsi$

$x_{ehwsi,ehwsj}^{EHWS}$: Decision variable of available types of electrical heating - DHW systems $ehwsj$ of available categories $ehwsi$

$x_{nehwsi,nehwsj}^{NEHWS}$: Decision variable of available types of non - electrical heating - DHW systems $nehwsj$ of available categories $nehwsi$

DHW system summation constraint:

$$\sum_{ewsi=1}^{EWSI} \sum_{ewsj=1}^{EWSJ_{ewsi}} x_{ewsi,ewsj}^{EWS} + \sum_{newsi=1}^{NEWSI} \sum_{newsj=1}^{NEWSJ_{newsi}} x_{newsi,newsj}^{NEWS} + \sum_{ehwsi=1}^{EHWSI} \sum_{ehwsj=1}^{EHWSJ_{ehwsi}} x_{ehwsi,ehwsj}^{EHWS} + \sum_{nehwsi=1}^{NEHWSI} \sum_{nehwsj=1}^{NEHWSJ_{nehwsi}} x_{nehwsi,nehwsj}^{NEHWS} = 1 \quad \text{(A10)}$$

$$x_{ewsi,ewsj}^{EWS} = \begin{cases} 1, if\ available\ types\ of\ electrical\ DHW\ systems\ ewsj \\ of\ available\ categories\ ewsi\ is\ selected \\ 0, else \end{cases}$$

$$x_{newsi,newsj}^{NEWS} = \begin{cases} 1, if\ available\ types\ of\ non - electrical\ DHW\ systems\ newsj \\ of\ available\ categories\ newsi\ is\ selected \\ 0, else \end{cases}$$

$$x_{ehwsi,ehwsj}^{EHWS} = \begin{cases} 1, if\ available\ types\ of\ electrical\ heating - DHW\ systems\ ehwsj \\ of\ available\ categories\ ehwsi\ is\ selected \\ 0, else \end{cases}$$

$$x_{nehwsi,nehwsj}^{NEHWS} = \begin{cases} 1, if\ available\ types\ of\ non - electrical\ heating - DHW\ systems\ nehwsj \\ of\ available\ categories\ nehwsi\ is\ selected \\ 0, else \end{cases}$$

$x_{ewsi,ewsj}^{EWS}$: Decision variable of available types of electrical DHW systems $ewsj$ of available categories $ewsi$

$x_{newsi,newsj}^{NEWS}$: Decision variable of available types of non - electrical DHW systems $newsj$ of available categories $newsi$

Solar collector system summation constraint

$$\sum_{slci=1}^{SLCI} x_{slci}^{SLC} \le 1 \quad \text{(A11)}$$

x_{slci}^{SLC}: Decision variable of available types of solar collector systems $slci = 1, \dots, SLCI$

Building lighting systems:

$$\sum_{li=1}^{LI} x_{li}^{L} = 1 \quad \text{(A12)}$$

$$x_{li}^{L} = \begin{cases} 1, if\ lamp\ type\ li\ is\ selected \\ 0, else \end{cases}$$

x_{li}^{L}: Decision variable of available types of lamps $li = 1, \dots, LI$

Electrical appliances in building:

$$\sum_{eaLP=1}^{EALP} x_{eaLP}^{EA} = 1 \quad \text{(A13)}$$

$$x_{eaLP}^{EA} = \begin{cases} 1, if\ laptop\ type\ eaLP\ is\ selected \\ 0, else \end{cases}$$

x_{eaLP}^{EA}: Decision variable of available types of laptops $eaLP = 1, \ldots, EALP$

$$\sum_{eaPC=1}^{EAPC} x_{eaPC}^{EA} = 1 \tag{A14}$$

$$x_{eaPC}^{EA} = \begin{cases} 1, if\ computer\ type\ eaPC\ is\ selected \\ 0, else \end{cases}$$

x_{eaPC}^{EA}: Decision variable of available types of computers $eaPC = 1, \ldots, EAPC$

Energy consumption (total)

$$Q_T = Q_H + Q_{DHW} + Q_L + Q_A \tag{A15}$$

Q_T: Energy consumption, annual (MJ/year)

Q_H: Energy consumption for heating systems, annual (MJ/year)

Q_{DHW}: Energy consumption for DHW systems, annual (MJ/year)

Q_L: Energy consumption for lighting systems, annual (MJ/year)

Q_A: Energy consumption for electrical appliances, annual (MJ/year)

Total annual energy consumption for heating systems

Primary energy consumption for heating (MJ/year)

$$Q_H = \frac{Q_{el}^{H} f^{grid}}{n_{grid}} + Q_{nel}^{H} \tag{A16}$$

Q_{el}^{H}: Power utilized by an electrical system for heating (MJ/year)

f^{grid}: Power supply from the electrical grid (%)

n_{grid}: The typical efficiency of the power supply from the grid to the building

Q_{nel}^{H}: Power utilized by a non-electrical system for heating (MJ/year)

The power utilized by an electrical heating and heating-DHW system

$$Q_{el}^{H} = Q^{HDY} SEH_{el} \tag{A17}$$

$$SEH_{el} = \sum_{ehsi=1}^{EHSI} \sum_{ehsj=1}^{EHSJ_{ehsi}} \left(\frac{x_{ehsi,ehsj}^{EHS}}{n_{ehsi,ehsj}^{EHS}} \right) + \sum_{ehwsi=1}^{EHWSI} \sum_{ehwsj=1}^{EHWSJ_{ehwsi}} \left(\frac{x_{ehwsi,ehwsj}^{EHWS}}{n_{ehwsi,ehwsj}^{EHWS}} \right) \tag{A18}$$

The energy consumed by a nonelectrical heating and heating-DHW system

$$Q_{nel}^{H} = Q^{HDY} SEH_{nel} \tag{A19}$$

$$SEH_{nel} = \sum_{nehsi=1}^{NEHSI} \sum_{nehsj=1}^{NEHSJ_{nehsi}} \left(\frac{x_{nehsi,nehsj}^{NEHS}}{n_{nehsi,nehsj}^{NEHS}} \right) + \sum_{nehwsi=1}^{NEHWSI} \sum_{nehwsj=1}^{NEHWSJ_{nehwsi}} \left(\frac{x_{nehwsi,nehwsj}^{NEHWS}}{n_{nehwsi,nehwsj}^{NEHWS}} \right) \tag{A20}$$

Q^{HDY}: Heating energy demand, annual (MJ/year)

SEH_{el}: The efficiency an electrical system for heating

SEH_{nel}: The efficiency a non-electrical system for heating

Heating energy demand, annual

$$Q^{HDY} = \sum_{m=1}^{12} Q_m^{HD} \tag{A21}$$

$$Q_m^{HD} = \begin{cases} HS_m F_{conv}\left(Q_{HT,m} + Q_{VEN,m} - Q_{INHG,m} - Q_{SL,m}\right) & if\ positive \\ 0, & else \end{cases} \tag{A22}$$

$$Q_{HT,m} = BLC\left(T_{IH} - T_{o,m}\right)t_m \tag{A23}$$

$$Q_{VEN,m} = \frac{\rho_{air} c_{p_{air}} ACH\ \cdot V\ \cdot \left(T_{IH} - T_{o,m}\right)t_m}{3600} \tag{A24}$$

$$Q_{INHG,m} = \left(n_{people} Q_{people,m} + Q_{eah,m}\right)t_m \tag{A25}$$

$$Q_{SL,m} = \sum_{wn=1}^{WN} \left(A_{wn}^{WIN} F_{F,wn} F_{S,wn} F_{CM,wn} t_{d,m} I_{SL,wn,m} \sum_{z=1}^{Z} (x_z^{WIN} g_z^{WIN}) \right) \tag{A26}$$

Q_m^{HD}: The monthly heat demand (kWh/month)

HS_m: The monthly heating required indicating parameter (binary 0 or 1)

F_{conv}: Conversion factor (MJ/kWh)

$Q_{HT,m}$: Monthly heat loss during transmission (kWh/month)

$Q_{VEN,m}$: Monthly heat loss during ventilation (kWh/month)

$Q_{INHG,m}$: Monthly internal heat gains (kWh/month)

$Q_{SL,m}$: Monthly solar gains (kWh/month)

BLC: Load coefficient of building (W/K)

T_{IH}: Indoor temperature for the heating season (K)

$T_{o,m}$: Outdoor temperature for month *m* (K)

t_m: Month duration in hours (h/month)

ρ_{air}: Air density (kg/m^3)

$c_{p_{air}}$: Heat capacity of air (kJ/kgK)

ACH: Air changes per hour (h^{-1})

V: Interior volume of the building (m^3)

n_{people}: Occupancy count in the building

$Q_{people,m}$: Heat released per person from radiation (W/person)

$Q_{eah,m}$: Heat generated by electrical devices

A_{wn}^{WIN}: Area of window (m^2)

$F_{F,wn}$: Window frame ratio (%)

$F_{S,wn}$: Window shading adjustment factor (%)

$F_{CM,wn}$: Window adjustment factor for movable shades (%)

$t_{d,m}$: Length of the month in days (days/month)

$I_{SL,wn,m}$: Solar radiation on the window at a specific tilt and orientation (kWh/m^2/day)

g_z^{WIN}: Effective total solar energy transmittance (%) for window type z

Building load coefficient

$$BLC = \sum_{dr=1}^{DR}(A_{dr}^{DOOR}b_{dr}^{DOOR})\sum_{d=1}^{D}(x_d^{DOOR}U_d^{DOOR}) + \sum_{wn=1}^{WN}(A_{wn}^{WIN}b_{wn}^{WIN})\sum_{z=1}^{Z}\sum_{t=1}^{T_z}(x_{zt}^{WIN}U_{zt}^{WIN}) + \sum_{wl=1}^{WL}(A_{wl}^{WALL}b_{wl}^{WALL})\sum_{w=1}^{W}(x_w^{WALL}U_w^{WALL}) + \sum_{ce=1}^{CE}(A_{ce}^{CEIL}b_{ce}^{CEIL})\sum_{r=1}^{R}(x_r^{CEIL}U_r^{CEIL}) + \sum_{fl=1}^{FL}\left(A_{fl}^{FLO}b_{fl}^{FLO}\right)\sum_{h=1}^{H}(x_h^{FLO}U_h^{FLO}) \quad (A27)$$

$$U_d^{DOOR} = \left(\frac{1}{h_i} + \frac{1}{U_{value,d}} + \frac{1}{h_o}\right)^{-1} \quad (A28)$$

$$U_z^{WIN} = \left(\frac{1}{h_i} + \frac{1}{U_{value,z}} + \frac{1}{h_o}\right)^{-1} \quad (A29)$$

$$U_w^{WALL} = \left(\frac{1}{h_i} + \sum_{y=1}^{Y_w}\left(\frac{l_{w,y}^{WALL}}{kk_{w,y}^{WALL}}\right) + \sum_{p=1}^{P_w}\left(\frac{l_{w,p}^{mWALL}}{k_{w,p}^{mWALL}}x_{w,p}^{mWALL}\right) + \frac{1}{h_o}\right)^{-1} \quad (A30)$$

$$U_r^{CEIL} = \left(\frac{1}{h_i} + \sum_{f=1}^{F_r}\left(\frac{l_{r,f}^{CEIL}}{kk_{r,f}^{CEIL}}\right) + \sum_{a=1}^{A_r}\left(\frac{l_{r,a}^{mCEIL}}{k_{r,a}^{mCEIL}}x_{r,a}^{mCEIL}\right) + \frac{1}{h_o}\right)^{-1} \quad (A31)$$

$$U_h^{FLO} = \left(\frac{1}{h_i} + \sum_{e=1}^{E_h}\left(\frac{l_{h,e}^{FLO}}{kk_{h,e}^{FLO}}\right) + \sum_{g=1}^{G_h}\left(\frac{l_{h,g}^{mFLO}}{k_{h,g}^{mFLO}}x_{h,g}^{mFLO}\right) + \frac{1}{h_o}\right)^{-1} \quad (A32)$$

Primary energy usage for domestic hot water

$$Q_{DHW} = \frac{Q_{el}^{W}f^{grid}}{n_{grid}} + Q_{nel}^{W} \quad (A33)$$

Q_{el}^{W}: Energy consumed by an electrical system for DHW (MJ/year)

Q_{nel}^{W}: Energy consumed by a non-electrical system for DHW (MJ/year)

Primary energy consumption electrical DHW and heating-DHW system

$$Q_{el}^{W} = Q^{WD}SEW_{el} \quad (A34)$$

$$SEW_{el} = \sum_{ewsi=1}^{EWSI}\sum_{ewsj=1}^{EWSJ_{ewsi}}\left(\frac{x_{ewsi,ewsj}^{EWS}}{n_{ewsi,ewsj}^{EWS}}\right) + \sum_{ehwsi=1}^{EHWSI}\sum_{ehwsj=1}^{EHWSJ_{ehwsi}}\left(\frac{x_{ehwsi,ehwsj}^{EHWS}}{n_{ehwsi,ehwsj}^{EHWS}}\right) \quad (A35)$$

Primary energy consumption non-electrical DHW and heating-DHW system

$$Q_{nel}^{W} = Q^{WD} SEW_{nel} \tag{A36}$$

$$SEW_{nel} = \sum_{newsi=1}^{NEWSI} \sum_{newsj=1}^{NEWSJ_{newsi}} \left(\frac{x_{newsi,newsj}^{NEWS}}{n_{newsi,newsj}^{NEWS}} \right) + \sum_{nehwsi=1}^{NEHWSI} \sum_{nehwsj=1}^{NEHWSJ_{nehwsi}} \left(\frac{x_{nehwsi,nehwsj}^{NEHWS}}{n_{nehwsi,nehwsj}^{NEHWS}} \right) \tag{A37}$$

Q^{WD}: The total annual DHW energy demand (MJ/year)

SEH_{el}: The efficiency an electrical system for DHW

SEH_{nel}: The efficiency a non-electrical system for DHW

The total annual hot water energy demand

$$Q^{WD} = \sum_{m=1}^{12} (DQ_m^{DHW}) \tag{A38}$$

$$DQ_m^{DHW} = \begin{cases} WS_m F_{conv} \left(Q_{dhwu,m} - Q_{dSLC,m} \right), if\ Q_{dhwu,m} \geq Q_{dSLC,m} \\ 0, \qquad else \end{cases} \tag{A39}$$

$$Q_{dhwu,m} = \dot{m}_w \rho_w c_{p_w} \left(T_{DHW} - T_{DCW,m} \right) t_m \tag{A40}$$

$$Q_{dSLC,m} = F_{conv} A_{SLC} F_{S,SLC} I_{SL,SLC,m} t_d \sum_{slci=1}^{SLCI} x_{slci}^{SLC} n_{slci}^{SLC} \tag{A41}$$

WS_m: Parameter indicating whether domestic hot water is needed for month m (binary variable)

$Q_{dhwu,m}$: Average monthly demand for domestic hot water supply (MJ/month)

$\dot{m}_w$: Daily rate of hot water consumption (m^3/s)

ρ_w: The density of water (kg/m^3)

c_{p_w}: Heat capacity of water (kJ/kg K)

T_{DHW}: The base temperature set for the domestic hot water system (K)

$T_{DCW,m}$: The temperature of the cold water supply during month m (K)

$Q_{dSLC,m}$: The monthly hot water demand (MJ/month) supplied by a solar collector system

A_{SLC}: Area of the solar collector (m^2)

$F_{S,SLC}$: Adjustment factor for shading (%)

$I_{SL,SLC,m}$: Solar radiation received by a solar collector of type *slci* at a specific tilt and orientation ($kWh/m^2/day$)

n_{slci}^{SLC}: solar collector type *slci* efficiency (%)

Primary energy consumption for lighting

$$Q_L = \frac{Q_{el}^{L} f^{grid}}{n_{grid}} \tag{A42}$$

$$Q_{el}^{L} = Q^{LDY} SEL_{el} \tag{A43}$$

$$Q^{LDY} = \sum_{m=1}^{12} Q_m^{LD} \tag{A44}$$

$$Q_m^{LD} = F_{conv} t_{d,m} \sum_{l=1}^{L} \left(P_{L,l} f_{use,l}\right) \sum_{li=1}^{LI} x_{li}^{L} \tag{A45}$$

Q_{el}^{L}: Annual electrical energy consumed for lighting (MJ/year)

Q^{LDY}: Total annual demand for electricity for lighting (MJ/year)

$P_{L,l}$: Power rating of the lamp (kW)

$f_{use,l}$: Duration of device usage (h/day)

Primary energy usage for electrical appliances

$$Q_A = \frac{Q_{el}^{A} f^{grid}}{n_{grid}} \tag{A46}$$

$$Q_{el}^{A} = Q^{ADY} SEA_{el} \tag{A47}$$

$$Q^{ADY} = \sum_{m=1}^{12} Q_m^{AD} \tag{A48}$$

$$Q_m^{AD} = F_{conv} t_{d,m} \sum_{eaj=1}^{EAJ} \left(P_{A,eaj} f_{useEA,eaj} f_{load,eaj} x_{eaj}^{EA}\right) \tag{A49}$$

Q_{el}^{A}: Annual electricity usage for operating electrical appliances (MJ/year)

Q^{ADY}: Total annual electricity demand for operating electrical appliances (MJ/year)

$P_{A,eaj}$: Power rating of the electrical appliance (W)

$f_{useEA,eaj}$: Duration of device operation (h/day)

$f_{load,eaj}$: Load ratio of the device (%)

The total annual electricity demand

$$Q_{EL}^{D} = Q_{el}^{H} + Q_{el}^{W} + Q_{el}^{L} + Q_{el}^{A} \tag{A50}$$

Total initial investment cost

$$\begin{aligned} INVCOST = {} & COST_{DOR} + COST_{WIN} + COST_{WAL} + COST_{CEIL} + COST_{FLO} + COST_{HS} + COST_{WS} \\ & + COST_{HWS} + COST_{SLC} + COST_{LIGHT} + COST_{EA} \end{aligned} \tag{A51}$$

$$COST_{DOR} = \sum_{dr=1}^{DR} (A_{dr}^{DOOR}) \sum_{d=1}^{D} (x_d^{DOOR} c_d^{DOOR}) \tag{A52}$$

$$COST_{WIN} = \sum_{wn}^{WN} (A_{wn}^{WIN}) \sum_{z=1}^{Z} (x_z^{WIN} c_z^{WIN}) \tag{A53}$$

$$COST_{WAL} = \sum_{wl=1}^{WL} (A_{wl}^{WALL}) \sum_{w=1}^{W} \left(x_w^{WAL} \left(\sum_{y=1}^{Y_w} \left(CK_{w,y}^{mWALL}\right) + \sum_{p=1}^{P_w} (x_{w,p}^{mWALL} C_{w,p}^{mWALL}) \right) \right) \tag{A54}$$

$$COST_{CEIL} = \sum_{ce=1}^{CE} (A_{ce}^{CEIL}) \sum_{r=1}^{R} \left(x_r^{CEIL} \left(\sum_{f=1}^{F_r} \left(CK_{r,f}^{mCEIL}\right) + \sum_{a=1}^{A_r} (x_{r,a}^{mCEIL} C_{r,a}^{mCEIL}) \right) \right) \tag{A55}$$

$$COST_{FLO} = \sum_{fl=1}^{FL}\left(A_{fl}^{FLO}\right)\sum_{h=1}^{H}\left(x_h^{FLO}\left(\sum_{e=1}^{E_h}\left(CK_{h,e}^{mFLO}\right)+\sum_{g=1}^{G_h}\left(x_{h,g}^{mFLO}C_{h,g}^{mFLO}\right)\right)\right) \quad (A56)$$

$$COST_{HS} = \sum_{ehsi=1}^{EHSI}\sum_{ehsj=1}^{EHSJ_{ehsi}}\left(x_{ehsi,ehsj}^{EHS}CST_{ehsi,ehsj}^{EHS}\right)+\sum_{nehsi=1}^{NEHSI}\sum_{nehsj=1}^{NEHSJ_{nehsi}}\left(x_{nehsi,nehsj}^{NEHS}CST_{nehsi,nehsj}^{NEHS}\right) \quad (A57)$$

$$COST_{WS} = \sum_{ewsi=1}^{EWSI}\sum_{ewsj=1}^{EWSJ_{ewsi}}\left(x_{ewsi,ewsj}^{EWS}CST_{ewsi,ewsj}^{EWS}\right)+\sum_{newsi=1}^{NEWSI}\sum_{newsj=1}^{NEWSJ_{newsi}}\left(x_{newsi,newsj}^{NEWS}CST_{newsi,newsj}^{NEWS}\right) \quad (A58)$$

$$COST_{HWS} = \sum_{ehwsi=1}^{EHWSI}\sum_{ehwsj=1}^{EHWSJ_{ehwsi}}\left(x_{ehwsi,ehwsj}^{EHWS}CST_{ehwsi,ehwsj}^{EHWS}\right) + \sum_{nehwsi=1}^{NEHWSI}\sum_{nehwsj=1}^{NEHWSJ_{nehwsi}}\left(x_{nehwsi,nehwsj}^{NEHWS}CST_{nehwsi,nehwsj}^{NEHWS}\right) \quad (A59)$$

$$COST_{SLC} = \sum_{slci=1}^{SLCI}\left(x_{slci}^{SLC}CST_{slci}^{SLC}\right) \quad (A60)$$

$$COST_{LIGHT} = L\sum_{li=1}^{LI}\left(x_{li}^{L}CST_{li}^{L}\right) \quad (A61)$$

$$COST_{EA} = \sum_{eaj=1}^{EAJ}x_{eaj}^{EA}CST_{eaj}^{EA} \quad (A62)$$

A_{dr}^{DOOR}: Area of door *dr* [m^2]

A_{wn}^{WIN}: Area of window *wn* [m^2]

A_{wl}^{WALL}: Area of wall *wl* [m^2]

A_{ce}^{CEIL}: Area of ceiling *ce* [m^2]

A_{fl}^{FLO}: Area of floor *fl* [m^2]

c_d^{DOOR}: cost of a type *d* door [\$/m^2]

c_z^{WIN}: cost of a type z window [\$/m^2]

$CK_{w,y}^{mWALL}$: Total investment costs for the materials used in the known layers y of wall structure w [\$/m^2]

$C_{w,p}^{mWALL}$: Total investment costs for the materials used in the unknown layers p of wall structure w [\$/m^2]

$CK_{r,f}^{mCEIL}$: Total investment costs for the materials used in the known layers f of ceil structure r [\$/m^2]

$C_{r,a}^{mCEIL}$: Total investment costs for the materials used in the unknown layers a of ceil structure r [\$/m^2]

$CK_{h,e}^{mFLO}$: Total investment costs for the materials used in the known layers e of floor structure h [\$/m^2]

$C_{h,g}^{mFLO}$: Total investment costs for the materials used in the unknown layers g of floor structure h [\$/m^2]

$CST_{ehsi,ehsj}^{EHS}$: Total investment cost for the electrical heating system ehsj of category ehsi [\$]

$CST_{nehsi,nehsj}^{NEHS}$: Total investment cost for the non-electrical heating system nehsj of category nehsi [\$]

$CST_{ewsi,ewsj}^{EWS}$: Total investment cost for the electrical DHW system ewsj of category ewsi [\$]

$CST_{newsi,newsj}^{NEWS}$: Total investment cost for the non-electrical heating-DHW system nehwsj of category nehwsi [\$]

$CST_{ehwsi,ehwsj}^{EHWS}$: Total investment cost for the electrical heating-DHW system ehwsj of category ehwsi [\$]

$CST^{NEHWS}_{nehwsi,nehwsj}$: Total investment cost for the non-electrical heating-DHW system nehwsj of category nehwsi [$]

CST^{SLC}_{slci}: Total investment cost for the solar collector system slci [$]

CST^{L}_{li}: Total investment cost for the lamp li [$]

CST^{EA}_{eaj}: Total investment cost for the electrical appliances eaj [$]

2.2. Constraints

By structuring the constraints, we must ensure that the energy demands for heating, DHW, lighting, and appliances are adequately met while allowing for the appropriate selection and optimization of equipment. This balanced approach will lead to more effective energy management in campus buildings equations A16 through A62.

2.3. Parameters

To effectively structure an optimization model, it is essential to clearly define the parameters that will be input by the decision-maker. We can divide the parameters of our model into the Parameters Required for Energy Demand Calculations, Parameters Required for Primary Energy Consumption Calculations, and Cost Parameters for Investment Calculations. Parameters Required for Energy Demand Calculations depend on the air temperature, solar radiation and its duration, the temperature of the water used, the number of building users, and the parameters of the building envelope. Parameters Required for Primary Energy Consumption Calculations depend on the number of lamps and electrical appliances, the duration of use of lamps and electrical appliances, and their efficiency. Cost Parameters for Investment Calculations depend on the investment cost of materials and technologies given in Tables A-1 – A-9.

Table A-1. Door types (Diakaki & Grigoroudis, 2021)

Type	Thermal Transmittance (W/m^2 °C)	Cost ($/$m^2$)
Double Wing Photocell Door (available)	3.1	0
Metal Heat Insulated Door	4	1220.43
Hollow-Core Flush Door	2.7	859.28
Solid-Core Flush Door with Single Glazing	2.1	1074.1

Table A-2. Window types (Diakaki & Grigoroudis, 2021)

Type	Thermal Transmittance (W/m^2 °C)	Effective Total Solar Energy Transmittance (%)	Cost ($/$m^2$)
Double glazing 4-10-4, coated, air filled (available)	2.7	0.7	0
Single Typical glazing	5	0.8	44.53
Double glazing 4-20-4, uncoated, air filled	2.6	0.72	61.23
Double glazing 4-12-4, coated, argon filled	1.6	0.76	72.36

Table A-3. Wall types (Diakaki & Grigoroudis, 2021)

Material	Thickness (m)	Thermal Transmittance (W/m² °C)	Cost ($/m²)
Brick (available)	0.09	0.45	0
Coat (available)	0.01	0.51	0
Plaster (available)	0.013	0.7	0
Stonewool	0.03	0.04	24.61
Humid	0.0004	0.02	10.07
Isolation Band	0.00013	0.032	0.33
Bondeks	0.025	0.02	17.51
Eps	0.0005	0.24	2.07

Table A-4. Ceiling types (Diakaki & Grigoroudis, 2021)

Material	Thickness (m)	Thermal Transmittance (W/m² °C)	Cost ($/m²)
Concrete (available)	0.15	0.72	0
Box Profile	0.0006	0.032	3.05
Stonewool	0.012	0.04	15.07
Galvanized Carrier	0.0009	0.405	61
Green Plasterboard	0.0125	0.035	50.85
White Plasterboard	0.0125	0.03	11.92
Ekstrude	0.01	0.031	42.72

Table A-5. Floor types (Diakaki & Grigoroudis, 2021)

Material	Thickness (m)	Thermal Transmittance (W/m² °C)	Cost ($/m²)
Cement (available)	0.03	1.4	0
Slope Concrete	0.025	0.11	1
Bitumex Membrane	0.002	0.55	70.488
Roofmate Sl	0.0032	0.031	91.5
Rigid Polyurethane Foam	0.03	0.035	4.88
Stonewool	0.01	0.042	193.34

Table A-6. Heating Systems (Diakaki & Grigoroudis, 2021)

Type	Efficiency (%)	Cost ($/m²)
Electrical Resistance-based, Dry core storage boiler type 1	100	5370.49
Electrical Resistance-based, Dry core storage boiler type 2	85	4511.21
Non-electrical Oil-based, Condensing	83	5692.72
Non-electrical Oil-based, Standard oil boiler	62	5048.26
Non-electrical Natural-gas based, Condensing (available)	85	0
Non-electrical Natural-gas based, Floor mounted boiler	55	4833.44

Table A-7. Heating-DHW Systems (Diakaki & Grigoroudis, 2021)

Type	Efficiency (%)	Cost ($/m²)
Electrical Resistance-based, Electric CPSU	100	7733.51
Electrical Resistance-based, Water storage boiler	85	6229.77
Non-electrical Oil-based, Condensing combi	81	6659.41
Non-electrical Oil-based, Combi	70	6229.77
Non-electrical Natural-gas based, Condensing combi	84	7733.51
Non-electrical Natural-gas based, Combi	65	6122.36

Table A-8. DHW Systems (Diakaki & Grigoroudis, 2021)

Type	Efficiency (%)	Cost ($/m²)
Electrical Resistance-based, Electric immersion	100	1288.92
Electrical Resistance-based, Electric instantaneous at point of use	85	1074.1
Non-electrical Oil-based, Oil boiler/circulator	80	1074.1
Non-electrical Oil-based, Oil single burner	60	859.28
Non-electrical Natural-gas based, Circulator built into a gas warm air system type 1	73	912.98
Non-electrical Natural-gas based, Circulator built into a gas warm air system type 2	60	698.16

Table A-9. Solar Collector Systems (Diakaki & Grigoroudis, 2021)

Type	Efficiency (%)	Cost ($/m²)
Flat collector Type 1	90	966.69
Flat collector Type 2	80	644.46
Vacuum hear pipe CPC collector Type 1	72	837.8
Vacuum hear pipe CPC collector Type 2	67	537.05

2.4. Objective functions

To improve the energy efficiency of a campus building, it is necessary to minimize energy consumption and do so at minimal cost. For this reason, the objective functions of our study are to minimize the primary energy consumption and to minimize the investment cost as follows equations A63 and A64:

$$\min[g_1(\boldsymbol{x})] = Q_T \tag{A63}$$

$$\min[g_2(\boldsymbol{x})] = INVCOST \tag{A64}$$

Where $g_1(\boldsymbol{x})$ represents the total annual consumption of primary energy and $g_2(\boldsymbol{x})$ is the total investment cost.

The total annual consumption of primary energy in the campus building includes energy used for heating systems, domestic hot water (DHW) systems, lighting systems, and electrical appliances, providing a comprehensive overview of the building's energy use. In some cases campus buildings have cooling systems, then the calculation can be extended to include the cooling system data in the formulation. Total investment cost consists of the cost of materials for doors, windows, walls, ceilings, and floors, and the cost of purchasing and installing heating systems, hot water supply, solar collector, lighting, and electrical appliances.

2.5. Case Study

The calculations for this study were performed for the R&D Park Building of Erciyes University. The technical details of the building are presented in Table 2. The sample building comprises three blocks and is actively utilized by both academics and students. As illustrated in Figure 2, the optimization calculation is performed for a single input block.

Table 2. Technical details of the R&D Park Building of Erciyes University (Authors)

Total Volume	13,047.44 m³
Total Wall Area	1,279.407 m² (excluding windows and doors)
Total Floor Area	1,412.41 m²
Total Ceiling Area	1,412.41 m²
Windows	350 (each 0.7 m²)
Doors	1 (6.89 m²)
Occupancy	110 people

Figure 2. R&D Park Building of Erciyes University (Earth, 2024)

Details on the selection of building materials and technology are provided below. Data on existing and alternative types of doors and windows in the building can be found in equations A1 through A62. Information regarding existing and alternative materials for walls, ceilings, and floors is presented in Tables A-3 to A-5. Additionally, data on existing and alternative heating systems are included in Tables A-6 and A-7, while alternative domestic hot water (DHW) systems are detailed in Tables A-7 and A-8. Finally, information on alternative solar collector systems is available in Table A-9.

3. Findings and Discussion

The model's calculations were executed using the GAMS programming language, employing SCIP and LINDO solvers. The results from both solvers yielded very close values, differing by only 0.2%, ultimately leading the model to produce the optimal solution. The optimal results obtained are presented in Table 3 and illustrated in Figure 3. As shown in Figure 3, energy consumption declines as investment costs rise. As the building's heating system is the most efficient option available, the model did not suggest any changes. However, since the building lacks a hot water system, it is advisable to install the most efficient type of boiler for hot water.

Table 3. Data on primary energy consumption and initial investment costs (Authors)

QT (MJ/year)	INVCOST ($)	QT (MJ/year)	INVCOST ($)	QT (MJ/year)	INVCOST ($)
1240450000.00	**127544.00**	2005750000.00	87378.20	2091830000.00	36118.80
1241490000.00	120144.00	2005850000.00	86828.20	2091910000.00	34892.80
1283850000.00	115641.00	2045570000.00	53847.00	2092660000.00	32862.70
1286720000.00	108966.00	2045690000.00	52447.00	2092860000.00	28718.20
1287740000.00	103382.00	2045570000.00	53847.00	2647600000.00	23590.70
1842480000.00	97287.90	2046240000.00	51516.90	2648440000.00	20334.60
1843140000.00	94957.80	2046340000.00	50966.90	2648820000.00	14575.30
1843340000.00	94271.90	2046610000.00	46446.40	3277620000.00	11891.50
1843520000.00	89887.40	2088780000.00	43719.60	3277350000.00	9859.97
1843550000.00	88876.30	2088970000.00	41943.60	**3277520000.00**	**8934.03**

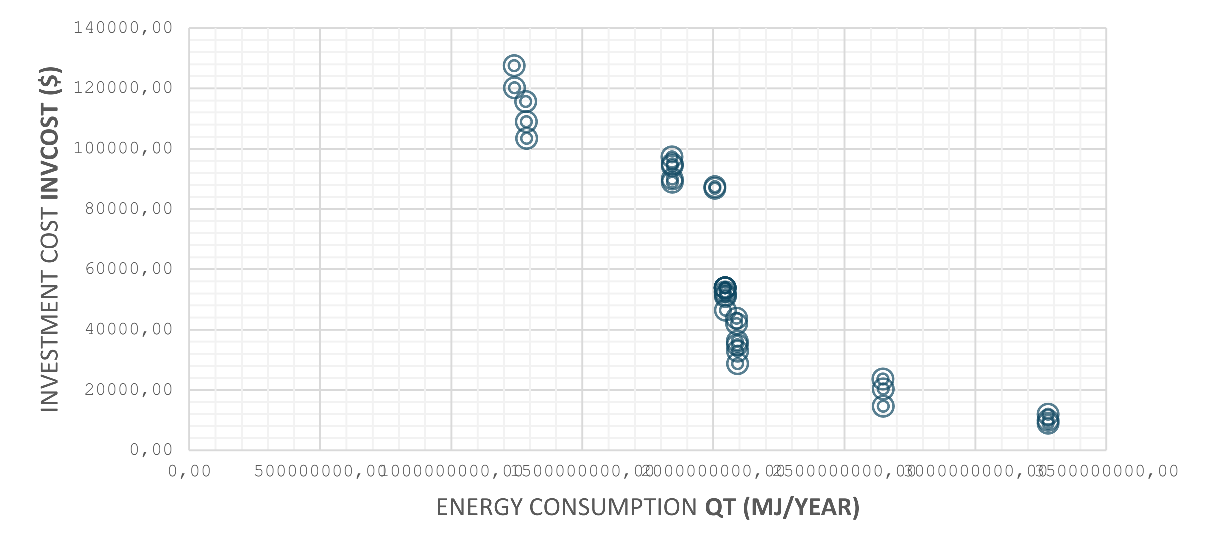

Figure 3. Chosen feasible solution values for primary energy consumption and initial investment cost (Authors)

The building's energy consumption is predominantly attributed to heating, with an annual usage of 5,044,230,000 MJ/year. Analyses indicate that a minimum investment of $8,934.03 in insulation materials could yield a 35% reduction in energy consumption per year by enhancing the thermal performance of the building envelope. Additionally, the replacement of existing insulation and heating technologies with advanced, energy-efficient alternatives is projected to incur a cost of $127,544. Implementing these upgrades is expected to achieve a significant reduction of 75.5% in the building's annual energy consumption (Figure 4).

Due to the absence of a hot water system in the building, the model identified and recommended the most cost-effective and energy-efficient technologies for implementation (Figure 5). 572 lamps currently installed have not been replaced, as they were upgraded to energy-efficient types during recent renovations. Additionally, it is recommended to replace the existing desktop computers with energy-efficient models, which would further optimize the building's overall energy consumption and efficiency (Figure 6). The selection of optimal energy-efficient measures leads to a significant reduction in energy demand, resulting in substantial primary energy savings.

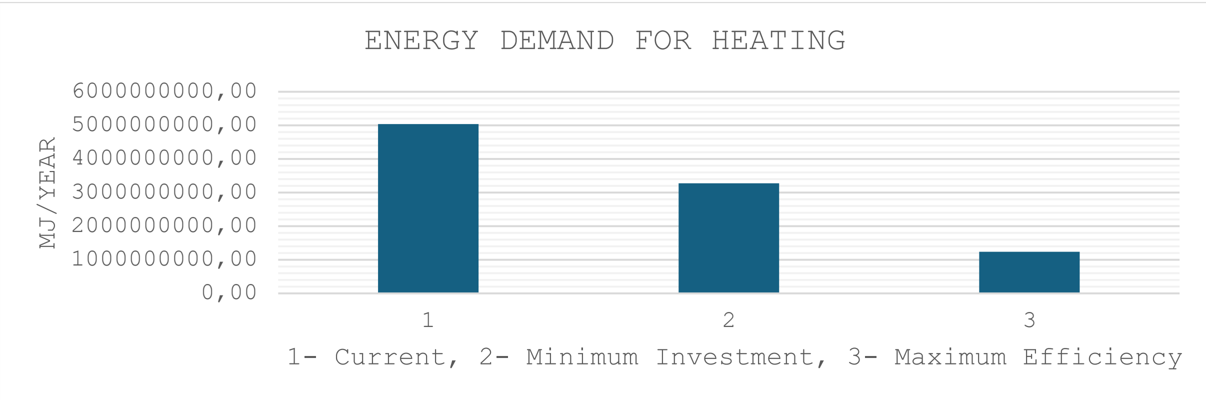

Figure 4. Annual heating energy demand before and after the retrofit (Authors)

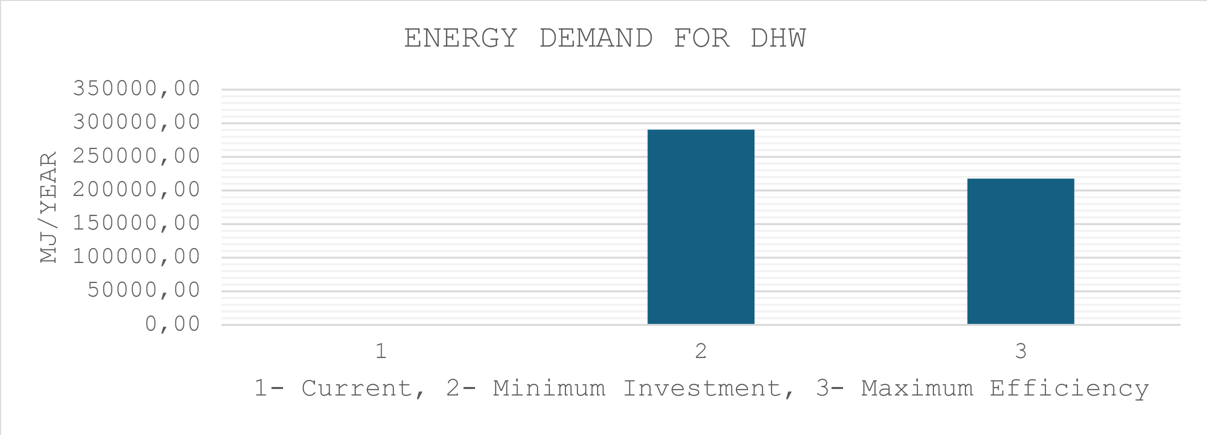

Figure 5. Annual energy demand for DHW systems before and after the retrofit (Authors)

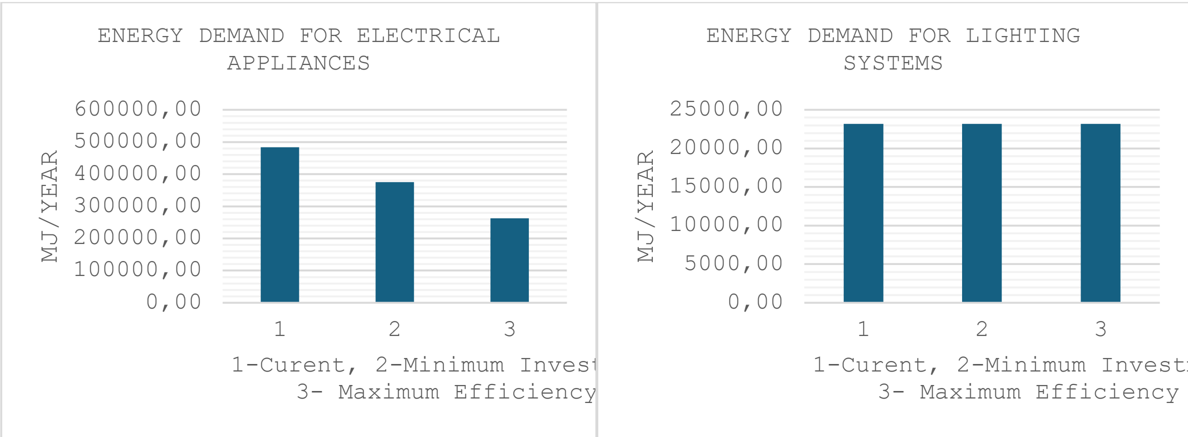

Figure 6. Annual energy demand for Electrical Appliances and Lighting Systems before and after the retrofit (Authors)

4. Conclusion and Suggestions

The scope of this article is prioritizing energy efficiency measures specifically within university campus buildings. By evaluating these measures in terms of their energy performance and initial costs, the framework aims to provide campus decision-makers with a clear strategy for implementing effective energy-saving interventions. This approach not only addresses the unique energy demands of campus facilities but also aligns with institutional sustainability goals. By optimizing energy efficiency, universities can significantly reduce operational costs, minimize their environmental impact, and create a more sustainable campus environment for students and faculty alike.

This study uses the SCIP and LINDO algorithms to address the MINLP multi-objective problem. To enhance energy efficiency on the university campus, future investigations should explore the integration of renewable energy sources, such as solar photovoltaic systems and wind turbines, into the existing energy infrastructure. This integration can reduce reliance on fossil fuels and lower greenhouse gas emissions. Additionally, further studies can examine the design and implementation of optimal parking solutions for electric vehicles, including the installation of charging stations and the allocation of space to encourage electric vehicle adoption.

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Author Contribution and Conflict of Interest Declaration Information

All authors contributed equally to the article. There is no conflict of interest.

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