Modeling energy consumption and heat exchange of buildings

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Abstract

This research thesis investigates energy consumption and thermal dynamics in buildings, with a focus on achieving energy efficiency and indoor comfort in cold-climate regions like Norway. There is a necessity for the exploration of innovative approaches to combat energy waste and reduce consumption[22].

Understanding various factors, including energy usage patterns, occupant behavior, climate conditions, heat transfer characteristics, and ventilation requirements, is crucial for energy optimization. This thesis presents the development of a continuous-time mathematical heating model for a building unit based on discretized formulas of mass and energy balances. To achieve precise predictions, the model integrates a correlation between numerical and analytical results. The model simulates indoor temperature under various scenarios and environments. The model simulates the building's response and tests its adaptability to different parameters to test its accuracy.

Diverse buildings with varying criteria are also included to evaluate the model's behavior under different conditions. The study explores the dynamic heating models integrating smart sensors and energy control units to address heating challenges and improve energy efficiency. Findings hold relevance beyond Norway, offering valuable insights for other regions. The model's versatility paves the way for further research by validating the model with additional data, analyzing energy efficiency for various building designs, and evaluating its performance in complex residential buildings.

Abbreviations

UiS University of Stavanger

NORCE Norwegian Research Centre

ODE Ordinary differential equation

TEK10 Norwegian Building Acts and Reg

K Kelvin

W Watt

kg kilogram

C Capacitance

R Resistance

J Joule

Pa Pascal

CSV Comma separated values

ISO International Organization for Standardization

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Chapter 1

Introduction

The ever-increasing energy demand and the detrimental impact of greenhouse gases are pressing issues in today's world. With the rise of renewable energy sources, there is a growing opportunity to mitigate the impact of greenhouse gases on the planet [13]. Despite the rise of renewable energy sources, simply relying on renewable infrastructure alone cannot meet future energy demands. The current options for addressing energy needs boil down to a choice between tackling energy poverty or continuing to rely on fossil fuels and greenhouse gases, with their associated environmental consequences [4]. Heating, cooling, and lighting are the primary consumers of energy in buildings. In northern countries, such as Scandinavian nations, heating is particularly significant due to the cold climate conditions that persist for a considerable portion of the year. As a result, there is a higher demand for energy to provide heating in buildings. To address this issue, governments have implemented regulatory policies aimed at reducing energy consumption in the building sector. In order to improve energy efficiency and decrease energy usage, it is crucial to understand various factors, including energy usage patterns, occupant behavior, appliance operation, climate conditions, heat transfer characteristics, and ventilation requirements. By gaining insight into these aspects, effective strategies can be developed to optimize energy consumption and enhance overall energy efficiency in buildings [22].

1.1 Buildings in Norway

Norway has been actively working towards reducing energy consumption in buildings and promoting energy efficiency. The country's cold climate and high heating demands make energy consumption a significant concern. According to the Norwegian Ministry of Petroleum and Energy, buildings in Norway account for a substantial portion of energy consumption. To achieve both indoor comfort and energy efficiency, precise heating strategies are essential [19]. The Norwegian Building Code, specifically the TEK10 regulations, provides guidelines to optimize energy economy and thermal comfort. Wood is a popular construction material in Norway due to its ability to withstand changing weather conditions, and wooden houses with low thermal mass exhibit reduced heating demands in cold climates. Building components such as walls, floors, and roofs consist of multiple layers of different materials, including insulation, vapor barriers, and cladding. Compliance with TEK10 requires maintaining low overall heat transfer coefficients for walls, roofs, floors, and windows/doors [1].

Even so, the energy consumption associated with buildings, particularly for heating purposes, has emerged as a significant concern. To address these issues, optimizing energy consumption while maintaining optimal thermal comfort has become a priority. One approach to achieving this optimization is through the implementation of dynamic heating models, which integrate smart sensors and energy control units to track and optimize energy usage in buildings. The knowledge and recommendations conveyed on energy efficiency in cold climates have broad implications beyond the Norwegian context, making them highly relevant for diverse regions and countries aiming to optimize energy efficiency in their built environments. Overall, while there may be deviations from the planned energy reduction targets outlined in the national code, there has been an overall improvement in energy use within the residential building sector in Norway [18].

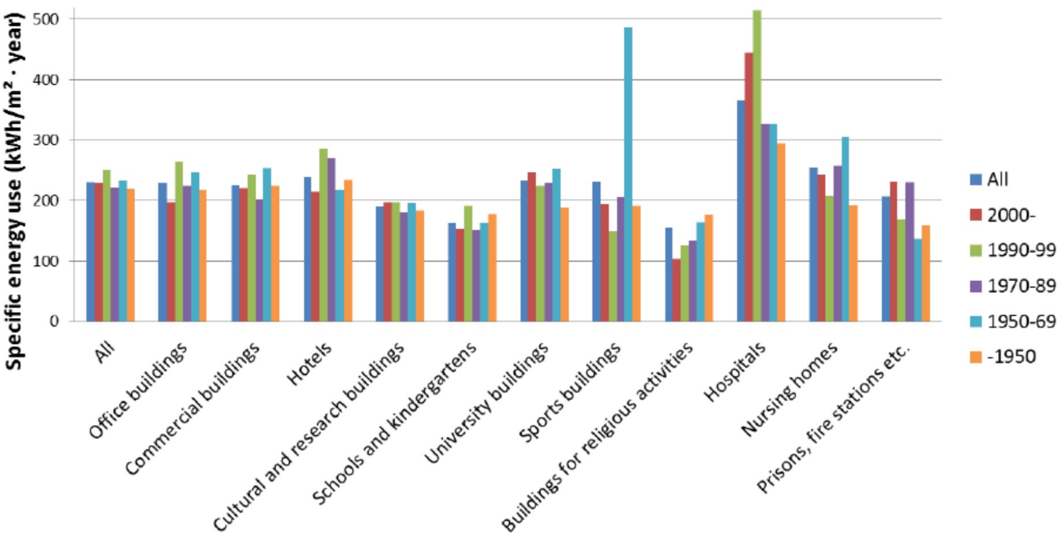


Figure 1.1: Norwegian statistical data on energy use in commercial buildings [18]

When it comes to solar energy, Norway experiences an annual average solar irradiation of approximately 100 W/m^2. However, during the cold winter periods, solar irradiation can drop below this average value. Solar irradiation refers to the amount of solar energy received per unit area on the Earth's surface. The average value indicates the typical solar energy flux reaching Norway throughout the year. During colder seasons, such as winter, weather conditions and reduced daylight hours can lead to a decrease in solar irradiation, which affects the amount of solar energy available for heating and other purposes [20].

1.2 Literature Review

Buildings worldwide are significant consumers of energy, with heating being a major contributor to their energy usage. This is especially evident in regions like Norway, characterized by cold climates that necessitate extensive heating for maintaining comfortable indoor environments. However, the energy consumption associated with heating presents several challenges, including high costs and adverse environmental impacts.

Extensive research conducted by reputable organizations like the International Energy Agency (IEA) has revealed that buildings account for approximately 40% of global energy consumption and contribute significantly to carbon dioxide emissions, making energy optimization in this sector a pressing concern [9]. The imperative to reduce energy consumption in buildings extends beyond financial implications for owners and occupants; it is a critical step in mitigating greenhouse gas emissions and addressing climate change on a global scale.

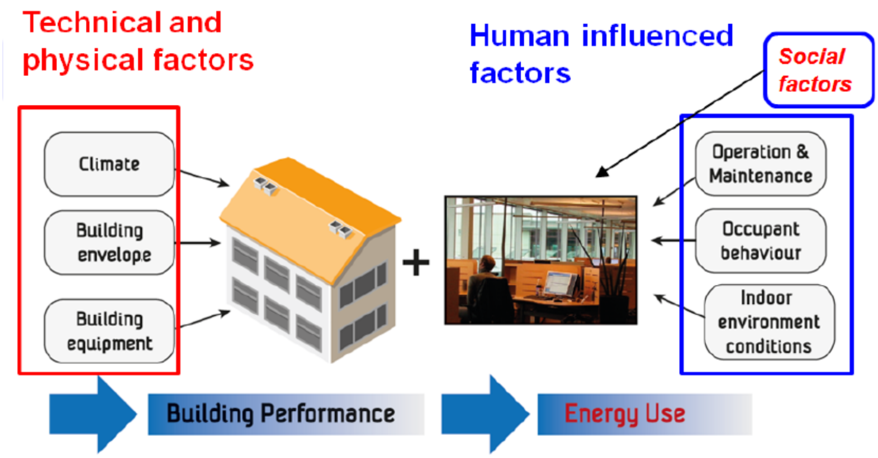


Figure 1.2: Influencing factors on building energy use [18].

To address the need for energy optimization, researchers and industry professionals are increasingly focusing on developing innovative strategies. The integration of smart sensors and energy control units has revolutionized the monitoring and management of heating systems in buildings [2]. These advanced sensors enable real-time tracking of temperature variations, occupancy patterns, and electricity consumption, providing valuable insights into energy usage patterns and identifying areas for improvement.

Smart building technologies, coupled with accurate thermal modeling and simulation, offer promising solutions for achieving sustainable and comfortable built environments. Chen [3] explored the role of smart building technologies in enhancing energy efficiency and occupant comfort. Their study analyzed the integration of Internet of Things (IoT) devices and sensors in buildings to optimize heating, cooling, and lighting systems based on real-time data. Results showed that smart technologies led to energy savings of up to 20% and provided personalized thermal comfort for occupants. The literature related to the heat transfer phenomenon inside a ventilated air space has been explored through a data-based mechanistic model [5]. There have been identified challenges in retrofitting existing buildings to improve energy efficiency [28].

Furthermore, the research landscape showcases a diverse collection of publications centered around simulating the heat dynamics of building units. Notably, most of these studies utilize proprietary software integrated with Computational Fluid Dynamics (CFD) methods [27]. Prior research has also focused on modeling the air temperature and floor temperature for a single-story non-ventilated two-zone building unit. Additionally, detailed investigations have been conducted to analyze the thermal energy released to the building interior by solar radiation. [22].

Despite the progress made in modeling building thermal behavior, there remains a critical gap in adequately capturing the heat loss. In fact, due to many complex and random factors, it is intractable to develop an explicit building thermal dynamics model that is accurate and efficient enough for building control [21]. However, ventilation is a vital aspect of building design, as it affects indoor air quality and occupant comfort. The lack of accurate representation of ventilation-related heat loss in current models limits their ability to provide precise predictions of energy consumption in real-world scenarios.

To optimize building energy efficiency and thermal comfort, it is crucial to address this limitation and incorporate ventilation heat loss in dynamic building models [14]. By doing so, researchers can gain valuable insights into the impact of ventilation strategies on overall energy consumption and indoor thermal conditions. Moreover, this improvement can guide the development of energy-efficient building designs and inform policymakers on effective energy-saving measures.

1.3 Analyzing Thermal Behavior

The mathematical description of thermal behavior in building systems is complex due to the interconnectedness of multiple subsystems, each with its own characteristics and uncertainties. Factors such as convection coefficients, material properties, and external perturbations like weather conditions and energy sources need to be considered. Building modeling involves analyzing thermal comfort and energy consumption, and various software tools are available for building simulation. With advancements in computer processing power, using mathematical packages has become a viable option for simulation-based building thermal analysis [16]. Python is a versatile programming language with a wide range of libraries that provides a user-friendly environment for configuring inputs and outputs of different subsystems, including HVAC (heating, ventilation, and air conditioning) systems, enabling efficient analysis of building and equipment performance.

However, the complexity of these models, influenced by various factors, presents a challenge in accurately predicting and controlling the heating process. This thesis aims to explore dynamic heating models, analyze their complexities, and discuss the results obtained.

1.4 Objectives and Research Scope

This thesis will reproduce a published dynamic heating model by D.W.U. Perera, C. F. Pfeiffer, and N.-O Skeie [22]. The first objective involves comparing numerical results obtained from the model with analytical solutions to assess the energy performance accuracy. This comparison will provide valuable insights into the model's reliability and effectiveness in predicting building energy consumption. The second objective focuses on applying the validated model to real-world data collected from *Arkivenes Hus* in Stavanger's innovation park. By simulating the building's energy performance using actual measurements, we aim to evaluate the model's performance in a practical setting. Furthermore, the study aims to explore the impact of various factors on energy consumption and provide recommendations for energy optimization. Based on the findings, the study aims to propose practical recommendations for optimizing energy efficiency in *Arkivenes Hus* and similar architectural structures. These recommendations will contribute to energy-saving strategies in the field of building design and operation.

1.5 Dynamic Heating Model

The application of the dynamic heating model to real data obtained from Arkivenes Hus presents a unique opportunity to validate and refine the model's accuracy. By leveraging various sensors to capture temperature, sunlight, airflow, and other essential parameters, a comprehensive understanding of the building's energy dynamics can be achieved. This in-depth analysis will contribute to the existing body of knowledge by uncovering valuable insights and potential advancements in the field of energy optimization.

Moreover, the implementation of the mathematical model and the subsequent numerical simulations undertaken in this thesis will facilitate a deeper exploration of the specific physical aspects related to heating dynamics. By simulating various scenarios and examining the model's response, a comprehensive understanding of the system's behavior under different conditions can be attained. This enhanced understanding will pave the way for more effective energy optimization strategies and solutions.

Furthermore, the collaboration of UiS with NORCE and involvement in the future energy hub project offers a practical dimension to this research. Engaging with industry experts and working within a research environment will provide valuable exposure to the practical applications of academic knowledge. This collaboration will shed light on the non-academic perspectives of energy optimization, including the real-world challenges and considerations that arise when implementing energy-efficient strategies in buildings.

Figure 1.3: Arkivenes Hus [11]

Chapter 2

Background and Modeling Approach

2.1 Key Concepts of Thermodynamics

Thermodynamics is the branch of physics that deals with the study of energy and its transformations in various systems. It provides fundamental principles and laws governing the behavior of energy, particularly in relation to heat, work, and their interactions with matter.

2.1.1 Energy and its Forms

Thermodynamics recognizes energy as a fundamental concept, encompassing various forms that are essential to understanding the behavior of systems. Among these forms, thermal energy (heat) and mechanical energy (work) are particularly important. Additionally, potential energy (PE) and kinetic energy (KE) play significant roles in the study of energy transformations.

2.1.2 Systems in Thermodynamics

In thermodynamics, a system refers to a specific portion of the physical world or region of space that is under consideration or analysis. By defining system boundaries, one can examine the behavior and properties of the system without being concerned with the intricacies of the surrounding environment. Thermodynamics deals with closed, open and isolated systems.

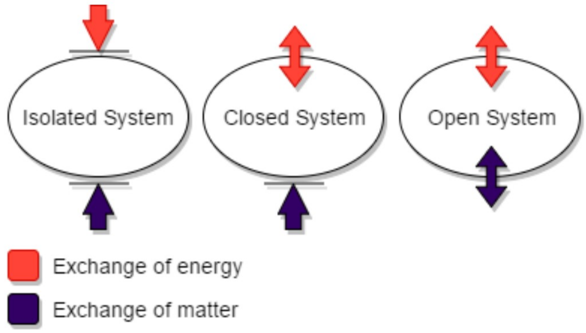


Figure 2.1: Thermodynamic systems [15]

- "A closed system", also known as a control mass, is a system that does not exchange matter with its surroundings. However, it can exchange energy with its surroundings in the form of heat or work. The total mass within a closed system remains constant.
- "A open system", also referred to as a control volume, is a system that can exchange both energy and matter with its surroundings. This includes systems where mass, energy, and momentum can flow in and out of the system boundaries. Open systems are commonly used to analyze fluid flow and heat transfer processes.
- "An isolated system" is a special case of a closed system where there is no exchange of matter or energy with the surroundings. It is a closed system with no interactions occurring across its boundaries. The total energy and mass of an isolated system remain constant.

2.1.3 Laws of Thermodynamics

Thermodynamics is based on a set of fundamental laws that govern energy and its transformations. These laws establish the limits and principles that apply universally to all systems.

i. First Law of Thermodynamics

The first law states that energy can neither be created nor destroyed; it can only be transferred or transformed from one form to another.

We can write the first law of thermodynamics as

$$dE = \delta Q - \delta W. \tag{2.1}$$

The first law suggests three possible interrelationships, as illustrated in Figure 2.2.

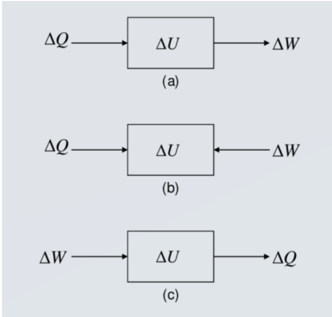


Figure 2.2: Interrelationships of heat, work, and energy [24]

ii. Second Law of Thermodynamics

The second law introduces the concept of entropy, which measures the degree of disorder or randomness in a system. It provides insights into the direction of energy flow and the efficiency of energy transformations. The second law encompasses principles such as the increase of entropy in isolated systems and the impossibility of achieving 100% energy conversion without any losses.

2.1.4 Thermodynamic Processes and Cycles

Thermodynamics deals with various processes and cycles through which energy is transferred and transformed. Some common processes include isothermal, adiabatic, isobaric, and isochoric processes.

- *An isothermal process* is characterized by a constant temperature. Since internal energy, U of the system depends on temperature, there is no change in the internal energy U of the system ($\Delta U = 0$).
- *An adiabatic process* is one in which there is no heat transfer between the system and its surroundings.

  $$PV^{\gamma} = \text{constant}.$$

  where γ is the heat capacity ratio or adiabatic index of the gas.
- *An isobaric process* occurs at a constant pressure.
- *An isochoric process*, also known as an isovolumetric process, is characterized by a constant volume,

  $$\Delta U = Q.$$

2.1.5 Heating Systems

Thermodynamics allows for the analysis of heat transfer mechanisms within heating systems by understanding conduction, convection, and radiation. It provides the foundation for studying heat transfer, which is the process of thermal energy transfer from a heat source to a heat sink.

a. Conduction

In conduction, heat transfer occurs between objects by direct contact. The rate of heat conduction through a material is given by Fourier's law of heat conduction:

$$Q = -kA\frac{dT}{dx}. \tag{2.2}$$

where Q represents the heat transfer, k is the thermal conductivity of the material, A is the cross-sectional area, and $\frac{dT}{dx}$ is the temperature gradient along the direction of heat flow.

b. Convection

In convection, the heat transfer takes within the fluid. The rate of heat transfer by convection is described by Newton's law of cooling or convective heat transfer:

$$Q = hA(T_{\text{surface}} - T_{\text{fluid}}). \tag{2.3}$$

where Q represents the heat transfer, h is the convective heat transfer coefficient, A is the surface area, T_{surface} is the surface temperature, and T_{fluid} is the temperature of the fluid.

c. Radiation

In radiation, heat transfer occurs through electromagnetic waves without involving particles. The rate of heat transfer by radiation is given by the Stefan-Boltzmann law for blackbody radiation.

$$Q = \sigma A(T^4_{\text{surface}} - T^4_{\text{surroundings}}). \tag{2.4}$$

where Q represents the heat transfer, σ is the Stefan-Boltzmann constant, A is the surface area, T_{surface} is the temperature of the radiating surface, and $T_{\text{surroundings}}$ is the temperature of the surroundings.

Process of heat transfer

Considering a door in a warm building with a cold exterior, heat conducts out of the building through the door's surface, from warm to cold. Radiation, driven by emissivity, area, and temperature differences, plays a role in heat transfer. If the door is a good thermal conductor, radiation heat transfer quickly sends heat away from the door's surface (Figure 2.3). Convection, influenced by air movement, also aids in removing thermal energy from the door. Windy conditions facilitate the whisking away of heat, while stagnant air reduces the temperature difference and slows down radiation heat transfer. Similar processes occur on the inside surface of the door, with radiation and convection working to transfer more heat to the surface. Heat loss through windows involves radiation within the glazing and conduction through the solid parts. Additionally, air infiltration through cracks in joints or underneath the door contributes to heat loss. While it is not possible to completely eliminate heat loss through doors, significant improvements can be achieved through various strategies [17].

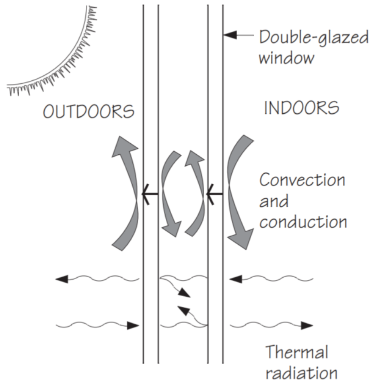


Figure 2.3: Mechanisms of heat transfer [17]

2.2 Simple Building Unit

The heating system which is considered for modeling is a well-ventilated and mixed building unit. The conservation of energy is a fundamental aspect of this building unit, operating on the principles of energy and mass. In order to achieve optimal energy efficiency, it is crucial to establish effective strategies for energy conservation. In this context, the building unit can be compared to a mixing tank, where the volume remains constant and the air temperature within the room is assumed to be uniform. By disregarding temperature variations within the room, a system resembling a perfectly mixed and equalized environment is created. This approach enables the application of the concept of a mixing tank to the building unit, ensuring the conservation of energy throughout the building unit. By considering this principle and incorporating relevant information, a comprehensive understanding of energy conservation within the building unit can be developed. A key component in this endeavor is a well-ventilated and mixed building unit, which operates on the principles of energy and mass. This building unit, as described in the literature, can be conceptualized as a mixing tank, where the volume remains constant, and the assumption is made that the air temperature within the room is uniform [22].

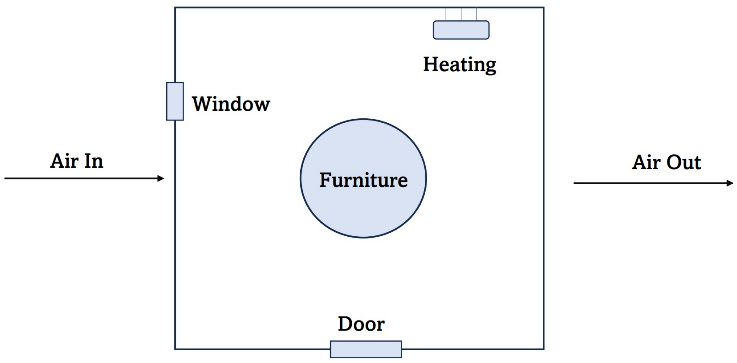


Figure 2.4: Sketch of conventional building unit [22]

2.3 Conservation of Mass

The mass balance equation states that the rate of change of mass within a control volume is equal to the net mass flow rate entering the control volume minus the net mass flow rate leaving the control volume.

$$\frac{dm}{dt} = m_{\text{in}} - m_{\text{out}}. \tag{2.5}$$

Equation 2.5 represents the mass balance for the selected control volume as it can be seen in 2.5. The mass of air within the building unit is equal to the volume of the unit (V_b) multiplied by the density of air (ρ_b).Similarly, the mass flow rates entering and leaving the unit can be expressed in terms of volumetric flow rates and densities.

$$m = V_b \rho_b. \tag{2.6}$$

$$m_{\text{in}} = V_{\text{in}} \rho_{\text{in}}. \tag{2.7}$$

$$m_{\text{out}} = V_{\text{out}} \rho_{\text{out}}. \tag{2.8}$$

Applying the mass balance equation, we have:

$$\frac{dm}{dt} = \dot{m}_{\text{in}} - \dot{m}_{\text{out}} = V_{\text{in}} \rho_{\text{in}} - V_{\text{out}} \rho_{\text{out}}. \tag{2.9}$$

From equation 2.6 we can constitute volumetric flow rates and densities within the mass balance equation.

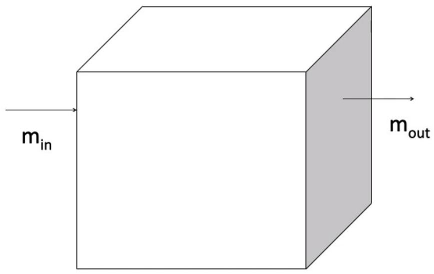


Figure 2.5: Mass balance [23]

$$\frac{d\rho_b}{dt} = \frac{\dot{V}_{\text{in}}\rho_{\text{in}} - \dot{V}_{\text{out}}\rho_b}{V_b}. \tag{2.10}$$

We assume that the inflow and outflow are well-mixed and that the density is uniform in the building. Here ρ_{in} is the density of air entering the building. This equation expresses the change in density over time due to the inflow and outflow of air, assuming a well-mixed and uniform density within the building. $\dot{V}_{\text{in}}$ and $\dot{V}_{\text{out}}$ are the volumetric flow rate of air entering and leaving the building.

2.4 Conservation of Energy

The energy balance equation states that the rate of change of energy within a control volume is equal to the net energy flow rate entering the control volume minus the net energy flow rate leaving the control volume, plus any energy generation or consumption within the control volume.

$$\frac{dE_b}{dt} = \dot{E}_{in} - \dot{E}_{out} + \dot{Q} + \dot{W}. \tag{2.11}$$

Equation 2.11 is derived based on the principle of conservation of energy. It states that the change in the energy content of a building unit over time ($\frac{dE_b}{dt}$) is equal to the net energy transfer into the system ($\dot{E}_{in} - \dot{E}_{out}$) plus the net heat transfer ($\dot{Q}$) and the net work done ($\dot{W}$). The signs of the terms will depend on the conventions used, with positive values indicating energy added to the system and negative values indicating energy leaving the system. It provides a quantitative framework to analyze and understand energy transformations and flows within the building unit. The total energy of the control volume encompasses various forms such as internal energy, kinetic energy (KE), and potential energy (PE).

$$E_b = U_b^E + KE + PE. \tag{2.12}$$

To facilitate the analysis of energy conservation within a system, certain simplifications are made. Firstly, it is assumed that the airflow velocity within the system is negligible, allowing us to disregard the contribution of kinetic energy (KE). Additionally, considering the gas as an ideal gas implies that there are no attractive or repulsive forces between its particles, thus eliminating the potential energy term (PE). By virtue of these assumptions, the energy balance equation simplifies to only internal energy of a system.

$$E_b = U_b^E. \tag{2.13}$$

The total amount of heat flowing in a room, not including ventilation, is defined as the difference between the amount of heat supplied and the amount of heat lost. This is represented by the equation $\dot{Q} = Q_{\text{supply}} - Q_{\text{loss}}$. Thus, in terms of internal energy, the energy balance equation is given by

$$\frac{dU}{dt} = U_{\text{in}} - U_{\text{out}} + \dot{W} + Q_{\text{supply}} - Q_{\text{loss}}. \tag{2.14}$$

This equation provides a comprehensive energy balance for the system, taking into account both work and heat interactions, as well as changes in system volume. To quantify and track the changes in the internal energy of a system over time, equation.

2.4.1 Work in building unit

Work is a combination of pressure work, expansion work, and friction work. As the volume of the room is fixed, expansion work is zero and friction work can be approximated to zero because air is the fluid of interest. Pressure work is the only term that signifies the energy transfer by work in this model.

$$\dot{W} = \int ((P_{\text{out}} - P_{\text{in}})\dot{V})dt. \tag{2.15}$$

$$\dot{W} = (P\dot{V})\text{in} - (P\dot{V})\text{out}. \tag{2.16}$$

For a building unit, the equation 2.16 relates the mechanical work ($\dot{W}$), and due to fluid flow to the pressure and volume flow rates at the inlet and outlet of the building unit. Thus, by accounting for energy input (U_{in}, PV_{in}, Q_{supply}) and energy output (U_{out}, PV_{out}, Q_{loss}), this equation allows us to understand how the internal energy of the building unit is changing.

$$\frac{dU_b}{dt} = U_{\text{in}} - U_{\text{out}} + P\dot{V_{\text{in}}} - P\dot{V_{\text{out}}} + Q_{\text{supply}} - Q_{\text{loss}}. \tag{2.17}$$

2.4.2 Enthalpy, internal energy, and pressure-volume work

From the definition of enthalpy, it is a thermodynamic property that accounts for the energy associated with both the internal energy (U) and the work done (PV) by or on the system due to volume changes.

$$H = U + PV. \tag{2.18}$$

Enthalpy represents the heat transfer, which is the energy transferred into or out of a system due to a temperature difference. It depends on the mass of the substance involved (m), the specific heat capacity of the substance (c) and the temperature change (ΔT). So the enthalpy of a building unit at constant pressure will give us the following expression.

$$H = m \cdot c_p \cdot T. \tag{2.19}$$

The "ideal gas law" states that the product of the pressure and volume of an ideal gas is directly proportional to the number of moles of the gas, the ideal gas constant, and the absolute temperature.

$$PV = n \cdot R \cdot T. \tag{2.20}$$

In equation 2.18 ideal gas law and heat transfer expression can be substituted to get the temperature-dependent internal energy of the building unit (U_b).

$$U_b = m_b c_{p,b} T_b - nRT_b = m_b \left(c_{p.b} - \frac{nR}{m_b} \right) T_b. \tag{2.21}$$

The relationship between the number of moles (n), the mass (m), and the molar mass (M) is given as $n = \frac{m}{M}$. Substituting the values of m from equation 2.6 and molar mass(M) we can get the following equation:

$$U_b = \rho_b V_b \left(c_{p,b} - \frac{R}{M_b} \right) T_b. \tag{2.22}$$

2.5 Indoor Temperature

We can express the rate of change of the total internal energy of the building unit with respect to time (t).

$$\frac{dU_b}{dt} = \frac{d\rho_b}{dt} V_b \left(c_{p,b} - \frac{R}{M_b} \right) T_b + \rho_b V_b \left(c_p - \frac{R}{M_b} \right) \frac{dT_b}{dt}. \tag{2.23}$$

The first law of thermodynamics in a control volume gives us the total energy of the building over time, considering the heat transfer, work done, and fluid flow in and out of the system. It is being presented by:

$$\frac{dU_b}{dt} = \frac{dE_b}{dt} = \dot{Q}_b - \dot{W}_b + \dot{V}_{\text{in}}\rho_{\text{in}}h_{\text{in}} - \dot{V}_{\text{out}}\rho_b h_{\text{out}}. \tag{2.24}$$

Ventilation heat losses are addressed by the term $\dot{V}_{\text{in}}\rho_{\text{in}}h_{\text{in}} - \dot{V}_{\text{out}}\rho_b h_{\text{out}}$. The rate of change of temperature of a building unit over time can be derived by comparing equations 2.23 and 2.24 to understand how the temperature within the system evolves over time.

$$\frac{dT_b}{dt} = \frac{\dot{V}_{\text{in}}\rho_{\text{in}}h_{\text{in}} - \dot{V}_{\text{out}}\rho_b h_{\text{out}} + \dot{Q}_{\text{supply}} - \dot{Q}_{\text{loss}}}{V_b\rho_b(c_{p,b} - \frac{R}{M_b})} - \frac{d\rho_b}{dt}. \tag{2.25}$$

Equation 2.25 takes into account various factors that contribute to the temperature variation within the building unit. It calculates the rate of temperature change based on the various heat transfer rates (inflow, outflow, heat supply, and heat loss), the thermodynamic properties of the substance (volume, density, specific heat capacity), and the rate of density change. Here $\frac{d\rho_b}{dt}$ represents the rate of change of density with respect to time, accounting for any density variations within the system. V_b represents the volume of the system, c_p represents the specific heat capacity of the substance at constant pressure, and R is the gas constant. It is valuable for analyzing and predicting the thermal behavior of processes, optimizing system design, and ensuring efficient energy management.

2.6 Total Heat Input to the Building Unit

The total heat supply to the building unit can be written as:

$$\dot{Q}_{\text{Supply}} = \dot{Q}_{\text{Heater}} + \dot{Q}_{\text{People}} + \dot{Q}_{\text{Appliances}} + \dot{Q}_{\text{Solar}}. \tag{2.26}$$

where:

- $\dot{Q}_{\text{Heater}}$ is the heat generated by the heating system within the building, which is usually modeled as a fixed heat source.
- $\dot{Q}_{\text{People}}$ is the heat generated by the occupants within the building. This can be estimated based on the number of people, their activity level, and the building occupancy schedule.
- $\dot{Q}_{\text{Appliances}}$ is the heat generated by electrical appliances within the building, such as computers, refrigerators, and lights. This can be estimated based on the power consumption of the appliances and their usage schedule.

- $\dot{Q}_{\text{Solar}}$ is the heat gained by the building due to solar radiation. This can be estimated based on the orientation and size of the windows, the solar radiation intensity, and the shading provided by external structures.

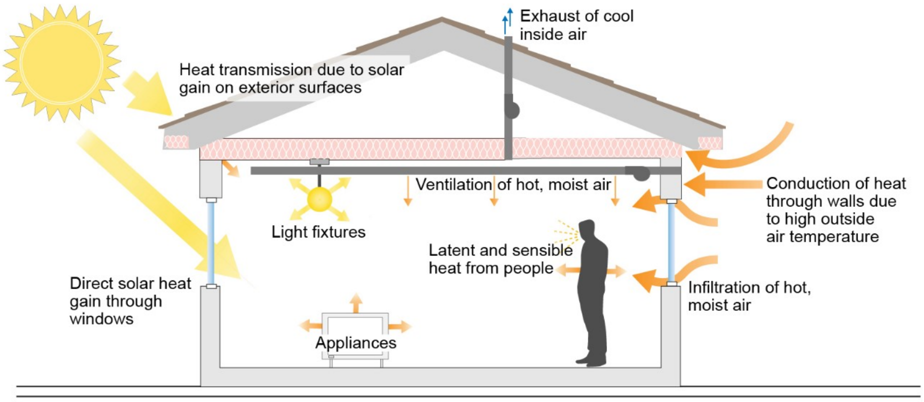


Figure 2.6: Sources of heat gain in a building unit [26]

Chapter 3

Transient Heat Equations

3.1 Partials differential equations

The walls, floor, roof, window, and door are the main items that allow heat to leave. Additionally, furniture can absorb thermal energy, which means that it can act as a heat sink. The building (see 2.4) comprises various layers of materials, with wooden panels commonly used for constructing the walls in many Norwegian residential houses. To prevent heat losses, insulation materials are added between the inner and outer wooden coverings. The equation 3.1 proposes ordinary differential equations to model the heat dynamics within the different layers. These equations help in understanding and analyzing how heat is transferred and distributed through the building elements [12]. The heat equation represents a balance between the rate of change of temperature, heat conduction, and heat generation.

$$\frac{\partial T}{\partial t} - \alpha \nabla^2 T - \frac{q}{\rho Cp} = 0. \tag{3.1}$$

This equation describes the heat transfer through the layers from the inside to the outside of the building considering the temperature (T), and the parameters related to heat transfer such as the thermal diffusivity (α), heat generation ($\dot{q}$), density (ρ), and specific heat capacity (C_p).

To simplify the modeling of furniture, it is often assumed to behave like a sphere with the same mass and an equivalent average thermal diffusivity. This assumption allows for experimental determination of the thermal behavior of furniture.

$$r^2 \frac{\partial T}{\partial t} - \alpha \frac{\partial}{\partial r} \left(r^2 \cdot \frac{\partial T}{\partial r} \right) - r^2 \frac{\dot{q}}{\rho C_p} = 0. \tag{3.2}$$

Equation (3.2) represents the heat equation, which involves the radial distance (r) [22].

3.2 Differential equations for layers of walls, roof and floor

To simplify the analysis of heat transfer in the wall/roof/floor, it is assumed that the temperature remains constant within each layer. This simplifies the analysis by considering the temperature as a function of time only.

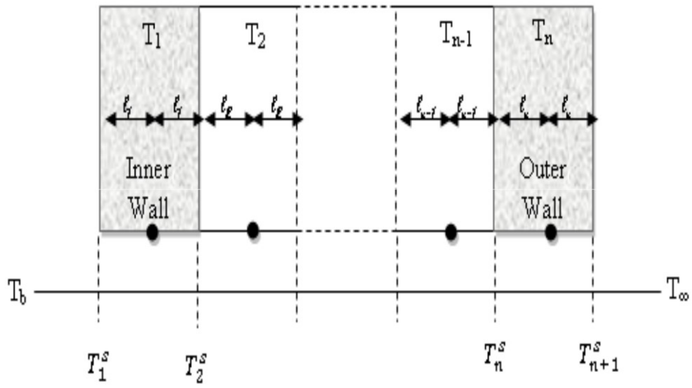


Figure 3.1: Distribution of temperature in a longitudinal section of a wall [22]

The surface temperatures of the layers are approximated as the average temperature between two consecutive layers. This assumption allows for a simplified representation of the temperature distribution across the wall.

To simplify the problem, the one-dimensional heat transfer equation (3.1) is converted into a set of ordinary differential equations using the finite difference method. This method discretizes the spatial domain and approximates the derivatives.

Expanding the time derivative term using the chain rule. In mathematical terms, it is as following:

$$\frac{\partial T}{\partial t} = \frac{dT_{i,x}}{dt}. \tag{3.3}$$

Laplacian operator $\nabla^2 T$ in terms of the second derivative with respect to the spatial variable x can be expresses as:

$$\nabla^2 T = \frac{d^2 T}{dx^2}. \tag{3.4}$$

Substituting the derivatives and expressions into the equation 3.1 gives the following expression:

$$\frac{dT_{i,x}}{dt} - \alpha \frac{d^2 T_{i,x}}{dx^2} - \frac{\dot{q}}{\rho C_p} = 0. \tag{3.5}$$

Approximating the second derivative $\frac{d^2T_{i,x}}{dx^2}$ using a finite difference scheme. In this case, a uniform grid with spacing $l_{i,w}$ between grid points is assumed.

$$\frac{d^2T_{i,x}}{dx^2} \approx \frac{T_{i+1,x} - 2T_{i,x} + T_{i-1,x}}{l_{i,x}^2} \tag{3.6}$$

Substituting this approximation into equation 3.5, the discretized form can be obtained s:

$$\frac{dT_{i,x}}{dt} = \alpha_{i,x}\frac{T_{i+1,x} - 2T_{i,x} + T_{i-1,x}}{l_{i,x}^2} + \frac{\dot{q}}{\rho C_p}. \tag{3.7}$$

Equation 3.7 represents the energy balance for the i^{th} layer of the wall/roof/floor. This equation ensures that the energy transferred into a layer is equal to the energy transferred out of that layer.

3.3 Differential equations for furniture

The modeling of household furniture is crucial because it plays a significant role in the heating and cooling of a room. Depending on the surrounding temperature, furniture can act as either a heat sink or a heat source. When a heater is used to warm up a room, a portion of the energy supplied is stored in the furniture as thermal energy. This process continues until the furniture reaches an equilibrium temperature with the indoor air.

However, this heat storage in furniture can also lead to slower heating and cooling of the room. It takes more time to heat up the room to a desired temperature because some of the heat energy is absorbed by the furniture. Similarly, when the room needs to cool down, the furniture releases heat slowly, extending the cooling time. The rate of heat absorption or release by furniture depends on its heat capacity and thermal conductivity, which are properties determined by the material of construction.

Equation (3.2) is the heat equation in spherical coordinates, which is employed to describe the temperature distribution within the furniture.

Expand the second term using the product rule for differentiationcan be expresses as:

$$\frac{\partial}{\partial r}\left(r^2 \cdot \frac{\partial T}{\partial r}\right) = \frac{\partial}{\partial r}\left(r^2\right) \cdot \frac{\partial T}{\partial r} + r^2 \cdot \frac{\partial^2 T}{\partial r^2}. \tag{3.8}$$

There is no heat generation occurring within the layers of furniture ($\dot{q} = 0$). Divide the equation by r^2:

$$\frac{\partial T}{\partial t} - \frac{2\alpha}{r}\frac{\partial T}{\partial r} - \alpha\frac{\partial^2 T}{\partial r^2} - 0 = 0. \tag{3.9}$$

Rearrange the terms involving spatial derivatives and substitute finite difference approximations for derivatives:

$$\frac{\partial T}{\partial r} \approx \frac{T^s_{i+1,fur} - T^s_{i,fur}}{\delta r_{i,fur}} \quad \text{and} \quad \frac{\partial^2 T}{\partial r^2} \approx \frac{T^s_{i+1,fur} - 2T^s_{i,fur} + T^s_{i-1,fur}}{\delta r^2_{i,fur}}. \tag{3.10}$$

The equation 3.9 then becomes as follow:

$$\frac{dT_{i,fur}}{dt} = \alpha_{i,fur}\left(\frac{T^s_{i+1,fur} - 2T_{i,fur} + T^s_{i,fur}}{\delta r^2_{i,fur}}\right) + \alpha_{i,fur}\left(\frac{1}{r}\frac{T^s_{i+1,fur} - T^s_{i,fur}}{\delta r_{i,fur}}\right). \tag{3.11}$$

Equation 3.11 presents the boundary condition for the outer layer of the furniture, specifying the rate of temperature change with respect to time ($\frac{dT_{i,fur}}{dt}$) based on the temperature values of adjacent layers and the radial distance ($\delta r_{i,fur}$). It is obtained for each spherical layer (i) within the furniture. This equation is crucial for simulating the heat transfer within the furniture and understanding its impact on the overall thermal behavior of the room.

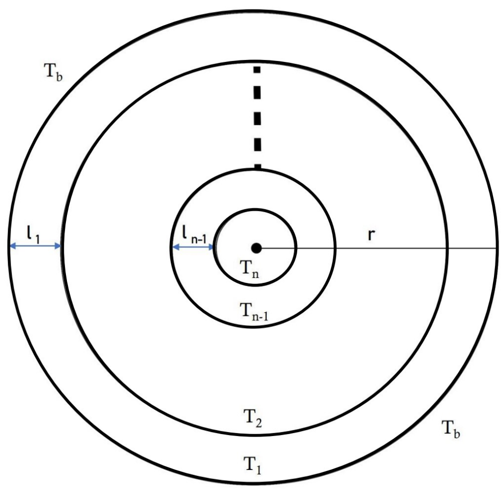


Figure 3.2: Distribution of temperature in spherical layers of furniture

3.4 Internal boundary conditions for the wall, roof, and floor

The heat transfer within the layers of the wall/roof/floor is described by the heat conduction, given by equation 2.2. To approximate the heat flux at the boundary, a finite difference approximation is used.

$$q = -k_1 A \frac{T^s_2 - T^s_1}{2l_1}. \tag{3.12}$$

The temperature gradient between the inner layer and the adjacent layer $\left(T^s_{2,x} - T^s_{1,x}\right)$ determines the rate of heat transfer. $K_{1,x}$ is the thermal conductivity of the inner layer. The convective heat transfer is described by Newton's law of cooling, given in equation 2.3. Thus, heat transfer across the same layer and room temperature through convection is given by:

$$q = h_b A(T_b - T_1^s). \tag{3.13}$$

Here, T_b represents the temperature inside the building. The term h_b represents the convective heat transfer coefficient between the layers and the building temperature. By equating the expressions, the equation for internal boundary conditions can be obtained as follow:

$$h_{b,x}(T_b - T_{i,x}^s) = \frac{-K_{1,x}}{2l_{1,x}}(T_{2,x}^s - T_{1,x}^s). \tag{3.14}$$

3.5 Internal Boundary condition for furniture

Using the equation (3.14) we can create an internal boundary condition for furniture as well.

$$h_{b,fur}\left(T_b - T_{i,fur}^s\right) = \frac{-K_{1,fur}}{2l_{1,fur}}\left(T_{2,fur}^s - T_{1,fur}^s\right). \tag{3.15}$$

3.6 External boundary conditions for the wall and roof

The previous equation can be generalized to include the convective and radiative heat transfer at the outer surface of the wall and roof. The expression for the radiative heat is shown by equation (2.4). Hence, the convective heat transfer coefficient $h_{\infty,x}$ accounts for the convective heat transfer between the outer surface and the surroundings. Thus, equation 3.16 combines the contributions of convection and radiation at the outer surface, incorporating the respective temperature differences, in order to accurately model the heat transfer in this region.

$$\frac{-K_{i,x}A_{i+1,x}}{2l_{i,x}}\left(T_{i+1,x}^s - T_{i,x}^s\right) = h_{\infty,x}A_{i+1,x}\left(T_{i+1,x}^s - T_\infty\right) + \sigma\varepsilon_{i+1,x}\left({T_{i+1,x}^s}^4 - {T_\infty}^4\right). \tag{3.16}$$

The heat transfer between the outermost layer ($T_{i+1,x}^s$) and the outside temperature (T_∞) is obtained from the above expression. The term $\sigma\varepsilon_{i+1,x}\left({T_{i+1,x}^s}^4 - {T_\infty}^4\right)$ accounts for radiative heat transfer, taking into consideration the temperature difference between the surface temperature $T_{i+1,x}^s$ and the outside temperature T_∞. It is important to consider the specific surface area of the layer that is in direct contact with the convective and radiative heat transfer processes. Hence, $A_{i+1,x}$ is used to represent the surface area of the outermost layer in the equation. The term $l_{i,x}$ represents the thickness or length of the i^{th} layer at the outside boundary.

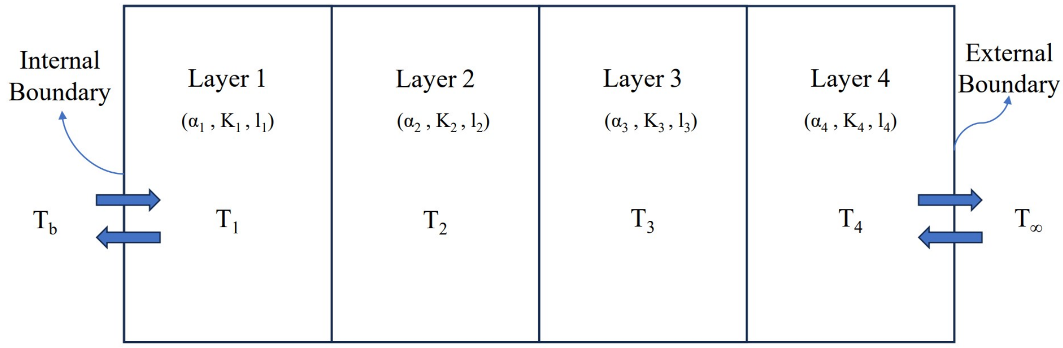


Figure 3.3: Layers of walls and roof

3.7 Heat Loss in the Building Unit

The loss of heat is usually modeled as a first-order rate equation, using T_∞ as the temperature outside, the loss of heat due to The heat losses via walls, floor, roof, windows, door, and furniture can be seen from equation 3.17 to equation 3.22. They are all based on Fourier's law of Heat Conduction, which states that the rate of heat transfer through a material is directly proportional to the temperature gradient across the material.

$$\dot{Q}_{\text{window}} = U_{\text{window}} A_{\text{window}} (T_b - T_\infty). \tag{3.17}$$

$$\dot{Q}_{\text{door}} = U_{\text{door}} A_{\text{door}} (T_b - T_\infty). \tag{3.18}$$

$$\dot{Q}_{\text{walls}} = U_{\text{walls}} A_{\text{walls}} (T_b - T_\infty). \tag{3.19}$$

$$\dot{Q}_{\text{floor}} = U_{\text{floor}} A_{\text{floor}} (T_b - T_\infty). \tag{3.20}$$

$$\dot{Q}_{\text{roof}} = U_{\text{roof}} A_{\text{roof}} (T_b - T_\infty). \tag{3.21}$$

$$\dot{Q}_{\text{fur}} = h_{\text{fur}} A_{\text{fur}} (T_b - T_{\text{center}}). \tag{3.22}$$

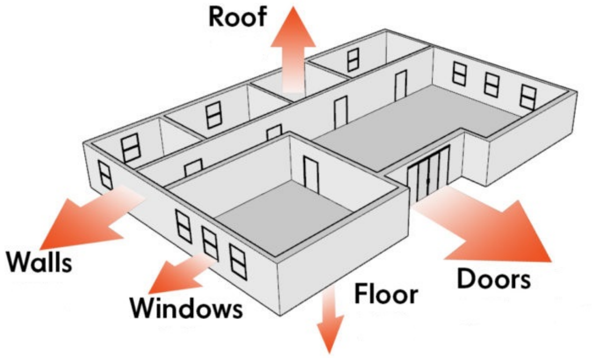


Figure 3.4: Elements of heat loss in a building [17]

3.8 Integrated Ventilation Heat Recovery

This section explores the integration of an advanced ventilation heat recovery system in buildings, which allows for higher air inflow temperatures compared to the outside environment. The estimation of air inflow temperature is discussed, considering the energy efficiency parameter (η) and assuming balanced heat transfer between counter-current air streams. Equation 3.23 is introduced as a means to calculate the post-economizer air inflow temperature (T_{in}), accounting for the thermal properties of the incoming air. The complete dynamic heating model, encompassing heat transfer equations, boundary conditions, and considerations for different building layers, is presented. This model provides a robust framework for analyzing the thermal behavior of buildings, incorporating conduction, convection, radiation, and heat storage in furniture. By leveraging this model, researchers and practitioners can optimize heating strategies and enhance energy efficiency in building environments [22]. "(The ventilation heat recovery system and equation 3.23 are included for informational purposes and are not further explored in this thesis.)"

$$T_{in} = \left(\frac{\eta V_{out} \rho_b c_{p,b} (T_b - T_\infty)}{V_{in} \rho_{in} c_{p,in}} \right) + T_\infty. \tag{3.23}$$

Chapter 4

Modelling in Python

4.1 Ordinary Differential Equations (ODE's)

The ordinary differential equation for the indoor temperature is given by,

$$\frac{dT_b}{dt} = \frac{\dot{V}_{\text{in}}\rho_{\text{in}}h_{\text{in}} - \dot{V}_{\text{out}}\rho_b h_{\text{out}} + \dot{Q}_{\text{supply}} - \dot{Q}_{\text{loss}}}{V_b\rho_b(c_{p,b} - \frac{R}{M_b})} - \frac{d\rho_b}{dt}. \tag{4.1}$$

Differential equations for walls

In the implemented code, the walls of the building are divided into four layers, denoted by the index i $= 1, 2, 3, 4$. These layers serve as thermal insulation and contribute to the overall heat transfer process. It is important to note that within each layer, there is no heat generation occurring ($\dot{q} = 0$). This assumption implies that the heat transfer within the layers is solely driven by the temperature difference between the inside and the outside of the building. The equation (3.7) will have $\dot{q} = 0$. Thus, the rate of change of temperature within each layer of the wall can be represented by:

$$\frac{dT_{i,w}}{dt} = \alpha_{i,w}\frac{T^s_{i+1,w} - 2T_{i,w} + T^s_{i,w}}{l^2_{i,w}}. \tag{4.2}$$

The heat transfer at the internal boundary of the wall can be determined using equation (3.14)

$$h_{b,w}\left(T_b - T^s_{i,w}\right) = \frac{-K_{1,w}}{2l_{1,w}}\left(T^s_{2,w} - T^s_{1,w}\right). \tag{4.3}$$

Equation (3.16) provides a method for calculating the heat transfer at the boundary of the wall exposed to the outside environment.

$$\frac{-K_{i,w}A_{i+1,w}}{2l_{i,w}}\left(T^s_{i+1,w}-T^s_{i,w}\right)=h_{\infty,w}A_{i+1,w}\left(T^s_{i+1,w}-T_\infty\right)+\sigma\varepsilon_{i+1,w}\left({T^s_{i+1,w}}^4-{T_\infty}^4\right). \tag{4.4}$$

Differential equations for roof

For the roof, the heat transfer equation for each layer follows a similar form as in the wall case.

$$\frac{dT_{i,r}}{dt}=\alpha_{i,r}\frac{T^s_{i+1,r}-2T_{i,r}+T^s_{i,r}}{l^2_{i,r}}. \tag{4.5}$$

$$h_{b,r}\left(T_b-T^s_{i,r}\right)=\frac{-K_{1,r}}{2l_{1,r}}\left(T^s_{2,r}-T^s_{1,r}\right). \tag{4.6}$$

$$\frac{-K_{i,r}A_{i+1,r}}{2l_{i,r}}\left(T^s_{i+1,r}-T^s_{i,r}\right)=h_{\infty,r}A_{i+1,r}\left(T^s_{i+1,r}-T_\infty\right)+\sigma\varepsilon_{i+1,r}\left({T^s_{i+1,r}}^4-{T_\infty}^4\right). \tag{4.7}$$

Differential equations for floor

In the code, the floor is modeled as consisting of three layers, denoted by $i=1,2,3$. Unlike the walls and the roof, the floor energy balance equations incorporate a heat source term, denoted as $\dot{q}$. This term represents any heat generation or input into the floor system, which could arise from various sources such as underfloor heating systems or other thermal sources present within the floor structure.

$$\frac{dT_{i,f}}{dt}=\alpha_{i,f}\frac{T^s_{i+1,f}-2T_{i,f}+T^s_{i,f}}{l^2_{i,f}}-\frac{q_{i_f}}{\rho_{i,f}c_{p_{i,f}}}. \tag{4.8}$$

Only internal boundary conditions will be considered for the floor, which will remain the same as the walls and roof.

$$h_{b,f}\left(T_b-T^s_{i,f}\right)=\frac{-K_{1,f}}{2l_{1,f}}\left(T^s_{2,f}-T^s_{1,f}\right). \tag{4.9}$$

Differential equations for furniture

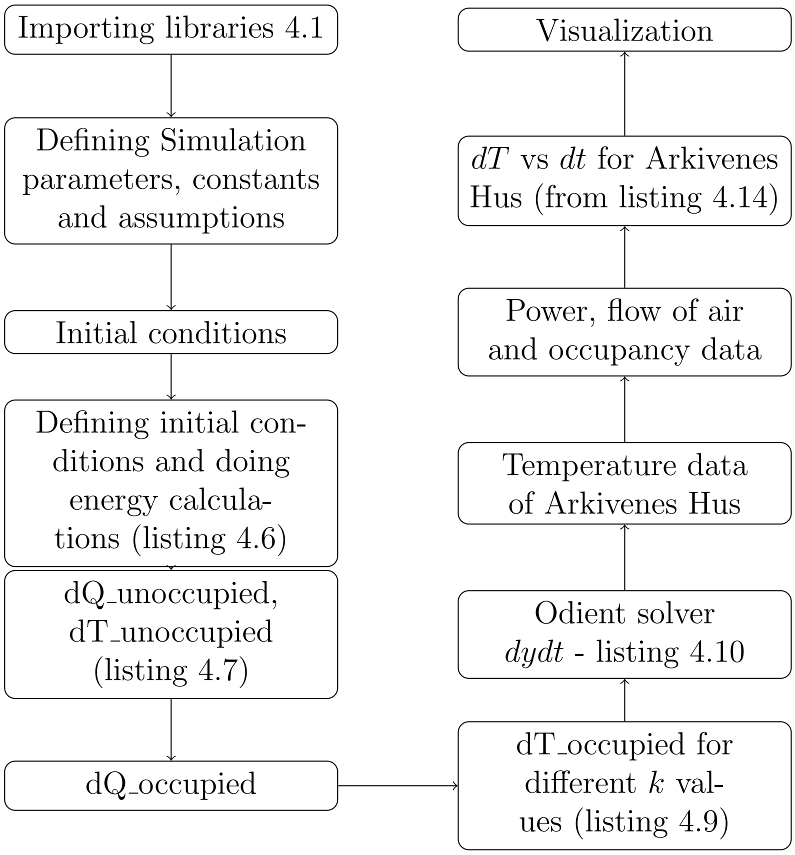
The heat transfer equations for the furniture can be derived from equations (3.11) and (3.15). For our analysis, we will only consider one layer of furniture.

$$\frac{dT_{i,fur}}{dt}=\alpha_{i,fur}\frac{T^s_{i+1,fur}-2T_{i,fur}+T^s_{i,fur}}{\partial r^2_{i,fur}}+\alpha_{i,fur}\frac{T^s_{i+1,fur}-T^s_{i,fur}}{\partial r_{i,fur}}. \tag{4.10}$$

$$h_{b,fur}\left(T_b-T^s_{i,fur}\right)=\frac{-K_{1,\mathrm{fur}}}{2l_{1,fur}}\left(T^s_{2,fur}-T^s_{1,fur}\right). \tag{4.11}$$

4.2 Python Implementation

4.2.1 Flow chart



4.2.2 Code snippets

In the script 4.1, it can be seen that the code is using *scipy.integrate.odeint* library, which is a numerical ODE solver that can be used to solve differential equations. This library is being used to solve the transient heat conduction equations for the building. The transient heat conduction equations are nonlinear and can be difficult to solve analytically. However, the **scipy.integrate.odeint** library can be used to solve these equations numerically. The code is using the **numpy** library to create and manipulate the arrays that store the temperature data. The **matplotlib** library creates a plot of the temperature data.

```

import numpy as np
import matplotlib.pyplot as plt
import math
from scipy.integrate import odeint
```

Listing 4.1: Importing libraries

In this simulation, the variable **duration** is set to 100 hours, indicating that the simulation will run for a total of 100 hours. The **times_step** is set to 1 hour, meaning that the simulation will update the temperature values of the building's internal elements every 1 hour. Area of the building is considered in square meter. The maximum four layers are considered which different specific heat capacity of each layer.

```

duration = 100
time_step = 1
layers = 4
area_room = 3.65 * 4
height_room = 3.3
cp = np.array([835, 1317, 835, 835])
```

Listing 4.2: Simulation parameters

```

A_window = A_door = A_walls = A_floor = A_roof = area_room # it's an
    approximation

U_window = U_door = U_walls = U_floor = U_roof = 1.2 # W/(m^2 K )
    approximation
```

Listing 4.3: Assumptions

To calculate the heat transfer through the walls, roof, floor, and furniture, their parameters are defined. This includes the thermal diffusivity, thickness, heat transfer coefficients, and thermal conductivity of each layer of a building (walls, roof, floor), as well as the density and specific heat capacity of the furniture material. Air density at the inlet and the outlet of the building is also defined. **T_outside** is the outside temperature in Kelvin, which will be used as a boundary condition for the simulation. The code also sets some parameters related to furniture, such as volume, thermal diffusivity, and radius.

```
T_outside = 270.95

# Thermal diffusivity
alpha_w = [1.7e-7, 1.4e-6, 2.25e-2, 1.7e-7]
alpha_r = [1.7e-7, 1.4e-6, 1.8e-7, 4e-7]
alpha_f = [4.0e-7, 1.7e-7, 1.4e-6]
alpha_fur = 1.8e-7

# Thickness of each layer (walls, roof, floor)
l_w = [6e-3, 75e-3, 8.5e-3, 8.5e-3]
l_r = [6e-3, 100e-3, 11e-3, 6.5e-4]
l_f = [1e-3, 9e-3, 75e-3]

# Thermal conductivity
K_w = [0.14, 0.038, 0.026, 0.14]
K_r = [0.14, 0.038, 0.12, 0.027]
K_f = [0.027, 0.14, 0.038]
K_fur = 2

# Density and specific heat capacity of furniture material
rho_f = [55.0, 615.0, 32.0]
c_p_f = [1210.0, 1317.0, 835.0]

# Air density kg/m^3
rho_in = 1.2
rho_out = 1.2

# Heat transfer coefficients
h_walls = 2
h_furniture = 2

furniture_volume = 1
furniture_alpha = 1.8e-7
furniture_radius = 0.5
```

Listing 4.4: Constants and parameters

The code snippet 4.5 calculates various parameters related to the indoor environment of a building. Firstly, it calculates the volume of the room (**V_b**) as the product of its floor area and height. The ventilation rate (**Ventilation_rate**) is then determined by dividing the volume of incoming air (**V_in**), which is assumed to be equal to the volume of outgoing air (**V_out**), by the volume of the room (**V_out**). The atmospheric pressure (**P_atm**) is set to 101300 Pa.
The initial temperatures of the building when occupied and unoccupied are denoted as **T_b_occupied_initial** and**T_b_unoccupied_initial**, respectively. Both are given in degrees Kelvin.
The initial air density inside the building, for both occupied and unoccupied scenarios (**rho_b_occupied** and **rho_b_unoccupied**), is calculated using the ideal gas law. The building pressure (**P_b**) is set to the same value as atmospheric pressure (**P_atm**). The molar mass of air and the gas constant is also used in the calculations.
The specific heat capacity of air (**c_p_b**) is assumed to be constant and set to $1005 J/(kgK)$.

```
V_b = area_room * height_room
V_out = air_flow
V_in = V_out
Ventilation_rate = V_in / V_b
P_atm = 101300

T_b_occupied_initial = 293.15
T_b_unoccupied_initial = 288.15

P_b = P_atm
rho_b_occupied = (P_b * M_b) / (R * T_b_occupied_initial)
rho_b_unoccupied = (P_b * M_b) / (R * T_b_unoccupied_initial)
c_p_b = 1005
```

Listing 4.5: Initial conditions

The rate of energy exchange (**dE_dt**) in two scenarios of occupied and unoccupied is taken into account(listing 4.6). It calculates the rates of energy transfer into and out of the building based on temperature differences between the outside environment and the initial indoor temperatures when the building is occupied or unoccupied, along with other relevant parameters such as air density and specific heat capacity.

```
dE_in_dt_occupied = rho_b_occupied * c_p_b * (T_outside -
    T_b_occupied_initial) * (area_room * h_in)
dE_out_dt_occupied = rho_b_occupied * c_p_b * (T_b_occupied_initial -
    T_outside) * (area_room * h_out)

dE_in_dt_unoccupied = rho_b_unoccupied * c_p_b * (T_outside -
    T_b_unoccupied_initial) * (area_room * h_in)
dE_out_dt_unoccupied = rho_b_unoccupied * c_p_b * (T_b_unoccupied_initial -
    T_outside) * (area_room * h_out)
```

Listing 4.6: Energy Calculations

The code **4.7** initializes the variable **firstPart** as an array of zeros with a length (**num_steps**). Three main loops calculate the temperature derivatives **dT_w_dt_unoccupied**, **dT_r_dt_unoccupied**, **dT_fur_dt_unoccupied**, and **dT_f_dt_unoccupied** for walls, roof, furniture, and floor, respectively. The temperature variations are computed based on the heat transfer equations, considering the thermal properties of the materials (**alpha_w**, **alpha_r**, **alpha_f**) and the temperature differences between adjacent layers.

```python

for i in range(1, num_steps):
    dQ_window_dt_unoccupied = U_window * A_window * (T_infinity)
    dQ_door_dt_unoccupied = U_door * A_door * (T_infinity)
    dQ_walls_dt_unoccupied = U_walls * A_walls * (T_infinity)
    dQ_floor_dt_unoccupied = U_floor * A_floor * (T_infinity)
    dQ_roof_dt_unoccupied = U_roof * A_roof * (T_infinity)

    # Additional calculations and updates for dQ_dt_loss_unoccupied,
        rho_in_unoccupied, rho_out_unoccupied, etc.
    # ...

    dT_w_dt_unoccupied = np.zeros(len(l_w))
    for i in range(len(l_w)):
        if i == 0:
            dT_w_dt_unoccupied[i] = alpha_w[i] * ((T_w_unoccupied[i + 1][step
                - 1] - 2 * T_w_unoccupied[i][step - 1] + T_b_unoccupied[step
                - 1]) / (l_w[i] ** 2))
        elif i == len(l_w) - 1:
            dT_w_dt_unoccupied[i] = alpha_w[i] * ((T_w_unoccupied[i - 1][step
                - 1] - 2 * T_w_unoccupied[i][step - 1] +
                T_w_unoccupied[i][step - 1]) / (l_w[i] ** 2))
        else:
            dT_w_dt_unoccupied[i] = alpha_w[i] * ((T_w_unoccupied[i + 1][step
                - 1] - 2 * T_w_unoccupied[i][step - 1] +
                T_w_unoccupied[i][step - 1]) / (l_w[i] ** 2))

    # Similar calculations and updates for T_r_unoccupied, T_f_unoccupied,
        T_fur_unoccupied
    # ...
```

Listing 4.7: Temperature variations in an unoccupied scenario

Then heat transfer rates for different elements within the building in the occupied scenario are calculated. These elements include windows, doors, walls, floor, and roof, each characterized by its respective heat transfer coefficient and surface area. The total heat transfer rate (**dQ_dt_loss_occupied**) for the occupied scenario is calculated by summing the individual heat transfer rates of all elements. The total heat supply rate comprises heat generated by people (**dQ_people_dt**), appliances (**dQ_appliances_dt**), solar radiation (**dQ_solar_dt**), and a heater (**dQ_heater_dt**). The heat generated by people is assumed to be proportional to the room area, with 58.2 representing the rate of heat generated by an individual person [7]. The heat generated by appliances is treated as a constant value, the solar radiation heat is calculated based on the room area and insulation, and the heater's heat output is considered to be 1000 watts for the starting analysis.

```

dQ_window_dt_occupied = U_window * A_window * (T_infinity)
dQ_door_dt_occupied = U_door * A_door * (T_infinity)
dQ_walls_dt_occupied = U_walls * A_walls * (T_infinity)
dQ_floor_dt_occupied = U_floor * A_floor * (T_infinity)
dQ_roof_dt_occupied = U_roof * A_roof * (T_infinity)

dQ_dt_loss_occupied = dQ_window_dt_occupied + dQ_door_dt_occupied +
    dQ_walls_dt_occupied + dQ_floor_dt_occupied + dQ_roof_dt_occupied

dQ_people_dt = 58.2 * area_room  # Heat generated by people
dQ_appliances_dt = Appliances  # Heat generated by appliances (constant value
    in this case)
dQ_solar_dt = Insolation * area_room  # Solar radiation heat
Q_heater = 1000  # Heat generated by the heater
dQ_heater_dt = np.zeros(num_steps)  # Heater is initially off

dQ_supply_dt = dQ_appliances_dt + dQ_solar_dt + dQ_people_dt + Q_heater
```

Listing 4.8: Heat transfer rates for occupied scenario

After iterating through each time step and calculating heat transfer rates for windows, doors, walls, floor, and roof. The coefficients $k1$ and $k2$ are then computed based on these heat transfer rates and other relevant parameters, shown as $k1\_occupied[i]$ and $k2\_occupied[i]$. Using these coefficients, the temperature variations **T_b_occupied[i]** and **T_b_occupied_unbiased[i]** for the occupied building are determined for both the first half ($i \leq 50$ **hours**) and the second half ($i > 50$ **hours**) of the simulation time. The temperature variations are calculated based on the heat transfer equations and energy balance for the building elements. This code was tried on two scenarios. The first scenario for $t_f < 50$ was analyzed using specific coefficients: $k1 = 70$, $k1(0) = 70$, and $k2 = 0.2$. The second half, where $tf > 50$ hours, was assessed with different coefficients: $k1 = 50$, $k1(50) = 50$, and $k2 = 0.17$. These coefficient values were selected to accurately model and predict the temperature variations throughout the defined time periods.
But the second scenario was evaluated by changing coefficients $k1$ to 58.7 for the first half. For the second half, where the time tf exceeded 50 hours, the $k1$ was taken as 90. This was done for hit and trial purposes to get the result closer to the numerical solution.

```python

 # Coefficients for the occupied scenario

if i <= 50:

    k1_occupied_0 = 70
    k1 = 70
    k2 = 0.23

    # Calculating coefficients k1 and k2 for the occupied scenario
    k1_occupied[i] = ((V_in * rho_in_occupied * h_in - V_out *
        rho_out_occupied * h_out) + dQ_dt_supply[i] + dQ_dt_loss_occupied) /
        (V_b * rho_b_occupied * (c_p_b - R / M_b))
    k2_occupied[i] = dQ_dt_loss_occupied / T_infinity + (V_in *
        rho_in_occupied - V_out * rho_out_occupied) / (rho_b_occupied * V_b)
    # Calculate the temperature variation of the occupied building over time
    T_b_occupied[i] = (1 / k2) * (k1_occupied_0 - (k1 - k2 * T_b_occupied[0])
        * math.exp(-k2 * i))
    T_b_occupied_unbiased[i] = (1 / k2) * (k1_occupied_0 - (k1_unbiased - k2
        * T_b_occupied[0]) * math.exp(-k2 * i))
else:
    k1_occupied_50 = 50
    k1 = 50
    k2 = 0.19

    # Calculate coefficients k1 and k2 for the occupied scenario
    k1_occupied[i] = ((V_in * rho_in_occupied * h_in - V_out *
        rho_out_occupied * h_out) + dQ_dt_supply[i] + dQ_dt_loss_occupied) /
        (V_b * rho_b_occupied * (c_p_b - R / M_b))
    k2_occupied[i] = dQ_dt_loss_occupied / T_infinity + (V_in *
        rho_in_occupied - V_out * rho_out_occupied) / (rho_b_occupied * V_b)

    # Calculate the temperature variation of the occupied building over time
    T_b_occupied[i] = (1 / k2) * (k1_occupied_50 - (k1 - k2 *
        T_b_occupied[50]) * math.exp(-k2 * (i - 50)))

# Using K[i] variable instead
    #  T_b_unoccupied[i] = (1 / k2_unoccupied[i]) * (
    #     k1_unoccupied[i]
    #     - (k1_unoccupied[i] - k2_unoccupied[i] * T_b_unoccupied[0])
    #     * math.exp(-k2_unoccupied[i] * (i))
```

Listing 4.9: Temperature variations in an occupied scenario

Then the function **dydt** is created to represent the system of ordinary differential equations related to the building's internal temperature (code 4.10). It uses the **odeint** function from **scipy.integrate** to numerically solve these equations and calculate the temperature variation over time. The solver considers the outside temperature (**T_outside**) as an additional argument. The initial temperature condition **y0** is set, and the solver is called with odeint(**dydt, y0, time, args=(T_outside,), rtol=tolerance, atol=tolerance**). The **sol** variable contains the numerical solutions for the building's temperature over time.

```python
def dydt(y0, time, T_outside):
    for i in range(1, num_steps):
        deltaRhoB = (V_in * rho_in - V_out * rho_b_occupied) / V_b
        firstPart[i] = (V_in * rho_in * h_in - V_out * rho_b_occupied * h_out
            + dQ_dt_supply[i] - dQ_dt_loss_occupied) / (V_b *
            rho_b_unoccupied * (c_p_b - (R / M_b))) - (y0 / rho_b_occupied) *
            deltaRhoB
    return firstPart[i]

K = 273.15
y0 = 15 + K
tolerance = 1e-5

# Use `odeint` to solve the differential equation for the new scenario
sol = odeint(dydt, y0, time, args=(T_outside, ), rtol=tolerance,
    atol=tolerance)
```

Listing 4.10: Differential Equation Solver (odeint)

Then a multi-line plot is created to show how the temperatures of various building elements (e.g., walls, roof, floor, and furniture) change over 100 hours in the occupied scenario. The labels of each plotted element, make it easy to identify which line represents which element. Additionally, to visualize the density (**rho**) of the building over **time** the plot is visualized using **rho_b_occupied** and **time** values.

```python
# Temperature variation over 100 hours
plt.figure(figsize=(10, 6))
plt.plot(time, T_b_occupied, label="T building occupied")
# plt.plot(time, sol, label="T numerical building occupied")
# plt.plot(time, T_b_occupied_unbiased, label="T different coefficients
    building occupied")
for i in range(len(l_w)):
    plt.plot(time, T_w_occupied[i], label=f'Wall Layer {i+1} occupied')
for i in range(len(l_r)):
    plt.plot(time, T_r_occupied[i], label=f'Roof Layer {i+1} occupied')
for i in range(len(l_f)):
    plt.plot(time, T_f_occupied[i], label=f'Floor Layer {i+1} occupied')
plt.plot(time, T_fur_occupied, label='Furniture occupied')
plt.xlabel('Time (hours)')
plt.ylabel('Temperature ( K )')
plt.title('Temperature Variations of Internal Elements - Occupied')
plt.legend()
plt.grid(True)
plt.show()

#Density (rho) of the building over time
plt.figure(figsize=(10, 6))
plt.plot(time, rho_b_occupied, label="Building Density - Occupied")
plt.xlabel('Time (hours)')
plt.ylabel('Density (kg/m^3)')
plt.title('Density Variation of the Building - Occupied')
plt.legend()
plt.grid(True)
plt.show()
```

Listing 4.11: Visualization

The data of *Arkivenes Hus* taken from *NORCE* was converted from the **ISO format** to integers. A similar **temperature** has also been converted from string to floats.

```python

with open(csc_file_path1, "r") as csv_file:
    csv_file_reader1 = csv.reader(csv_file)
    rows1 = list()
    for row in csv_file_reader1:
        rows1.append(row)
with open(csc_file_path2, "r") as csv_file:
    csv_file_reader2 = csv.reader(csv_file)
    rows2 = list()
    for row in csv_file_reader2:
        rows2.append(row)

#Similarly for next 4 CSV files of temperature as well

def time_temp(rows):
    time_csv = list()
    temp_csv = list()
    for i, row in enumerate(rows):
        # print(i, row)
        if i == 0 or len(row) == 0:
            # print(row)
            continue
        time_csv.append(datetime.datetime.fromisoformat(row[0])
        .strftime("%Y%m%d%H%M%S"))
        temp_csv.append(float(row[1]))
    time_csv = [int(time)-20210224140252 for time in time_csv]
    temp_csv = [temp + K for temp in temp_csv]
    return time_csv, temp_csv

time_csv1, temp_csv1 = time_temp(rows1)
time_csv2, temp_csv2 = time_temp(rows2)
time_csv3, temp_csv3 = time_temp(rows3)
time_csv4, temp_csv4 = time_temp(rows4)
time_csv5, temp_csv5 = time_temp(rows5)
time_csv6, temp_csv6 = time_temp(rows6)
time_csv7, temp_csv7 = time_temp(rows7)
```

Listing 4.12: Temperature of Arkivenes Hus

In the same way, **power**, **airflow**, and **occupancy data** was retrieved from **CSV** files for analysis. The data is used to observe the trend of temperature over the time period.

```python

with open(csc_file_path8, "r") as csv_file:
    csv_file_reader8 = csv.reader(csv_file)
    rows8 = list()
    for row in csv_file_reader8:
        rows8.append(row)
with open(csc_file_path9, "r") as csv_file:
    csv_file_reader9 = csv.reader(csv_file)
    rows9 = list()
    for row in csv_file_reader9:
        rows9.append(row)

def time_power(rows):
    time_csv = list()
    power_csv = list()
    for i, row in enumerate(rows):
        # print(i, row)
        if i == 0 or len(row) == 0:
            # print(row)
            continue
        time_csv.append(datetime.datetime.fromisoformat(row[0])
        .strftime("%Y%m%d%H%M%S"))
        power_csv.append(float(row[1]))
    print(time_csv[0])
    time_csv = [int(time)-20201026123209 for time in time_csv]
    power_csv = [power for power in power_csv]
    return time_csv, power_csv

time_csv8, power_csv8 = time_power(rows8)
time_csv9, power_csv9 = time_power(rows9)

#Similar for flow and occupancy

def time_flow(rows)
    time_csv = list()
    #....
def time_people(rows)
    time_csv = list()
    #....
```

Listing 4.13: Power, flow of air and occupancy data

For mathematical model analysis, the data from *Arkivenes Hus* was used, taken from table 5.6 [23].

```
A_window = 1996/1000 # NOTE: Combined with Adoor! 1.2 # [m^2] Area of window
A_door = 1996/1000 # 0.75*2.1 # [m^2] Area of door
A_walls = 3486/1000 #2*(self.l+self.w)*self.h - (self.Awindow+self.Adoor) #
    [m^2] Area of walls
A_wallsBase = 1878/1000 # [m^2] Area of walls
A_roof = 3090/1000 # self.l*self.w # [m^2] Area of roof
A_floor = 2269/1000 #  self.l*self.w # [m^2] Area of floor

# Ventilation
V_in =  (1*1375) / (A_floor) # (airflow )/(3600*(self.Afloor))
    #(self.l*self.w)
V_out = V_in
# Overall heat transfer coefficients
U_window = 0 # NOTE: Combined with Adoor!  1.2 # [W/m^2K] Heat transfer coeff
    of window
U_door = 0.8 #1.2 # [W/m^2K] Heat transfer coeff of door
U_walls = 0.17# 0.18 # [W/m^2K] Heat transfer coeff of walls
U_wallsBase = 0.15# [W/m^2K] Heat transfer coeff of walls
U_roof = 0.13 # [W/m^2K] Heat transfer coeff of roof
U_floor = 0.18 #  0.15 # [W/m^2K] Heat transfer coeff of floor
```

Listing 4.14: Change of temperature over time on Arkivenes Hus

Odient solver used on *Arkivenes Hus's* building parameters to plot the results and observe the temperature over time.

Chapter 5

Results

5.1 Analytical Solution

The expression for indoor temperature in the building unit is given by:

$$\frac{dT_b}{dt} = \frac{\dot{V}_{\text{in}}\rho_{\text{in}}h_{\text{in}} - \dot{V}_{\text{out}}\rho_b h_{\text{out}} + \dot{Q}_{\text{supply}} - \dot{Q}_{\text{loss}}}{V_b\rho_b(c_{p,b} - \frac{R}{M_b})} - \frac{d\rho_b}{dt}. \tag{5.1}$$

Using the reference from paper [8], equation (5.1) can now be written as,

$$\frac{dT_b}{dt} = \kappa_1(t) - \kappa_2 T_b. \tag{5.2}$$

$$\kappa_1(t) = \frac{\dot{V}_i\rho_i h_i - \dot{V}_e\rho_e h_e + \dot{Q}_{\text{supply}}\ (t) + T_\infty \sum_j U_j A_j}{\rho_b V_b \left(c_p - \frac{R}{M_b}\right)} + \frac{\dot{V}_i\rho_i - \dot{V}_e\rho_e}{\rho_b V_b}. \tag{5.3}$$

$$\kappa_2 = \frac{\sum_j U_j A_j}{\rho_b V_b \left(c_p - \frac{R}{M_b}\right)}. \tag{5.4}$$

The $\dot{Q}_{\text{supply}}$ is a function of time, and the density of air will also vary as the air is heated. The steady-state temperature can be found by setting $dT_b/dt = 0$, in the equation above.

$$T_b \rightarrow \frac{\kappa_1}{\kappa_2}. \tag{5.5}$$

We assume that $Q_1(t)$ is on/off, and ignore the temperature dependency of ρ, we can solve the equation analytically for T_b values.

$$T_b = \frac{1}{\kappa_2}\left(\kappa_1(0) - (\kappa_1 - \kappa_2 T_b(0))\, e^{-\kappa_2 t}\right), t < t_f. \tag{5.6}$$

$$T_b = \frac{1}{\kappa_2}\left(\kappa_1\left(t_f\right) - \left(\kappa_1 - \kappa_2 T_b\left(t_f\right)\right)e^{-\kappa_2\left(t-t_f\right)}\right), t \geq t_f. \tag{5.7}$$

The notation is sightly unusual because we assume that $\dot{Q}_{\text{supply}}$ is constant in equation (5.6), and zero in equation (5.7). We get $\kappa_1(0) = 46$ K/ hours $(t < t_f)$, $\kappa_1(\infty) = 46$ K/ hours, and $\kappa_2 = 0.000159$ /s from calculations in Python environment which can be seen from the work of [8] in Appendix A. These values can help us in eventually getting the analytical result shown in Figure 5.1.

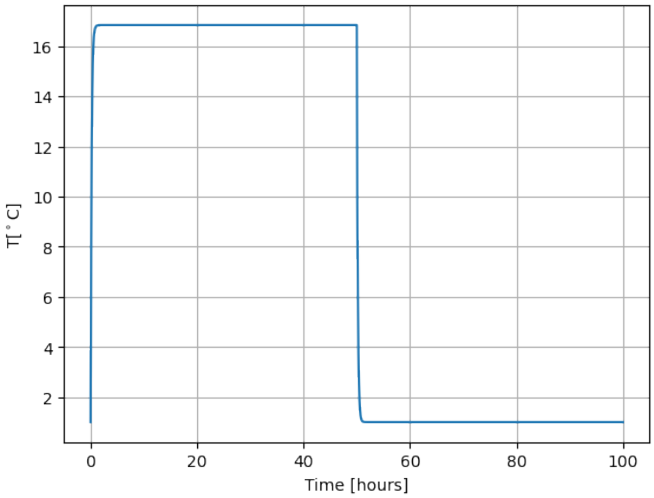


Figure 5.1: Temperature variations of the air in the buildings [8]

5.2 Setting up parameters for simulation scenarios

The analysis and evaluation of the building's energy performance rely on carefully chosen parameters and coefficients. Table 5.1 provides thermal parameters for the building enclosure and furniture, specifically tailored for typical Norwegian buildings. These values are estimated to help understand and analyze the heat transfer characteristics of the building components and the furniture in the context of thermal performance [6].

Parameter		Layer 1 (Inside)	Layer 2	Layer 3	Layer 4
$K_{i,w}$	[W/(mK)]	0.14	0.038	0.026	0.14
$K_{i,r}$	[W/(mK)]	0.14	0.038	0.12	0.027
$K_{i,f}$	[W/(mK)]	0.027	0.14	0.038	
K_{fur}	[W/(mK)]	2			
$\alpha_{i,w}$	[m^2/s]	1.7x10^{-7}	1.4x10^{-6}	2.25x10^{-2}	1.7x10^{-7}
$\alpha_{i,r}$	[m^2/s]	1.7x10^{-7}	1.4x10^{-6}	1.8x10^{-7}	4x10^{-7}
$\alpha_{i,f}$	[m^2/s]	4x10^{-7}	1.7x10^{-7}	1.4x10^{-6}	
α_{fur}	[m^2/s]	1.8x10^{-7}			
$l_{i,w}$	[m]	6x10^{-3}	75x10^{-3}	8.5x10^{-3}	8.5x10^{-3}
$l_{i,r}$	[m]	6x10^{-3}	100x10^{-3}	11x10^{-3}	6.5x10^{-4}
$l_{i,f}$	[m]	1x10^{-3}	9x10^{-3}	75x10^{-3}	
$\rho_{i,f}$	[kg/(m^3)]	55	615	32	
$c_{p,f}$	[J/(kgK)]	1210	1317	835	

Table 5.1: Parameters applicable to walls, floor, roof and furniture

The heat transfer coefficients in this study are determined according to the TEK10 standards, which provide guidelines for building regulations. For each layer of the walls, floor, and roof, the values of thermal conductivities, thermal diffusivity, and half thicknesses are provided in 5.2. Additionally, the densities and specific heat capacities of each layer of the floor are also given. These properties and coefficients play a significant role in the development of the dynamic heating model.

Parameter	Value
$h_{b,w}$	2
$h_{\alpha,w}$	1
$h_{b,r}$	2
$h_{\alpha,r}$	1
$h_{b,f}$	2
$h_{b,fur}$	2
U_{window}	1.2
U_{door}	1.2

Table 5.2: Heat transfer coefficient $[W/(m^2K)]$

To make things simpler for our analysis, U_{walls}, U_{floor}, and U_{roof} are taken as $1.2W/(m^2K)$ as well. Additionally, it is assumed that the area of all these elements is also equal to each other. The performance of the developed model is assessed through three cases. The building unit with one door and one window are utilized for all the cases as shown in Figure 2.4. Table 5.3 contains the data taken from [22]. This provides a concise summary of the different variations in input parameters and physical settings of the building unit for each case.

Property	C1	C2	C3
Heat supply, kW	1-0	1	1
Heating control	No	On/Off	On/Off
Air flow, $m^3/(m^2.h)$	0.7	TEK10	0
Outside T, ^{0}C	-2.2	Varying	Varying
Outside RH	0.77	Varying	Varying
Occupancy	No	Yes	Yes
Insolation, W/m^2	0	100	100
Appliances, W	0	150	150
Furniture vol., m^3	1	1	1
Furniture material	Wood	Wood	Wood
Heat recovery	No	No	No
Area, m^2	3.65×4	3.65×4	3.65×4
No of units	1	1	1

Table 5.3: Properties of variants in simulated scenarios

5.3 Case 1

The simulation starts with an outside temperature taken as **270.95 Kelvin** (-2.2 °C). The simulation runs for 100 hours, throughout which uniform outside temperature and relative humidity profiles are maintained. A constant heat supply of **1 kW** is given. In this specific case, the building unit remains unoccupied throughout the entire simulation period. There are no occupants present, and no electrical appliances are in use, leading to an absence of internal heat sources. The outdoor relative humidity (RH) is set to a fixed value of 0.77, representing the moisture content in the surrounding air.

5.3.1 Temperature variations which constant heat supply

For the simulation $\kappa 1_{\text{occupied}}[i]$ and $\kappa 2_{\text{unoccupied}}[i]$ are defined in Python which stores the computed values to find temperature ($T_{b_{\text{unoccupied}}}[i]$) for each time step i (Listing 4.9). After the simulation is taken place, the temperature profiles of indoor air, the internal temperature of walls, roof, floor, and the external surface temperature of the furniture are visualized. However, the results were not entirely accurate because the form of the equation did not support what we wanted to achieve.

First assumption

Then, to match the results, κ values were assumed once again. As shown in Figure 5.2, which displays the scenario which closely relates to T_b value calculated in the analytical solution (Figure 5.1). To achieve the result in the plot below, we assumed that $\kappa 1(0) = 90$ K/hours, $\kappa_1 = 58.70$ K/hours, and $\kappa_2 = 0.2$ /hours.

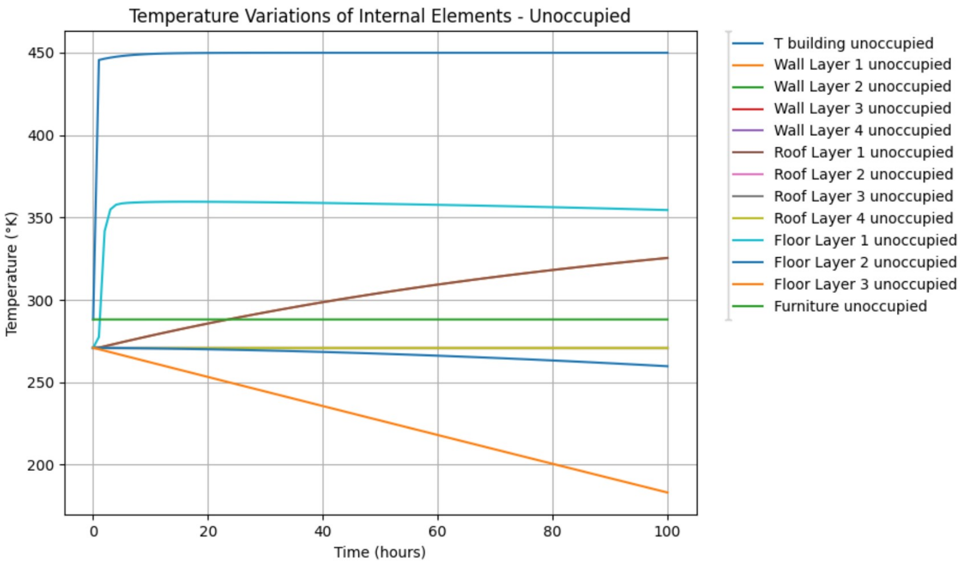


Figure 5.2: Temperature over time with heat supply of 1 KW

However, the temperature rises up to **450 K** which is not feasible for physical scenarios.

Second assumption

Then the modified coefficients $\kappa 1(0) = 70$ K/hours, $\kappa_1 = 70$ K/hours, and $\kappa_2 = 0.23$/hours for **T_building** were assumed. The temperature of the building had much better results with these modified coefficients. The temperature raises up to **305 K** which is more probable considering the temperature outside is **270.95 K**. Also, T_b closely propagates to **floor layer 1** as can be seen in Figure 5.3. Normally it should propagate to all equations, however, the form of the equation does not permit to terrace the same shape as **T_building** for the other rest of the elements.

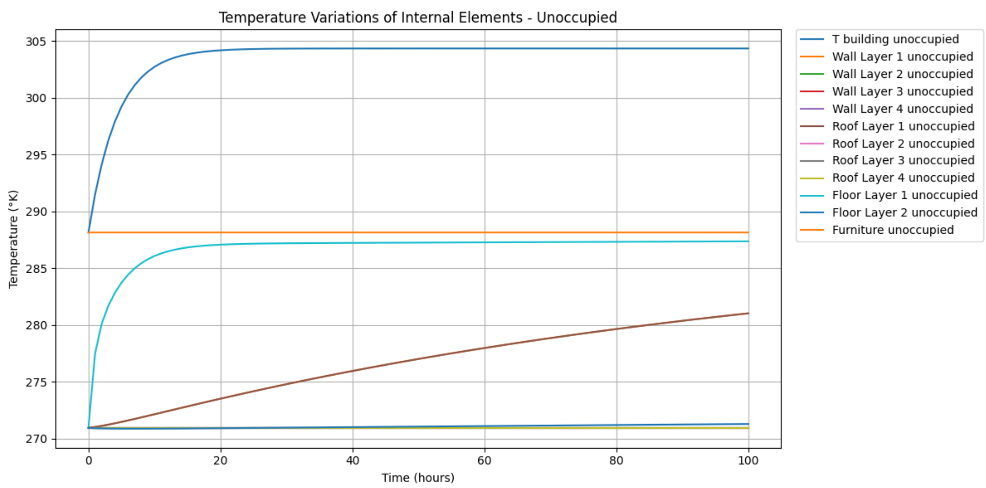


Figure 5.3: Temperature over time (modified coefficient κ_1, κ_2, $\kappa_1(0)$

5.3.2 Temperature variation of wall layers

For the analysis, we are considering four layers of wall (**i=1,2,3,4**). In the analysis of temperature variation with wall layers, it is observed that the walls exhibit a gradual increase in temperature when subjected to a constant heat supply. This observation indicates that the wall layers take some time to reach their desired temperature, which is crucial for understanding the overall thermal behavior of the building.

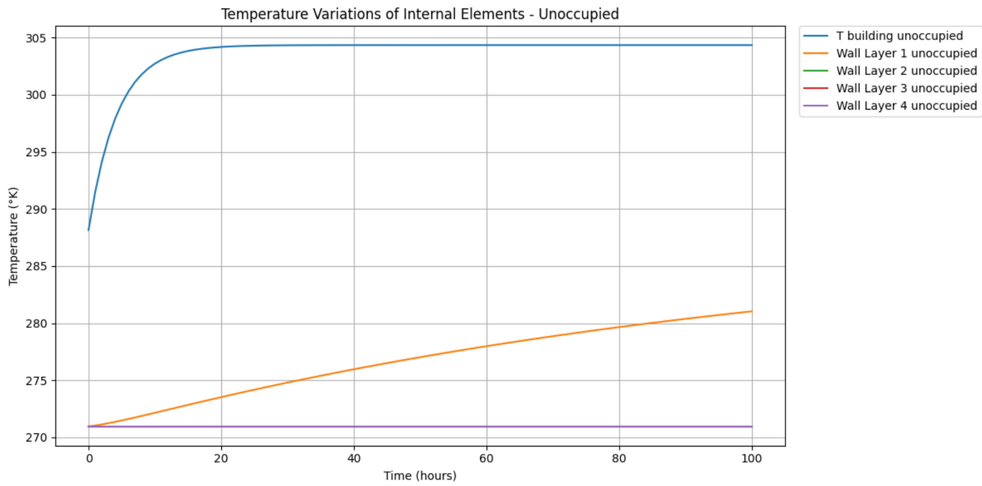


Figure 5.4: Subplot of $T_{building}$ with wall layers

In the mathematical model, the internal and external boundary conditions have been carefully observed. The innermost layers of the walls tend to show a gradual rate of temperature increase, as can be seen in Figure (5.4). The effects of the external environment, which encompass ambient temperature, solar radiation, wind, and humidity, are assumed to remain constant and have little to no impact on the outside layer.

5.3.3 Temperature variation of roof layers

The subplot of the temperature variation in the building with roof layers exhibits similarities to the wall layers. This is due to the similarity in the numerical form of the equations and the similarity in the coefficients, which helps to simplify the model. Four layers are considered for the roof, and it is exposed to similar environmental factors as the walls. The temperature variation in these layers follows a pattern that is influenced by external conditions.

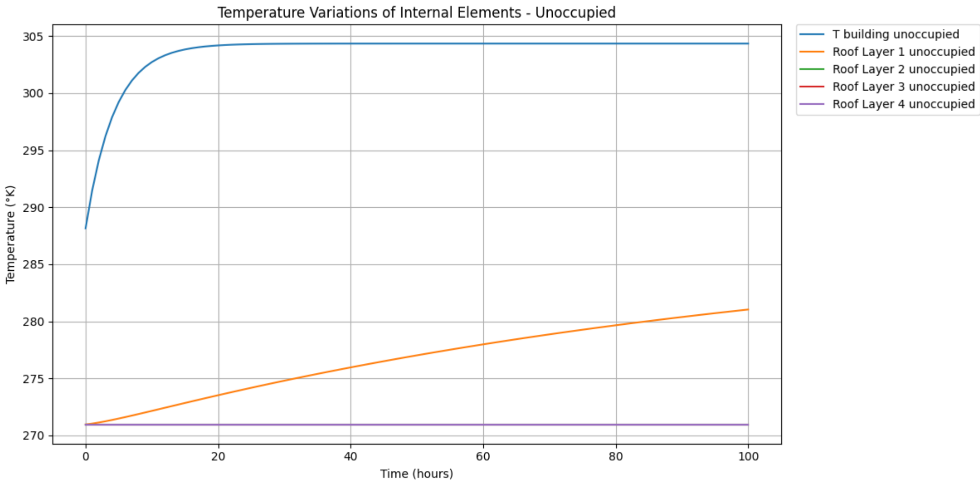


Figure 5.5: Subplot of T building with roof layers

5.3.4 Temperature variation of floor layers

The subplot of the temperature variation in the building with floor layers is seen to have variations quite different from the walls and roof. Layer 1 temperature change (the internal boundary) closely follows the shape of the T_building. This is because the equation form used for the floor layers is more descriptive and allows for a better representation of the temperature variation.

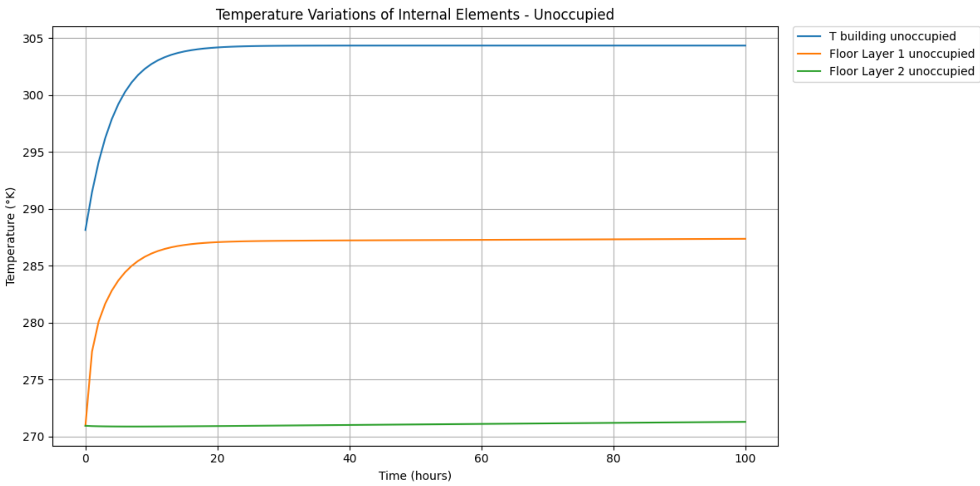


Figure 5.6: Subplot of T_building and floor layers

Three layers of the floor (**i=1,2,3**) are considered in the analysis, and since it is not exposed to the external environment, the temperature variation in these layers follows a similar pattern to T_building. Layer 3 due to some missing parameters had a continuous decrease of temperature for 100 hours, which is also not practically possible. Hence, it is not shown in the graph above.

5.3.5 Temperature variation of furniture layer

The furniture is represented as a single layer with no variation over time in the simulation. The unintended constraints or limitations in the mechanistic model when only one layer of furniture is taken into account can be seen in Figure 5.7. That can lead to no change in the furniture's temperature.

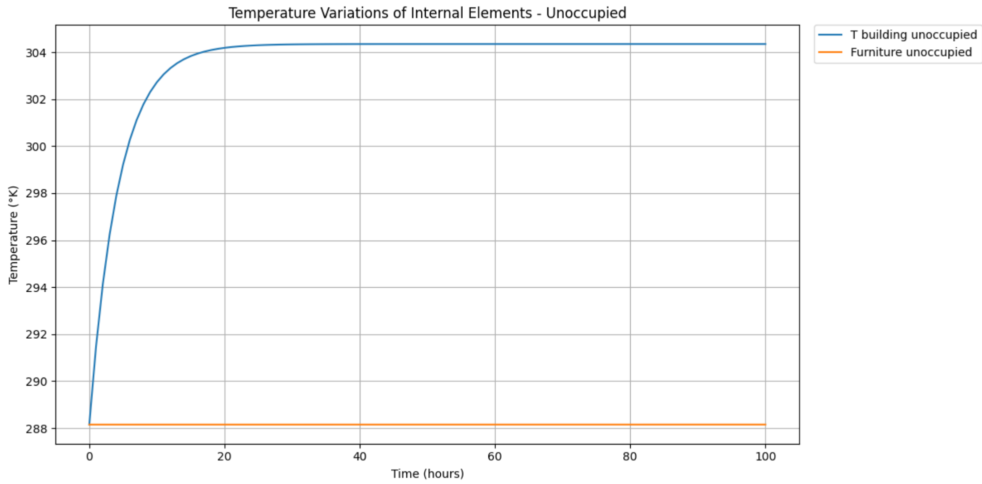


Figure 5.7: Subplot of T_building and furniture temperature

If the furniture has low thermal mass, it would heat up or cool down quickly when exposed to a heat source or a change in the room temperature.

5.4 Case 2

Without these internal heat sources and insulation, the building's temperature can experience faster fluctuations in response to external conditions, especially considering the fixed heater operation. The uncontrolled heating process leads to a continuous rise in the indoor temperature without any moderation, creating a unique and challenging scenario for understanding the building's energy performance under specific conditions.

To counter that, the next focus is on examining the heat dynamics of a building unit using a heater controlled by an **On/Off controller**. For this case, the building is occupied, and the set temperature is maintained at **293.15 K** (20°C) to ensure the comfort of the occupants. However, during unoccupied periods, the temperature can be reduced to **288.15 K** (15°C) by appropriately controlling the heater. The simulation considers outdoor temperature and relative humidity profiles, which vary over time. The control strategies in this case, compared to case 1, provided a more realistic representation of the building's thermal behavior. The same values are used for basic measurement of $\frac{dV}{dt}$, ρ, h, and Q as in the previous case. The building unit has a circulating air flow, as required by TEK10 regulations.

5.4.1 Temperature variations with On/Off control

First assumption

The analytical model for the temperature distribution within the building consists of different components: T_{wall} and T_{roof}, each with layers 1, 2, 3, and 4, following a similar numerical equation format. Assuming values of κ coefficients, which are shown in table 5.4 for the first half ($t_f < 50$ hours) and the second half ($t_f > 50$ hour)s.

	$t \leq 50$ hours	$t > 50$ hours
κ_1	58.7	90
κ_2	0.2	0.2
$\kappa(t)$	90	50

Table 5.4: κ values to match accuracy to analytical results

Similar to case 1, the graph (5.8) is showing the raise to 450 K for constant heat supply. This isn't feasible in practical conditions.

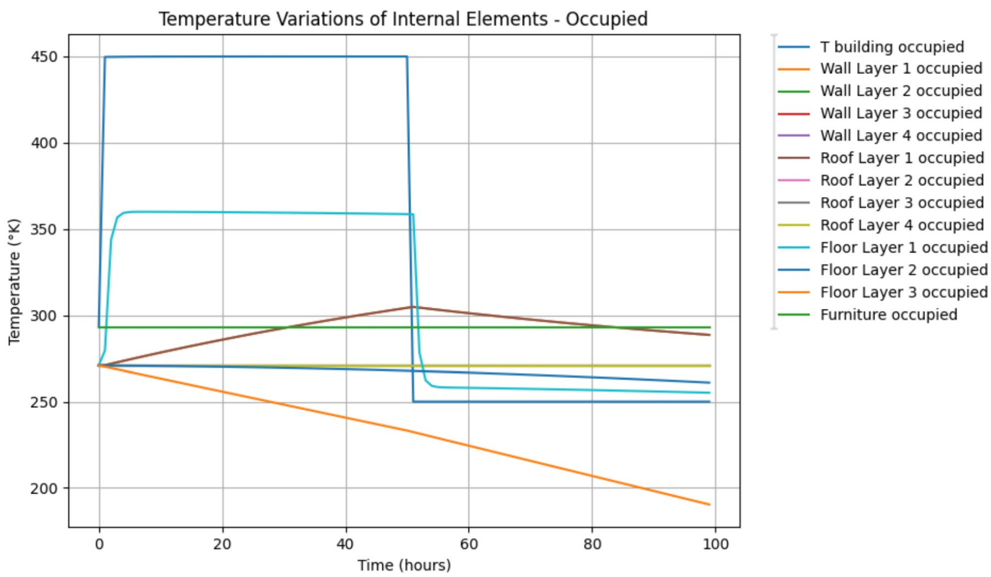


Figure 5.8: Temperature over time (building occupied)

Second assumption

The values are again assumed for κ in order to match the article [22]. The temperatures are calculated for the first half ($t_f < 50$ hours) and the second half ($t_f > 50$ hours) using modified coefficients in table 5.5.

	$t \leq 50$ hours	$t > 50$ hours
κ_1	70	50
κ_2	0.23	0.19
$\kappa(t)$	70	50

Table 5.5: κ values to match accuracy with article [22]

The visual analysis of Figure 5.9 provides a more realistic depiction of the temperature variations, effectively conveying the impact of different coefficient values on the building's temperature distribution. The representation offers valuable insights into how these coefficients influence the temperature dynamics over time, especially concerning the heating controls employed within the building unit.

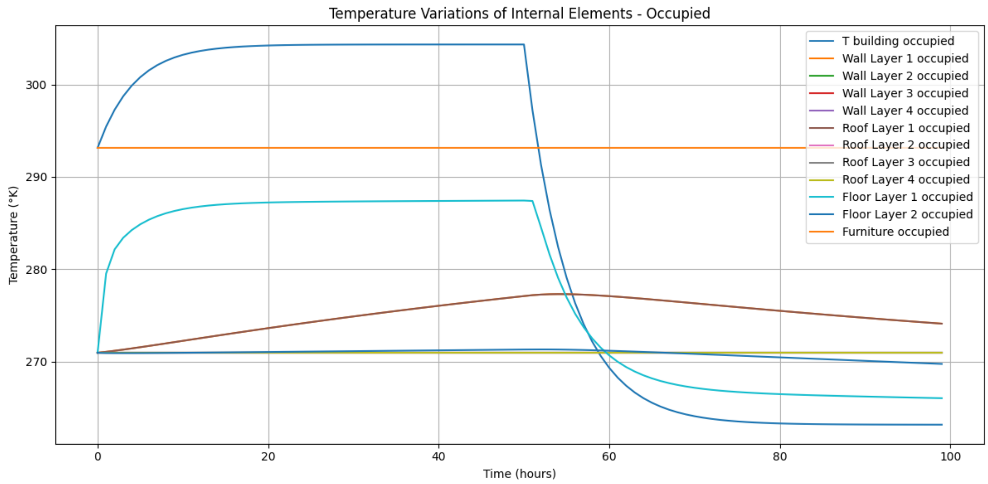


Figure 5.9: Temperature over time (modified coefficient κ_1, κ_2, $\kappa_1(0)$)

This realistic representation of the building's thermal behavior can be compared to the article [22].

Comparison with Article

The following model was created by [22] for case 2.

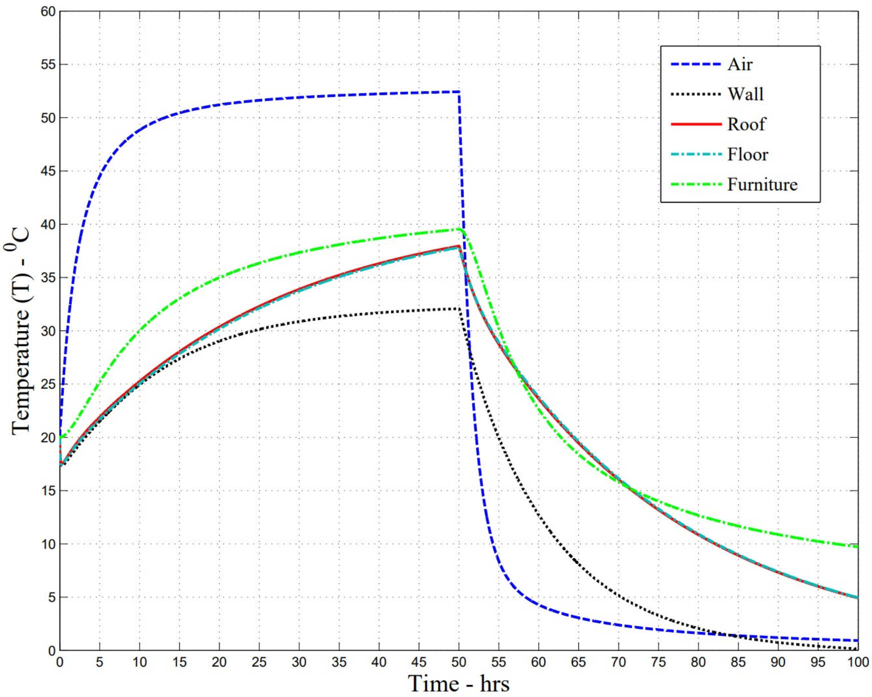


Figure 5.10: Temperature variations of air and other elements internal to the building unit with On/Off control [22]

When comparing our model (Figure 5.9) with the model presented in the article (Figure 5.10), we observe similarities in the temperature variations for the building unit and floor. Both models demonstrate similar trends before and after the heat supply is applied and subsequently removed.

However, some slight differences are apparent in the temperature variations of the individual building elements, such as walls and furniture, between the two models. These discrepancies can be attributed to the presence of certain missing potential factors in our model.

5.4.2 Walls and roof layers for On/Off heater

The analysis of temperature variation with wall layers indicates that when the walls are subjected to heat supply for a duration of up to 50 hours, the temperature gradually increases across the layers similar to that case 1. After 50 hours, the temperature in the innermost layers gradually starts to decrease as the heater is no longer providing additional heat. This temperature decrease is due to the heat dissipating to the building's interior and the surrounding environment.

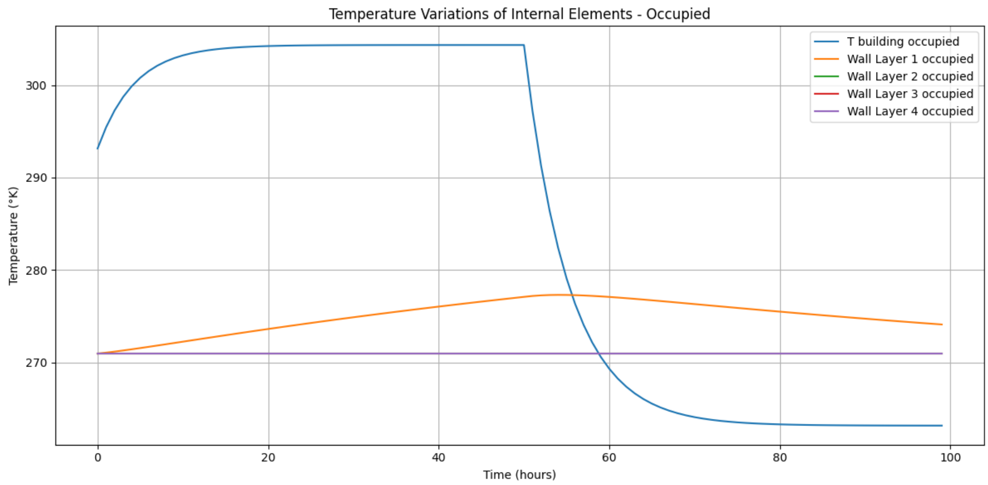


Figure 5.11: Subplot of $T_{building}$ with wall layers

Figure (5.11) displays the temperature profiles of the wall layers, revealing an interesting pattern in their behavior. During the first half of the simulation, the internal layer's temperature shows a steady increase, while in the second half, it exhibits a gradual decrease at a consistent rate. This observation suggests that the time required to cool down the walls is almost equivalent to the time needed to heat them initially.

Similar to case 1, The roof exhibits a temperature variation pattern similar to the walls.

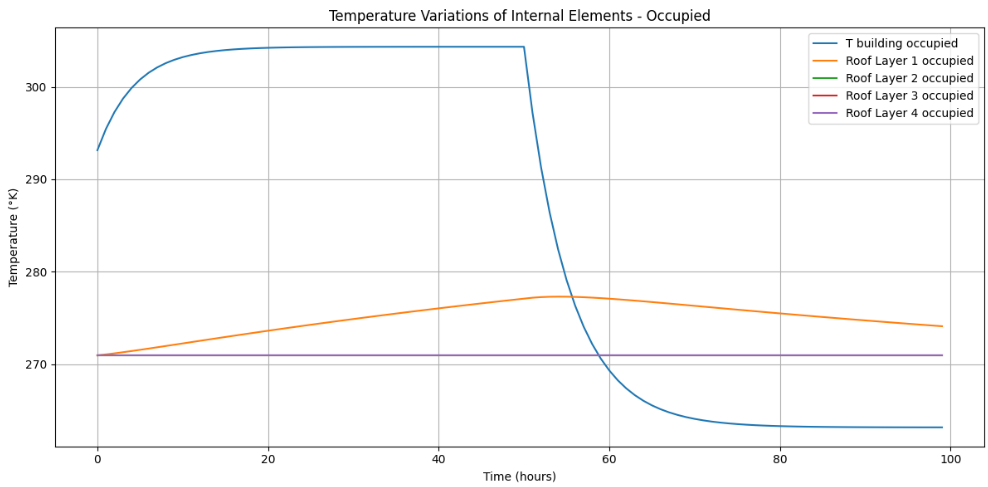


Figure 5.12: Subplot of $T_{building}$ with roof layers

The building's roof and walls both give a controlled and steady response to the heat source.

5.4.3 Floor layers for On/Off heater

For the first half, the internal boundary layer of the floor is seen to have an increment in temperature similar to that of T_b. But when the heat supply becomes zero in the second half, the decrease in temperature of this layer is seen to have a slow decrease in temperature than building temperature.

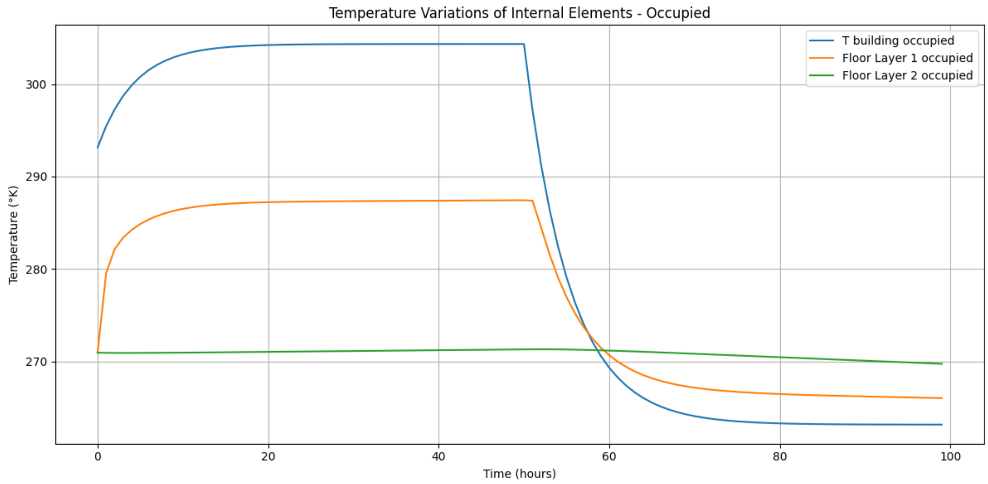


Figure 5.13: Subplot of $T_{building}$ and floor layers

The results shown in Figure 5.13 demonstrate that the floor temperature increases rapidly, similar to the building temperature, but it requires significantly more time to cool down. This observation highlights the thermal inertia of the floor, which leads to a slower response to changes in external conditions compared to the building's interior temperature.

5.4.4 Furniture layers for On/Off heater

$T_{furniture}$ is also calculated numerically as part of the comprehensive analytical model of the building's temperature distribution. The model considers various factors (from table 5.1) influencing its heat exchange. It has shown no temperature change, which might be because we are using a simplistic model for the furniture, neglecting certain factors or heat transfer mechanisms that are crucial for accurately representing the furniture's temperature response.

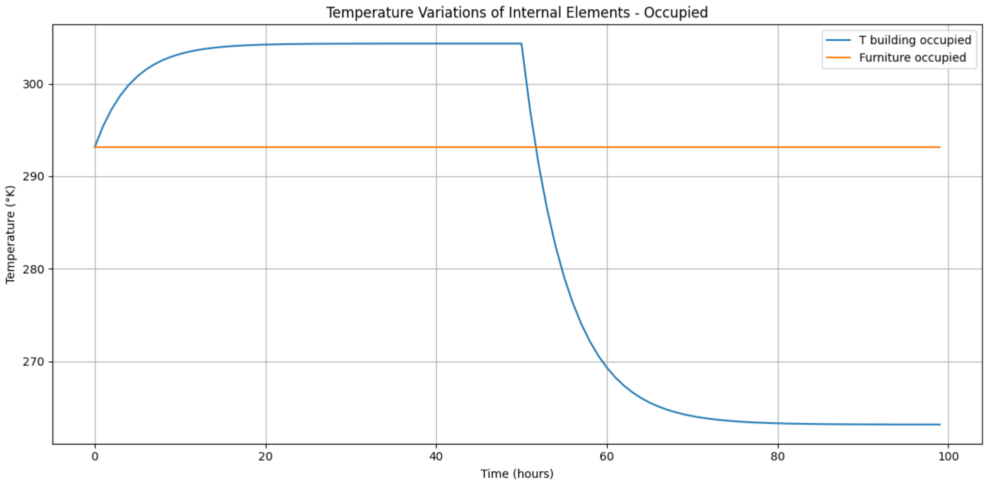


Figure 5.14: Subplot of T building and furniture temperature

5.5 Case 3

In this case, the graphs are similar to case 2 because the equations separate T_outside from the actual numerical formulations. However, to compare the density with article [22], density ($\rho_{building}$) is observed for 100 hours. Figure 5.15 provides a change in density during the first 50 hours when heat is supplied and then later when heat supply is removed.

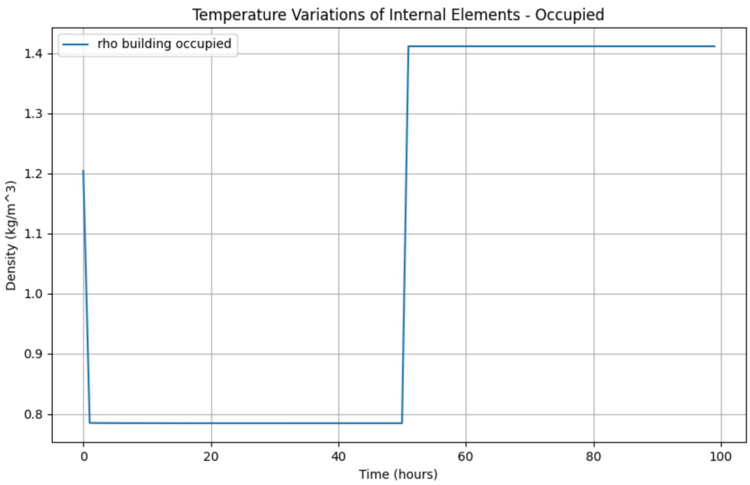


Figure 5.15: Density of air in the building with respect to time

When heat is supplied to the room, the temperature increases, and the air inside the room expands, leading to a decrease in density. Conversely, when the heat supply is removed, the air cools down, causing a decrease in volume and an increase in density. Humidity and ventilation are also influencing the density change.

5.5.1 Comparison with article

The article [22] has less density fluctuations within the building unit compared to our results. Although the parameters (for Figure 5.16) are the same as they are in our model (Figure 5.15), discrepancies in the code or algorithms used in the simulation might have impacted the density.

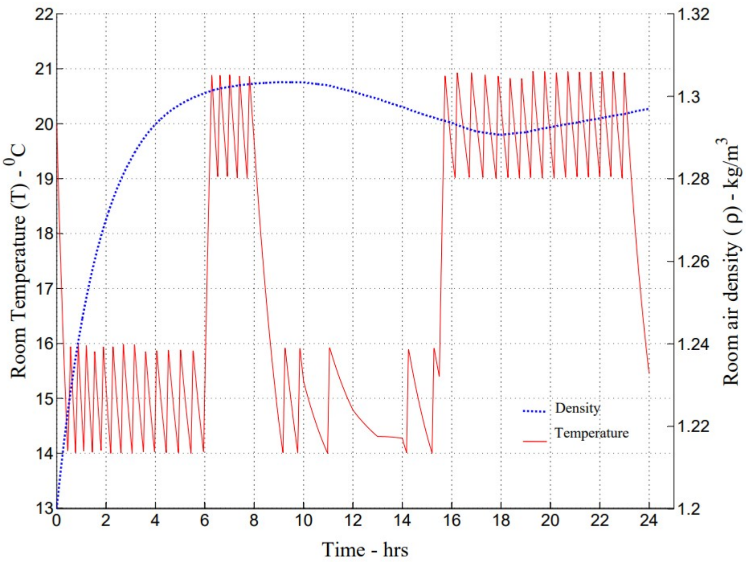


Figure 5.16: Density variations inside the building unit with On/Off control[22]

5.6 Case of Arkivenes Hus

The information utilized in this study was sourced from *Arkivenes Hus* data, which was originally obtained from *NORCE* (Appendix C). To ensure compatibility with our analysis, the time data was converted from the ISO format to integers, while the temperature data was converted from strings to floating-point numbers. Prior to analysis, data cleaning procedures were implemented, particularly for flow rates, where numerous blank and zero values were present. These instances were effectively removed from the dataset to ensure data integrity and accuracy in our study.

5.6.1 Data from NORCE

The NORCE research is utilizing sensors to measure various parameters in the building environment, which are then used to calculate the heat flux ($\hat{q}i = qi + q_{\sigma i}$) and temperature related quantities ($\hat{T}i = Ti - T_{amb}$).

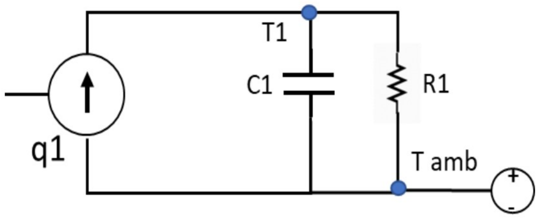


Figure 5.17: RC sensor circuit of NORCE C

The equation to find the heat flux ($\hat{q}i$) in terms of the corrected indoor temperature ($\hat{T}_i$) through the sensor is:

$$\hat{q}i = \frac{\hat{T}i}{R_i} + C_i \cdot \frac{d\hat{T}_i}{dt}. \tag{5.8}$$

The temperature difference dT is calculated by the sensors by:

$$dT = \boldsymbol{T}\text{extract} - \boldsymbol{T}\text{supply}. \tag{5.9}$$

$$T_1 = \boldsymbol{T}_{\text{extract}}. \tag{5.10}$$

All graphical representations of the data which were used for analysis can be found in Section D.0.1,Section E.0.1, Section F.0.1, and Section G.0.1.

5.6.2 Temperature and Power Comparison

For April 2021, the temperature in Stavanger, Norway, was monitored using previous forecasts, and it was found that the average temperature during that week remained at approximately 283 Kelvin [25]. It can be seen from the graphical representations in Appendix G. There are deviations in some graphs made from the data, but these may have been caused because of missing information in the data from NORCE.

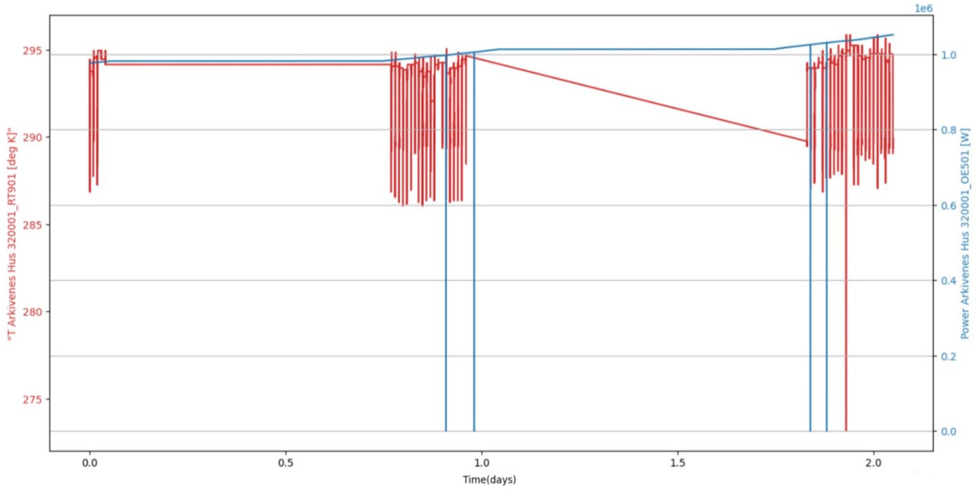


Figure 5.18: Temperature of Arkivenes Hus and power vs time

To raise the temperature in Arkivenes Hus significantly, a considerable amount of kilowatts would be required.

5.6.3 Temperature and flow comparison

Throughout these days, the average flow rate was approximately 1950 m^3/s, as calculated from the data presented in the two files shown in the Appendix section.

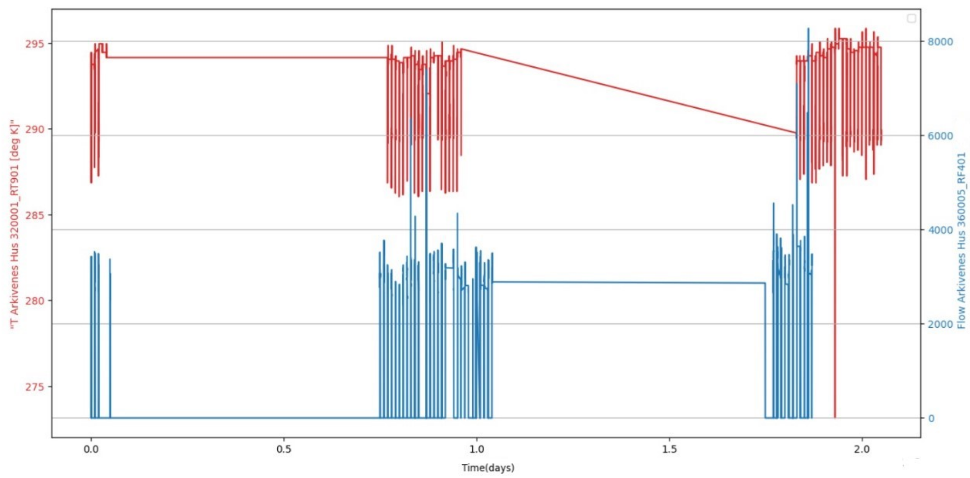


Figure 5.19: Temperature of Arkivenes Hus and flow of air (m^3/s) vs time

It lays the foundation for further analysis and modeling to assess the water resource's sustainability and plan for any potential fluctuations in the future.

5.6.4 Temperature and occupancy comparison

Figure 5.20 shows that as the number of people in the *Arkivenes Hus* increases over time, the power is turned on to maintain an adequate temperature for thermal comfort.

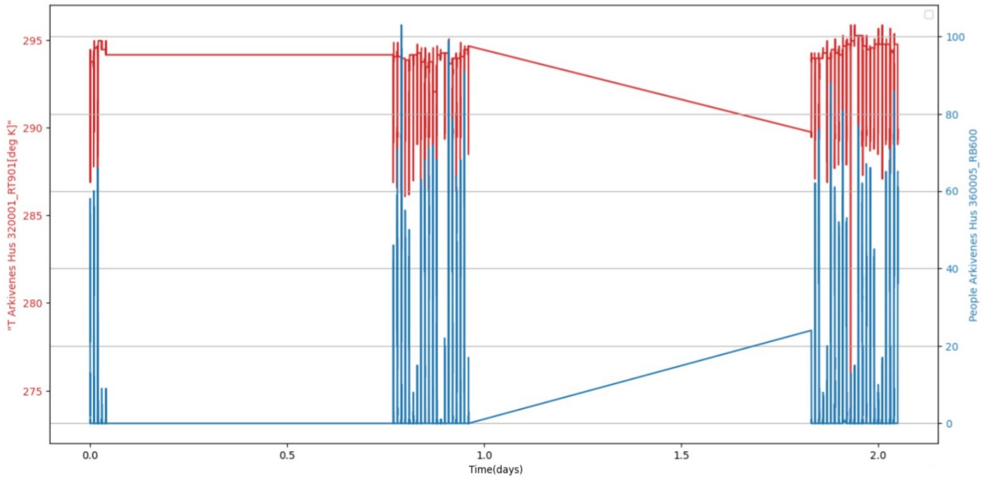


Figure 5.20: Temperature of Arkivenes Hus and People vs time

5.6.5 Case 2 on Arkivenes Hus

Using the area and heat values for the *Arkivenes Hus* building taken from [23] which mentions a simulation done by *Smi Energi* and *Miljø AS*. This can be seen in Appendix B.

Part of building	**Value**$[\frac{W}{m^2K}]$	**Area**$[m^2]$
Total area heated	-	12904
Total heate volume	-	47267
Outer walls	0.17	3486
Basement walls	0.15	1878
Roof	0.13	3090
Floor	0.18	2269
Windows and doors	0.8	1996

Table 5.6: Area and their heat transfer coefficient

The values of the outer wall, basement walls, roof, floor, and doors were obtained from Table (5.6) and integrated into the simulation, resulting in the model depicted in Figure 5.21 for Arkivenes Hus.

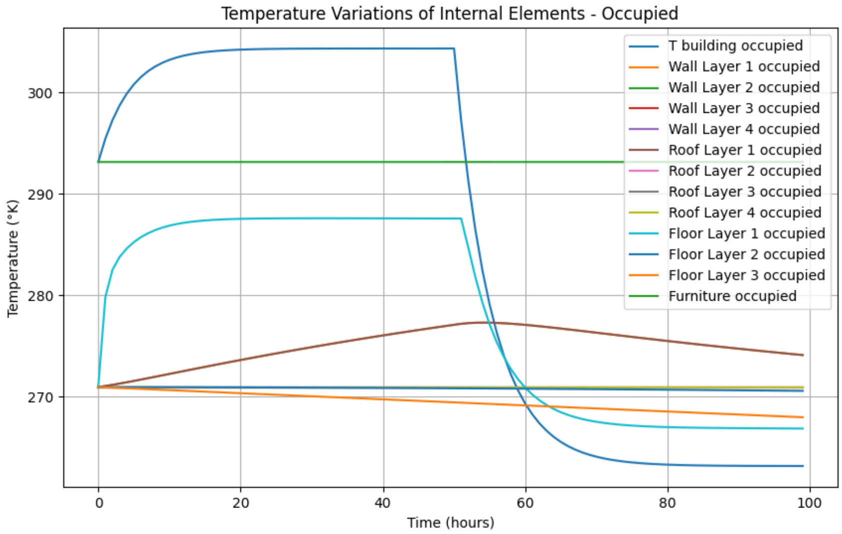


Figure 5.21: Temperatures calculated for *Arkivenes Hus* using Table 5.6 parameters

By incorporating the values from the table, we achieved a graph resembling that of case 2, with the floor parameters significantly influencing the behavior of layer 3 to be more realistic compared to the previous cases. However, it is important to acknowledge that for the sake of simplicity, we assumed uniform values for the area and internal energy of all other building elements. This simplification may have introduced some limitations in accurately predicting the exact heat loss through these elements.

Despite this simplification, the parameters provided in Table (5.6) can be valuable references for future efforts aimed at refining the model's accuracy. By considering the specific area and internal energy of each element in a more detailed manner, we can enhance the model to provide more precise simulations of Arkivenes Hus's thermal behavior. This refinement will contribute to a comprehensive understanding of the building's thermal performance and allow for more reliable energy efficiency assessments in real-world scenarios.

Chapter 6

Conclusion

6.1 Summary

This thesis presents a comprehensive mathematical model for indoor temperature simulation and analysis, with practical applications in energy-efficient building management. The model's development and validation involved testing, using a hypothetical building unit and real-world data from *Arkivenes Hus*. The primary objective was to accurately simulate indoor air temperature dynamics under various scenarios, such as controlled heating and changing environmental conditions. The integration of an analytical model ensured precise predictions, yielding closely related results between models. The simulations on *Arkivenes Hus* gave significant insights into the interplay between outdoor temperature, occupancy, airflow rates, and indoor temperature regulation. While the current model for *Arkivenes Hus* may have certain limitations, it serves as a stepping stone for further research and development. The study emphasizes the importance of considering these factors for optimizing energy consumption and enhancing building energy efficiency. This research lays a strong foundation for future investigations into sustainable building energy management strategies.

6.2 Contribution and Learning Outcomes

Successfully reproducing the published dynamic heating model by Perera et al. allowed me to gain a deeper understanding of thermodynamics and energy balance. It involved a comprehensive study of the original model's equations and their implementation, significantly improving my proficiency in mathematical modeling. Applying the model to the *Arkivenes Hus* provided valuable insights into its behavior under real-life conditions. This experience reinforced the importance of bridging the gap between theoretical knowledge and real-world applications.

Implementing the model in Python involved complex numerical computations and simulations, which significantly enhanced my programming skills, particularly in

Python, and exposed me to advanced modeling techniques.

The study required a deep exploration of heating systems, including the interplay between external factors (e.g., outdoor temperature and airflow) and internal control strategies. This knowledge not only contributed to my research but also enriched my understanding of building thermal dynamics.

Overall, my thesis provided a valuable opportunity to deepen my knowledge in the areas of thermodynamics, energy modeling, and heating systems. The acquired skills and insights will serve as a strong foundation for my continued research and contributions to the field of sustainable building design and energy management.

6.3 Limitations

In the comparison of our results with the Perera's model [22], we observed slight differences, which could be attributed to various factors. Human errors might have inadvertently been overlooked during data input and processing. Additionally, even minor differences in assumptions made during the modeling process can lead to significant discrepancies in the simulation outcomes. Moreover, the possibility of discrepancies in the code or algorithms used in our simulation cannot be ruled out.

There are some limitations in our model. First, it does not account for all the factors that influence indoor temperature dynamics. For example, it does not account for the effects of solar radiation, building material properties in detail, and control strategies. Second, the model was validated using data from a single building, so its accuracy may not be generalizable to other buildings. Third, the model is computationally complex, so in order to understand it in detail, all the dependencies should be thoroughly researched. Fourth, the model is not user-friendly, so it may be difficult for non-technical users to use.

Some additional limitations that could be mentioned are:

- The model does not account for the effects of occupant behavior, such as opening windows or using fans.
- The model is based on a number of assumptions, such as constant heat transfer coefficients and uniform temperature distribution. These assumptions may not be accurate in all cases.
- As the original Perera model was implemented in MATLAB, this choice could result in a more accurate simulation of the model.

Overall, the model presented in this thesis is a valuable tool for understanding and optimizing the heat dynamics of residential buildings. However, it is important to be aware of its limitations when using it.

6.4 Recommendations for Future Work

Despite these limitations, the model presented in this thesis is a valuable tool for understanding and optimizing the heat dynamics of residential buildings.

Firstly, the model can be expanded to incorporate additional factors that influence indoor temperature dynamics. One important aspect is the ventilation heat recovery system, which plays a crucial role in heating and cooling processes. The equation 3.23 in section 3.8 will serve as a foundation for developing an Integrated Ventilation Heat Recovery (IVHR) system for further analysis [22].

The existing model of *Arkivenes Hus*, provides a foundation for future research and advancement in this field. It can be improved using the information from Appendix B.

Currently, the model includes a single furniture layer. Further work can involve expanding the layered structure to account for multiple furniture layers within the building. Also, conducting analysis with various materials for furniture, beyond wood, will provide valuable insights into how different furnishing options impact the building's thermal dynamics.

Comparing the Perera model with alternative dynamic heating models can provide insights into the strengths and weaknesses of each approach. Conducting comparative analyses can assist in understanding which model performs best under specific conditions and can inform the selection of appropriate models for different building types or climates.

Lastly, the development of a user-friendly interface for the model is essential to facilitate its usability and accessibility to a wider range of users. A user-friendly interface will enable architects, engineers, and building managers to effectively utilize the model for energy optimization and decision-making processes.

6.5 Conclusion

This thesis has provided valuable insights into thermodynamics, energy balance, and heating systems by successfully reproducing Perera et al.'s dynamic heating model. The application of this model to *Arkivenes Hus* has demonstrated its real-life relevance, underscoring the importance of integrating theoretical concepts with practical applications.

The presented first principles modeling approach offers a versatile tool for understanding the thermal performance and indoor comfort in residential building heat dynamics, accommodating complex configurations and diverse architectural designs. To achieve optimal thermal performance and comfort, meticulous indoor temperature monitoring and regulated heater power based on usage patterns are essential.

While our model somewhat aligns with existing literature, some minor discrepancies in the temperature variations of individual building elements have been observed. These disparities may be attributed to factors such as the complexity of heat transfer mechanisms considered, less detailed material properties, possible external influences, and boundary condition accuracy. To enhance our model's precision, we intend to address these concerns by incorporating the missing factors and refining the representation of heat transfer processes and material properties. This endeavor will lead to a more comprehensive understanding of the building's thermal behavior and enhance the model's predictive accuracy in real-world scenarios.

Despite the identified limitations, our model remains a valuable resource for optimizing residential building heat dynamics. Rectifying the observed discrepancies will result in more consistent and reliable results. Furthermore, we plan to enhance the model's user-friendliness through the development of an intuitive interface, fostering broader adoption and facilitating its effective utilization by energy professionals in decision-making processes.

Future research should focus on comparing the model with additional experimental and simulated data, accurate measurement of solar irradiation data, and evaluation of its performance in complex residential buildings with diverse features, including attic roofs commonly found in Norwegian buildings.

Thanks to its flexibility, the model serves as a valuable tool for analyzing heat dynamics in various scenarios and addressing questions related to temperature and energy efficiency. To strengthen its applicability, further validation of the model with additional data, consideration of factors like the ventilation system and existing elements' heat irradiation, and assessment of energy efficiency in various building designs will inform construction and renovation decisions. This continuous development and refinement of the model will pave the way for more sustainable and energy-efficient building practices.

Chapter 7

Nomenclature

Symbol	Unit	Description
$c_{p,b}$	$\frac{J}{kgK}$	Specific heat capacity of air
h_x	$\frac{J}{kg}$	Specific enthalpy if air in direction x
$h_{b,j}$	$\frac{W}{m^2K}$	Convection heat transfer coefficient of jth element inside building
$h_{\infty,j}$	$\frac{W}{m^2K}$	Convection heat transfer coefficient of jth element outside building
$K_{i,j}$	$\frac{W}{mK}$	Thermal conductivity of ith layer of jth element
M_b	$\frac{kg}{mol}$	Molar mas of air in building
$\dot{Q}_j$	W	Heat gain or loss due to jth element
ρ	$\frac{kg}{m^3}$	Density
R	$\frac{Pam^3}{molK}$	Gas constant
$l_{i,j}$	m	Half of ith layer of jth element thickness
A	m^2	Area
V	m^3	Volume
t	s	Time
$r_{i,fur}$	m	Half thickness of ith element in a spherical furniture
U_j	$\frac{W}{m^2K}$	Overall heat transfer coefficient of jth element
$T_{i,j}$	K	Temperature of ith layer of jth element
$T^s_{i,j}$	K	Surface temperature of ith layer of jth element
T_b	K	Temperature of air in the building unit
T_∞	K	Temperature outside of building
$\alpha_{i,j}$	$\frac{m^2}{s}$	Thermal diffusivity ith layer of jth element
σ	$\frac{W}{m^2K^4}$	Stefan-Boltzmann constant
ϵ	-	Emissivity of the surface

Table 7.1: Symbols and abbreviations used

Appendix A

Programming Code

A.1 Thesis programming code

The code done for all the simulations can be found on my GitHub repository [10].

A.2 Analytical solution

Values of κ_1 and κ_2 are calculated in Python using the code A.1 done by [8]. We get $\kappa_1(0) = 46$ K/ hours $(t < t_f)$, $\kappa_1(\infty) = 46$ K/ hours, and $\kappa_2 = 0.000159$ /s from the following code:

```

T_outside=1 # degree
def calc_k(Q=1e3):
    U=1.2 # W/m^2K
    A=3.65*3.3*2+4*3.3*2 #m^2
    A_vent = 0.75*3.3 # m^2
    Vb=3.65*3.3*4 # m^3
    rho=1.1041 #kg/m3 density of air
    C_b= 1.005e3# Specific heat of air J/ k g K
    R = 8.314 # J/Kmol
    Mb=28.97e-3 #kg/mol Molar mass air
    T_inf = T_outside +273.15 # K Temp outside
    Vin=Vout=0.7/(60*60)*A_vent
    hout=30.184e3+10*(2501 + 1.84 * 30) # J/Kg enthalpi of air @ 30C
    hin=30.184e3+10*(2501 + 1.84 * T_outside) # J/Kg enthalpi of air @ 1C
    k1=Vin*rho*hin-Vout*rho*hout
    k1 += Q
    k1 += T_inf*U*A
    k1 = k1/(Vb*rho*(C_b-R/Mb))
    k2 = U*A/(Vb*rho*(C_b-R/Mb))+(Vin*rho-Vout*rho)/(Vb*rho)
    return k1,k2
k1,k2=calc_k()
k1b,k2b=calc_k(Q=0)
```

Listing A.1: Python code for finding the analytical solution

This is later used to calculate the rate of change of temperature for these κ values (Code A.2).

```python

def T(t,k1=k1,k2=k2,T0=T_outside+273.15):
    print('k1 = ', k1, 'k2 = ', k2, 'K1/k2=', k1/k2)
    return 1/k2*(k1-(k1-k2*T0)*np.exp(-k2*t))

def T2(t,k1=k1b,k2=k2,tf=10):
    f=T(t[t<=tf],k1=k1,k2=k2)
    f=np.append(f,T(t[t>tf]-tf,k1=k1b,k2=k2,T0=k1/k2))
    return f
```

Listing A.2: The analytical solution

Appendix B

Arkivenes Hus

Title **Energy note Archives' house**	
Implementing organization **smi energi & miljø as** PO Box 8034, 4068 Stavanger Prof. O. Hanssensvei 7A, 4021 Stavanger Tel: 51 87 44 90 E-mail: post@smigruppen.no Website: www.smigruppen.no **Project manager,**	**Principal** **iPark eiendom as** PO Box 8034 4068 Stavanger Contact: Rune Augenstein E-mail: ra@smedvig.no Tel: 992 12 414
implementing organization Jan Tang jat@niras.dk + 47 458 01 652 **Project staff** Pål	
Bårdsen, Åsta Vaaland Veen (smi energi & miljø as)	
Summary The archives' house will be built with high environmental and energy ambitions. Energy simulations have been carried out with performances adapted to the current building model. With the performances listed in table 1, the building meets the requirements for energy in terms of Technical regulation (TEK). With these performances, the building also ends up within energy class A, assuming energy supply as specified in energy label simulations from GK. With sun shading on exposed facades, you will get an acceptable indoor temperature in most areas The zone within the glass atrium is a challenging area with regard to indoor climate. Several possible measures are listed to maintain comfort requirements Measures to reduce heat loss from the horizontal glass surface in the atrium ceiling should be considered. The area will have a problem with high temperatures in the summer and low temperatures in the winter. A U-value better than 0.5/0.7W/m2K is recommended in the separation between archives and offices Indoor climate simulations should be carried out for exposed areas to ensure that office areas do not have problems with drafts or radiation loss from large window surfaces.	
Project no . 14-0743	
Date 22/06/2015	**Edition** 02
Performed **by** Åsta Vaaland Veen	**Signature** Åsta Vaaland Veen
Quality Assurance Pål Bårdsen	**Signature** Pål Bårdsen

1 General

Arkivenes hus is a new building on Ullandhaug with 4 office floors above ground and 3 floors of archives in the lower floors and houses archive functions for several public agencies.
The building has high energy and environmental ambitions, including BREAM-NOR excellent certification and requirements for energy class A.

The building is to be built with a structure in standing and concrete, but with an external light climate screen. The building must have external solar shading in the form of micro-perforated screens on exposed facades.

This report deals with optimizing the building's energy efficiency. No decision is taken on an energy supply solution, beyond the fact that in the simulations supply from a heat pump and gas boiler has been included as assumed by GK in energy label simulations.

2 Input

All areas are taken from the BIM model dated 26 February 2015.03.16, except window areas which have been updated with data from the IFC file dated 08.06.2015.
Preliminary performances for building components have been assessed based on building targets in the BIM model Data on ventilation systems has been received from GK 10.06.2015.
Operating times and internal loads use values in NS3031 for office buildings, with the exception of archival plans where tap water has not been calculated. Building body and technical equipment are entered into a simulation model in the energy simulation program Simien version 5.502.

A base model (Simulation A) is set up to be able to assess whether the building meets the requirements for construction works in relation to energy use in technical regulations. Several performances in the model have been chosen better than minimum values in TEK 10 where this is common practice or requirements from the client are stricter than minimum requirements in technical regulations.

The following inputs and outputs are used in the simulations:

Building part	Performance	Areal [m2]	Comment
Heated part of BRA	-	12904	The entire building including archive
Heated air volume	-	47267	
External walls [W/m2 K]	0,17	3486	Corresponds to approx. 25cm insulation
Basement walls (underground) [W/m2 K]	0,15	1878	Externally insulated 200mm against the culvert with a b value of 0.7W/m2 K.
Tak [W/m2 K]	0,13	3090	Corresponds to approx. 300mm insulation
Floor to ground (archive) [W/m2 K]	0,18	2269	Minimum requirements in TEK
Separate archives and offices [W/m2 K]	0,5/0,7	2150	Corresponds to approx. 50mm insulation in separation. U-value 0.5 W/m2 K downwards and 0.7 W/m2 K upwards.
Windows and doors outer wall [W/m2 K]	0,8	1996	Minimum requirements Smedvig. Horizontal glass surfaces: (422m2, U=1.0 W/m2K) Vertical glass surfaces/windows: (1574 m2, Ugj=0.75 W/m2 K)
Share of windows and doors [%]		15.5	Including basement, 30% in office part**
Leakage figures	0,5	-	N50 [1/t]
Nominal thermal bridge value	0,05	-	External suspended wall with low thermal bridges
Heat efficiency ventilation [%]	87	-	Data GK 10.06.2015. (Annual average with air volumes in winter)
SFP ventilation [kW/m3 /s]	1,5	-	Data GK 10.06.2015
Power requirements lighting offices [W/m2]	4		Minimum requirements builder and NS3701
Power requirement lighting Archive [W/m2]	2		4W/m2 is used in TEK evaluation according to NS 3031
Power requirements technical equipment offices [W/m2]	8		Set lower than standard in order not to underestimate future heat demand (NS3031 standard value 11 W/m2)
Power requirement technical equipment Archive[W/m2]	2		11W/m2 is used in TEK evaluation according to NS 3031
Personlast contortor [W/m2]	4		Standardverdi NS3031
Personlast magazine [W/m2]	0,5		4W/m2 is used in TEK evaluation according to NS 3031
Tap water offices [W/m2]	0,8		Standardverdi NS3031
Tap water tank [W/m2]	0		

Table 1 Input base model

**Window area in the office area makes up 30% of the heated area. This is high, but is compensated by the U-value of 0.8 for windows. 0.8*0.3=0.24 and meets requirements in TEK for the office part alone.

The energy model takes into account shielding from vegetation and possible future buildings, and the model enables simulation in extreme conditions in summer and winter as well as verification against regulations.

3 Energy simulations

3.1 Simulation base model (Simulation A)

The model that has been set up has many performances which are in some cases significantly better than requirements in TEK10.
An annual simulation is first carried out where net energy demand and annual budget with local climate. The operating strategy for heating and ventilation is set as close to expected operation as possible.

It is for the magazines simulated with a lower energy demand for technical equipment and personal cargo than in NS3031, and the values are assumed to be closer to reality than standard values from NS3031.
This is described in the input table

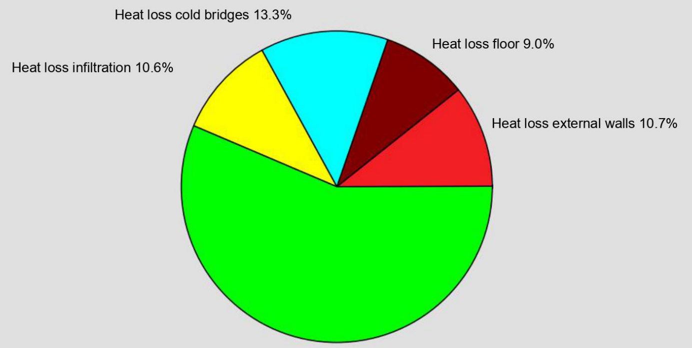
Annual simulation

Net energy demand from basic simulation for the entire building:

Energy budget		
Energy item	Energy needs	Specific energy demand
1a Space heating 1b	81532 kWh	6.3 kWh/m²
Ventilation heating (heating batteries)	24107 kWh	1.9 kWh/m²
2 Hot water (tap water)	33208 kWh	2,6 kWh/m²
3a Vifter	112562 kWh	8,7 kWh/m²
3b Pumper	11282 kWh	0,9 kWh/m²
4 Lighting	155102 kWh	12,0 kWh/m²
5 Technical	202086 kWh	15,7 kWh/m²
equipment 6a	0 kWh	0,0 kWh/m²
Room cooling 6b Ventilation cooling (cooling coils)	34232 kWh	2,7 kWh/m²
Total net energy demand, sum 1-6	654111 kWh	50,7 kWh/m²

Of the building's energy needs, only 16% of the energy is heating. The remainder is electrical demand for fan operation, pumps, lighting and technical equipment, as well as some cooling.
The building has a cooling requirement of approx. 5% of the energy requirement.

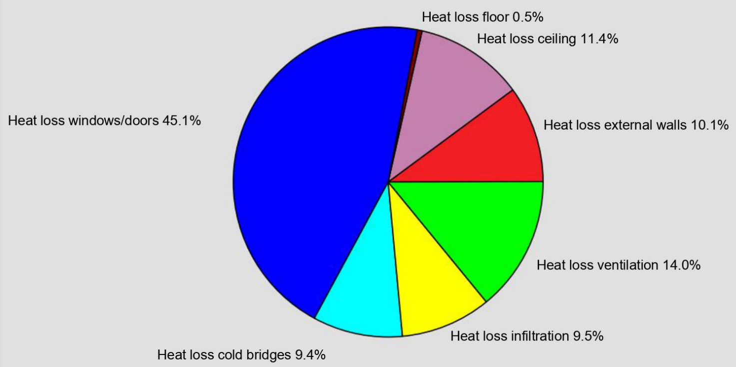
Heat loss budget (heat loss figure)



Heat loss figures for external walls	0,04 W/m²K
Heat loss ceiling	0,00 W/m²K
Heat loss figure floor on ground/against the open air	0,03 W/m²K
Heat loss figure glass/windows/doors	0,00 W/m²K
Heat loss figures cold bridges	0,05 W/m²K
Heat loss figure infiltration	0,04 W/m²K
Heat loss figure ventilation	0,21 W/m²K
Total heat loss figure	0,38 W/m²K

Heat loss figures Archives

Heat loss budget (heat loss figures)



Heat loss figures for external walls	0,05 W/m²K
Heat loss ceiling	0,06 W/m²K
Heat loss figure floor on ground/against the open air	0,00 W/m²K
Heat loss figure glass/windows/doors	0,24 W/m²K
Heat loss figures cold bridges	0,05 W/m²K
Heat loss figure infiltration	0,05 W/m²K
Heat loss figure ventilation	0,08 W/m²K
Total heat loss figure	0,53 W/m²K

Heat loss figure office part

Energy budget

Energy budget offices

Energy budget		
Energy item	Energy demand	Specific energy demand
1a Space heating 1b	76721 kWh	11.6 kWh/m²
Ventilation heating (heating batteries)	1331 kWh	0.2 kWh/m²
2 Hot water (tap water) 3a Fans	33208 kWh	5.0 kWh/m²
	42288 kWh	6.4 kWh/m²
3b Pumper	8866 kWh	1.3 kWh/m²
4 Lighting	83023 kWh	12.5 kWh/m²
5 Technical	166046 kWh	25.1 kWh/m²
equipment 6a	0 kWh	0.0 kWh/m²
Room cooling 6b Ventilation cooling (cooling coils)	16539 kWh	2.5 kWh/m²
Total net energy demand, sum 1-6	428022 kWh	64.6 kWh/m²

Energy budget magazines

Energy budget		
Energy item	Energy demand	Specific energy demand
1a Space heating 1b	904 kWh	0.1 kWh/m²
Ventilation heating (heating batteries)	21750 kWh	3.5 kWh/m²
2 Hot water (tap water) 3a Fans	0 kWh	0.0 kWh/m²
	70663 kWh	11.3 kWh/m²
3b Pumper	2262 kWh	0.4 kWh/m²
4 Lighting	72079 kWh	11.5 kWh/m²
5 Technical	36040 kWh	5.7 kWh/m²
equipment 6a	0 kWh	0.0 kWh/m²
Room cooling 6b Ventilation cooling (cooling coils)	17740 kWh	2.8 kWh/m²
Total net energy demand, sum 1-6	221439 kWh	35.3 kWh/m²

The archive section reduces energy requirements significantly compared to the office section.
Actual needs in archives can be expected to have an even lower energy need for, among other things, ventilation and lighting.

For the office part, individual zones such as the atrium and the canteen area have significantly higher energy requirements than the remaining zones. This will be discussed in later sections.

3.2 Validation against TEK10

A new building must meet requirements for energy measures (§14.3-1) or heat loss framework (§14.3-4)
Energy measures list several predefined minimum values that must be met if this is chosen, otherwise the building must have a net energy requirement that is less than 150kWh/m2 in the Oslo climate.
Operating times, internal loads etc. that have been changed for the annual simulation will be overridden and calculated with standard values in accordance with NS3031. Validation against TEK is carried out in Simien. The result is shown in the table below

Results of the evaluation Evaluation of	Description
Energy measures	The building satisfies the requirements for energy measures in section §14-3 (1)
Heat loss frame	The building satisfies energy redistribution measures (heat loss figures) in accordance with §14-3 (3)
Energy framework	The building satisfies the energy framework according to §14-4 The
Minimum requirements	building meets the minimum requirements in §14-5 The air
Air volume ventilation	volumes meet the minimum requirements given in NS3031:2010 (table A.6)
Energy supply	The building meets the requirements for energy supply in §14-7 The
Overall evaluation	building meets the building regulations' energy requirements

The building meets energy requirements in TEK10 both through the measures model and energy framework.

3.3 Passive house evaluation

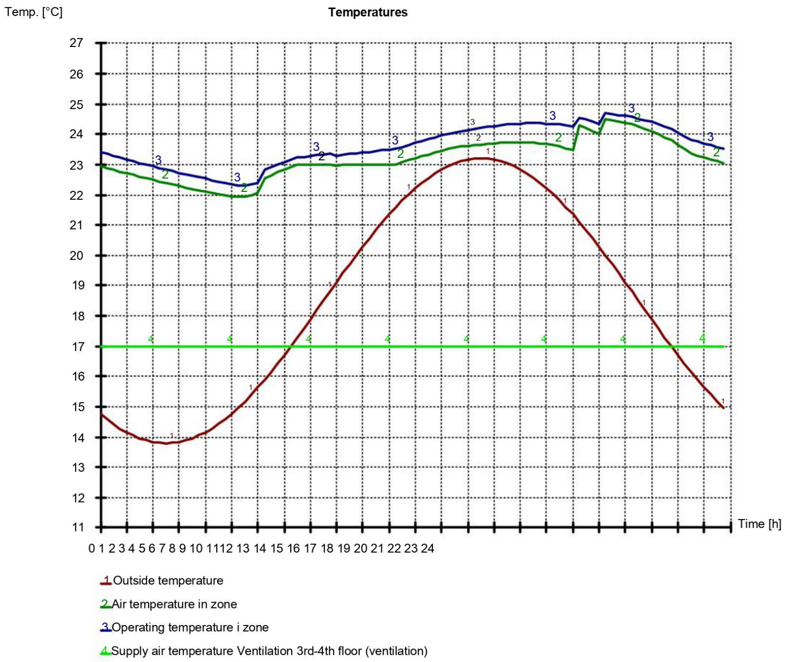
A passive house evaluation of the building in SIMIEN has been carried out. The building does not meet minimum requirements for thermal bridge values, and therefore also does not meet requirements for energy performance for passive houses.

If the normalized thermal bridge value can be reduced from 0.05 to a documented 0.03, the building will satisfy all requirements for passive houses if the entire building is evaluated in the building category office building. When evaluating the entire building against the building category kutlur building, the building will not be able to meet the requirements for the passive house standard. When evaluated separately, the office building will not be able to achieve the passive house standard

Results of the evaluation Evaluation against NS 3701	Description
Heat loss frame	The building meets the requirement for heat loss figures
Energy performance	The building meets requirements for energy performance
Minimum requirements	The building does not meet the minimum requirements for individual components
Air volume ventilation	The air volumes meet the minimum requirements given in NS3701 (table A.2)
Overall evaluation	The building does not meet all requirements for passive houses

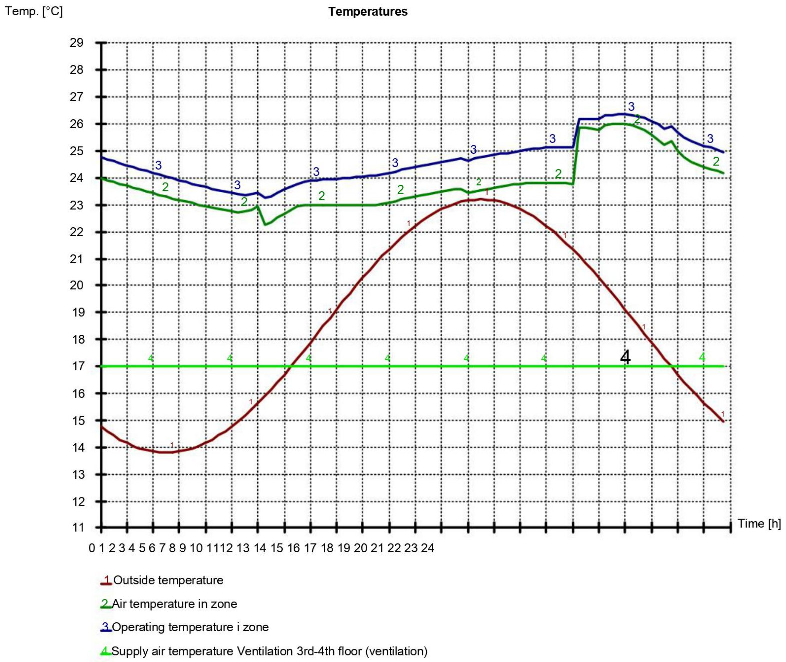
Passive house evaluation of the entire building as an office building, without improved thermal bridge value

Temperature development in Zone 3-4 floor side wing:



The maximum operating temperature during working hours will be <25°C. When ventilation is stopped at At 18.00 there is a slight increase in the temperature, i.e. the sun shading reduces the solar load on the rooms so that the indoor temperature will be within the desired temperature range all day long.

Temperature development in Zone 3-4 floor west wing:

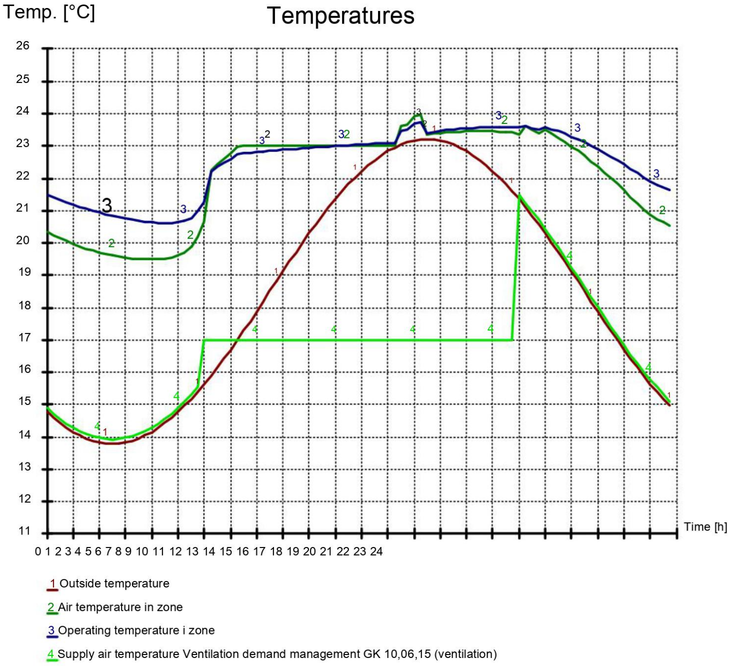


The operating temperature will be higher for the west-facing facade than for the south-facing facade, but throughout the working hours the temperature in the premises will be <25°C. When ventilation is stopped at At 18.00 you get a temperature jump. This can be avoided by extending the operating time of the ventilation systems when there are high outside temperatures.

The reason why the temperature is higher on the west facade is that the facade has a larger proportion of windows than the south facade. The southern facade will be able to accumulate more heavy materials, but this effect diminishes during the afternoon. The temperatures will be an average temperature in the zone. As the zones in the energy model are relatively small and the premises are ventilated with stirring ventilation, it can be assumed that the room temperature in the zones will be approximately as simulated.

A supply air temperature of 17°C has been used, which is the standard value in NS3031 in buildings with cooling. After the simulations, there will be no need to reduce this further, but in the case of higher internal loads or operation other than standard, there may be a need to further reduce the supply air temperature.

Temperature development in glass yard canteen area: Temp. [°C]



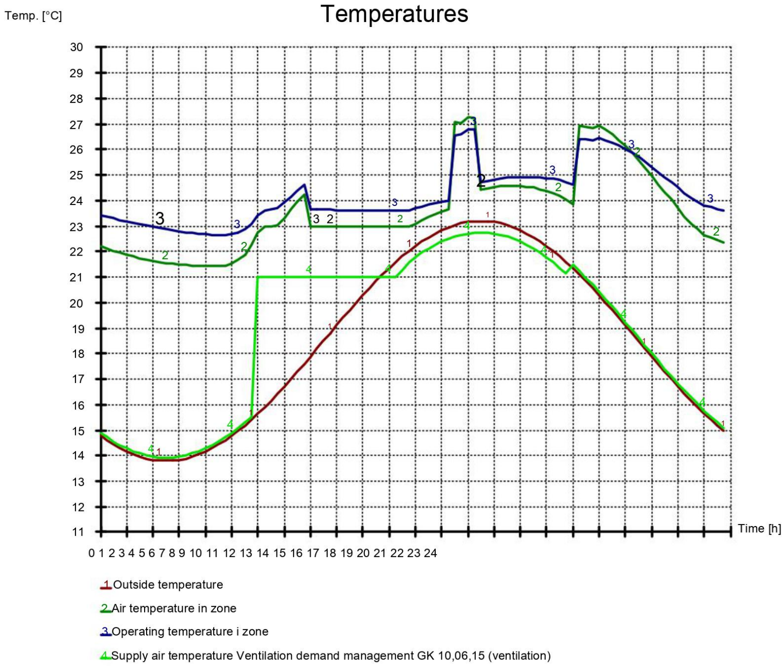
Operating temperature in the zone will be below 24°C. This with a minimum supply air temperature of 17°C.
The simulation assumes standard heat loads from the NS3031.
It is assumed that there is no cooling of ventilation air beyond the operating hours of the building.

In practice, the canteen zone will have a significantly higher load at lunchtime, but have a lower internal load for technical equipment and lighting. Total load must not be higher than the simulation shows.

temperature development in the north-facing conservatory

North-facing glazing has been identified as a challenging area with regard to thermal comfort.

In the indoor climate simulation for the north-facing conservatory, a maximum air volume of 27,000 is assumed 3 m /h, with a temperature of 21 degrees (overflow from other areas). The possibility of free cooling with 10m3 / h*m2 outside operating hours is assumed . The fixed solar factor in glass is set to 0.5, and the contribution from technical equipment is set to 0 W/m2 .



The temperature in the zone will be too high with an operative up to 27°C at 2 p.m. The temperature graph shows temperature peaks in the morning when the sun is in the east, and in the afternoon when the sun is in the west. SIMIEN does not give any picture of how the temperature distribution is in the atrium. Typically, the temperature will be highest at the top of the atrium, and here there will be corridors on several floors, and windows from office areas and out towards the zone right up to the top of the atrium.

With an air volume of approximately 50,000m3 /h drawn off via the atrium, the maximum operating temperature will drop to 26 degrees.

There are several ways to reduce the room temperature. Simulations have been carried out with internal and external solar shading, airgel glass and natural ventilation with input data and results listed in the table below

All of the proposed measures below will help to keep the temperature in the zone below 26 degrees.

Technical regulation §14-5 (3)b, requires that the Total solar factor for glass/window (gt) must be less than 0.15 on a solar-exposed facade, unless it can be documented that the building does not require cooling. A total solar factor of 0.15 can only be met with external solar shading or internal solar shading combined with very dark glass. As long as the ventilation in the glass atrium is based on exhaust air from other zones, and no cooled air is supplied to the zone, it can be argued that the zone does not need cooling, so that comfort requirements can be met in other ways than with a total solar factor of 0.15.

Measures	Tmax [°C]	Top max [°C]
base model	27,3	26,8
With air volume 50,000 m3/h With internal	26,8	26,3
solar shading Solar factor 0.35 activated, 0.5 not activated With external solar shading Solar factor	26,0	25,7
0.04 activated, 0.5 not activated With external solar shading and solar factor 0.75 in glass	24,1	23,9
Solar factor 0.04 activated, 0.75 activated With 1500m3/h natural ventilation With airgel glass in glass atrium and ext.	25,2	24,9
shielding facade glass Airgel fixed solar factor 0.3	26,5	25,9
U-greens 0.3 Facade glass Solar factor 0.04 activated, 0.5 not activated	25,2	24,8

4.2 Winter simulations In
order to find the necessary heating needs, a winter simulation of the building is carried out.

The building has large window areas in the office area and heat loss from these could cause frostbite at the windows. This is not the subject of this report.

The model is divided into 8 zones for areas that belong together in relation to loads.

A constant supply air temperature of 19°C is assumed for all zones. In practice, this should be regulated based on the outside temperature and increased towards the set point of the rooms when the outside temperature drops.

Automatic solar shading is assumed, which is activated with a solar flux of 100W/m2 .
The maximum power for space heating is set to 25W/m2 .
Air volume during operation is in accordance with minimum value in TEK of 7m3 /m2 .
This will be high at design outdoor temperatures so that a reduced amount of air is introduced at outdoor temperatures lower than -10°C of 5m3 /m2 demand management in practice can often be even lower. a value that with

The simulations assume 3 consecutive cold winter days in January. (Dimensioning outdoor temperatures 3 consecutive days)

The archives below ground level are included in the simulations.

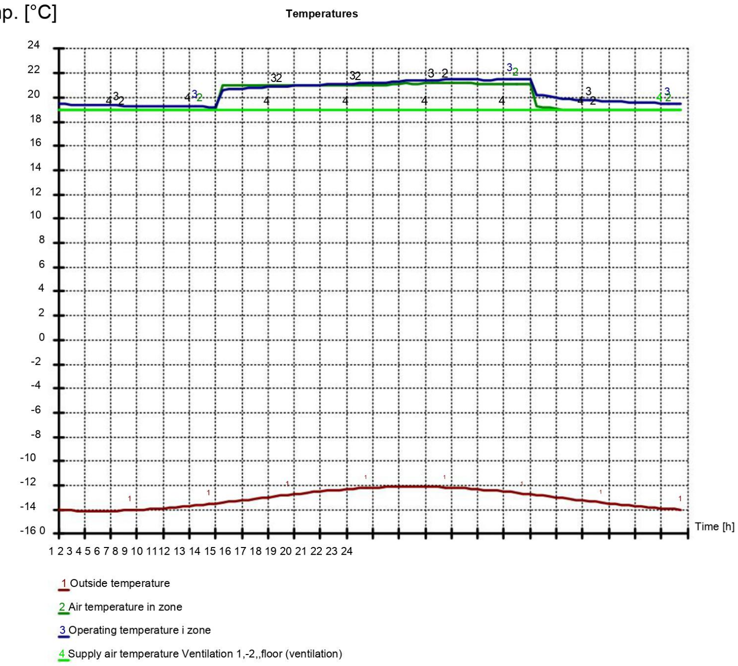
Winter simulation of buildings gives the following power requirements:

Dimensioning values		
Description	Verdi Tidspunkt 74.3	
Max. simultaneous effect heating batteries:	kW / 5.8 W/m² 324.4	06:00
Total installed power heating batteries	kW / 25.1 W/m² 100.1 kW /	06:00
Max. simultaneous power space heating:	7.8 W/m² 322.6 kW / 25.0	06:00
Total installed power space heating Min.	W/m²	06:00
room air temperature: Min.	14,7 °C	06:00
operational temperature:	15,8 °C	06:00
Maximum CO2 concentration (archive plan U1, U2, U3)	675 PPM	21:00

The set point in simulations is 21°C for all premises without the archives which is in accordance with NS3031 and a night lowering to 19°C outside of operating hours. In practice, one would like a slightly higher room temperature in office premises with sedentary work. This can be ensured either with local room heating, or a careful increase in supply air temperature and reduced night-time lowering.
It is a project requirement that you must be able to control the temperature within your own zone. The solution chosen must take care of this.

Temperature development north-facing offices 1-2 floor

Temp. [°C]



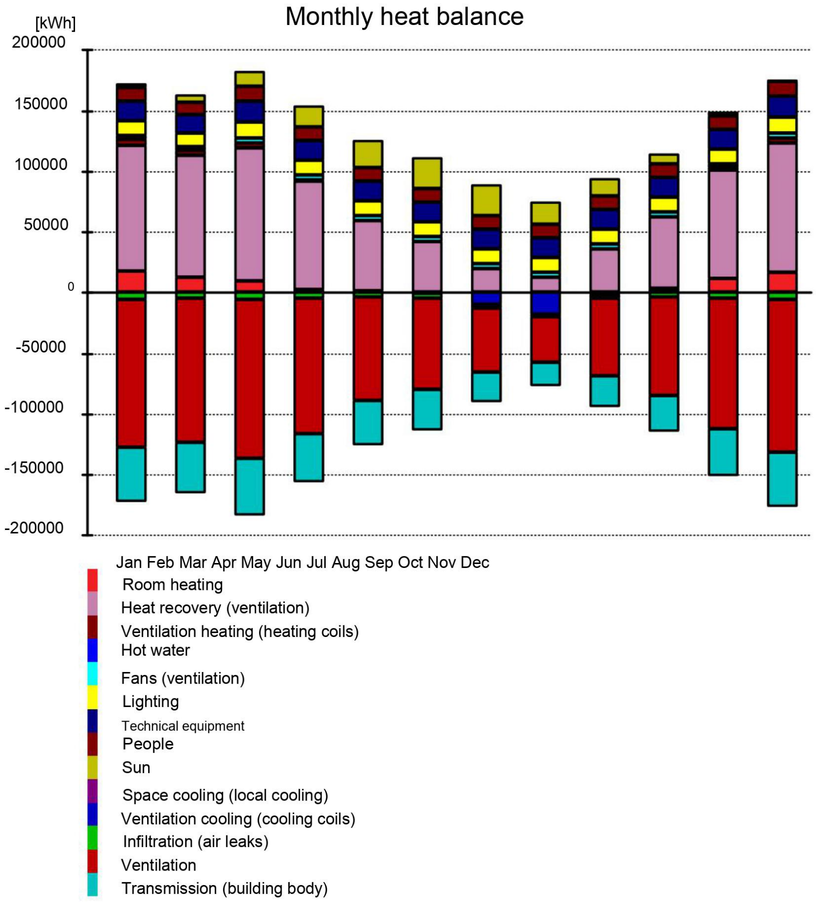
During working hours, the operating temperature is at the set point. As the temperature in the premises drops at night, it is important that the space heating has the capacity to raise the temperature sufficiently quickly when people enter the premises.

5 Power requirement for heating and cooling

Power needs for heating are found based on annual simulation based on the base simulation, as none of the measures will have a particular impact on the assessment of power needs.

Distribution between ventilation heating and room heating will depend on temperature control of ventilation, and a large part should be provided via the ventilation so that the supply air temperature is increased up to the set point for the room (but not above).

The monthly net heat balance is distributed over the year with a larger share of solar subsidies the summer

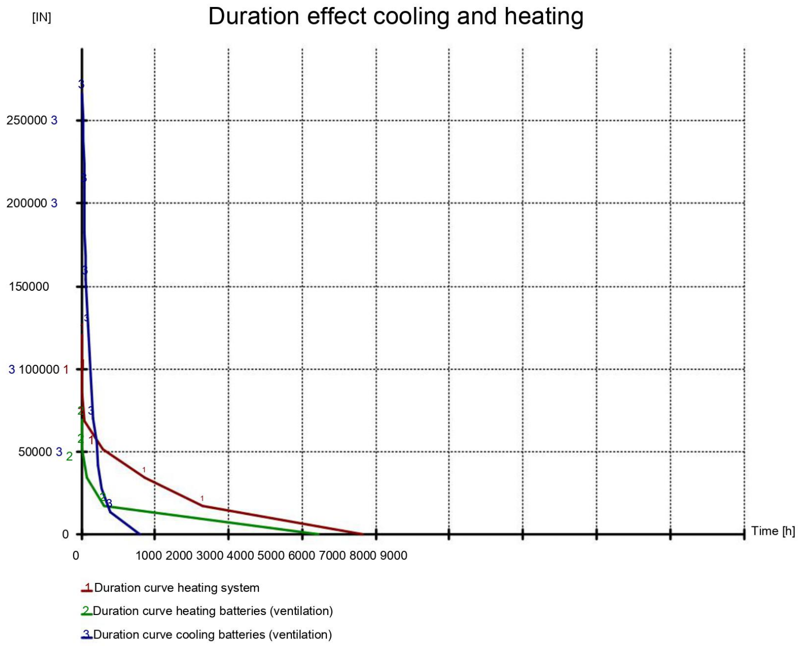


The heating system must cover only a small part of the energy needs, and it is only needed for a small part of the year.

Technical equipment, lighting, people and the sun account for a good part of the heating beyond what the heat recovery unit covers, and constitutes in the winter.
Technical equipment is located in the energy model with a heat load of 11W/m2, which are values from NS3031. With today's technical equipment (computers/printers etc.) this is somewhat high in relation to real values, and with more energy-efficient equipment you may in the long term experience that the heating needs in the premises increase - and the cooling needs are reduced because of this.

In premises such as the canteen, corridors etc, there will be minimal technical equipment. This must be taken into account when designing the heating system in the building. Detailed indoor climate simulations will be able to show this.

The duration diagram for heating shows the relationship between energy and power:



The simulation shows a maximum power requirement for cooling of approx. 280kW, while it is more difficult to read the power requirements for heating the figure.

The table below shows effect and energy coverage with different effects.
The calculation shows that 70% power coverage covers the entire heating requirement. This means that there are only a few hours during a year when you are above this effect.

Coverage rate effect/energy heating	
Effect (coverage)	Coverage rate energy use
144 kW (90%)	100%
128 kW (80%)	100 %
112 kW (70%)	100 %
96 kW (60%)	99 %
80 kW (50%)	98 %
64 kW (40%)	96 %
48 kW (30%)	88 %
32 kW (20) %)	73 %
16 kW (10%)	47 %
The required power for heating tap water is not included	

The peak power for heating will be approx. 180kW including tap water. As the peaks are very high, in practice this can be smoothed out with some accumulation, but this depends on the system, management and distribution. Tap water makes up only a small part of the total effect.

Appendix C

NORCE

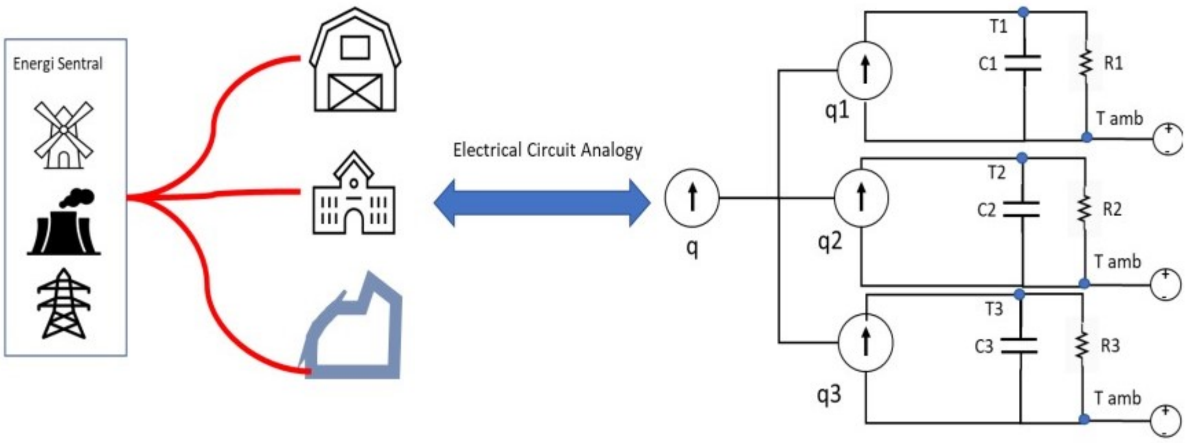


Figure C.1: Simplified model - RC

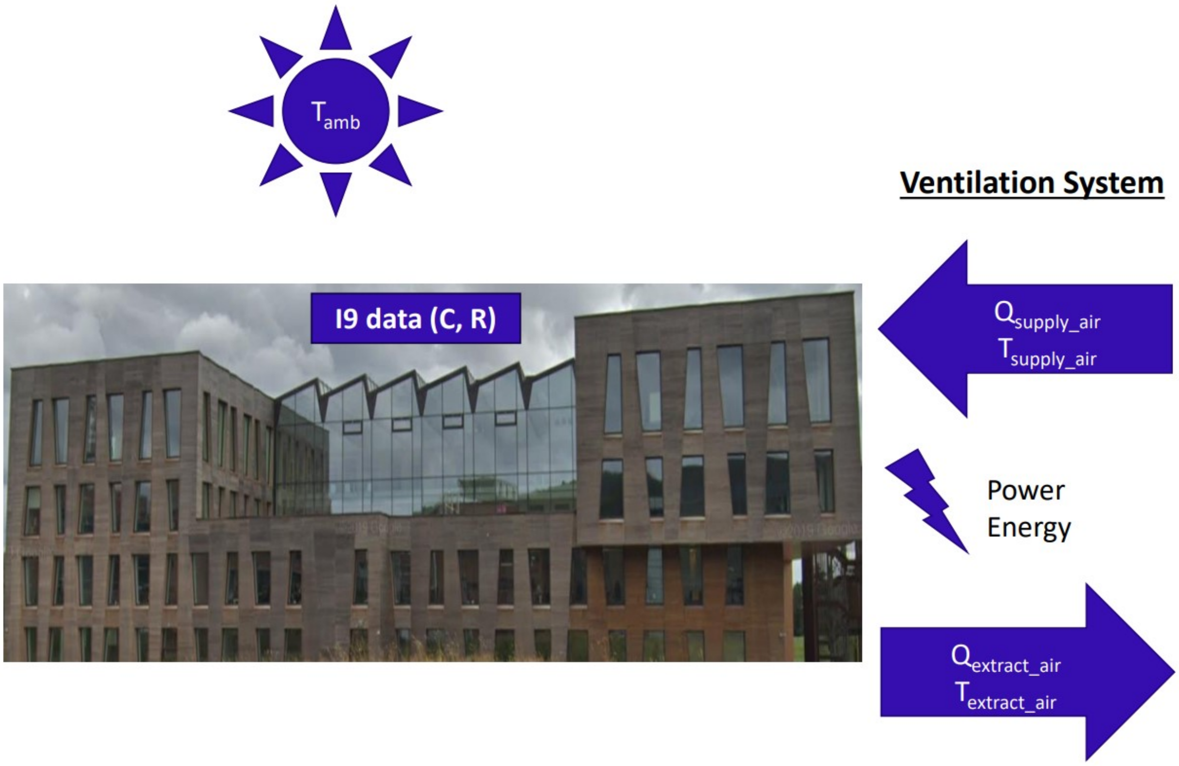


Figure C.2: Setup

MQTT Topic	Ventilation	
i9/360005/RT901/Temp	Ventilation system 360.005 - Outdoor temperatur	
i9/360005/RT401/Temp	Ventilation system 360.005 - Supply air temperatur	
i9/360005/RT501/Temp	Ventilation system 360.005 - Extract air temperatur	
i9/360005/RF401/Flow	Ventilation system 360.005 - Supply air flow	
i9/360005/RF501/Flow	Ventilation system 360.005 - Extract air flow	
i9/360005/RB600/Occupancy	Ventilation system 360.005 - Motion detectors	
i9/360006/RT401/Temp	Ventilation system 360.006 - Supply air temperatur	
i9/360006/RT501/Temp	Ventilation system 360.006 - Extract air temperatur	
i9/360006/RF401/Flow	Ventilation system 360.006 - Supply air flow	
i9/360006/RF501/Flow	Ventilation system 360.006 - Extract air flow	
i9/360006/RB600/Occupancy	Ventilation system 360.006 - Motion detectors	

Figure C.3: Measurements

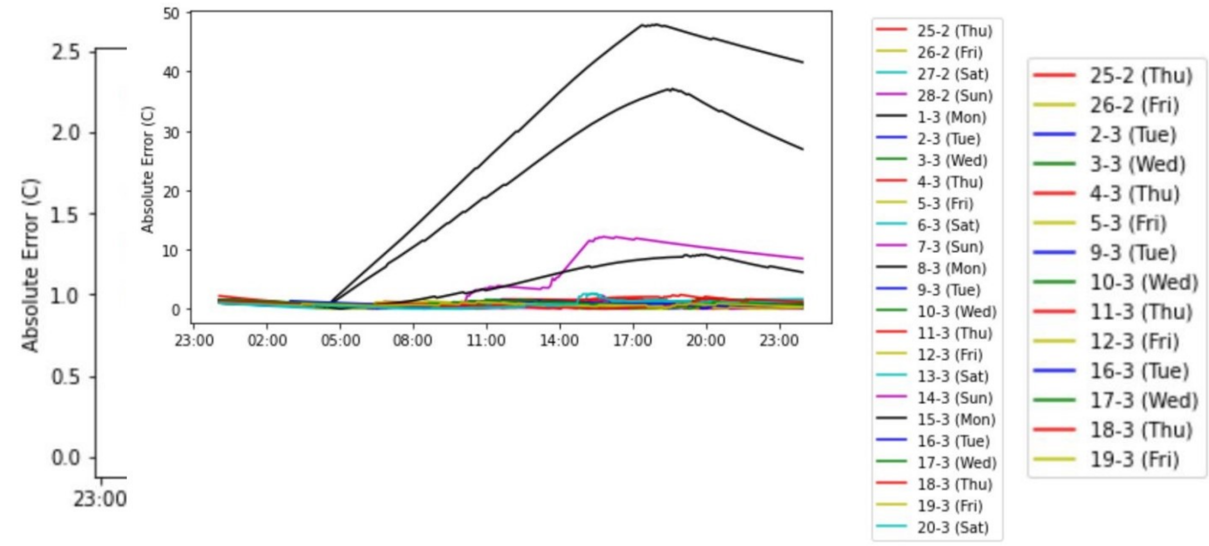


Figure C.4: Predicting using the data of entire days before

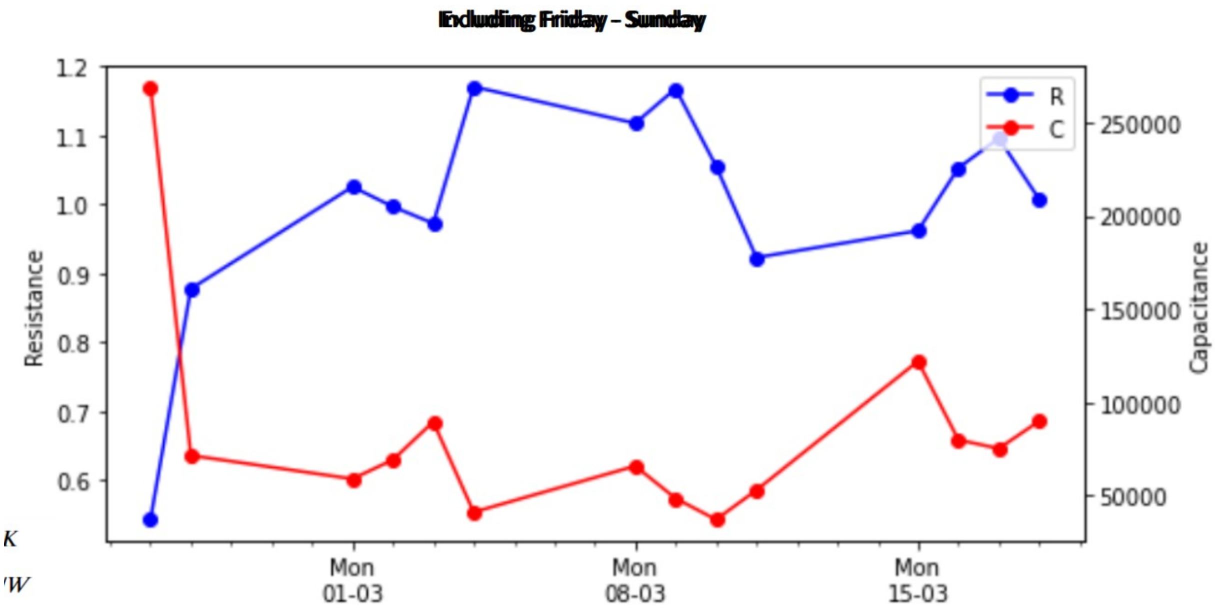


Figure C.5: R vs C using the data of entire days before

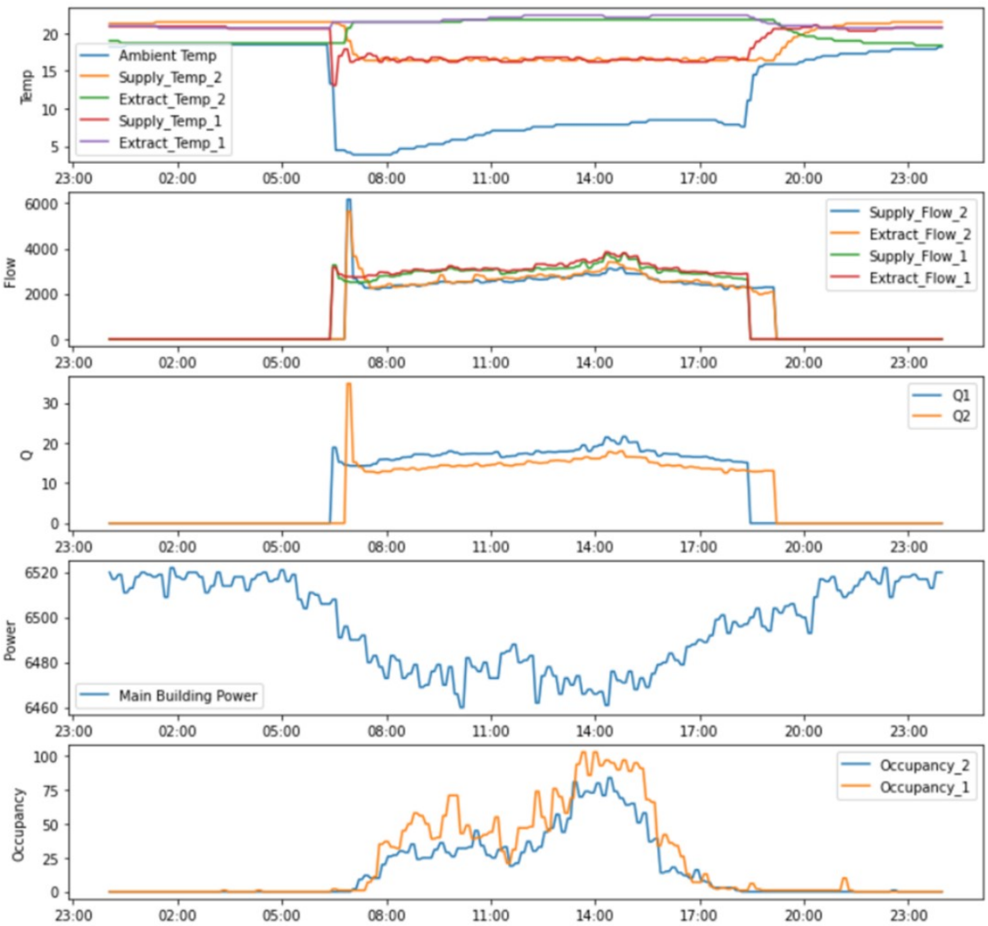


Figure C.6: Training the data

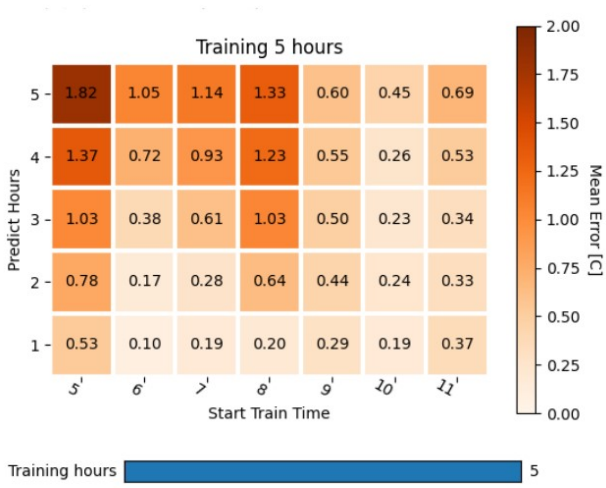


Figure C.7: Measured values

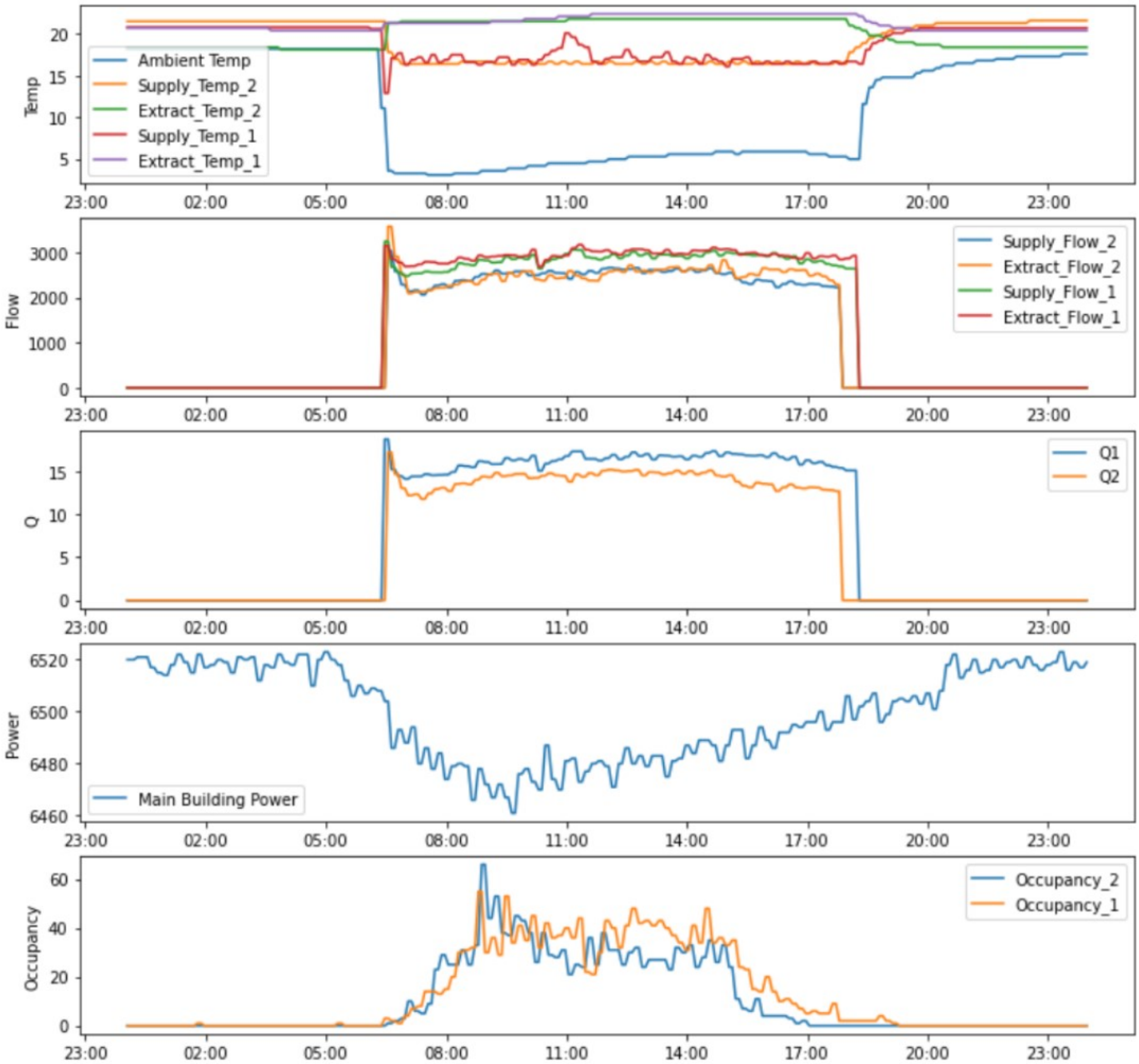


Figure C.8: Predicting for next day

Appendix D

Flow Data

D.0.1 Flow over the time

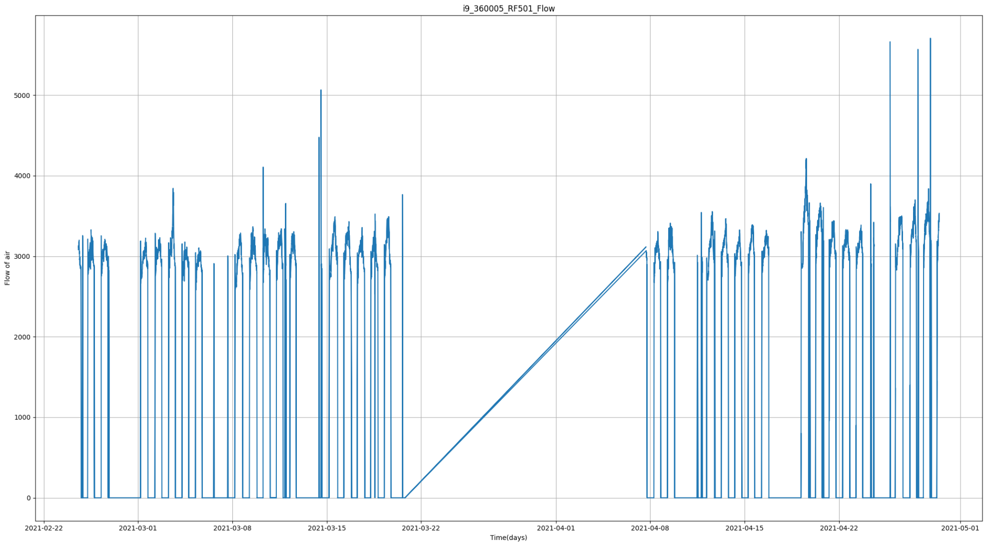


Figure D.1: Flow of air (m^3/s) vs time for case, 360005RF501

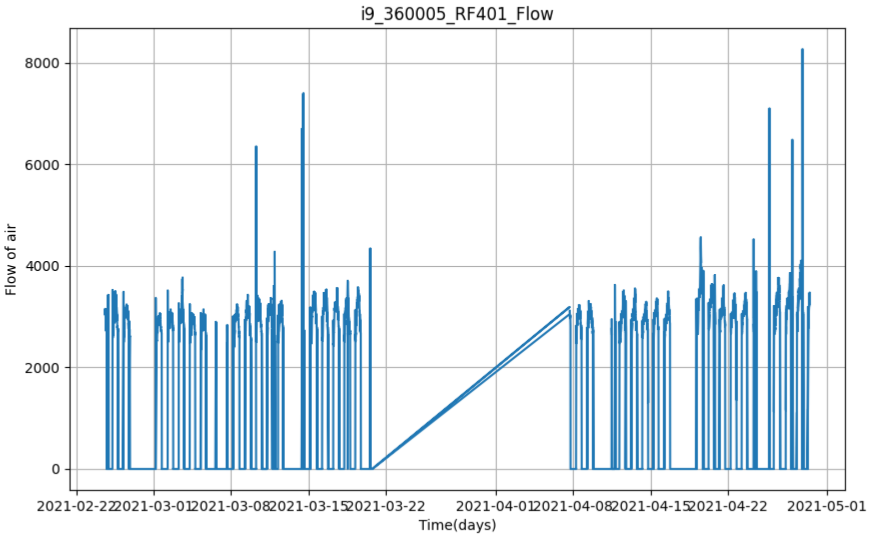


Figure D.2: Flow of air (m^3/s) vs time for case 360005RF401

time	value
2/24/2021 13:42	3065
2/24/2021 13:47	3097
2/24/2021 13:52	3097
2/24/2021 14:07	3114
2/24/2021 14:02	3111
2/24/2021 13:57	3111
2/24/2021 14:12	3114
2/24/2021 14:17	3078
2/24/2021 14:37	3153
2/24/2021 14:27	3125
2/24/2021 14:32	3125
2/24/2021 14:22	3078
2/24/2021 14:57	3035
2/24/2021 14:42	3153
2/24/2021 14:47	3070
2/24/2021 14:52	3070
2/24/2021 15:17	3013
2/24/2021 15:07	3137
2/24/2021 15:12	3137
2/24/2021 15:02	3035
2/24/2021 15:22	3013
2/24/2021 15:37	2997
2/24/2021 15:27	2973
2/24/2021 15:42	2997

time	value
2/24/2021 15:32	2973
2/24/2021 15:47	2916
2/24/2021 16:12	2796
2/24/2021 15:57	2958
2/24/2021 15:52	2916
2/24/2021 16:02	2958
2/24/2021 16:07	2796
2/24/2021 16:32	2859
2/24/2021 16:22	2721
2/24/2021 16:27	2859
2/24/2021 16:17	2721
2/24/2021 16:52	2742
2/24/2021 16:37	2763
2/24/2021 16:42	2763
2/24/2021 16:47	2742
2/24/2021 17:12	2769
2/24/2021 17:02	2740
2/24/2021 17:07	2769
2/24/2021 16:57	2740
2/24/2021 17:17	2762
2/24/2021 17:32	2745
2/24/2021 17:22	2762
2/24/2021 17:37	2738
2/24/2021 17:27	2745
2/24/2021 17:57	2709
2/24/2021 17:47	2704
2/24/2021 17:42	2738
2/24/2021 17:52	2704
2/24/2021 18:02	2709
2/24/2021 18:07	2696
2/24/2021 18:27	2667
2/24/2021 18:17	2681
2/24/2021 18:12	2696
2/24/2021 18:32	2667
2/24/2021 18:22	2681
2/24/2021 21:27	2780
2/24/2021 21:17	3429
2/24/2021 21:22	3429
2/24/2021 21:32	2780
2/24/2021 21:47	2537
2/24/2021 21:42	2625
2/24/2021 21:37	2625
2/24/2021 21:52	2537
2/25/2021 6:27	3528
2/25/2021 6:32	3528

time	value
2/25/2021 6:47	2621
2/25/2021 6:37	2769
2/25/2021 6:42	2769
2/25/2021 6:52	2621
2/25/2021 7:12	2633
2/25/2021 7:02	2581
2/25/2021 7:07	2633
2/25/2021 6:57	2581
2/25/2021 7:32	2637
2/25/2021 7:17	2692
2/25/2021 7:37	2700
2/25/2021 7:22	2692
2/25/2021 7:27	2637
2/25/2021 7:57	2832
2/25/2021 7:42	2700
2/25/2021 7:47	2699
2/25/2021 7:52	2699
2/25/2021 8:02	2832
2/25/2021 8:17	2925
2/25/2021 8:07	2792
2/25/2021 8:22	2925
2/25/2021 8:12	2792
2/25/2021 8:42	3065
2/25/2021 8:32	2983
2/25/2021 8:27	2983
2/25/2021 8:37	3065
2/25/2021 8:47	2992
2/25/2021 9:07	3061
2/25/2021 8:57	3010
2/25/2021 9:02	3010
2/25/2021 8:52	2992
2/25/2021 9:12	3061
2/25/2021 9:32	3015
2/25/2021 9:27	3015
2/25/2021 9:17	3045
2/25/2021 9:22	3045
2/25/2021 9:52	2918
2/25/2021 9:37	3081
2/25/2021 9:42	3081
2/25/2021 9:57	2879
2/25/2021 9:47	2918
2/25/2021 10:12	2962
2/25/2021 10:07	2962
2/25/2021 10:02	2879
2/25/2021 10:17	3185

time	value
2/25/2021 10:22	3185
2/25/2021 10:27	3121
2/25/2021 10:37	3241
2/25/2021 10:42	3241
2/25/2021 10:32	3121
2/25/2021 10:57	3132
2/25/2021 10:47	3251
2/25/2021 11:07	3036
2/25/2021 10:52	3251
2/25/2021 11:02	3132
2/25/2021 11:12	3036
2/25/2021 11:32	2890
2/25/2021 11:27	2890
2/25/2021 11:17	2917
2/25/2021 11:22	2917
2/25/2021 11:37	2964
2/25/2021 11:52	3013
2/25/2021 11:42	2964
2/25/2021 11:47	3013
2/25/2021 11:57	3116
2/25/2021 12:02	3116
2/25/2021 12:22	3501
2/25/2021 12:12	3286
2/25/2021 12:17	3501
2/25/2021 12:07	3286
2/25/2021 12:42	3430
2/25/2021 12:27	3453
2/25/2021 12:47	3381
2/25/2021 12:32	3453
2/25/2021 12:37	3430
2/25/2021 13:07	3350
2/25/2021 12:52	3381
2/25/2021 12:57	3369
2/25/2021 13:02	3369
2/25/2021 13:27	3064
2/25/2021 13:22	3282
2/25/2021 13:12	3350
2/25/2021 13:17	3282
2/25/2021 13:47	3134
2/25/2021 13:32	3064
2/25/2021 13:37	3107
2/25/2021 13:42	3107
2/25/2021 14:07	3437
2/25/2021 14:02	3239
2/25/2021 14:12	3437

time	value
2/25/2021 14:22	3339
2/25/2021 14:17	3339
2/25/2021 14:37	3208
2/25/2021 14:27	3207
2/25/2021 14:32	3207
2/25/2021 13:52	3134
2/25/2021 14:42	3208
2/25/2021 14:57	3100
2/25/2021 14:47	3061
2/25/2021 14:52	3061
2/25/2021 13:57	3239
2/25/2021 15:17	3185
2/25/2021 15:02	3100
2/25/2021 15:07	3154
2/25/2021 15:12	3154
2/25/2021 15:37	2919
2/25/2021 15:27	3055
2/25/2021 15:32	3055
2/25/2021 15:47	3025
2/25/2021 15:52	3025
2/25/2021 15:22	3185
2/25/2021 15:42	2919
2/25/2021 15:57	3019
2/25/2021 16:17	2995
2/25/2021 16:07	3003
2/25/2021 16:12	3003
2/25/2021 16:02	3019
2/25/2021 16:22	2995
2/25/2021 16:42	2840
2/25/2021 16:27	2911
2/25/2021 16:37	2840
2/25/2021 16:32	2911
2/25/2021 16:47	2777
2/25/2021 17:02	2812
2/25/2021 16:52	2777
2/25/2021 16:57	2812
2/25/2021 17:07	2818
2/25/2021 17:12	2818
2/25/2021 17:17	2738
2/25/2021 17:32	2745
2/25/2021 17:37	2773
2/25/2021 17:22	2738
2/25/2021 17:27	2745
2/25/2021 17:57	2728
2/25/2021 17:52	2711

time	value
2/25/2021 17:42	2773
2/25/2021 17:47	2711
2/25/2021 18:02	2728
2/25/2021 18:07	2762
2/25/2021 18:12	2762
2/26/2021 6:27	3489
2/26/2021 6:32	3489
2/26/2021 6:47	2616
2/26/2021 6:42	2744
2/26/2021 6:37	2744
2/26/2021 6:52	2616
2/26/2021 7:07	2603
2/26/2021 6:57	2498
2/26/2021 7:02	2498
2/26/2021 7:12	2603
2/26/2021 7:17	2688
2/26/2021 7:27	2628
2/26/2021 7:32	2628
2/26/2021 7:22	2688
2/26/2021 7:37	2606
2/26/2021 7:42	2606
2/26/2021 7:57	2691
2/26/2021 8:02	2691
2/26/2021 7:47	2765
2/26/2021 7:52	2765
2/26/2021 8:07	2773
2/26/2021 8:22	2873
2/26/2021 8:17	2873
2/26/2021 8:12	2773
2/26/2021 8:27	3056
2/26/2021 8:32	3056
2/26/2021 8:52	3000
2/26/2021 8:42	3010
2/26/2021 8:47	3000
2/26/2021 8:37	3010
2/26/2021 9:12	3033
2/26/2021 8:57	3113
2/26/2021 9:02	3113
2/26/2021 9:07	3033
2/26/2021 9:32	3058
2/26/2021 9:22	2982
2/26/2021 9:27	3058
2/26/2021 9:17	2982
2/26/2021 9:37	3104
2/26/2021 9:42	3104

time	value
2/26/2021 9:57	3097
2/26/2021 9:47	3054
2/26/2021 10:02	3097
2/26/2021 9:52	3054
2/26/2021 10:22	3129
2/26/2021 10:12	3104
2/26/2021 10:07	3104
2/26/2021 10:17	3129
2/26/2021 10:27	3083
2/26/2021 10:47	2983
2/26/2021 10:37	3108
2/26/2021 10:42	3108
2/26/2021 10:32	3083
2/26/2021 11:07	3090
2/26/2021 10:52	2983
2/26/2021 10:57	3086
2/26/2021 11:02	3086
2/26/2021 11:27	3017
2/26/2021 11:17	3046
2/26/2021 11:22	3046
2/26/2021 11:12	3090
2/26/2021 11:32	3017
2/26/2021 11:52	3068
2/26/2021 11:47	3068
2/26/2021 11:37	3036
2/26/2021 11:42	3036
2/26/2021 12:12	3170
2/26/2021 11:57	3102
2/26/2021 12:02	3102
2/26/2021 12:07	3170
2/26/2021 12:32	3170
2/26/2021 12:27	3170
2/26/2021 12:47	3165
2/26/2021 12:17	3103
2/26/2021 12:22	3103
2/26/2021 12:42	3192
2/26/2021 12:52	3165
2/26/2021 12:57	3233
2/26/2021 12:37	3192
2/26/2021 13:02	3233
2/26/2021 13:22	3206
2/26/2021 13:12	3240
2/26/2021 13:17	3206
2/26/2021 13:07	3240
2/26/2021 13:42	3200

time	value
2/26/2021 13:27	3133
2/26/2021 13:47	3161
2/26/2021 13:32	3133
2/26/2021 13:37	3200
2/26/2021 14:07	3171
2/26/2021 13:52	3161
2/26/2021 13:57	3180
2/26/2021 14:12	3171
2/26/2021 14:02	3180
2/26/2021 14:27	3208
2/26/2021 14:22	3186
2/26/2021 14:17	3186
2/26/2021 14:32	3208
2/26/2021 14:52	3107
2/26/2021 14:37	3081
2/26/2021 14:47	3107
2/26/2021 14:42	3081
2/26/2021 14:57	3208
2/26/2021 15:17	3089
2/26/2021 15:02	3208
2/26/2021 15:22	3089
2/26/2021 15:07	3192
2/26/2021 15:12	3192

Appendix E

Power Data

E.0.1 Power data

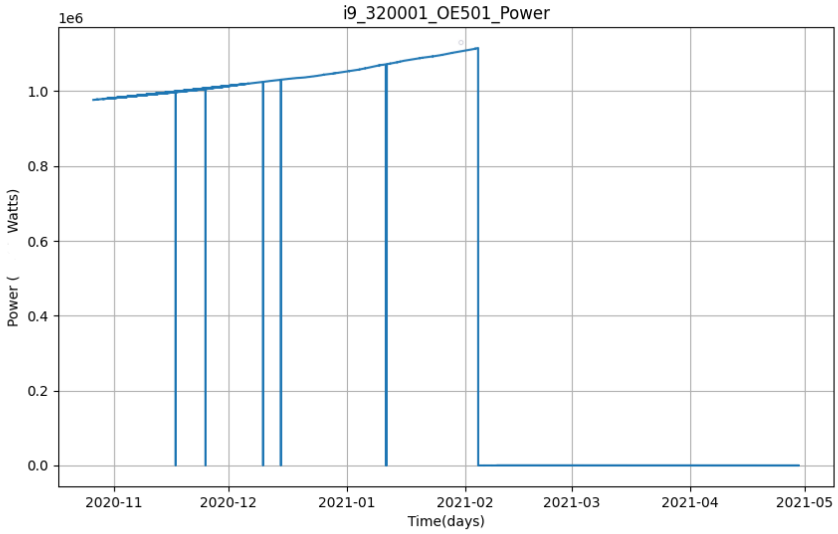


Figure E.1: Power vs time for the case 320001OE501

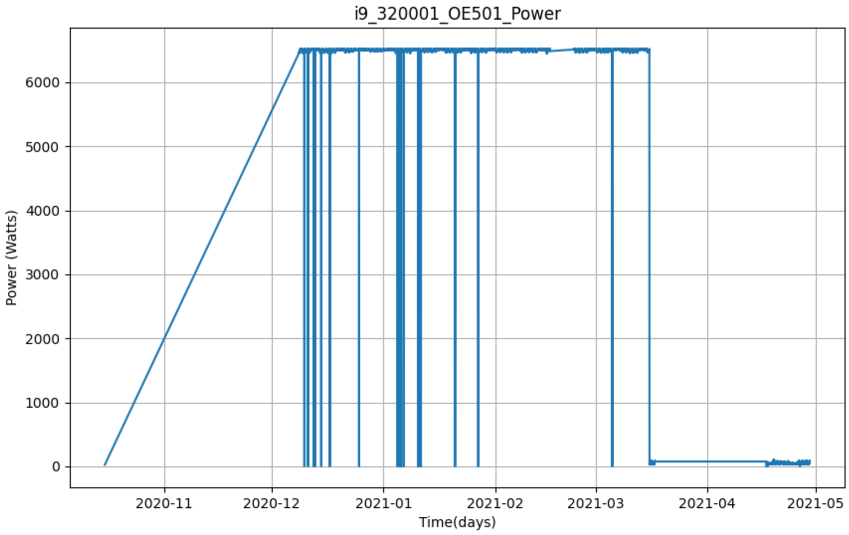


Figure E.2: Power vs time for the case 432001XZ001

time	value
10/26/2020 12:32	976500
10/26/2020 12:32	976500
10/26/2020 12:37	976510
10/26/2020 12:42	976510
10/26/2020 12:47	976520
10/26/2020 12:52	976520
10/26/2020 12:57	976520
10/26/2020 13:02	976520
10/26/2020 13:07	976530
10/26/2020 13:12	976530
10/26/2020 13:17	976540
10/26/2020 13:21	976540
10/26/2020 13:26	976540
10/26/2020 13:31	976540
10/26/2020 13:36	976550
10/26/2020 13:41	976550
10/26/2020 13:46	976550
10/26/2020 13:51	976550
10/26/2020 13:56	976560
10/26/2020 14:01	976560
10/26/2020 14:06	976560
10/26/2020 14:11	976560
10/26/2020 14:16	976570
10/26/2020 14:21	976570

time	value
10/26/2020 14:26	976570
10/26/2020 14:31	976570
10/26/2020 14:36	976580
10/26/2020 14:41	976580
10/26/2020 14:46	976580
10/26/2020 14:51	976580
10/26/2020 14:56	976590
10/26/2020 15:01	976590
10/26/2020 15:06	976590
10/26/2020 15:11	976590
10/26/2020 15:16	976600
10/26/2020 15:21	976600
10/26/2020 15:26	976610
10/26/2020 15:31	976610
10/26/2020 15:36	976610
10/26/2020 15:41	976610
10/26/2020 15:46	976620
10/26/2020 15:51	976620
10/26/2020 15:56	976630
10/26/2020 16:01	976630
10/26/2020 16:06	976630
10/26/2020 16:11	976630
10/26/2020 16:16	976640
10/26/2020 23:34	977040
10/26/2020 16:21	976640
10/26/2020 16:26	976650
10/26/2020 16:31	976650
10/26/2020 16:36	976660
10/26/2020 16:41	976660
10/26/2020 16:46	976660
10/26/2020 16:51	976660
10/26/2020 16:56	976670
10/26/2020 17:01	976670
10/26/2020 17:06	976680
10/26/2020 17:11	976680
10/26/2020 17:16	976690
10/26/2020 17:21	976690
10/26/2020 17:26	976700
10/26/2020 17:31	976700
10/26/2020 17:36	976700
10/26/2020 17:41	976700
10/26/2020 17:46	976710
10/26/2020 17:51	976710
10/26/2020 17:56	976720
10/26/2020 18:01	976720

time	value
10/26/2020 18:06	976730
10/26/2020 18:11	976730
10/26/2020 18:16	976740
10/26/2020 18:20	976740
10/26/2020 18:25	976750
10/26/2020 18:30	976750
10/26/2020 18:35	976750
10/26/2020 18:40	976750
10/26/2020 18:45	976760
10/26/2020 18:50	976760
10/26/2020 18:55	976770
10/26/2020 19:00	976770
10/26/2020 19:05	976780
10/26/2020 19:10	976780
10/26/2020 19:15	976790
10/26/2020 19:20	976790
10/26/2020 19:25	976800
10/26/2020 19:30	976800
10/26/2020 19:35	976810
10/26/2020 19:40	976810
10/26/2020 19:45	976820
10/26/2020 19:50	976820
10/26/2020 19:55	976830
10/26/2020 20:00	976830
10/26/2020 20:05	976830
10/26/2020 20:10	976830
10/26/2020 20:15	976840
10/26/2020 20:20	976840
10/26/2020 20:25	976850
10/26/2020 20:30	976850
10/26/2020 20:35	976860
10/26/2020 20:40	976860
10/26/2020 20:45	976870
10/26/2020 20:50	976870
10/26/2020 20:55	976880
10/26/2020 21:00	976880
10/26/2020 21:05	976890
10/26/2020 21:10	976890
10/26/2020 21:15	976900
10/26/2020 21:20	976900
10/26/2020 21:25	976910
10/26/2020 21:30	976910
10/26/2020 21:35	976920
10/26/2020 21:40	976920
10/26/2020 21:45	976930

time	value
10/26/2020 21:50	976930
10/26/2020 21:55	976940
10/26/2020 22:00	976940
10/26/2020 22:05	976950
10/26/2020 22:10	976950
10/26/2020 22:15	976960
10/26/2020 22:20	976960
10/26/2020 22:25	976970
10/26/2020 22:30	976970
10/26/2020 22:35	976980
10/26/2020 22:40	976980
10/26/2020 22:45	976990
10/26/2020 22:50	976990
10/26/2020 22:55	977000
10/26/2020 23:00	977000
10/26/2020 23:05	977010
10/26/2020 23:10	977010
10/26/2020 23:15	977020
10/26/2020 23:19	977020
10/26/2020 23:24	977030
10/26/2020 23:29	977030
10/26/2020 23:39	977040
10/26/2020 23:44	977040
10/26/2020 23:49	977040
10/26/2020 23:54	977050
10/26/2020 23:59	977050
10/27/2020 0:04	977060
10/27/2020 0:09	977060
10/27/2020 0:14	977060
10/27/2020 0:19	977060
10/27/2020 0:24	977070
10/27/2020 0:29	977070
10/27/2020 0:34	977080
10/27/2020 0:39	977080
10/27/2020 0:44	977080
10/27/2020 0:49	977080
10/27/2020 0:54	977090
10/27/2020 0:59	977090
10/27/2020 1:04	977100
10/27/2020 15:56	977650
10/27/2020 1:09	977100
10/27/2020 1:14	977110
10/27/2020 1:19	977110
10/27/2020 1:24	977110
10/27/2020 1:29	977110

time	value
10/27/2020 1:34	977110
10/27/2020 1:39	977120
10/27/2020 1:44	977120
10/27/2020 1:49	977120
10/27/2020 1:54	977120
10/27/2020 1:59	977130
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10/27/2020 2:09	977130
10/27/2020 2:14	977130
10/27/2020 2:19	977140
10/27/2020 2:24	977140
10/27/2020 2:29	977140
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10/27/2020 2:39	977150
10/27/2020 2:44	977150
10/27/2020 2:49	977150
10/27/2020 2:54	977150
10/27/2020 2:59	977160
10/27/2020 3:04	977160
10/27/2020 3:09	977160
10/27/2020 3:14	977160
10/27/2020 3:19	977170
10/27/2020 3:24	977170
10/27/2020 3:29	977170
10/27/2020 3:34	977170
10/27/2020 3:39	977180
10/27/2020 3:44	977180
10/27/2020 3:49	977180
10/27/2020 3:54	977180
10/27/2020 3:59	977190
10/27/2020 4:04	977190
10/27/2020 4:09	977190
10/27/2020 4:14	977190
10/27/2020 4:18	977200
10/27/2020 4:23	977200
10/27/2020 4:28	977200
10/27/2020 4:33	977200
10/27/2020 4:38	977200
10/27/2020 4:43	977200
10/27/2020 4:48	977210
10/27/2020 4:53	977210
10/27/2020 4:58	977210
10/27/2020 5:03	977210
10/27/2020 5:08	977220
10/27/2020 5:13	977220

time	value
10/27/2020 5:18	977220
10/27/2020 5:23	977220
10/27/2020 5:28	977230
10/27/2020 5:33	977230
10/27/2020 5:38	977230
10/27/2020 5:43	977230
10/27/2020 5:48	977230
10/27/2020 5:53	977230
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10/27/2020 6:08	977240
10/27/2020 6:13	977240
10/27/2020 6:18	977250
10/27/2020 6:23	977250
10/27/2020 6:28	977250
10/27/2020 6:33	977250
10/27/2020 6:38	977260
10/28/2020 20:10	978780
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10/27/2020 6:48	977270
10/27/2020 6:53	977270
10/27/2020 6:58	977280
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10/27/2020 7:08	977300
10/27/2020 7:13	977300
10/27/2020 7:18	977310
10/27/2020 7:23	977310
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10/27/2020 7:38	977330
10/27/2020 7:43	977330
10/27/2020 7:48	977340
10/27/2020 7:53	977340
10/27/2020 7:58	977350
10/27/2020 8:03	977350
10/27/2020 8:08	977360
10/27/2020 8:13	977360
10/27/2020 8:18	977370
10/27/2020 8:23	977370
10/27/2020 8:28	977380
10/27/2020 8:33	977380
10/27/2020 8:38	977390
10/27/2020 8:43	977390
10/27/2020 8:48	977400

time	value
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10/27/2020 8:58	977410
10/27/2020 9:03	977410
10/27/2020 9:08	977410
10/27/2020 9:13	977410
10/27/2020 9:17	977420
10/27/2020 9:22	977420
10/27/2020 9:27	977430
10/27/2020 9:32	977430
10/27/2020 9:37	977430
10/28/2020 20:15	978790
10/27/2020 9:42	977430
10/27/2020 9:47	977440
10/27/2020 9:52	977440
10/27/2020 9:57	977440
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10/27/2020 10:07	977450
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10/27/2020 10:17	977460
10/27/2020 10:22	977460
10/27/2020 10:27	977460
10/27/2020 10:32	977460
10/27/2020 10:37	977470
10/27/2020 10:42	977470
10/27/2020 10:47	977470
10/27/2020 10:52	977470
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10/27/2020 11:02	977480
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10/27/2020 11:17	977490
10/27/2020 11:22	977490
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10/27/2020 11:32	977500
10/27/2020 11:37	977500
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10/27/2020 11:57	977520
10/27/2020 12:02	977520
10/27/2020 12:07	977520
10/27/2020 12:12	977520
10/27/2020 12:17	977530
10/27/2020 12:22	977530
10/27/2020 12:27	977530

time	value
10/27/2020 12:32	977530
10/27/2020 12:37	977540
10/27/2020 12:42	977540
10/27/2020 12:47	977540
10/27/2020 12:52	977540
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10/27/2020 13:02	977550
10/27/2020 13:07	977550
10/27/2020 13:12	977550
10/27/2020 13:17	977560
10/27/2020 13:22	977560
10/27/2020 13:27	977570
10/27/2020 13:32	977570
10/27/2020 13:37	977570
10/27/2020 13:42	977570
10/27/2020 13:47	977580
10/27/2020 13:52	977580
10/27/2020 13:57	977580
10/27/2020 14:02	977580
10/27/2020 14:07	977590
10/27/2020 14:12	977590
10/27/2020 14:16	977600
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10/27/2020 14:26	977600
10/27/2020 14:31	977600
10/27/2020 14:36	977610
10/27/2020 14:41	977610
10/27/2020 14:46	977610
10/27/2020 14:51	977610
10/27/2020 14:56	977620
10/27/2020 15:01	977620
10/27/2020 15:06	977620
10/27/2020 15:11	977620
10/27/2020 15:16	977630
10/27/2020 15:21	977630
10/27/2020 15:26	977630
10/27/2020 15:31	977630
10/27/2020 15:36	977640
10/27/2020 15:41	977640
10/27/2020 15:46	977650
10/27/2020 15:51	977650
10/27/2020 16:01	977650
10/27/2020 16:06	977660
10/27/2020 16:11	977660
10/27/2020 16:16	977670

time	value
10/27/2020 16:21	977670
10/27/2020 16:26	977670
10/27/2020 16:31	977670
10/27/2020 16:36	977680
10/27/2020 16:41	977680
10/27/2020 16:46	977690
10/27/2020 16:51	977690
10/27/2020 16:56	977700
10/27/2020 17:01	977700
10/27/2020 17:06	977700
10/27/2020 17:11	977700
10/27/2020 17:16	977710
10/27/2020 17:21	977710
10/27/2020 17:26	977720
10/27/2020 17:31	977720
10/27/2020 17:36	977730
10/27/2020 17:41	977730
10/27/2020 17:46	977740
10/27/2020 17:51	977740
10/27/2020 17:56	977740
10/27/2020 18:01	977740
10/27/2020 18:06	977750
10/27/2020 18:11	977750
10/27/2020 18:16	977760
10/27/2020 18:21	977760
10/27/2020 18:26	977770
10/27/2020 18:31	977770
10/27/2020 18:36	977780
10/27/2020 18:41	977780
10/27/2020 18:46	977790
10/27/2020 18:51	977790
10/27/2020 18:56	977790
10/30/2020 11:03	980330
10/27/2020 19:01	977790
10/27/2020 19:06	977800

Appendix F

Occupants Data

F.0.1 People over the time

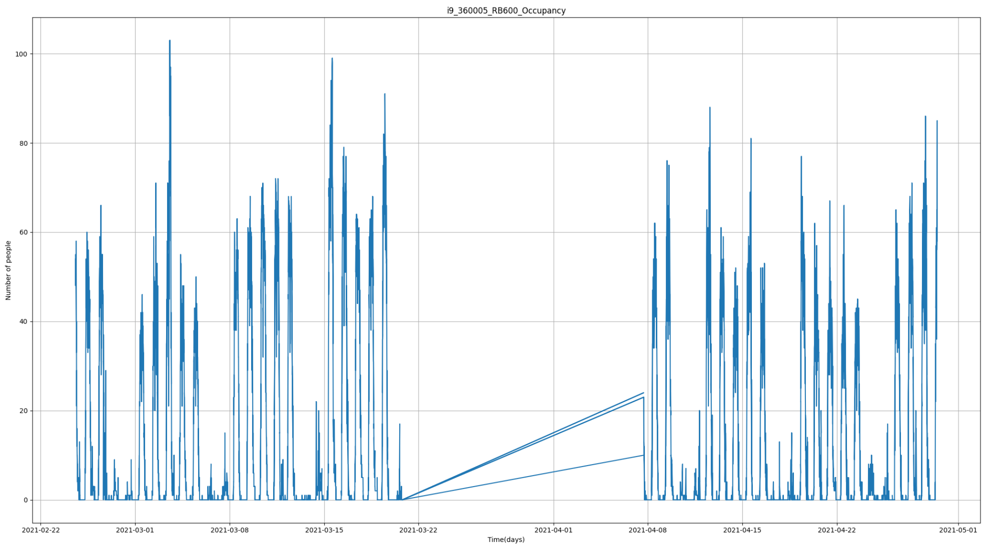

Figure F.1: Occupancy vs time for case 360005RB600

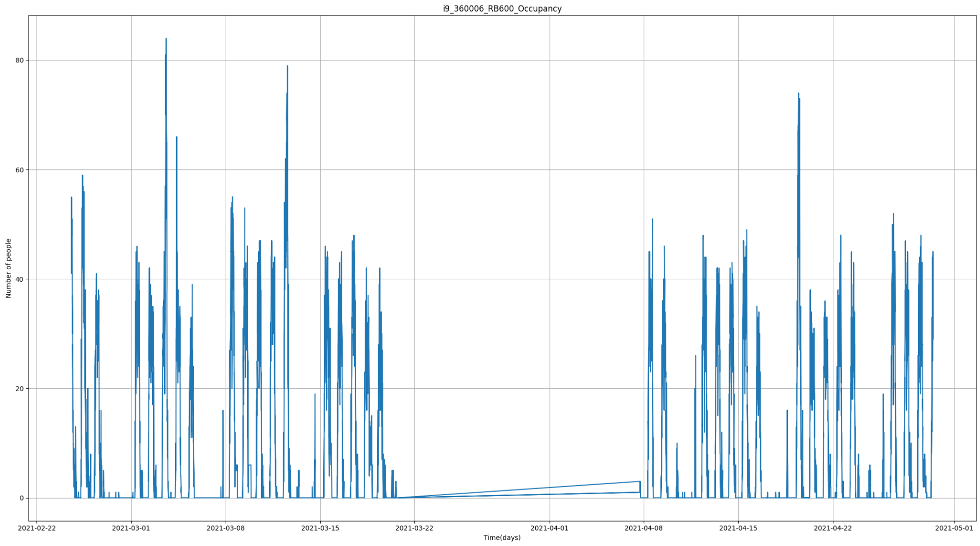

Figure F.2: Occupancy vs time for case 360006RB600

time	value
2/24/2021 13:47	54
2/24/2021 13:52	54
2/24/2021 13:57	48
2/24/2021 14:07	55
2/24/2021 14:02	48
2/24/2021 14:12	55
2/24/2021 14:22	54
2/24/2021 14:17	54
2/24/2021 14:37	54
2/24/2021 14:27	51
2/24/2021 14:32	51
2/24/2021 14:47	48
2/24/2021 14:42	54
2/24/2021 14:52	48
2/24/2021 15:02	44
2/24/2021 14:57	44
2/24/2021 15:17	40
2/24/2021 15:07	58
2/24/2021 15:12	58
2/24/2021 15:32	33
2/24/2021 15:22	40
2/24/2021 15:27	33
2/24/2021 15:42	40

time	value
2/24/2021 15:37	40
2/24/2021 15:47	21
2/24/2021 15:52	21
2/24/2021 16:02	29
2/24/2021 15:57	29
2/24/2021 16:07	14
2/24/2021 16:17	12
2/24/2021 16:12	14
2/24/2021 16:32	16
2/24/2021 16:22	12
2/24/2021 16:27	16
2/24/2021 16:42	15
2/24/2021 16:37	15
2/24/2021 16:47	11
2/24/2021 16:57	10
2/24/2021 16:52	11
2/24/2021 17:12	8
2/24/2021 17:02	10
2/24/2021 17:07	8
2/24/2021 17:22	6
2/24/2021 17:17	6
2/24/2021 17:27	4
2/24/2021 17:37	8
2/24/2021 17:32	4
2/24/2021 17:42	8
2/24/2021 17:52	4
2/24/2021 17:47	4
2/24/2021 18:07	2
2/24/2021 17:57	3
2/24/2021 18:02	3
2/24/2021 18:17	2
2/24/2021 18:12	2
2/24/2021 18:22	2
2/24/2021 18:27	2
2/24/2021 18:37	2
2/24/2021 18:32	2
2/24/2021 18:42	2
2/24/2021 18:52	2
2/24/2021 18:47	2
2/24/2021 19:07	2
2/24/2021 18:57	2
2/24/2021 19:02	2
2/24/2021 19:12	2
2/24/2021 19:17	2
2/24/2021 19:22	2

time	value
2/24/2021 19:27	2
2/24/2021 19:32	2
2/24/2021 19:37	5
2/24/2021 19:47	0
2/24/2021 19:42	5
2/24/2021 19:52	0
2/24/2021 19:57	0
2/24/2021 20:07	0
2/24/2021 20:02	0
2/24/2021 20:22	0
2/24/2021 20:12	0
2/24/2021 20:17	0
2/24/2021 20:32	0
2/24/2021 20:27	0
2/24/2021 20:37	0
2/24/2021 20:47	0
2/24/2021 20:42	0
2/24/2021 21:02	4
2/24/2021 20:52	0
2/24/2021 20:57	4
2/24/2021 21:12	13
2/24/2021 21:07	13
2/24/2021 21:17	7
2/24/2021 21:27	4
2/24/2021 21:22	7
2/24/2021 21:32	4
2/24/2021 21:37	1
2/24/2021 21:47	1
2/24/2021 21:42	1
2/24/2021 21:52	1
2/24/2021 22:02	0
2/24/2021 21:57	0
2/24/2021 22:17	0
2/24/2021 22:07	0
2/24/2021 22:12	0
2/24/2021 22:27	0
2/24/2021 22:22	0
2/24/2021 22:32	0
2/24/2021 22:37	0
2/24/2021 22:47	0
2/24/2021 22:42	0
2/24/2021 22:52	0
2/24/2021 23:02	0
2/24/2021 23:07	0
2/24/2021 22:57	0

time	value
2/24/2021 23:12	0
2/24/2021 23:22	0
2/24/2021 23:17	0
2/24/2021 23:27	0
2/24/2021 23:37	0
2/24/2021 23:42	0
2/24/2021 23:47	0
2/24/2021 23:52	0
2/24/2021 23:57	0
2/25/2021 0:02	0
2/25/2021 0:07	0
2/24/2021 23:32	0
2/25/2021 0:17	0
2/25/2021 0:22	0
2/25/2021 0:12	0
2/25/2021 0:27	0
2/25/2021 0:37	0
2/25/2021 0:32	0
2/25/2021 0:42	0
2/25/2021 0:47	0
2/25/2021 0:52	0
2/25/2021 1:02	0
2/25/2021 0:57	0
2/25/2021 1:07	0
2/25/2021 1:17	0
2/25/2021 1:12	0
2/25/2021 1:22	0
2/25/2021 1:27	0
2/25/2021 1:37	0
2/25/2021 1:32	0
2/25/2021 1:42	0
2/25/2021 1:47	0
2/25/2021 1:57	0
2/25/2021 1:52	0
2/25/2021 2:02	0
2/25/2021 2:12	0
2/25/2021 2:07	0
2/25/2021 2:27	0
2/25/2021 2:17	0
2/25/2021 2:22	0
2/25/2021 2:37	0
2/25/2021 2:32	0
2/25/2021 2:42	0
2/25/2021 2:47	0
2/25/2021 2:57	0

time	value
2/25/2021 2:52	0
2/25/2021 3:02	0
2/25/2021 3:12	0
2/25/2021 3:07	0
2/25/2021 3:17	0
2/25/2021 3:27	0
2/25/2021 3:22	0
2/25/2021 3:32	0
2/25/2021 3:47	0
2/25/2021 3:37	0
2/25/2021 3:42	0
2/25/2021 4:02	0
2/25/2021 3:52	0
2/25/2021 3:57	0

Appendix G

Temperature Data

G.0.1 Temperature data from NORCE

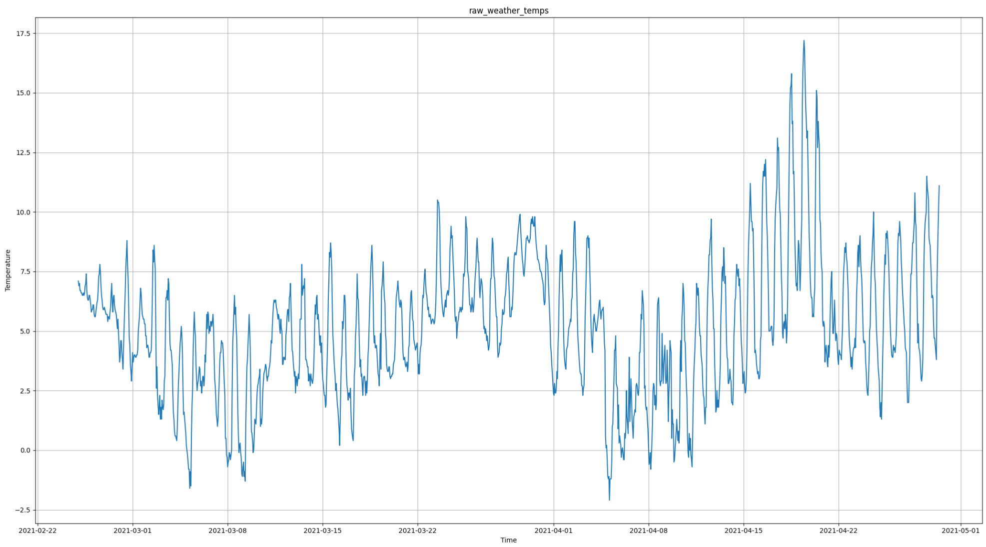

Figure G.1: Raw Temperature (°C) vs time over a few days

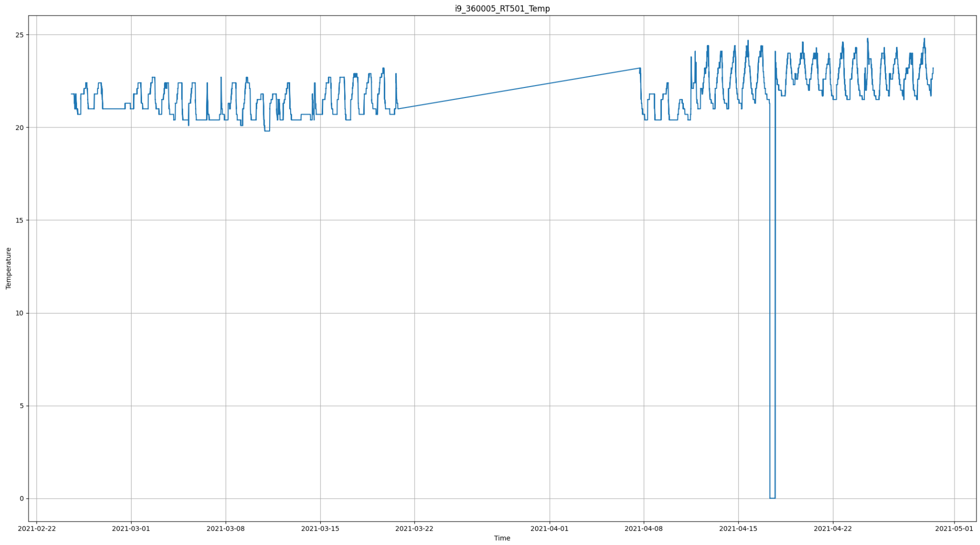

Figure G.2: Temperature(°C) from data 360005RT501 vs time over a few days

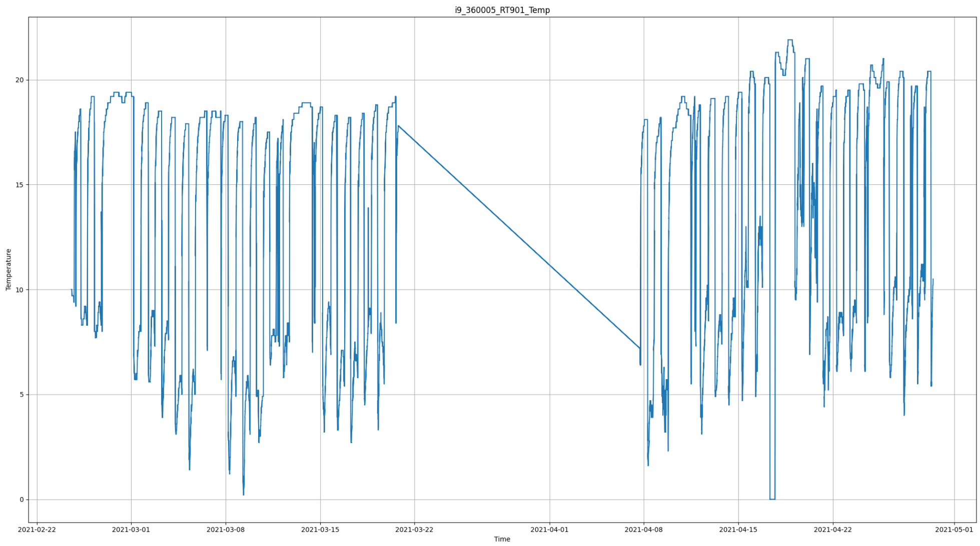

Figure G.3: Temperature (°C) from data 360006RT401 vs time over a few days

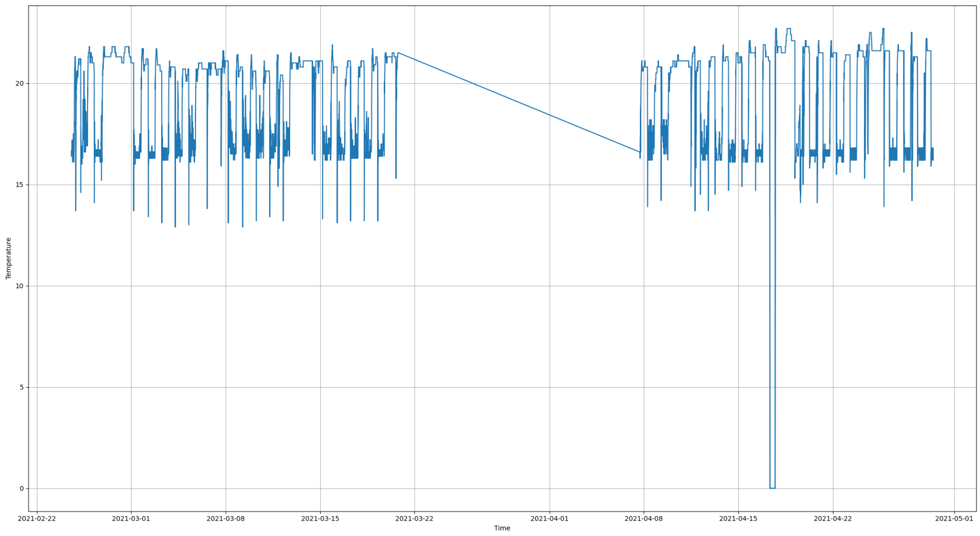

Figure G.4: Temperature (°C) from data 320001RT901 vs time over a few days

time	value
4/12/2021 9:32	4.6
4/12/2021 9:22	4.6
4/12/2021 9:27	4.6
4/12/2021 9:42	4.8
4/12/2021 9:47	4.8
4/12/2021 9:57	4.9
4/12/2021 10:07	5
4/12/2021 9:20	4.6
4/12/2021 9:37	4.6
4/12/2021 9:52	4.9
4/12/2021 10:02	5
4/12/2021 10:12	5.1
4/12/2021 10:27	5.1
4/12/2021 10:22	5.1
4/12/2021 10:17	5.1
4/12/2021 10:32	5.3
4/12/2021 10:47	5.3
4/12/2021 10:37	5.3
4/12/2021 10:42	5.3
4/12/2021 10:52	5.5
4/12/2021 10:57	5.5
4/12/2021 11:17	5.6
4/12/2021 11:07	5.6
4/12/2021 11:12	5.6
4/12/2021 11:02	5.6

time	value
4/12/2021 11:22	5.7
4/12/2021 11:42	6.1
4/12/2021 11:37	5.9
4/12/2021 11:27	5.7
4/12/2021 11:32	5.9
4/12/2021 12:02	6.1
4/12/2021 11:47	6.1
4/12/2021 11:52	6
4/12/2021 11:57	6
4/12/2021 12:22	6.5
4/12/2021 12:12	6.3
4/12/2021 12:17	6.3
4/12/2021 12:07	6.1
4/12/2021 12:42	6.7
4/12/2021 12:27	6.5
4/12/2021 12:47	6.7
4/12/2021 12:32	6.7
4/12/2021 12:37	6.7
4/12/2021 12:52	6.9
4/12/2021 13:07	7
4/12/2021 12:57	6.9
4/12/2021 13:12	7.1
4/12/2021 13:02	7
4/12/2021 13:27	7.3
4/12/2021 13:22	7.3
4/12/2021 13:17	7.1
4/12/2021 13:32	7.6
4/12/2021 13:47	7.6
4/12/2021 13:37	7.6
4/12/2021 13:42	7.6
4/12/2021 13:52	7.8
4/12/2021 14:17	8.7
4/12/2021 13:57	7.8
4/12/2021 14:07	8.2
4/12/2021 14:02	8.2
4/12/2021 14:12	8.7
4/12/2021 14:32	8.4
4/12/2021 14:37	8.4
4/12/2021 14:42	8.4
4/12/2021 14:52	8.5
4/12/2021 15:07	8.4
4/12/2021 15:17	8.5
4/12/2021 15:22	8.7
4/12/2021 15:32	9.2
4/12/2021 14:27	8.4

time	value
4/12/2021 14:47	8.4
4/12/2021 14:57	8.5
4/12/2021 15:02	8.4
4/12/2021 15:12	8.5
4/12/2021 15:27	8.7
4/12/2021 15:37	9.2
4/12/2021 14:22	8.4
4/12/2021 15:42	8.9
4/12/2021 15:47	8.9
4/12/2021 16:07	10
4/12/2021 15:57	9.6
4/12/2021 16:02	10
4/12/2021 15:52	9.6
4/12/2021 16:12	10.2
4/12/2021 16:17	10.2
4/12/2021 16:32	9.8
4/12/2021 16:22	10.1
4/12/2021 16:27	10.1
4/12/2021 16:52	10.1
4/12/2021 16:42	10.7
4/12/2021 16:37	9.8
4/12/2021 16:57	10.1
4/12/2021 17:02	9.9
4/12/2021 17:07	9.9
4/12/2021 17:12	9.9
4/12/2021 17:17	9.9
4/12/2021 17:22	9.4
4/12/2021 17:27	9.4
4/12/2021 17:32	9
4/12/2021 16:47	10.7
4/12/2021 17:52	8.6
4/12/2021 17:42	8.8
4/12/2021 17:47	8.8
4/12/2021 17:37	9
4/12/2021 17:57	8.6
4/12/2021 18:17	8.2
4/12/2021 18:12	8.2
4/12/2021 18:02	8.6
4/12/2021 18:07	8.6
4/12/2021 18:27	7.7
4/12/2021 18:37	7.7
4/12/2021 18:32	7.7
4/12/2021 18:42	7.8
4/12/2021 18:22	7.7
4/12/2021 18:47	7.8

time	value
4/12/2021 19:02	7.5
4/12/2021 18:52	7.6
4/12/2021 19:07	7.5
4/12/2021 19:27	8.5
4/12/2021 19:12	7.6
4/12/2021 19:17	7.6
4/12/2021 19:37	7.9
4/12/2021 19:47	7.7
4/12/2021 19:52	8.5
4/12/2021 20:02	8.3
4/12/2021 20:17	9.2
4/12/2021 18:57	7.6
4/12/2021 19:22	8.5
4/12/2021 19:42	7.7
4/12/2021 19:57	8.5
4/12/2021 20:07	8.3
4/12/2021 20:12	9.2
4/12/2021 20:22	9.2
4/12/2021 19:32	7.9
4/12/2021 20:32	8.2
4/12/2021 20:27	9.2
4/12/2021 20:47	7
4/12/2021 20:37	8.2
4/12/2021 20:52	6.5
4/12/2021 20:42	7
4/12/2021 20:57	6.5
4/12/2021 21:12	5.6
4/12/2021 21:07	6
4/12/2021 21:02	6
4/12/2021 21:17	5.6
4/12/2021 21:32	5.2
4/12/2021 21:22	5.3
4/12/2021 21:27	5.3
4/12/2021 21:37	5.2
4/12/2021 21:52	5.2
4/12/2021 21:47	5.1
4/12/2021 21:42	5.1
4/12/2021 21:57	5.2
4/12/2021 22:02	5.4
4/12/2021 22:07	5.4
4/12/2021 22:27	4.9
4/12/2021 22:22	4.9
4/12/2021 22:12	5.4
4/12/2021 22:17	5.4
4/12/2021 22:47	4.1

time	value
4/12/2021 22:32	4.5
4/12/2021 22:37	4.5
4/12/2021 22:42	4.1
4/12/2021 23:07	3.4
4/12/2021 22:57	3.7
4/12/2021 23:02	3.4
4/12/2021 22:52	3.7
4/12/2021 23:27	2.9
4/12/2021 23:12	3.1
4/12/2021 23:17	3.1
4/12/2021 23:22	2.9
4/12/2021 23:47	2.5
4/12/2021 23:37	2.7
4/12/2021 23:42	2.5
4/12/2021 23:32	2.7
4/12/2021 23:52	2.4
4/12/2021 23:57	2.4
4/13/2021 0:12	2.3
4/13/2021 0:02	2.3
4/13/2021 0:17	2.3
4/13/2021 0:07	2.3
4/13/2021 0:27	2.1
4/13/2021 0:37	1.8
4/13/2021 0:22	2.1
4/13/2021 0:32	1.8
4/13/2021 0:42	1.5
4/13/2021 0:57	2.1
4/13/2021 0:47	1.5
4/13/2021 1:02	2.5
4/13/2021 1:07	2.5
4/13/2021 0:52	2.1
4/13/2021 1:12	2.6
4/13/2021 1:32	2.9
4/13/2021 1:22	2.6
4/13/2021 1:27	2.6
4/13/2021 1:17	2.6
4/13/2021 1:52	3
4/13/2021 1:37	2.9
4/13/2021 1:42	2.9
4/13/2021 1:47	2.9
4/13/2021 1:57	3
4/13/2021 2:17	2.8
4/13/2021 2:12	2.8
4/13/2021 2:02	2.8
4/13/2021 2:07	2.8

time	value
4/13/2021 2:37	3
4/13/2021 2:22	2.8
4/13/2021 2:27	2.8
4/13/2021 2:42	2.8
4/13/2021 2:32	3
4/13/2021 3:02	2.4
4/13/2021 2:47	2.8
4/13/2021 2:52	2.5
4/13/2021 2:57	2.5
4/13/2021 3:22	2.4
4/13/2021 3:17	2.3
4/13/2021 3:07	2.4
4/13/2021 3:12	2.3
4/13/2021 3:27	2.4
4/13/2021 3:42	2.4
4/13/2021 3:32	2.5
4/13/2021 3:47	2.4
4/13/2021 3:37	2.5
4/13/2021 4:07	2
4/13/2021 3:57	2.1
4/13/2021 3:52	2.1
4/13/2021 4:02	2
4/13/2021 4:12	1.9
4/13/2021 4:17	1.9
4/13/2021 4:37	2.1
4/13/2021 4:27	1.8
4/13/2021 4:32	2.1
4/13/2021 4:22	1.8
4/13/2021 4:52	2.1
4/13/2021 4:42	2.1
4/13/2021 4:47	2.1
4/13/2021 4:57	2.1
4/13/2021 5:02	2.1
4/13/2021 5:22	2.2
4/13/2021 5:12	2
4/13/2021 5:17	2
4/13/2021 5:32	2.2
4/13/2021 5:37	2.2
4/13/2021 5:07	2.1
4/13/2021 5:27	2.2
4/13/2021 5:42	2.2
4/13/2021 5:47	2.2
4/13/2021 6:07	1.9
4/13/2021 6:02	1.9
4/13/2021 5:52	2

time	value
4/13/2021 5:57	2
4/13/2021 6:27	2.2
4/13/2021 6:12	2
4/13/2021 6:17	2
4/13/2021 6:32	2.3
4/13/2021 6:22	2.2
4/13/2021 6:52	2.6
4/13/2021 6:42	2.5
4/13/2021 6:57	2.6
4/13/2021 7:02	2.8
4/13/2021 7:07	2.8
4/13/2021 7:12	2.9
4/13/2021 7:17	2.9
4/13/2021 7:22	3
4/13/2021 7:27	3
4/13/2021 7:32	3.3
4/13/2021 7:37	3.3
4/13/2021 6:37	2.3
4/13/2021 6:47	2.5
4/13/2021 7:57	3.9

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