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Abstract

High energy demand and the use of greenhouse gases are issues of today's world. The world has a higher energy consumption now than ever before, and it is estimating to increase further[10]. With the rise of renewable energy, we can help decrease the greenhouse gases on the planet.[10] However, by just building renewable infrastructure, which has a lower energy outcome than fossil fuels, we will not overcome the energy demands required in the future[13].

Introducing new and improved ways of combating the energy waste quotidian can help reduce energy consumption. This thesis will present a dynamic heating model made with discretized formulas of mass and energy balances. The model will simulate the indoor temperature with scenarios and environments on both a small and a more extensive scale.

This thesis will research with the help of the presented heating model to see if such a model can help learn more about the environment of a building and how the energy or temperature is affected. By introducing both average and extreme cases, this model will simulate the building's reaction. The model will also implement different buildings with different criteria to test how the physical model will react when given other parameters.

The simulations show results in which the model behaves as intended. The results show how the temperature of the building reacts when introducing different parameters, such as outdoor temperature or sunlight, and how parameters such as airflow can help reduce the temperature. Moreover, the results show how energy is consumed by the building during a typical day, depending on the scenario. This model can help make alterations on how to keep the energy at a minimum.

Abbreviations

UiS - University of Stavanger

NORCE - Norwegian Research Centre

ODE - Ordinary differential equation

DAE - Differential Algebraic Equations

TEK10 - Norwegian Building Acts and Regulations technical requirements

W - Watts

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Chapter 1

Introduction

Heating is one of the primary energy consumers of a building in Norway, principally because of the cold climate it experiences. With *smart* sensors, a building can easily track the temperature and the amount of electricity consumed. Because of the vast amount of energy used by buildings, a dynamic heating model can be implemented into the building's energy control unit to optimize the energy consumption.

However, these kinds of models are complex. With several factors contributing to the system, elements inside a room either try to contribute or prevents the room from reaching its desired temperature. For example, appliances that use electricity give out heat as a bi-product, and furniture can act as a heat sink, obtaining heat from the air.

This paper will take a look at a dynamic heating model and discuss the results.

1.1 Task description

The purpose of this thesis is to reproduce a published dynamic heating model and apply it to some actual data received from *Arkivenes Hus* in the *innovation park* in Stavanger. Some sensors capture temperature, sunlight, airflow, and more data from the building to provide them with information that can help them develop a mathematical model of this building. By analyzing the model produced by this thesis, we could find something similar and perhaps contribute to the research.



Figure 1.1: Arkivenes Hus

By implementing a mathematical model and conducting a numerical simulation, I hope to have a

deeper and more sound understanding of this specific physical topic and take knowledge from my master's degree courses to another level.

Also, by working together with *NORCE* and been part of a research project as *the future energy hub* project, I hope to learn how a degree such as my own can be a part of a research environment. I also am looking forward to learning how my degree can be used on a more professional level. A question from my time as a student has always been: *how* can my degree contribute and be used in a non-academic perspective? Hopefully, this will be more clear after this semester.

1.2 A heat model for a building unit

The model this thesis will take a close look at is the model introduces by Perera, Pfeiffer, and Skeie [16]. The published paper introduces a set of ordinary differential equations describing five states within a building: the temperature of the air, walls, roof, floor, and furniture.

That paper[16] writes about how one can use a one-dimensional model to help with heat recovery and energy saving. They describe their building unit as a basic unit meant to be a representing room of a building. This thesis will take advantage of the same building in its first task and later scale up with the dimensions of *Arkivenes hus*. This task intends to highlight an in-depth dynamic heating model to integrate it with an open architectural energy control system.

A well-mixed zone theory is used to model the air temperature within the building unit. It is also merged with the thermal masses of walls, floor, roof, and household goods. Ventilation plays a significant role in determining the total energy loss. The primary model of the building unit can be used with relevant adjustments to develop models for complex architectures.

Chapter 2

Brief background on thermodynamics

2.1 The First Law of Thermodynamics

The First Law of Thermodynamics is a statement about the conservation of energy. It says that energy can neither be created nor destroyed. It can only transform from a form into another. [2, p 4] For closed systems, in which mass is conserved, can the law be expressed mathematically as

$$\Delta U = Q - W. \quad (2.1)$$

In equation (2.1), ΔU is the change in *internal energy*, Q is the net *heat* energy with the surroundings and W is the sum of all *work* done on and by the system.

2.2 Internal Energy, Heat and Work

2.2.1 Internal Energy

Energy is the capacity to do work. A closed system's internal energy can be thought of as the sum of the potential and kinetic energies due to all atoms and molecules contained within the system. Internal energy cannot be measured on its own. Nevertheless, changes in internal energy can, as described by equation (2.1) [2, p 62].

2.2.2 Heat, and mechanisms of heat transfer

Heat is the transfer of energy between a system and its surroundings due to temperature differences. *Heat* is defined as energy transferred across the boundary of a system as a result of a difference in temperature between the surface of the system and the surroundings. The symbol Q represents heat. [17, p 110]. There are at least two fundamental heat transfer mechanisms: *Conduction*, and *Radiation*.

- Heat due to conduction is due to more energetic (higher temperature) molecules interacting with less energetic (lower temperature) molecules. Can be characterized by *Fourier's Law of Heat Conduction* [17, p 111]:

$$\frac{Q}{A} = -k \frac{\delta T}{\delta x}, \quad (2.2)$$

- Radiation is heat transfer due to emission or absorption of electromagnetic waves. It occurs without direct molecular interaction, and can therefore take place over long distances, even in

a vacuum. A good example from everyday life is heat transfer due to sunlight [17]. For the case of a single surface at temperature T interacting with the surroundings at temperature t_{sur} , both in units of Kelvin, the rate of radioactive heat transfer to the surface can be calculated from [17, p 111]:

$$\frac{Q}{A} = \sigma\epsilon(T^4 - T_{sur}^4). \quad (2.3)$$

In equation (2.3) $\sigma = 5.67 \cdot 10^{-8} W/m^2 K^4$ and is the *Stefan-Boltzmann* constant. ϵ is the surface emissivity. $\epsilon \approx 0$ means the surface reflects almost all of the radiation, while $\epsilon \approx 1$ means it absorbs most of the energy [17, p 112].

Convection is a third form of heat transfer. It is usually not thought of as a separate mechanism because it is the combined outcome of heat transfer due to conduction and advection (heat transfer caused by fluid flow). However, for practical purposes, one often refers to convection as a third heat transfer mechanism, and it can be captured mathematically with Newton's Law of Cooling [17, p 112]:

$$\frac{Q}{A} = h_{conv}(T - T_{sur}). \quad (2.4)$$

In equation (2.4), h_{conv} is the heat transfer coefficient that accounts for all the complex factors we do not model directly.

2.2.3 Work

In thermodynamics, *work* performed by a system is defined as the energy transferred by that system across its boundaries [19, p. 82]. A system cannot contain work; work is a process (done by or on the system).

An isobaric process takes place at constant pressure. An isobaric expansion requires heat transfer to keep the pressure constant [2, p 31].

An isochoric process is when the volume of the system is constant [2, p 31].

An isothermal process is when the temperature is constant, $\Delta T = 0$ [2, p 31]. This typically happens when a system is in contact with a thermal reservoir outside of the system. The change then occurs slowly enough to allow the system to continually adjust to the temperature from outside because of heat exchange.

Pressure-Volume Work

Pressure-volume work, often referred to as *P-V work* is mechanical work involving compression and expanding of a fluid [17, p 119]. *P-V work* is equal to the differential change in the volume contained within a system [17, p 119], can be expressed as:

$$W_{out} = \int_{V_1}^{V_2} P dV. \quad (2.5)$$

2.2.4 Enthalpy

Enthalpy is a frequently useful thermodynamic property. It is a thermodynamic property that is describing the total heat of a given system. Enthalpy is equal to the internal energy and the work done [19, p 127]. In mathematical terms, it is as following:

$$H = U + PV. \quad (2.6)$$

Enthalpy cannot be measured directly because all quantities within are thermodynamic properties[19, p 127]. The *change* of enthalpy from one state to another can be measured. This can help us when dealing with a system of constant pressure. The heat transfer in a constant pressure process is equal to the change in enthalpy[19, p 128]. To see this, note that in this particular case, the *First Law of Thermodynamics* says that:

$$\Delta U = Q - p\Delta V, \quad (2.7)$$

while:

$$\Delta H = \Delta(U + PV) = \Delta U + P\Delta V = Q. \quad (2.8)$$

In other words, the change in enthalpy is then equal to the net heat energy supplied to the system.

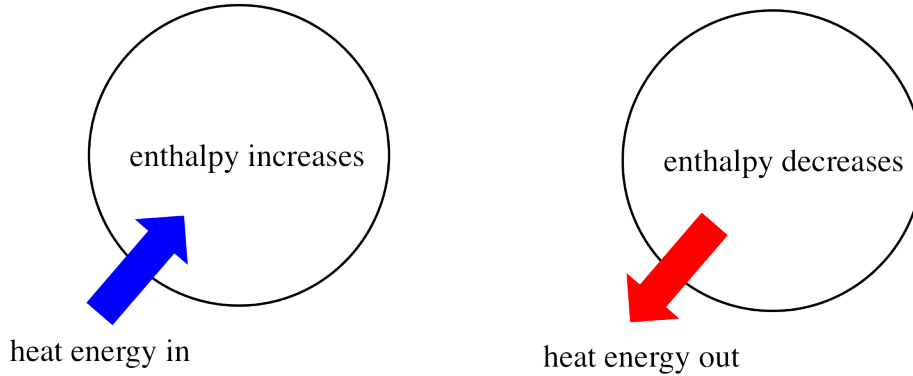


Figure 2.1: Enthalpy [9]

Specific Enthalpy

Enthalpy were described as the total heat of a given system. The *Specific enthalpy* is the total heat content divided by the total mass. Mathematically it is expressed:

$$h_i = H_i/m_i \quad (2.9)$$

where h_i is the specific enthalpy and H_i is the total enthalpy of the heat content of the system i . M_i is the total mass.

From this expression we can find the *specific heat*. In thermodynamics, *Specific Heat* can be seen from *at least* two different views. Constant pressure (C_p) or volume (C_v)[2, p 156]. *Specific heat* is defined as the energy required to raise the temperature of the unit mass of a substance by one degree as the volume (or pressure) is maintained constant[2, p 156].

The relation of specific heat and specific enthalpy at constant pressure can be defined as[2, p 157]:

$$C_p = \left(\frac{dh}{dT} \right)_p \quad (2.10)$$

2.2.5 Thermodynamics of an ideal gas

For a low-density gas, in which intermolecular forces are microscopic, we can use the ideal gas law to approximate the behavior of the gas. The ideal gas law relates the pressure, volume, and temperature of the gas via the following relationship[19, p 70]:

$$\rho V = nRT. \quad (2.11)$$

Chapter 3

Model presentation

3.1 Conservation of Energy for a Building Unit

Our system is a well-ventilated and mixed building unit with a fixed volume based on the physical principles of energy and mass. The building unit can be viewed as a mixing tank since we neglect temperature differences within the room and assume the air temperature inside the room to be uniform. A mixing tank can be viewed as a system where everything is completely mixed and *equal*. The unit in question is introduced in "[16]".

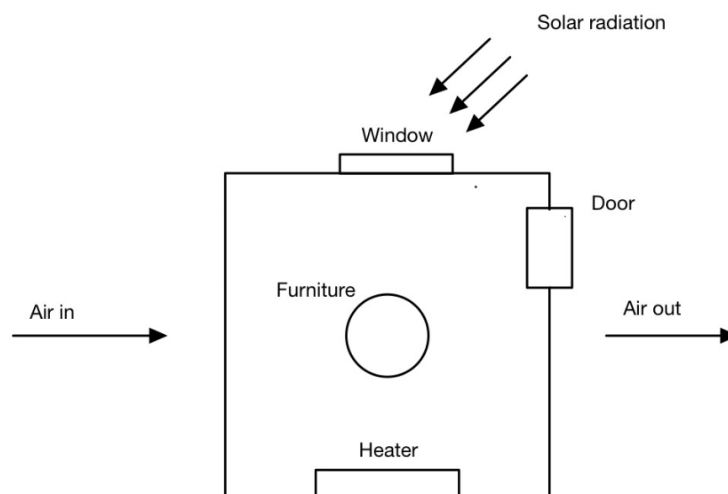


Figure 3.1: Sketch of building unit[16]

Mass and energy balance equations are used to derive a dynamic heat model for the building.

3.1.1 Differential equation for the air in the building unit

Mass balance are presenting the ventilation and infiltration on the system. Mass (Molecular) cannot be created or destroyed, meaning it will always be conserved. Referring to *the first law of thermodynamics* as described in chapter 2.1. [17, p 7]. Equation (3.1) is the general form of the *mass balance* equation.

$$\Delta m = m_{in} - m_{out}. \quad (3.1)$$

The mass balance equation is presented because airflow plays a part in the building unit system. m_{in} in equation (3.1) is the mass of air flowing into the system during a time interval (Δt). m_{out} is the mass flowing out of the system.

We can let \dot{V}_{in} denote the mass flow rate of the incoming air into the building and \dot{V}_{out} is the flow rate out of the building. Mass has an relation with density (ρ) which has the relation being $\rho = m/V$ where V is volume (and m is mass). This means that the variables in equation (3.1) can be written as: $m_{in} = \rho_{in}\dot{V}_{in}\Delta t$ and $m_{out} = \rho_{out}\dot{V}_{out}\Delta t$. The building unit is assumed to be in completely mixed conditions, meaning $\rho_{out} = \rho_b$, meaning the outgoing density is equal to the density inside of the building (ρ_b). Therefore, by letting $\Delta t \rightarrow 0$, we can write the mass balance equation (3.1) as:

$$\frac{d\rho_b}{dt} = \frac{\dot{V}_{in}\rho_{in} - \dot{V}_{out}\rho_b}{\dot{V}_b}. \quad (3.2)$$

Differential equation for the building temperature

Energy is also a property of the system. A system can possess energy in several forms, kinetic(KE), potential(PE), and internal energy (U^E). The total energy (E_b) of a system is the sum of these various forms of energy. [17, p 93].

$$E_b = U^E + KE + PE. \quad (3.3)$$

Equation (3.3) expresses the total sum of all energy on a system. Several adaptations have been made to simplify the *conservation of energy* on the system.

Airflow velocity inside the system is assumed low and insignificant; thus, we can ignore the kinetic energy. Air is an ideal gas [2, p 128]. When gas is in ideal conditions, we can assume the particles have no attractive or repulsive forces, thus no potential energy[22].

The result of these assumptions contributes to another version of the energy balance equation (3.3) with only internal energy as a contributing source:

$$E_b = U_b^E = H_b - P_bV_b = h_b m_b - P_bV_b = h_b m_b - n_b RT = m_b \left(h_b - \frac{RT}{M_b} \right) = \rho_b V_b \left(h_b - \frac{RT}{M_b} \right). \quad (3.4)$$

Looking at equation (3.4) where M_b is the molar mass of air and can be written as $M_b = \frac{m_b}{n_b}$. We have used equation (2.1) to express internal energy in terms of the system enthalpy, as well as the definitions of density and specific enthalpy, equation (2.9)[j/kg].

Conservation of energy requires that the net flowing energy per unit of time must be equal to the rate of change of energy inside the building- Since we assume a fixed volume of the building (V_b):

$$\dot{E}_{in} - \dot{E}_{out} = \frac{d\dot{E}_b}{dt} = V_b \cdot \frac{d}{dt} \left[\rho_b \left(h_b - \frac{RT}{M_b} \right) \right] = V_b \left[\frac{d\rho_b}{dt} \cdot \left(h_b - \frac{RT}{M_b} \right) + \rho_b \left(\frac{dh_b}{dt} - \frac{R}{M_b} \cdot \frac{dT}{dt} \right) \right], \quad (3.5)$$

with the left-hand side being:

$$\dot{E}_{in} - \dot{E}_{out} = \rho_{in}\dot{V}_{in}h_{in} - \rho_b\dot{V}_{out}h_{out} + \dot{Q}_b, \quad (3.6)$$

where the first two terms account for energy flow in the inlet and outlet streams, and \dot{Q}_b accounts for all heat gains/losses due to other sources.

$$h_B = h_{ref} + \int_{T_{ref}}^T c_p(T')dT' \approx h_{ref} + c_p \int_{T_{ref}}^T dT' = h_{ref} + c_p(T - T_{ref}). \quad (3.7)$$

We can approximate: $\frac{dh_b}{dt} = \frac{dh_b}{dT} \cdot \frac{dT}{dt} = c_p \cdot \frac{dT}{dt}$, (2.10), and include it to:

$$\frac{\rho_{in}\dot{V}_{in}h_{in} - \rho_b\dot{V}_{out}h_{out} + \dot{Q}_b}{V_b} = \frac{d\rho_b}{dt} \cdot h_b - \frac{RT}{M_b} + \rho_b \left(c_p - \frac{R}{M_b} \cdot \frac{dT}{dt} \right). \quad (3.8)$$

From the mass balance equation, (3.2), the first term on the right-hand side is:

$$\frac{d\rho_b}{dt} \cdot h_b = \frac{\rho_{in}\dot{V}_{in}h_{in} - \rho_b\dot{V}_{out}h_{out}}{V_b} \quad (3.9)$$

When subtracted from the left-hand side, the enthalpy terms will involve the expressions $h_{in} - h_b$ and $h_{out} - h_b$. This means that the reference enthalpy cancels out. We then can assume that $h = c_p T$ and move forward with our equation like this:

$$\frac{\rho_{in}\dot{V}_{in}h_{in} - \rho_b\dot{V}_{out}h_{out} + \dot{Q}_b}{V_b} = \frac{d\rho_b}{dt} \cdot \left(c_p - \frac{R}{M_b} \right) T_b + \rho_b \left(c_p - \frac{R}{M_b} \right) \frac{dT_b}{dt}. \quad (3.10)$$

Finally, we rearrange this equation and end up with equation (5) in [16]:

$$\frac{dT_b}{dt} = \frac{\dot{Q}_b + \dot{V}_i \rho_i h_i - \dot{V}_e \rho_e h_e}{\rho_b V_b \left(c_p - \frac{R}{M_b} \right)} - \frac{T_b}{\rho_b} \frac{d\rho_b}{dt}. \quad (3.11)$$

3.1.2 Work in building unit

From chapter 2.2.3, the work on the air is $W = P \cdot \Delta V$. Wood and other materials are the building materials used in constructing the test building. To further simplify the system, we assume a fixed volume. This means our system cannot expand its boundaries. Thus, the expansion work is zero. Since the medium in question is air, the ideal gas law assumes the particles never lose energy to motion or collision; thus, friction work can be neglected.

The only term of work that signifies the energy transfer is pressure work.

Equation (3.12) is defining the *Work* done on the building unit. Where $(P\dot{V})_x$ signifies pressure work in direction x.

$$\dot{W} = (P\dot{V})_{in} - (P\dot{V})_{out}. \quad (3.12)$$

3.1.3 Heat transfer in building unit

The rate of change of heat is $\dot{Q} = \dot{Q}_{supply} - \dot{Q}_{loss}$. Several elements contributes to both \dot{Q}_{supply} and \dot{Q}_{loss} .

Table 3.1 denotes some abbreviations used in the mathematical formulas describing the dynamic heat model.

Notation	Description
b	building
w	walls
f	floor
r	roof
fur	furniture

Table 3.1: Letters describing

$$\dot{Q}_{Supply} = \dot{Q}_{Heater} + \dot{Q}_{People} + \dot{Q}_{Appliances} + \dot{Q}_{Solar}. \quad (3.13)$$

Equation (3.13) applies all the elements that contributes to \dot{Q}_{supply} . For heat loss, equation (3.14) to (3.19) has been developed. They are all based on Fourier's law of Heat Conduction (2.2).

$$\dot{Q}_{window} = U_{window}A_{window}(T_b - T_{\infty}), \quad (3.14)$$

$$\dot{Q}_{door} = U_{door}A_{door}(T_b - T_{\infty}), \quad (3.15)$$

$$\dot{Q}_{walls} = U_{walls}A_{walls}(T_b - T_{\infty}), \quad (3.16)$$

$$\dot{Q}_{floor} = U_{floor}A_{floor}(T_b - T_{\infty}), \quad (3.17)$$

$$\dot{Q}_{roof} = U_{roof}A_{roof}(T_b - T_{\infty}), \quad (3.18)$$

$$\dot{Q}_{fur} = h_{fur}A_{fur}(T_b - T_{center}). \quad (3.19)$$

\dot{Q}_{loss} is

$$\dot{Q}_{loss} = \dot{Q}_{window} + \dot{Q}_{door} + \dot{Q}_{walls} + \dot{Q}_{floor} + \dot{Q}_{roof} + \dot{Q}_{fur}. \quad (3.20)$$

3.1.4 Differential equations for layers of the wall, roof, and floor

The initial equation for \dot{Q} are represented by the equations (3.13) to (3.20). We can take a further step to write the heat transfer equations as ODE's and divide them into layers for a more accurate heat loss. These equations are presented in this chapter.

The walls/roof/floor is divided into a number of layers. We are assuming uniform thermal properties for each layer within. Figure 3.2 shows the notation that will be used for the layer temperatures inside the wall, as well as boundary temperature between each layer inside the wall and between the wall and its surroundings.

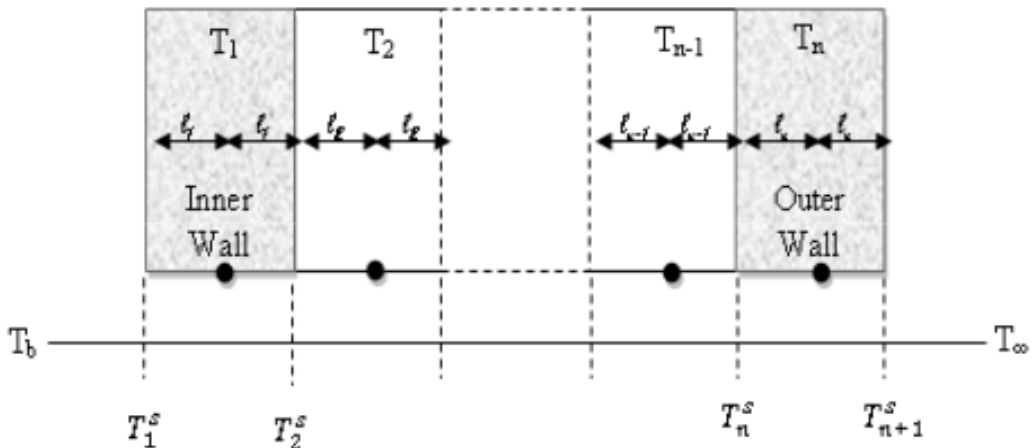


Figure 3.2: Temperature variables of a section of the wall[16]

The same notation is used for the other layered structures:

- $T_{i,x}$ describes the layer temperature. ($i = 1, 2, \dots, N$).
- $T_{i,x}^s$ describes the boundary temperature between the i^{th} layer starting from the inside.

From "[16]" a transient heat equation has been used as the energy balance for the layers of the walls, floor, and roof:

$$\frac{\partial T}{\partial t} - \alpha \nabla^2 T - \frac{\dot{q}}{\rho C_p} = 0, \quad (3.21)$$

where $\alpha = \frac{K}{\rho C_p}$ is the layer thermal diffusivity, K is the thermal conductivity, ρ is density, C_p is heat capacity, and \dot{q} is the source term. Since heat is mainly transferred from the building from the inside to the outside, we further assume the heat conduction to be one-dimensional[16]. Then, $\nabla^2 = \frac{\partial^2}{\partial x^2}$, and equation (3.21) becomes:

$$\frac{\partial T_{i,x}}{\partial t} - \alpha \frac{\partial^2 T}{\partial x^2} - \frac{\dot{q}}{\rho C_p} = 0. \quad (3.22)$$

Equation (3.22) can be discretized with the finite difference method. To get started, we first introduce another concept, the *Taylor series*. Taylor series is the representation of function, $f = f(x)$, as an infinite sum of polynomials involving the function's derivatives at a single point[6]:

$$f(x) = f(c) + f'(c)(x - c) + \frac{f''(c)}{2!}(x - c)^2 + \dots = \sum_{k=0}^{\infty} \frac{f^{(k)}(c)}{k!}(x - c)^k. \quad (3.23)$$

If the function is *smooth* enough, the Taylor series gives a good approximation to the function near x . Using equation (3.23), we now can expand it about $x \pm h$, where $h > 0$ is a small number. This gives us:

$$f(x + h) = f(x) + f'(x)h + \frac{h^2}{2}f''(x) + \frac{h^3}{3!}f'''(x) + \frac{h^4}{4!}f^{(4)}(x) + \dots \quad (3.24)$$

$$f(x - h) = f(x) - f'(x)h + \frac{h^2}{2}f''(x) - \frac{h^3}{3!}f'''(x) + \frac{h^4}{4!}f^{(4)}(x) - \dots \quad (3.25)$$

If we now add equation (3.24) and (3.25) together, and ignore the term of order ≤ 3 , we get an expression for the second derivative:

$$f''(x) = \frac{f(x + h) + f(x - h) - 2f(x)}{h^2}. \quad (3.26)$$

By inserting $f = T$ and $h = l$, where l_i is the half-thickness of layer i , we can use equation (3.26) to replace the second derivative of the temperature in layer i with a finite difference:

$$\frac{\partial^2 T_i}{\partial x^2} \approx \frac{T(x_i + l_i) + T(x_i - l_i) - 2T(x_i)}{l_i^2} \quad (3.27)$$

If $\dot{q} = 0$, the finite difference version of equation (3.22) becomes (see figure 3.2):

$$\frac{\partial^2 T}{\partial x^2} = \frac{T_{i+1,x}^s - 2T_{i,x}^s + T_{i,x}^s}{\Delta x^2}. \quad (3.28)$$

Differential equations for furniture

Furniture can act as either a heat source or a heat sink. For example, it takes a longer time to heat a room with furniture than one without because the furniture soaks up the temperature and will continue to do so until the furniture body reaches equilibrium with the indoor air temperature. A room with furniture will also take more time to cool down because of the heat flowing out from the furniture and into the room.

To simplify the modeling of furniture, we will use the same method as [16] and assume the furniture is a single sphere. Equation (3.21), by assuming one-dimensional spherical coordinates:

$$\frac{\partial T}{\partial t} - \alpha \frac{1}{r} \frac{\partial}{\partial r} \left(r \cdot \frac{\partial T}{\partial r} \right) - \frac{\dot{q}}{\rho C_p} = 0, \quad (3.29)$$

To discretize equation (3.29), we can again use Taylor series to obtain:

$$\frac{dT_{i, fur}}{dt} = \alpha_{i, fur} \left(\frac{T_{i+1, fur}^s - 2T_{i, fur} + T_{i, fur}^s}{\delta r_{i, fur}^2} \right) + \alpha_{i, fur} \left(\frac{1}{r} \frac{T_{i+1, fur}^s - T_{i, fur}^s}{\delta r_{i, fur}} \right). \quad (3.30)$$

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

We also need equations to describe what happens at the boundary of each element (wall/roof/floor) and its surroundings. We start by considering *Fourier's law of heat conduction*:

$$q = -k \frac{\partial T}{\partial x} \quad (3.31)$$

A finite difference approximation at $x=0$ gives:

$$q \approx -k_1 \frac{T_2^s - T_1^s}{2l_1}. \quad (3.32)$$

At the same time, Newton's law of cooling gives an expression for the convective heat transfer across the same boundary:

$$q = h_b(T_b - T_1^s), \quad (3.33)$$

and by setting the two expressions equal, we get:

$$h_{b,x}(T_b - T_{i,x}^s) = \frac{-K_{1,x}}{2l_{1,x}}(T_{2,x}^s - T_{1,x}^s). \quad (3.34)$$

The same procedure is applied to the boundary $x = L$. except with an extra radiation term:

$$\begin{aligned} \frac{-K_{i,x}A_{i+1,x}}{2l_{i,x}}(T_{i+1,x}^s - T_{i,x}^s) = & h_{\infty,x}A_{i+1,x}(T_{i+1,x}^s - T_{\infty}) + \\ & \sigma \varepsilon_{i+1,x}(T_{i+1,x}^s{}^4 - T_{\infty}^4). \end{aligned} \quad (3.35)$$

Inner boundary conditions for wall/floor/roof

Finally, we need the equation for calculating the surface temperature at the interface between two inner layers. We can assume that the heat flowing into a *inner surface* can be equal to the flow out of the *inner surface* and with the help of (3.32) we can get an approximation for heat transfer of two layers. the two consecutive layers can then be written as:

$$Q = -K(x) \cdot \frac{dT}{dx} \approx -K_i \cdot \frac{T_{i+1}^s - T_i}{l_i} \quad (3.36)$$

and

$$Q = -K(x) \cdot \frac{dT}{dx} \approx -K_{i+1} \cdot \frac{T_{i+1}^s - T_{i+1}}{l_{i+1}} \quad (3.37)$$

Combining them:

$$-K(x) \cdot \frac{T_{i+1}^s - T_i}{l_i} = -K_{i+1} \cdot \frac{T_{i+1}^s - T_{i+1}}{l_{i+1}}, i \rightarrow 1, 2, 3, \dots \quad (3.38)$$

Then we solve for T_{i+1}^s :

$$T_{i+1}^s = \frac{\frac{k_i}{l_i}T_i + \frac{k_{i+1}}{l_{i+1}}T_{i+1}}{\frac{k_i}{l_i} + \frac{k_{i+1}}{l_{i+1}}}, \quad (3.39)$$

Which is the inner layer surface temperature.

Boundary conditions for furniture

The boundary equation for the furniture can be written similarly to the internal boundary of the walls/roof and floor. See equation (3.34).

$$h_{b,fur}(T_b - T_{i,fur}^s) = \frac{-K_{1,fur}}{2l_{1,fur}}(T_{2,fur}^s - T_{1,fur}^s). \quad (3.40)$$

Chapter 4

Implementation in Python

The dynamic heat model, presented in chapter 2 was based on assumptions and equations from [16]. When everything is put together, we need to solve a system of coupled differential-algebraic equations (DAEs):

- A set of ordinary differential equations (ODEs); for the building + walls/floor/roof/furniture, and
- A number of boundary conditions (algebraic constraints).

After everything is implemented in Python, we can get to work on applying the building model. Note that in the presented code (see appendix B, and the Github repository [18]), a fixed number of layers have been assumed for the walls / roof / floor / furniture; the same as in case 1 of [16]. All layer properties used in the equations are given in table 5.2 and 5.3.

4.1 Full set of equations in the model

Energy and mass balance equation for the building unit:

4.1.1 ODE's indoor temperature in the model

$$\frac{dT_b}{dt} = \frac{\dot{Q}_b + \dot{V}_i \rho_i h_i - \dot{V}_b \rho_b h_b}{\rho_b V_b (c_p - \frac{R}{M_b})} - \frac{T_b \rho_b}{\rho_b dt}, \quad (4.1)$$

$$\frac{d\rho_b}{dt} = \frac{\dot{V}_{in} \rho_{in} - \dot{V}_{out} \rho_b}{\dot{V}_b}. \quad (4.2)$$

4.1.2 Wall ODE equations

In the code, the walls are assumed to consist of four layers (i=1, 2, 3, 4):

$$\frac{dT_{i,w}}{dt} = \alpha_{i,w} \frac{T_{i+1,w}^s - 2T_{i,w} + T_{i,w}^s}{l_{i,w}^2}, \quad (4.3)$$

$$h_{b,w}(T_b - T_{i,w}^s) = \frac{-K_{1,w}}{2l_{1,w}}(T_{2,w}^s - T_{1,w}^s), \quad (4.4)$$

$$\begin{aligned} \frac{-K_{i,w} A_{i+1,w}}{2l_{i,w}}(T_{i+1,w}^s - T_{i,w}^s) = & h_{\infty,w} A_{i+1,w}(T_{i+1,w}^s - T_{\infty}) + \\ & \sigma \varepsilon_{i+1,w}(T_{i+1,w}^s{}^4 - T_{\infty}{}^4). \end{aligned} \quad (4.5)$$

4.1.3 Roof ODE equations

In the code, the roof also has four layers (i=1, 2, 3, 4):

$$\frac{dT_{i,r}}{dt} = \alpha_{i,r} \frac{T_{i+1,r}^s - 2T_{i,r} + T_{i,r}^s}{l_{i,r}^2}, \quad (4.6)$$

$$h_{b,r}(T_b - T_{i,r}^s) = \frac{-K_{1,r}}{2l_{1,r}} (T_{2,r}^s - T_{1,r}^s), \quad (4.7)$$

$$\begin{aligned} \frac{-K_{i,r} A_{i+1,r}}{2l_{i,r}} (T_{i+1,r}^s - T_{i,r}^s) = & h_{\infty,r} A_{i+1,r} (T_{i+1,r}^s - T_{\infty}) + \\ & \sigma \varepsilon_{i+1,r} (T_{i+1,r}^s{}^4 - T_{\infty}^4). \end{aligned} \quad (4.8)$$

4.1.4 Floor ODE equations

In the code, the floor has three layers (i=1, 2, 3). The floor energy balance equations also have a heat source term, \dot{q} . However, this has been ignored due to poor explanations in "[16]".

$$\frac{dT_{i,f}}{dt} = \alpha_{i,f} \frac{T_{i+1,f}^s - 2T_{i,f} + T_{i,f}^s}{l_{i,f}^2} - \frac{q_{i,f}}{\rho_{i,f} c_{p_{i,f}}}, \quad (4.9)$$

$$h_{b,f}(T_b - T_{i,f}^s) = \frac{-K_{1,f}}{2l_{1,f}} (T_{2,f}^s - T_{1,f}^s). \quad (4.10)$$

4.1.5 Furniture ODE equations

In the code, a single layer is used for the furniture.

$$\begin{aligned} \frac{dT_{i,fur}}{dt} = & \alpha_{i,fur} \frac{T_{i+1,fur}^s - 2T_{i,fur} + T_{i,fur}^s}{\partial r_{i,fur}^2} + \\ & \alpha_{i,fur} \frac{T_{i+1,fur}^s - T_{i,fur}^s}{\partial r_{i,fur}}, \end{aligned} \quad (4.11)$$

$$h_{b,fur}(T_b - T_{i,fur}^s) = \frac{-K_{1,fur}}{2l_{1,fur}} (T_{2,fur}^s - T_{1,fur}^s). \quad (4.12)$$

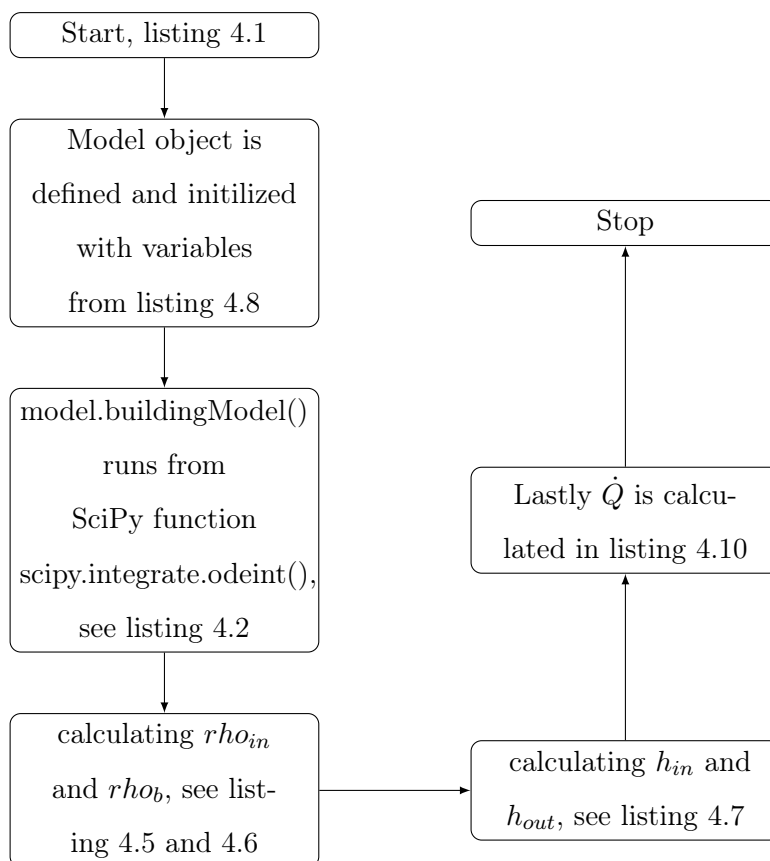
4.2 Algorithm for solving the system of equations

The python script is class-defined. This means we first create an object of the model, and all variables are saved within the python object for easy access and storage. The script that runs a simulation of our model is:

```
1
2 from scipy.integrate import odeint
3
4 K = 273.15 # kelvin
5 dt = 60*60 % # 1 hour
6 simTime = 23*dt #simulation time
7 tolerance = 1e-7 #odeint tolerance
8
9 tSimArray=np.arange(0,simTime,5) # timer array, one point per 5th second
10
11 y0 = 19+K # initlai indoor temperature
12 Toutside = -2.2 + K #-2.2 +K
13 model = model(Toutside ,dt = dt ,simTime=simTime) # create an object of model class
14 sol = odeint(model.buildingModel, y0, tSimArray, args=(False, False, False, False ), rtol=tolerance , atol=...
    tolerance) # use odeint on model.buildingModel to start simulation
```

Listing 4.1: Python script that runs the simulation of Arkivenes Hus

It listing 4.1 we see how our model object gets instantiated and with the help of *odeint* the simulation starts. Below now is a simple flow chart representing what happens in the *buildingmodel* method, which is the method required to calculate the indoor temperature.



Listing 4.2 shows an implementation of equation (4.1), the first ODE to be solved.

```

1  def buildingModel(self, Tb, t, varyingOutdoorTemp=False, varyingPeople=False, varyingQheater=False . . .
2  , varyingFlow=False, solar=False, percentOfWindow=1):
3      self.Tb = Tb
4
5      if varyingFlow:
6          flowIndex = self.QflowDataArray['time'].sub(t).abs().idxmin()
7          self.vIn = self.QflowDataArray["value"].loc[flowIndex]/ (self.Afloor)
8          self.vOut = self.vIn
9          if self.vIn == 0:
10             self.vOut = self.vIn = 0.7 / self.Afloor
11
12         self.varyingQheater = varyingQheater
13         rhoIn = self.rhoInFunc(self.Toutside)
14         self.rhoIn = rhoIn
15         rhoB = rhoRelative(self.Tb)
16         self.rhoB = rhoB
17         self.hIn, self.hOut = self.h_Air()
18
19         kelvin = 273.15
20
21         self.heaterControl(18.7+kelvin, t)
22         self.heaterOnOffLst.append([t, self.Qheater])
23
24         # Solar
25         if solar:
26             if t >= 10*self.dt and t <= 14*self.dt:
27                 self.Qsolar = 100 * self.Awindow*percentOfWindow
28             else:
29                 self.Qsolar = 0
30
31         # Varying Outside temperature
32         if varyingOutdoorTemp:
33             outdoorIndex = self.OutsideDataArray['time'].sub(t).abs().idxmin()
34             self.Toutside = self.OutsideDataArray["value"].loc[outdoorIndex]
35             self.ToutLst.append([t, self.Toutside])
36         if varyingPeople:
37             peopleIndex = self.peopleDataArray['time'].sub(t).abs().idxmin()
38             self.Qpeople = self.peopleDataArray["value"].loc[peopleIndex]*80
39             self.QpeopleList.append([t, self.Qpeople])
40
41         self.PowerList.append([t, self.Qheater])
42         self.FlowList.append([t, self.vIn])
43
44         # Update Q factor
45         self.Qdot(self.Tb, t)
46
47         dydt=self.dTbdt()
48         return dydt

```

Listing 4.2: Building model method

Some parts of the equations above should be mentioned. The implementation of the surface temperature can be seen in equation (4.13). Below we can also see the code snippet(4.4) on how the wall equations have been implemented in Python.

$$T_{i+1}^s = \frac{\frac{k_i}{l_i}T_i + \frac{k_{i+1}}{l_{i+1}}T_{i+1}}{\frac{k_i}{l_i} + \frac{k_{i+1}}{l_{i+1}}}. \quad (4.13)$$

```

1  def surfaceTemp(ki, ki2, li, li2, Ti, Ti2):
2      return ((ki/li)*Ti + (ki2/li2)*Ti2) / ((ki/li) + (ki2/li2))

```

Listing 4.3: Implementation of equation (4.13)

The internal functions are the boundary equations for the walls. Here they are been solved by an *fsolve* function, a function from the *scipy.optimize* library. The ODE's are computed at the bottom as *rh1 to 4*, meaning right-hand side 1-4. Lastly, the $\dot{Q}_{loss,wall}$ factor is computed from the indoors temperature T_b and the first surface area T_1^s . All temperatures have been given an initial value of 20 °C. Variables a1 to a4, l1 to l4 and K1 to K4 are all values from table 5.2. Here the values from other boundaries are mentioned as well.

```

1
2 def Qloss_walls(self, X, t, A, Tb, hb, Toutside=-2.2+273.15, fsolveTol = 0.01):
3     T1, T2, T3, T4 = X # temperatures of wall layers
4
5     hInf = 1
6     # Constants
7     a1, a2, a3, a4 = [1.7e-7, 1.4e-6, 2.25e-2, 1.7e-7]
8
9     l1, l2, l3, l4 = [6e-3, 75e-3, 8.5e-3, 8.5e-3]
10
11    K1, K2, K3, K4 = [0.14, 0.038, 0.026, 0.14]
12
13    def surfaceTemp(ki, ki2, li, li2, Ti, Ti2):
14        return ((ki/li)*Ti + (ki2/li2)*Ti2) / ((ki/li) + (ki2/li2))
15
16    # averages of the layer temperatures:
17    T2_s = surfaceTemp(K1, K2, l1, l2, T1, T2)
18    T3_s = surfaceTemp(K2, K3, l2, l3, T2, T3)
19    T4_s = surfaceTemp(K3, K4, l3, l4, T3, T4)
20
21    # Find temperatures of internal and external boundaries:
22    def internalEquation(T_surface):
23        return hb*(Tb-T_surface) - 0.5*K1*(T_surface-T2_s) / l1
24
25    def externalEquation(T_surface):
26        sigma = sp.constants.Stefan_Boltzmann
27        eps = 0.8
28        return hInf*A*(T_surface-Toutside) +
29        sigma*eps*(T_surface**4 - Toutside**4)
30        - 0.5*K4*A*(T4_s - T_surface)/l4
31
32    T1_s = fsolve(internalEquation, T2_s, xtol=fsolveTol)
33    T5_s = fsolve(externalEquation, T4_s, xtol=fsolveTol)
34
35    # Differential equations for wall layers:
36    rhs1 = a1*(T2_s - 2*T1 + T1_s)/l1**2
37    rhs2 = a2*(T3_s - 2*T2 + T2_s)/l2**2
38    rhs3 = a3*(T4_s - 2*T3 + T3_s)/l3**2
39    rhs4 = a4*(T5_s - 2*T4 + T4_s)/l4**2
40
41    # Calculate Qloss
42    model.qlossWalls = hb*A*(Tb-T1_s[-1]) #
43
44    return [rhs1, rhs2, rhs3, rhs4]

```

Listing 4.4: Walls heat loss

4.2.1 Code snippets

The ODE (4.1) has several parameters that change depending on the temperature. ρ_{in} is defined as a relationship between the relative outside humidity and the ideal gas law, this has been implemented in listing 4.5.

```
1 def rhoInFunc(self, Toutside, RH_out=0.77, P=101325):
2     #Coefficients to determine the saturation vapor pressure of water
3     p1=5.2623e-09
4     p2=-6.3323e-06
5     p3=0.003072
6     p4=-0.75032
7     p5=92.195
8     p6=-4556.2
9     p7=91.59
10
11     Psat = p1*pow(Toutside,6) + p2*pow(Toutside,5) + p3*pow(Toutside,4) + p4*pow(Toutside,3) + p5*pow(...
12     Toutside,2) + p6*Toutside + p7
13
14     PH2O = RH_out*Psat           # [Pa] Vapor presure of water at considering temperature and ...
15     pressure
16     f_H2O_in = PH2O/P           # [moles of water vapor/moles of moist air] Molar fraction of water ...
17     vapor in
18     self.f_H2O_in = f_H2O_in
19
20     M_in = self.M_air*(1-f_H2O_in) + self.M_H2O*f_H2O_in     # [kg/mol] Molar mass of incoming moist ...
21     air
22     Rho_in = P*M_in/(self.R*Toutside) # [kg/m3] Density of inlet air
23
24     return Rho_in
```

Listing 4.5: Density of air going into building

and ρ_b is easily defined by a relation with density at 25 °C and 1 atm. viewed in listings 4.6

```
1 def rhoRelative(T, rho0=1.1839, T0=298.15):
2     """Returns the density of given T
3
4     Args:
5         rho0 (float): density of air at latm
6         T0 (float): 25 degree celc
7         T (float): input temperature
8
9     Returns:
10         float: density of input temperature
11     """
12     return (rho0*T0) / T
```

Listing 4.6: Relative density function.

The specific enthalpy of incoming and outgoing airflow requires some calculations and common values.

```

1 def h_Air(self):
2     """ Return specific enthalpy of incoming air
3     """
4     self.xi=self.f_H2O_in*self.M_H2O/(1-self.f_H2O_in)/self.M_air
5     h_dryair=self.Cp_dryair*self.Toutside
6     h_H2O=self.Cp_H2O*self.Toutside+self.h_fg
7     h_air_in=h_dryair+self.xi*h_H2O
8
9     xo=self.vIn*self.rhoIn*self.xi/(self.vOut*self.rhoB)
10
11     h_air_out=self.Cp_dryair*self.Tb+xo*(self.Cp_H2O*self.Tb+self.h_fg)
12     self.Cp_air=self.Cp_dryair+self.Cp_H2O*xo
13
14     f_H2O_out = (xo/self.M_H2O)/(xo/self.M_H2O+(1-xo)/self.M_air)
15     M_out = self.M_air*(1-f_H2O_out) + self.M_H2O*f_H2O_out
16     self.Mb = M_out
17
18     return h_air_in, h_air_out

```

Listing 4.7: Specific enthalpy of ventilation air

Code snippet 4.5, 4.6 and 4.7 is been inspired by the github script from same author as the article [16, 15].

```

1
2 class model:
3     # Global/Static variable
4     qlossWalls = 0
5     QlossRoof = 0
6     QlossFloor = 0
7     Qlossfur = 0
8     def __init__(self, Toutside, peopleCount=1, airflow=0.7, dt=1, simTime=100, initBoundryTemp...
9         =20+273.15, OutsideDataArray=None, peopleDataArray=None, QheaterDataArray=None, QflowDataArray=...
10        None ):
11
12        # Time constants
13        self.dt = dt
14        self.deltaH = 1/self.dt
15        self.simulationTime = 0
16        self.simTimeEnd = simTime
17
18        # Building dimentions
19        self.l = 3.65 # building length [m]
20        self.w = 4 # building width [m]
21        self.h = 3.3 # building height [m]
22
23        self.Vb = 47267 # self.l*self.h*self.w
24
25        # Other variables
26        self.cPB = 1.005e3 # J/kg Specific heat capacity of moist air inside building
27        self.R = 8.314472 # Pa m^3/ mol K Gas constant
28        self.M_air = 28.97e-3 # [kg/mol] Molar mass of dry air
29        self.M_H2O = 18e-3 # [kg/mol] Molar mass of water
30        self.eta = 0.7
31        self.Cp_dryair=1006
32        self.Cp_H2O=1840
33        self.h_fg = 2260000
34        self.Toutside = Toutside
35
36        # Areas
37        self.Awindow = 1996 # NOTE: Combined with Adoor! 1.2 # [m^2] Area of window
38        self.Adoor = 1996 # 0.75*2.1 # [m^2] Area of door
39        self.Awalls = 3486 #2*(self.l+self.w)*self.h - (self.Awindow+self.Adoor) # [m^2] Area of walls
40        self.AwallsBase = 1878 # [m^2] Area of walls
41        self.Aroof = 3090 # self.l*self.w # [m^2] Area of roof

```

```

40     self.Afloor = 2269 # self.l*self.w # [m^2] Area of floor
41
42     # Ventilation
43     self.vIn = 1375 / (self.Afloor) # (airflow)/(3600*(self.Afloor)) #(self.l*self.w)
44     self.vOut = self.vIn
45
46     # Overall heat transfer coefficients
47     self.Uwindow = 0 # NOTE: Combined with Adoor! 1.2 # [W/m^2K] Heat transfer coeff of window
48     self.Udoor = 0.8 #1.2 # [W/m^2K] Heat transfer coeff of door
49     self.Uwalls = 0.17# 0.18 # [W/m^2K] Heat transfer coeff of walls
50     self.UwallsBase = 0.15# [W/m^2K] Heat transfer coeff of walls
51     self.Uroof = 0.13 # [W/m^2K] Heat transfer coeff of roof
52     self.Ufloor = 0.18 # 0.15 # [W/m^2K] Heat transfer coeff of floor
53
54     init_Temp = initBoundaryTemp
55     self.TwallInit = [init_Temp,init_Temp,init_Temp,init_Temp]
56     self.TroofInit = [init_Temp,init_Temp,init_Temp,init_Temp]
57     self.TfloorInit = [init_Temp,init_Temp,init_Temp]
58     self.TfurInit = [init_Temp]
59
60     self.lastTime = 0
61     self.Qwalls = 0
62     self.TempwallsLst = []
63     self.Qroof = 0
64     self.TemproofLst = []
65     self.Qfloor = 0
66     self.TempfloorLst = []
67     self.Qfur = 0
68     self.TempfurLst = []
69
70     # Q gain factors
71     self.Qheater = 0
72     self.Qpeople = 0
73     self.Qappliances = 150
74     self.Qsolar = 0
75
76     # Test values
77     self.ToutLst = list()
78     #self.ToutLst.append([0, self.Toutside])
79     self.QpeopleList = list()
80     self.PowerList = list()
81     self.FlowList = list()
82     self.timer = 6
83
84     self.heaterOnOffLst = []
85
86     # More people values
87     self.peopleCount = peopleCount
88
89     # NORCE data
90     self.OutsideDataArray = OutsideDataArray
91     self.peopleDataArray = peopleDataArray
92     self.QheaterDataArray = QheaterDataArray
93     self.QflowDataArray = QflowDataArray

```

Listing 4.8: Beginning of the class script and the constructor with the defined values

When everything is implemented, we can get to work on the building model method. Seen in listing 4.2. Here all methods are initialized and is rewritten with the correct temperature (T_b) for each iteration of the *scipy.integrate.odeint*.

From the documentation, the function to be solved with the *odeint* solver needs the input variable(T_b) and a time array(t). If the function to be solved needs other variables, they must be added as a set after the two mandatory parameters.

```

1  def dTbdt(self):
2      """Returns tempature of the room
3
4      """
5      #ventilation = (self.vIn*self.rhoIn*self.hIn - self.vOut*self.rhoB*self.hOut)
6      deltaRhoB = (self.vIn*self.rhoIn - self.vOut*self.rhoB) / self.Vb
7
8      firstPart = (self.vIn*self.rhoIn*self.hIn - self.vOut*self.rhoB*self.hOut + self.Q) / (self.Vb...
9      *self.rhoB*(self.Cp_air-(self.R/self.Mb))) - (self.Tb/self.rhoB)*deltaRhoB
10
11     #secondPart = (self.Tb/self.rhoB)*deltaRhoB
12     return firstPart

```

Listing 4.9: Indoor temperature calculations, equation (4.1)

```

1  def Qdot(self, Tb, time):
2      """Returns heat loss and gain of all elements on specific room temperature.
3
4      Args:
5          Tb (float): Room temperature at a given time
6      """
7      # Heat loss
8      self.Qwindow = QLossFunc(self.Uwindow, self.Awindow, Tb, self.Toutside) # W,
9      self.Qdoor = QLossFunc(self.Udoor, self.Adoor, Tb, self.Toutside) # W
10     self.Qwalls = QLossFunc(self.Uwalls, self.Awalls, Tb, self.Toutside) # W
11     self.QwallBase = QLossFunc(self.UwallsBase, self.AwallsBase, Tb, self.Toutside) # W
12     self.Qfloor = QLossFunc(self.Ufloor, self.Afloor, Tb, self.Toutside) # W
13     self.Qroof = QLossFunc(self.Uroof, self.Aroof, Tb, self.Toutside) # W
14
15     self.Qloss = self.Qwindow + self.Qdoor + self.Qwalls + self.QwallBase + self.Qroof + self....
16     Qfloor
17     self.lastTime = time
18
19     self.Qgain = self.Qheater + self.Qpeople + self.Qappliances + self.Qsolar
20     self.Q = self.Qgain - self.Qloss

```

Listing 4.10: Method for calculating heat transfer of building

The model has more implementations than the code snippets presented in this chapter. However, this is only for one of the simulations. The different simulations can be seen in the personal GitHub repository[18] or appendix B.

Chapter 5

Model results

5.1 Testing

As mentioned, physical systems can often be very complex. This complexity necessitates the use of numerical methods to help us solve the systems. With the almost unlimited power of the computer today, these methods can provide tools to help us analyze and simulate these kinds of systems that were not possible without these methods. However, the available computational power will be useless unless the model variables are appropriately defined, and the model is thoroughly tested. This means we need to validate our numerical model since an invalid model is going to lead to erroneous results.[1, p 16].

We will be testing our model with a scenario where the heater is turned on for 50 hours and turned off for the next 50 hours. This is to test the different equations presented in last chapter and to check if they are working as intended.

5.1.1 Analytical results

A valuable tool to verify the behaviour of a numerical solution of a mathematical problem is to solve it *analytically*. If all variables in the numerical and analytical solution are the same, the results from both should stay the same [1, p 314]. Here we present the analytical solution and compare it to the numerical solution of equation (3.11). However, first, we compute the heat gain/loss term in a different way than in the full model:

$$\dot{Q} = \dot{Q}_{supply} - \dot{Q}_{loss} \quad (5.1)$$

where \dot{Q}_{supply} is (3.13) and \dot{Q}_{loss} is (3.20). Because the heat loss is modeled as a first order equation with T_∞ as the outside temperature and T_b as the indoor air temperature, the loss of heat due to the (element) floor, roof, walls, windows and door can be written as:

$$\dot{Q}_j = U_j A_j (T_b - T_\infty). \quad (5.2)$$

U is the overall heat transfer coefficient, A is the surface area and j represent the element. Because each of the elements have the same variables we can sum them up. The general equation is then:

$$\dot{Q}_{loss} = (T_b - T_\infty) \Sigma_j U_j A_j. \quad (5.3)$$

Equation (4.1) can now be presented like this:

$$\frac{dT_b}{dt} = \kappa_1(t) - \kappa_2 T_b \quad (5.4)$$

$$\kappa_1(t) = \frac{\dot{V}_i \rho_i h_i - \dot{V}_b \rho_b h_b + \dot{Q}_{supply}(t) + T_{outside} \sum_j U_j A_j j}{\rho_b V_b (c_p - \frac{R}{M_b})} \quad (5.5)$$

$$\kappa_2 = \sum_j U_j A_j + \frac{\dot{V}_i \rho_i - \dot{V}_b \rho_b}{\rho_b V_b} \quad (5.6)$$

We then write:

$$T_b \rightarrow \frac{\kappa_1}{\kappa_2} \quad (5.7)$$

Assuming $Q(t)$ is a heater that is either on or off, we can solve the equation analytically with equation (5.8) and (5.9) (depending on the heater is on or off) below.

$$T_b = \frac{1}{\kappa_2} (\kappa_1(0) - \kappa_1(t) - \kappa_2 T_b(0)) e^{-\kappa_2 t}, t < t_f \quad (5.8)$$

$$T_b = \frac{1}{\kappa_2} (\kappa_1(t_f) - \kappa_1(t) - \kappa_2 T_b(t_f)) e^{-\kappa_2 (t-t_f)}, t \geq t_f \quad (5.9)$$

Since the analytical version of our model is of steady-state, more values that would be dynamically changed are set as constants. The analytical equations for creating T_b , equation (5.8) and (5.9), has an value of t_f which controls the break point of the simulation. The analytical simulation requires a steady state temperature at both $t < 50$ hours and $t > 50$ hours. $t_f=50$.

We also has several values which is needed to be set as constant. The values in question is in the next table:

Parameter	Value ($t_f = 0$)	Value ($t_f = 50$)
\dot{V}_i & \dot{V}_b [$\frac{m^3}{s}$ per m^2]	0.7	0.7
ρ_i & ρ_b [$\frac{kg}{m^3}$]	1.1041	1.1041
h_i [$\frac{J}{kg}$]	60179.47996	61173.08
h_b [$\frac{J}{kg}$]	60587.96	60587.96
$c_{p,b}$ [$\frac{J}{kg \cdot K}$]	1005	1005
R [$\frac{Pa \cdot m^3}{mol \cdot K}$]	8.314472	8.314472
M_b [$\frac{kg}{mol}$]	0.02897	0.02897
\dot{Q}_{supply} [W]	1000	0
$T_{outside}$ [K]	270.95	270.95
V_b [m^3]	48.18	48.18

Table 5.1: Constant used when calculating analytical results

With the help of these functions and the *kappa* variables, we can solve our model analytically. In figure 5.1 we have the result of the analytical equations. Here the analytical solution is split into two parts. First, the part where $\dot{Q}_{supply}(t)$ has a value of 1000(W) to represent a heater turned on, and the second part where the heater is off ($\dot{Q}_{supply}(t) = 0$).

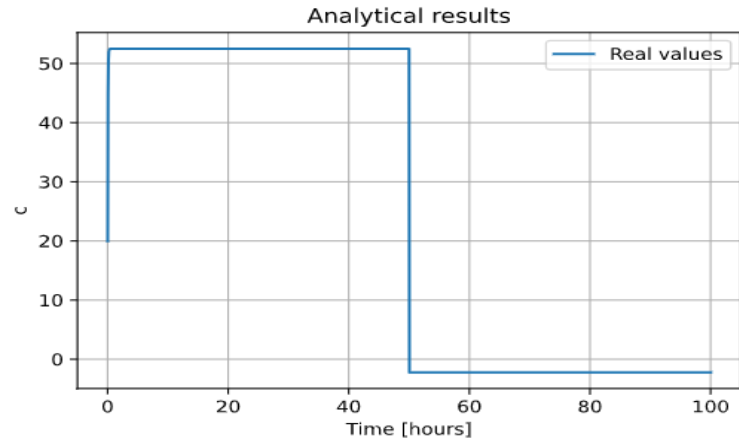


Figure 5.1: Analytical result

Here we can see in figure 5.1. The results rises quickly over 50°C and after 50 hours, we can see how it travels to -2.2°C . The analytical results are working as intended.

5.1.2 Numerical test solution

From chapter 3.1.3 we have the \dot{Q} equation. The \dot{Q}_{heater} will be used to test the adaptation of the model. The simulated scenario will first be by simulating the heater with a power of 1000W, and after 50 hours, the heater is off $\dot{Q}_{heater} = 0$. We should see a change in the temperature and a drop after 50 hours to verify the same results shown from the analytical results in figure 5.1.

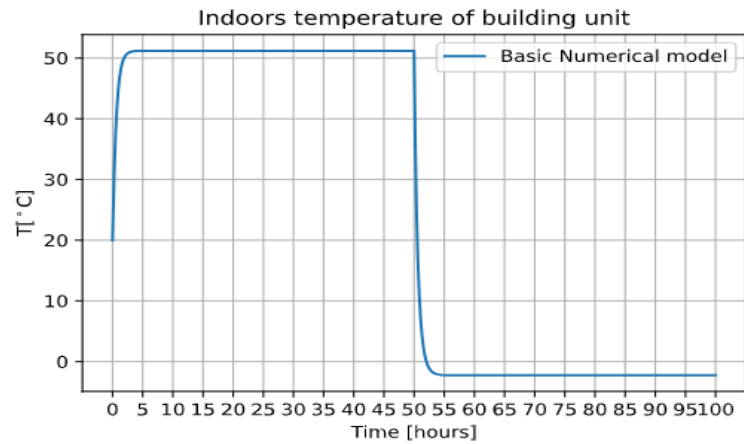


Figure 5.2: Numerical plot result with on/off heater

Looking at the results displayed in the figure 5.2 we can see the temperature rising fast towards 51°C , and after 50 hours, the temperature is decreasing. The temperature is stopping at approximately -2.2°C , which makes sense since this is the outdoor temperature of the simulation.

5.1.3 Analyzing numerical versus the analytical result

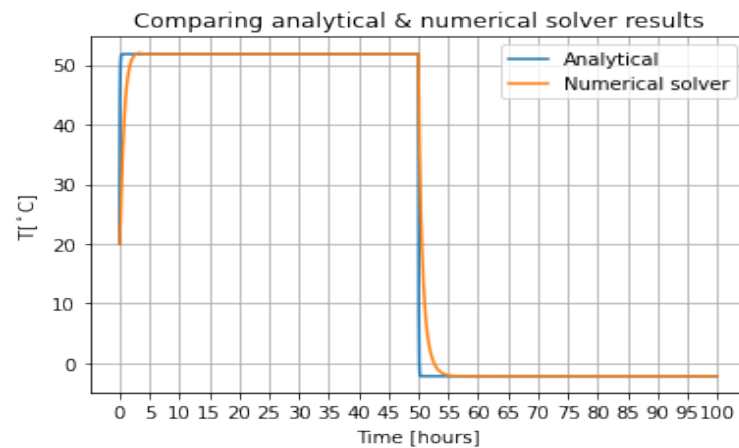


Figure 5.3: Analytical vs Numerical plot result with on/off heater

When comparing the results from the analytical and the numerical solution, we can see some similarities, seen in figure 5.3. We can compare some of them in the list below.

- We can see the numerical solution has more of a curve; this can be since, for each step, the different values that are dependent on a temperature are changing depending on temperature and time.
- The analytical temperature reaches a higher temperature than the numerical. However, this is a predefined value.
- Both reaches the outside temperature of $-2.2\text{ }^{\circ}\text{C}$ quickly after the heater is off.

5.1.4 Comparing numerical model with article

Since the first task of this thesis is to reproduce the results given in the article: “Modelling the heat dynamics of a residential building unit: Application to Norwegian buildings”[16], we can compare the result with our numerical solution.

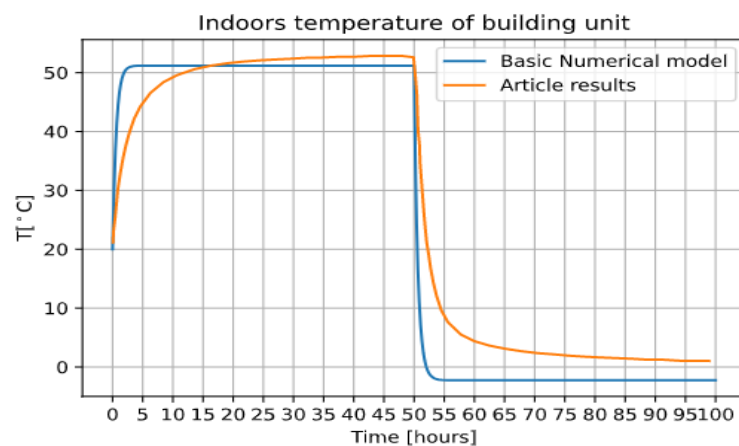


Figure 5.4: Numerical Results vs Article[16] results

(Worth noting the results from the article (Case 1[16]) were created with [WebPlotDigitizer](#). Thus the data might not be accurate)

Comparing the results, we see a more dynamically changing graph than our own. How come the article has a more natural curve than ours? Some assumptions are made in the bullet point list below:

- Some variables on the numerical solution are simplified. No explanation was provided by the article on how these were computed from their result.
- Our model is ignoring the furniture due to the explanation of its implementation is limited.

5.1.5 Expanding the model

To test the hypothesis from the last chapter, we can implement the equations that explain the temperature reaction inside the walls, roof, and floor layers. The equations which has been implemented is equation (3.28) to equation (3.35). The layer inside the building's walls, roof, and the floor has different material properties. These can be found in table 5.2 from "[16]".

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	0.38	
$\alpha_{i,w}$	$[m^2/s]$	1.7×10^{-7}	1.4×10^{-6}	2.25×10^{-2}	1.7×10^{-7}
$\alpha_{i,r}$	$[m^2/s]$	1.7×10^{-7}	1.4×10^{-6}	1.8×10^{-7}	4×10^{-7}
$\alpha_{i,f}$	$[m^2/s]$	4×10^{-7}	1.7×10^{-7}	1.4×10^{-6}	
$l_{i,w}$	[m]	6×10^{-3}	75×10^{-3}	8.5×10^{-3}	8.5×10^{-3}
$l_{i,r}$	[m]	6×10^{-3}	100×10^{-3}	11×10^{-3}	6.5×10^{-4}
$l_{i,f}$	[m]	1×10^{-3}	9×10^{-3}	75×10^{-3}	
$\rho_{i,f}$	$[kg/m^3]$	55	615	32	
$c_{p,f}$	$[J/kgK]$	1210	1317	835	

Table 5.2: Coefficients for walls, floor and roof

The heat transfer coefficients needed is written in table 5.3.

Table 5.3: Heat transfer coefficients $[W/(m^2K)]$

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

The plot of figure 5.5 shows the results compared to the basic model in the previous chapter.

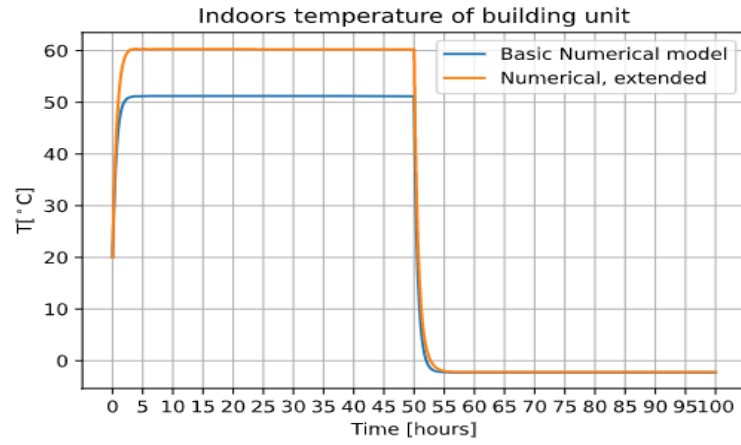


Figure 5.5: Numerical result, basic model vs Extended heat loss functions

Here we can see a higher temperature on the extended model. Almost 10 degrees higher. What is happening?

5.1.6 Adding furniture

Another factor that can have a difference in how the model data is created can be the furniture. By implementing the dynamics of the furniture as explained in the article[16], we can see if the model has a different result. The equation that needs to be implemented are (3.30) and (3.40). As written in chapter (3.1.3), the furniture can be seen as a heat sink and will "steal" temperature from the room when cold and prevent the room from cooling down as fast when the heater is off. This means the temperature should be lower since the furniture also needs to be heated up.

As the other boundaries, the furniture also needs a set of coefficients. These are represented in table 5.4 and the $h_{b, fur} = 2$ needed in equation (3.40)

Parameter		Layer 1
$K_{i, fur}$	$[W/(mK)]$	2
$\alpha_{i, fur}$	$[m^2/s]$	1.8×10^{-7}

Table 5.4: Coefficients for the furniture

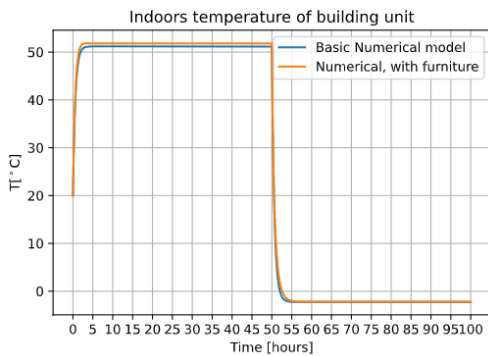


Figure 5.6: Expanded model with furniture heat loss

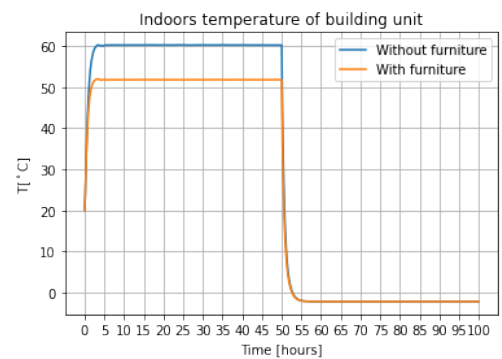


Figure 5.7: Comparing temperature with furniture and without

Comparing the results with figure 5.5 we can see the furniture has driven the max temperature of the room down(5.7), making it more like the basic model, which does not have the furniture heat loss implemented. However, as seen, the furniture did not alter the timing of the temperature, meaning the furniture was not the reason why the simulation behaves differently from the article.

5.1.7 Discussion

Although the curve in our temperature results does not line up with the article[16], we can compare with the analytical and see it is working as intended. It shows how the air temperature heats the room until the temperature difference between inside and outside is big enough that the heaters power is not enough to increase the air temperature inside. This can be seen in the case with the more complex boundary heat loss functions as well.

We are satisfied that our results are very similar to the results present in the paper. There are some discrepancies, they could be due to slightly different values used in our model and/or misprint in the journal paper.

5.2 Simulation of working build unit

After a sensitivity analysis of our model, we can further test our model for a "normal day" simulation. The simulation would mimic a typical day when a person is asleep, at home, or at work. Such a simulation aims to see how our model behaves if implemented into a system regulating the temperature of a house.

The simulation will be using three defined states, two states where the house is in use (person either *asleep* or *home*) and one where it is not in use (person *at work*).

The simulation values are based on demands by the Norwegian Building Acts and Regulations technical requirements (TEK10) [8].

TEK10 [8] mentions some demands for the airflow. Fresh airflow rate should be at a minimum of $1.2 \text{ m}^3/\text{h}$ each m^2 of floor space while the building is being used (at home), a flow rate of $0.7 \text{ m}^3/\text{h}$ per m^2 of floor space when not been used (at work) and they have a special requirement for bedrooms. The airflow rate should be a minimum of $26 \text{ m}^3/\text{h}$ per bed when used (asleep). Lack of air can give rise to a health problem. However, too much air flow rate is energy waste.

- From 23:00 until 6:40, the person is asleep
- From 6:30 until 8:00, the person is home
- From 8:00 until 16:00, the person is at work
- From 16:00 until 23:00 the person is home

Here *set temperatures* are also introduced to our model. These are temperatures *set* to specific values for when the building is in use or not. The *set temperature* can be viewed as a temperature control parameter.

When the person is at home (and not sleeping), the set temperature is 20°C , a temperature seen as a comfortable living temperature. When the person is away/sleeping, the set temperature is 15°C , a temperature of the air that is a little too low to be comfortable. However, it is more energy-efficient, and the building does not need to be set to a comfortable temperature when not in use. Thus, saving energy.

The appliances are always assumed to be on, $\dot{Q}_{\text{appliances}} = 150\text{W}$ (3.13). The appliances are constantly adding heat to the air. The persons' body is assumed to have a value of 80W ($\dot{Q}_{\text{People}} = 80$) (3.13) emitting throughout the room, as the human average heat release is assumed to be $58.2 \frac{\text{W}}{\text{m}^2}$ [5]. Meanwhile, from 10:00 to 14:00, some solar energy is emitted through the room at a rate of $100 \frac{\text{W}}{\text{m}^2}$ [12]. The area of the windows is 1.2m^2 the Q_{solar} (3.13) is assumed to be 120W .

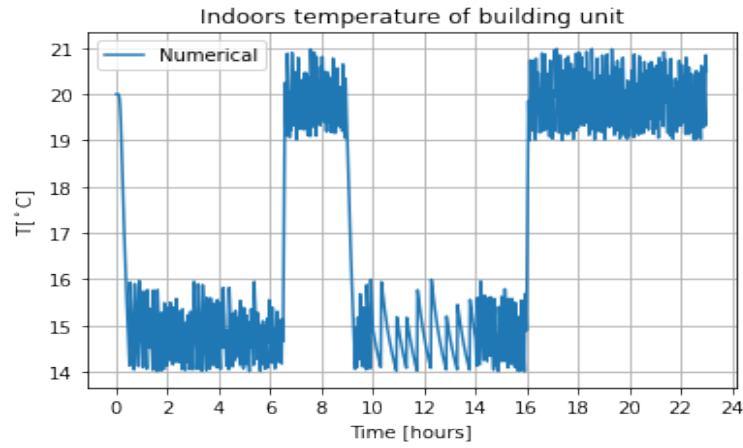


Figure 5.8: Daily life scenario

Comparing the numerical result with the article, we can see that the model is working as intended. The on/off heater is working and is not deviating from the set point temperature by more than one degree.

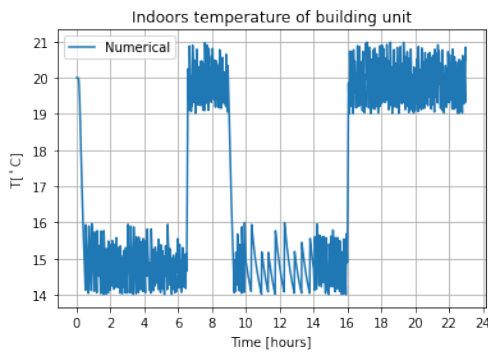


Figure 5.9: Numerical Result

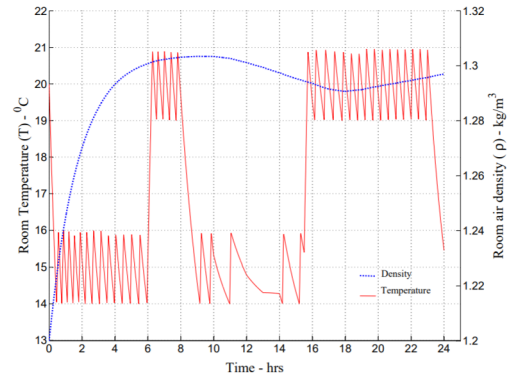


Figure 5.10: Case 2 from article[16]

By comparing the result with case 2 in the article[16], we can see the similarities. This model has a faster increase and decrease than the article. However, this is expected since every result has responded as such. We can also see the similarity of what happens when the sun hits the window. The heater is not working at the same interval due to the sunlight.

5.3 Sensitivity Analysis a working build unit

A sensitivity analysis of the model is necessary when trying to understand the model behavior. This paper will implement several scenarios to see how the temperature of the building unit is reacting to these scenarios. This can also help with understanding the concept of a dynamic heating model. As an example, by testing the model on physical temperature limits (world's coldest day?), we can see if the data the model produces can be trusted.

The next part features many simulations that were different modifications of our model. However, no values on our model have been altered further than the one mention. The different scenarios to test our model's behavior have been listed below in the bullet list.

- Changing outdoors temperature
- A high outdoors temperature

- A very sunny day
- More than one person inside
- Different ventilation speeds

5.3.1 Changing outdoor temperature

When simulating how air temperature inside a building unit behaves throughout 24 hours, the air temperature outside fluctuates constantly, meaning a constant outdoor temperature does not make sense. A scenario where the outdoors temperature is increasing and decreasing is necessary to simulate a more typical day kind of scenario. In this simulation, the outdoor temperature (T_∞) increases slightly during the first hours of the morning before increasing more rapidly throughout the day until 14:00, when the temperature has reached its highest point. Afterward, the outside temperature is decreasing until midnight at the end of the simulation.

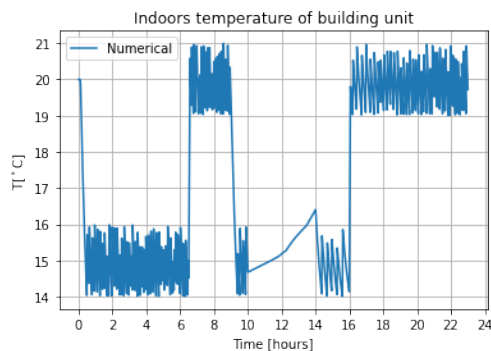


Figure 5.11:

Indoor temperature with regulating T_∞

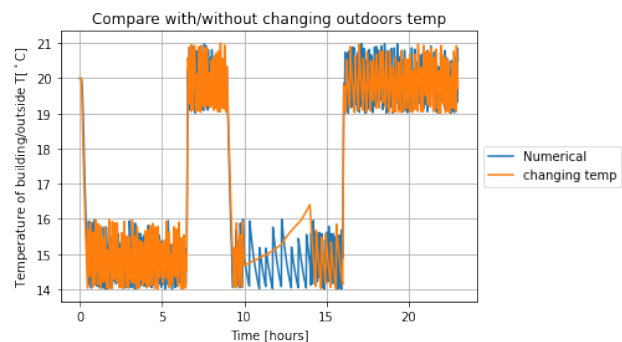


Figure 5.12:

Regulating versus constant T_∞

The result of this simulation is seen in figure 5.11. By comparing the result with the fixed outdoor temperature, we cannot see much of a difference, just a spike around 14:00, the warmest time of the day. We can also compare the outdoor temperature with the indoor temperature in a single figure.

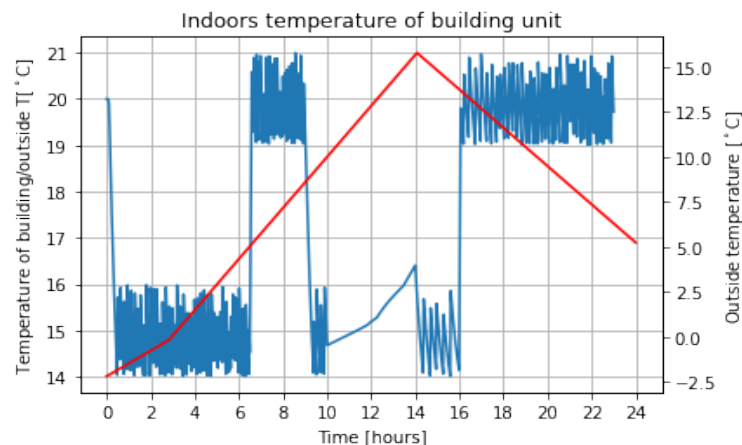


Figure 5.13: Daily life scenario compared to the changing outside temperature

Figure 5.13 shows how the temperature outside grows towards 15 °C at 14:00 and decreases afterward until the end of the simulation. At 14:00, we can see how the temperature grows over the set temperature threshold, and the heater should be off. What is the reason for this temperature spike?

This increase could be because the outdoor temperature is higher than the set temperature of the room (red graph, righty label on figure). This could mean that this model relies on the outside air temperature to be colder than the air inside the room to cool down the building.

To test this theory, we can run a simulation where the outside air temperature does not reach higher than the set temperature of 15°C.

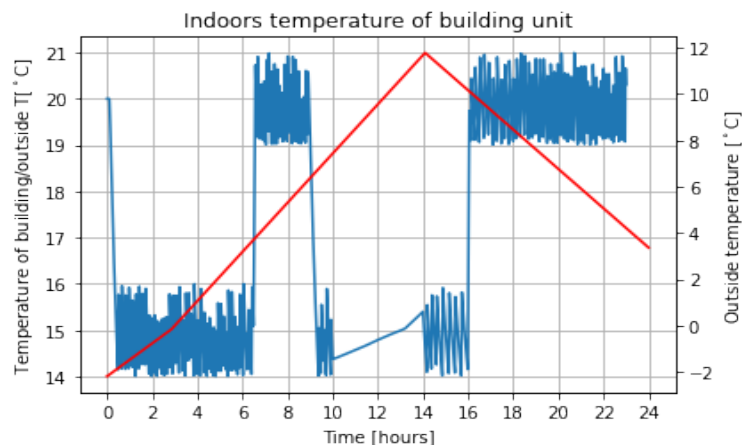


Figure 5.14: Same scenario with colder outdoors temperature

By looking at figure 5.14 we can see the spike on figure 5.13 is gone and the highest outdoor temperature has gone down to 12°C, which is below the set temperature of 15°C. We can thus conclude that the higher outdoors temperature can explain the temperature spike.

5.3.2 Extreme temperature

What happens with the temperature inside the building when the outside has extreme (and unrealistic) temperatures? Can the indoors temperature still sit comfortably at 20 °C even if the outdoors temperature reaches ± 60 °C?

With a new simulation of our model at these temperatures, we can see if the heat generated by a person is substantial or if the ventilation has a considerable effect when trying to keep the temperature constant. We still only change the T_{∞} variable in our model.

High temperature simulations

Three different simulations were conducted when the models outside temperature were set to 60 °C. One with the normal simulation setup as before, one where ventilation were constant and one where the ventilation were constant and with no heat gained from people inside the building.

1. A simulation with the normal parameters, $T_{\infty}=60^{\circ}\text{C}$.
2. A simulation with constant ventilation, $\dot{V}_{in} = \dot{V}_{out}=0.7 \frac{\text{m}^3}{\text{h}}$ per m^2
3. A simulation with constant ventilation and ignoring heat for people, $V_{in} = V_{out} = 0.7 \frac{\text{m}^3}{\text{h}}$ per m^2 , $\dot{Q}_{people} = 0\text{W}$ at all times

Normal simulation

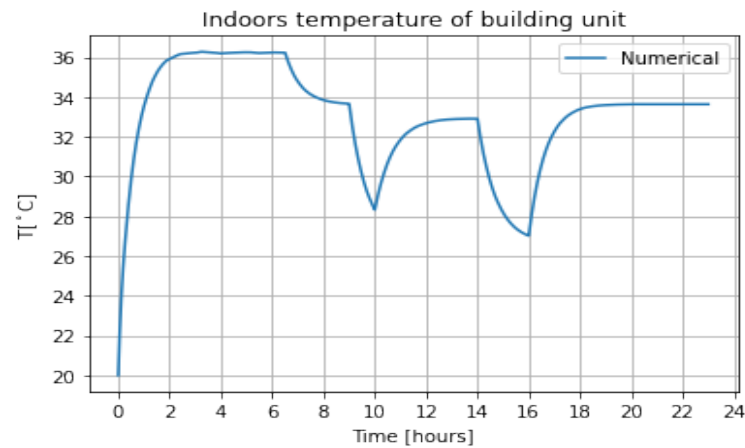


Figure 5.15: Extreme heat temperature outside

When looking at figure 5.15, we can see the building has a hard time keeping the temperature at 15 °C before the person wakes up at 6:30. Afterward, when the ventilation speed increases from 6:30, we can see a drop in the temperature. Afterward, when the person leaves, we can see the temperature dropping further before increasing again because of the sun heating the room through the window. Lastly, the temperature drops again and increases after 16:00 when both the ventilation speed increases and the person comes home.

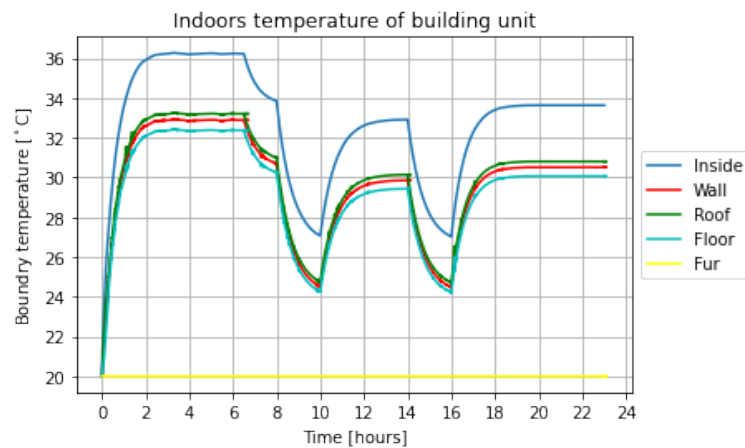


Figure 5.16: Extreme heat outside vs. Boundary temperature

When comparing the indoor temperature with the surface temperature of the boundaries in the building, we can see a similar pattern in the temperature increase and decrease. Which makes sense. However, their furniture temperature seems to be stable, which does not make sense. The reason can be in how its implemented.

Constant ventilation

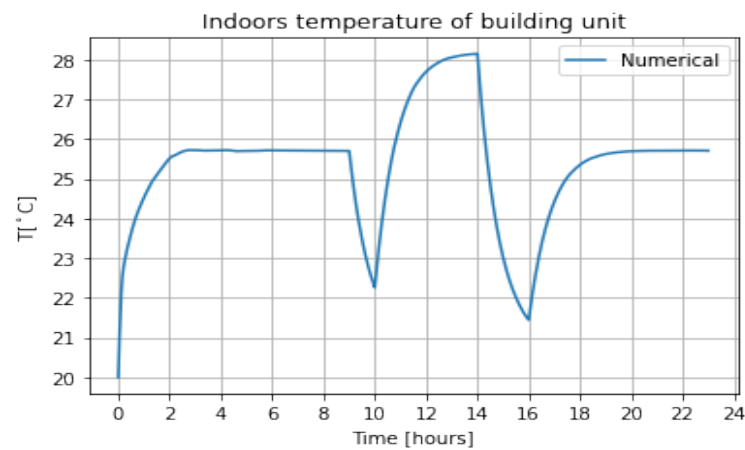


Figure 5.17: Constant ventilation

By not changing the ventilation speed throughout the simulation, we can check if it impacts the results. In figure 5.17 we can see the temperature reaches a constant temperature of 26 °C when the person is at home. Because the airspeed now is at constant $0.7 \frac{m^3}{h}$ per m^2 of floor space, we can also note the decrease of the temperature from 5.15.

Constant ventilation and no heat from people

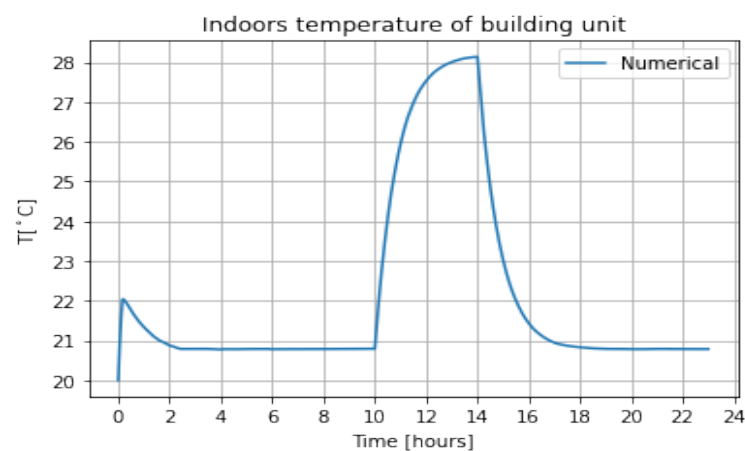


Figure 5.18: Constant ventilation and no heat gain from people

By neglecting the heat produced by people inside the room, as seen in figure 5.18, we can see that the temperature of the room is lower, which makes sense.

Low temperature simulations

At the world coldest temperature, $-89.2\text{ }^{\circ}\text{C}$ [23], we can see how our model behaves when exposed to a shallow temperature. Here we can see the temperature drops reasonably quickly when the building is in *sleep mode* at the start. It gains momentum when the person is awake, and the ventilation speed has a lower speed. The temperature is working as intended when the person is away.

The ventilation causes the result. It has a higher speed at night, as recommended by the official Building Acts and Regulations technical requirements (TEK10) [8] and from 8:00 until 16:00, when the temperature regulation is working as intended, the ventilation speed is at its lowest.

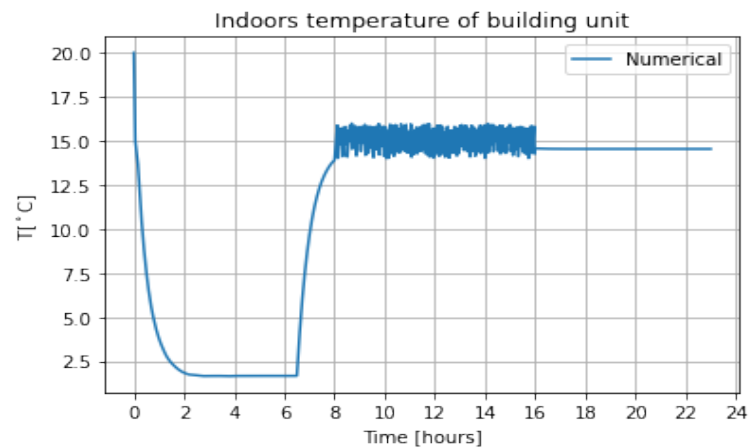


Figure 5.19: Outside temperature of $-89.2\text{ }^{\circ}\text{C}$

By keeping the ventilation at a constant speed ($V_{in} = V_{out} = 0.7\frac{m^3}{h}$ per m^2) we can see the building managed to keep its set temperatures(5.20) even when the outside temperature has an extremely cold value.

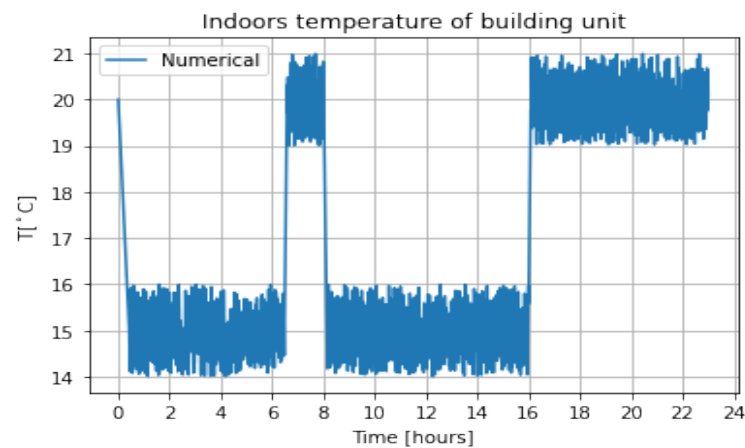


Figure 5.20: Outside temperature of $-89.2\text{ }^{\circ}\text{C}$, with constant ventilation speed

By these results, we can assume the building has pretty good isolation. Also, we can conclude that the ventilation speed has a good impact on the room temperature and that the ventilation speed should be kept at a minimum when the outdoor temperature is shallow. We can also conclude that the building unit's temperature relies on the outside temperature to cool down.

5.3.3 More people

Do more people have a high effect on the comfort temperature? By having four people in the room, we get an (approximately) 240W ($\dot{Q}_{people} = 320W$ total) heat gain extra than with only one person. The extra people were added after 16:00 and stayed until 23:00 to simulate a visit.

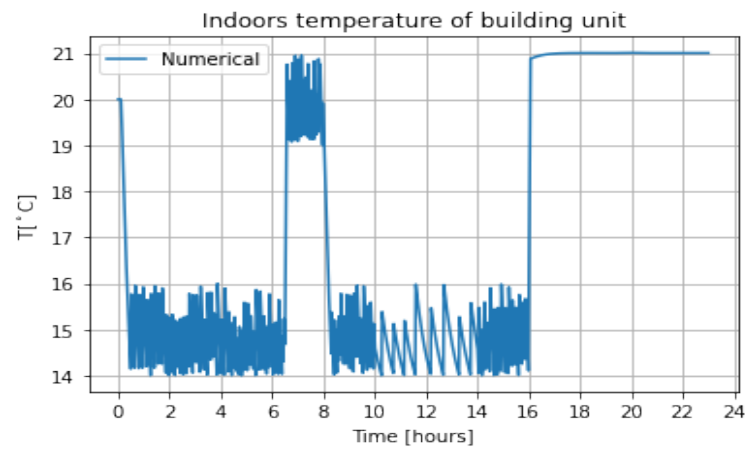


Figure 5.21: 4 people in the room

If we simulate with the same number of people, however, they leave early in this case. What will happen?

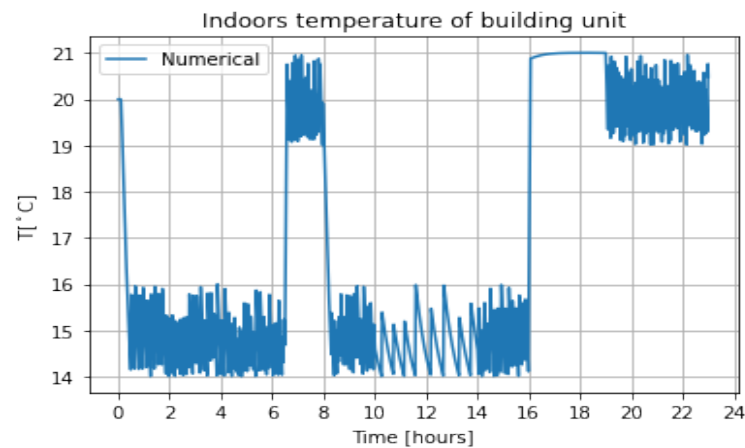


Figure 5.22: 4 people in the room, leave early

As shown in figure 5.22, the temperature starts to work as before. This makes sense since the increased heat gain "has left" and the regular heat from a person ($\dot{Q}_{people} = 80W$) is back to normal.

Looking at both results, we can see that the increase in heat increases the room's temperature. Can ventilation help to prevent the temperature from increasing into a more uncomfortable temperature?

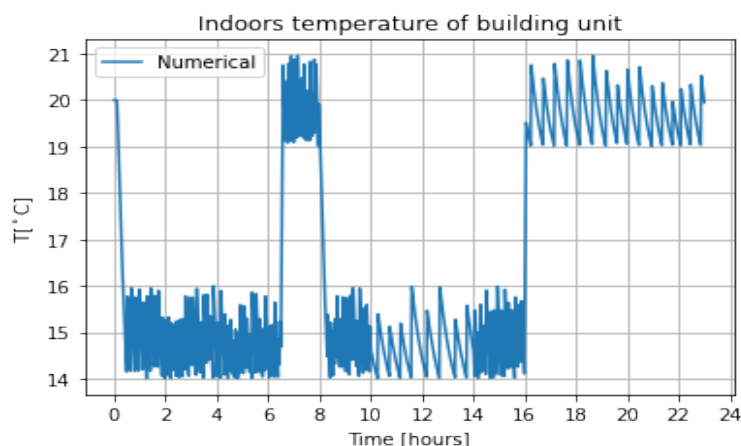


Figure 5.23: 4 people in the room, air speed set to 2

By increasing the airspeed to $2m^3/s$ per m^2 , we can see a how the temperature is regulated like before. As seen in figure 5.23. The data tells us that by regulating the airflow speed by how many people share the same room, the set temperature can be kept at its intended value.

5.3.4 Different air flow scenarios

The last analysis is to see how the model reacts to different airflow rates. By running a simulation where the airflow rate is changed to $9 m^3/s$ per m^2 after 16:00 instead of the standard 1.2 (recommended by TEK10[8]), we can see how the heater reacts.

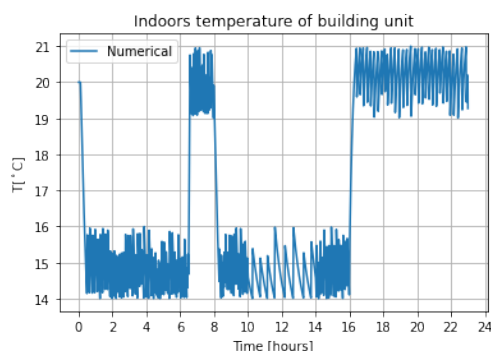


Figure 5.24:
air flow rate of $9m^3/s$ per m^2

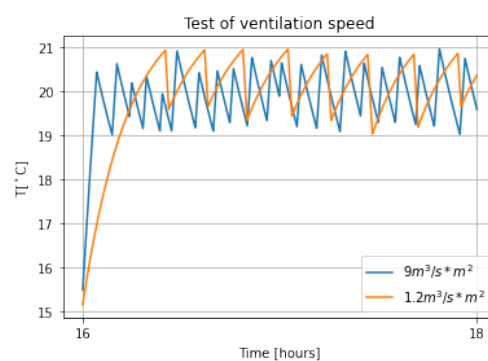


Figure 5.25:
air flow rate of $9m^3/s$ per m^2 Vs
 $1.2m^3/s$ per m^2

Figure 5.25 shows the better comparison of the two ventilation speeds. Here we can see how the faster airflow rate impacts the time the heater has to be turned off to keep the set temperature. This makes sense since the outdoor temperature is set to a constant -2.2°C as of per usual.

5.4 Temperature simulation of Arkivenes Hus

The previous result has focused on reviewing how the model behaves. Either by testing how the air is heating up when introducing heat inside the building or by testing how the building unit copes when given scenarios that might happen in real life.

Our model should also try to replica the behavior of a building by given the correct data input. Previously we have changed variables such as the \dot{Q}_{power} , \dot{Q}_{people} , $\dot{v}_{in}/\dot{v}_{out}$ and T_{∞} to simulate different behaviours of a building unit. By, for example, changing the $\dot{v}_{in}/\dot{v}_{out}$ variables to a higher value to compensate for an increased indoor temperature. We then learned that the building cools down because of the lower temperature outside. Some of these values (like the T_{∞} variables) are fictive data arrays to be changed over the simulation period. However, mostly the values have been changed to a new constant. Now, however, we will be using data from sensors on *Arkivenes hus*.

NORCE has a similar experiment of simulation temperature in the Regional State Archives of Stavanger. *Arkivenes hus*. Here they monitor the power consumed by the building, airflow, occupancy, and different temperatures, to mention a few things. With the help of the data provided by *Arkivenes hus*, we can try to recreate the indoor temperature pattern from *Arkivenes hus*.

To use our model on different buildings, much information about the building in question is necessary. We need to modify our model slightly to adapt it to the new building. Because of how the data, specifically the heat transfer coefficients, were given by *Smi Energi and Miljø AS* (Table 5.5), equation (3.14) to (3.19) were used instead of the more complex boundary equations used previously, presented in chapter 4.1.1. The more complex equations will be inaccurate by not having the necessary variables, like how many layers and their heat transfer coefficients of the layers. All other variables and coefficients are the same as previous adaptations of our model.

All information from *Arkivenes hus* can be viewed in appendix C. Table 5.5 mentions the buildings dimensional values and heat transfer coefficients which are needed to scale our model to its right side.

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 5.5: Area and their heat transfer coefficient

We can see by a simulation done by *Smi Energi and Miljø AS* (appendix C) that the ventilation starts at 6:00. By looking at figure 5.26, we can assume the ventilation stops at approximately 19:00 because of the drop in the flow chart (second chart) (This graph can also be seen in the appendix D). Our temperature is labeled *Extract Temp 2* and will be presented at a later stage. These graph results from *NORCE* have assumed some critical data.

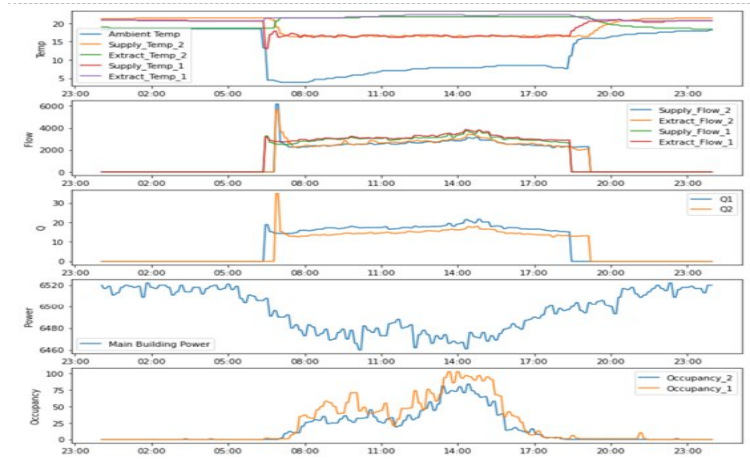


Figure 5.26: Sensor data from NORCE

Before going further with this thesis, one should mention that the data from figure 5.26 shows several temperature results from several sensors. Looking at the first graph of figure *Arkivenes Hus*, we can see five plots. Because of the nature of our model, where our model calculates only one indoor air temperature, *Extract Temp 2* has been picked as the temperature inside *Arkivenes Hus* and the rest is neglected. The same has been determined with the airflow. In the second graph, four different airflow sensors are visualized. This thesis will only focus on the *Extract flow 2* data. In the second figure on figure 5.26, we can see four different data visualized, which compares two different airflow data sets and two different temperatures. *Arkivenes Hus* has two sensors that measure the temperature and airflow. The thesis has assumed that the temperature from *Extract Temp 2* is the temperature for the whole building and that it is thoroughly mixed, as the building unit from previous results. We are assuming a mixing tank simulation. In graph number four in figure 5.26 we can see the power consumed by *Arkivenes Hus*

Important assumptions and information

- All data from *Arkivenes Hus* visualized in this chapter are from the third of March 2021.
- Initial T_{∞} assumption is still -2.2°C .
- The variables for $\dot{V}_{in}/\dot{V}_{out}$ has been changed. The value has been assumed to $1375 \text{ m}^3/\text{s}$ times the area of floor space. A quick average of the measured data on *Arkivenes Hus*.

Worth noting that the simulated data has some flaws. The sensors measures in a 5-second interval. Occasionally the measurement either did not *measure* resulting in a *Nan* value or the timestamp is wrong. When the measured data appears to move *backward*, the reason would then be because the timestamp is not correct. This thesis has not manipulated the data to combat this issue.

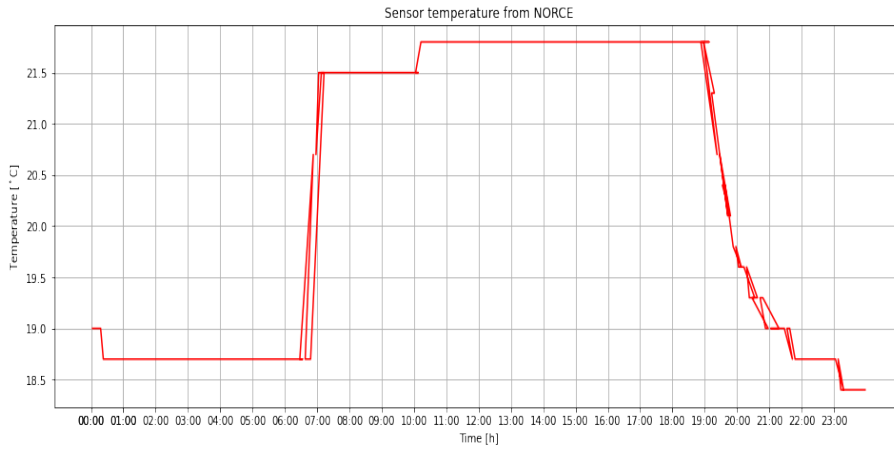


Figure 5.27: Temperature data from sensor (NORCE)

In figure 5.27 the extracted data from *Extract Temp 2* is visualised. The temperature grows when the ventilation is turning on and decreased when the ventilation speed reaches zero. Looking at the figure, we can assume the ventilation is important to temperature control.

To understand the data a little better, we should see if the number of people correlates to the temperature increase or explains the power decrease. In figure 5.28 we can see the visualized data of temperature, occupancy, and power.

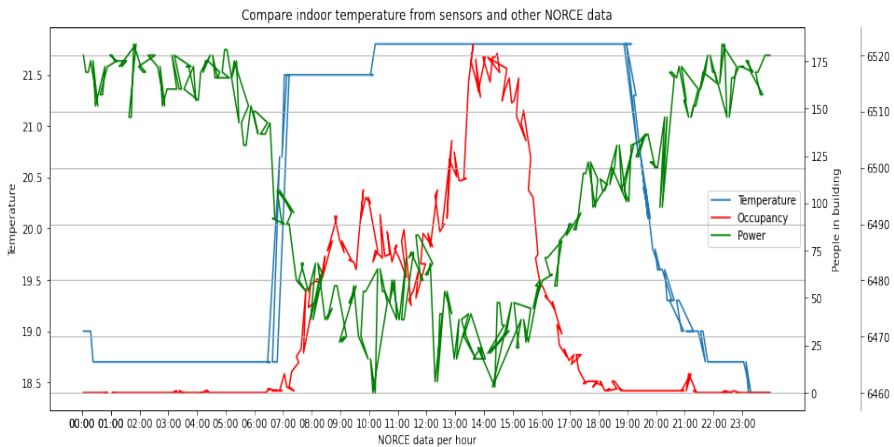


Figure 5.28: Temperature data from sensor vs Occupancy vs Power consumption(NORCE)

After reviewing 5.28, a clear pattern between the data sets cannot be determined. When reviewing the early hours, we might see a pattern in the temperature increase; however, as mentioned earlier. One average person radiates approximately 80W of heat[5]. Due to this fact, the temperature increase cannot be explained by occupancy(people) of the building since the highest increase of people happens when the temperature is at a constant value.

We can see a relation in power consumption and occupancy, where the power decreases when the building is in use. However, the power has reached approximately 6460 kW around 09:00 until 10:00, and between 14:00 & 15:00. Despite the occupancy, the number is double the amount in the later hour. It does not seem like the power decrease throughout the workday is because of the number of people inside Arkivenes Hus.

Arkivenes Hus has many windows. The power decrease might be compensating for increased sunlight. The weather report on this particular day, the third of March, were partly clouded[21]. However, we can only guesstimate since we have no data about the solar radiation on the building. This will be checked in our model simulation later.

5.4.1 Integrating power data

The power data measured in *Arkivenes Hus* measures around 6500kW, a mere 6500 times the amount of our previous test buildings \dot{Q}_{heater} value. Does it make sense that all that power is used to heat the building? By running a simulation where the Q_{heater} is changed depending on the timestamps of the power data of *Arkivenes Hus*, we can check if this holds up, it that kind of power is necessary, it should stabilize on a normal temperature. As seen in chapter 5.1.2.

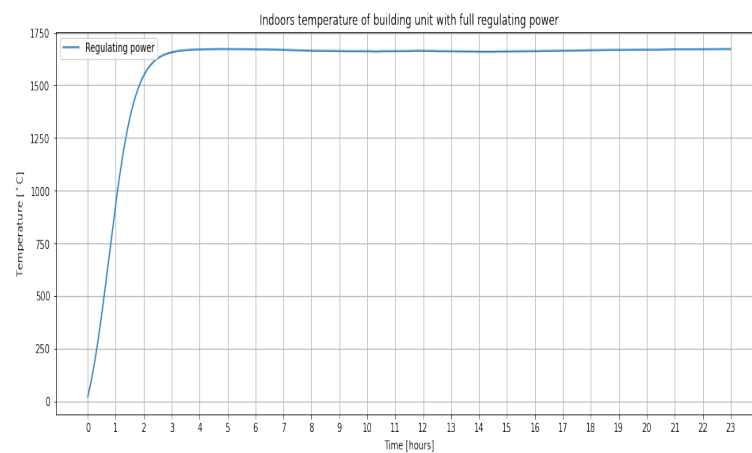


Figure 5.29: Indoor temperature results with full power

The temperature of the air inside *Arkivenes Hus* reaches 1650°C. An extremely unlikely indoor temperature. The extreme temperature can be an indication that not all of the power measured in *Arkivenes Hus* are used directly to warm up the temperature inside *Arkivenes Hus*. If we scale down the power by a fraction of 70, can the simulated temperature be of a more acceptable value?

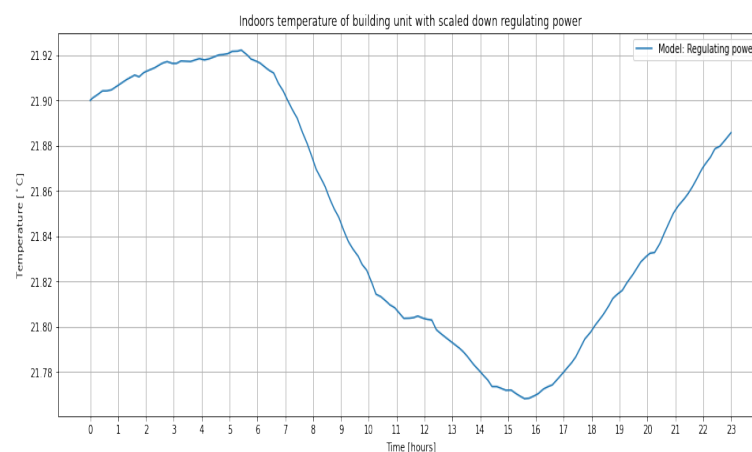


Figure 5.30: Indoor temperature with scaled down power

By scaling the power down, we can see a more acceptable 21°C in table 5.30. We have also moved the initial temperature of the inside to 21.9°C, to ensure our model does not waste simulation time by heating the building. Nevertheless, why does the indoor temperature of *Arkivenes Hus* behave

in such a way? Furthermore, how is the new temperature pattern compared to the new dynamic behavior of \dot{Q}_{heater} ? We can compare the indoor temperature with the heat received from \dot{Q}_{heater} :

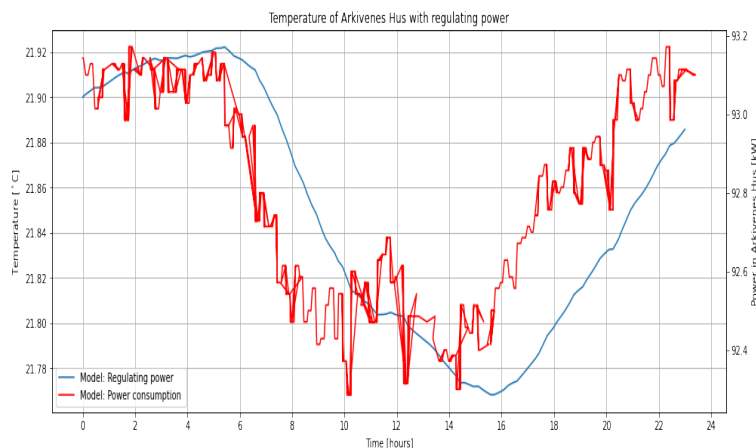


Figure 5.31: Compare the indoor temperature with \dot{Q}_{heater}

Seen in figure 5.31, the pattern of the indoor temperature makes more sense. The indoor temperature mimics the power from \dot{Q}_{heater} . The indoor temperature starts by increasing by .02 degrees because of the high number of \dot{Q}_{heater} . Afterward, it follows the \dot{Q}_{heater} pattern by decreasing until midday, and lastly, it increases with the power level.

Note the minor differences in indoor temperature. Here we can see a difference of approximately $0,15^{\circ}\text{C}$. We can also see that the power output difference is approximately 0.8kW .

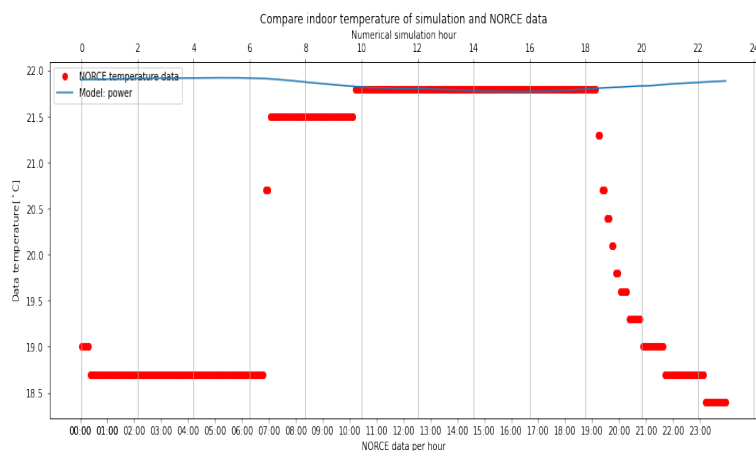


Figure 5.32: Comparing indoor temperature results, measured data versus our model

By comparing the measured temperature from *Arkivenes Hus* in figure 5.27, the temperature patterns are completely different. Because of the small difference in indoor temperature simulated with just the power input, the simulated air temperature looks more constant. Can we do better? By implementing more data, can the temperature simulated by our model fit the behavior of the measured temperature data in *Arkivenes Hus*?

What happens if we introduce the measured data for people, outdoor temperature, or airflow into our model? The next couple of sections will take a look at these questions. Further simulations will also have the power data implemented and not a constant.

5.4.2 Combining power and people data

We know that heat dissipating from a person to the air temperature is roughly 80W [5]. From figure 5.28 we can see how the amount of people increases as the amount of power decreases. By implementing the measured data of people inside *Arkivenes hus* into our model, we should see an increase in the temperature. This next simulation has the same variables as before, but now the \dot{Q}_{people} changes depending on the timestamps on the measured data from *Arkivenes hus*.

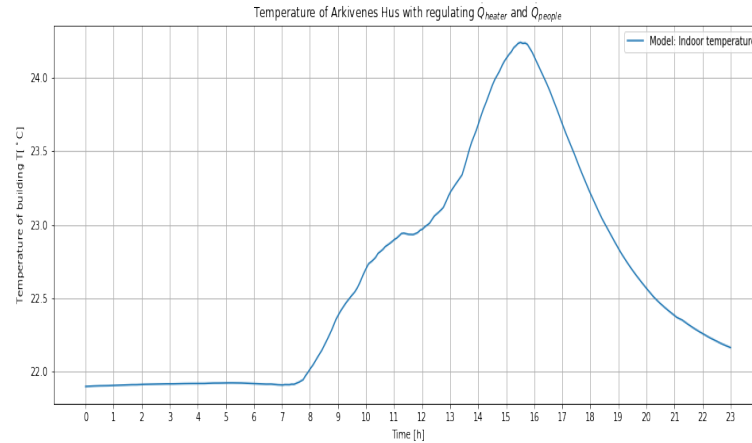


Figure 5.33: Indoor temperature with power and people data

The simulation results from our model now have a more considerable increase in air temperature. How do the regulation variables compare to the new temperature results?

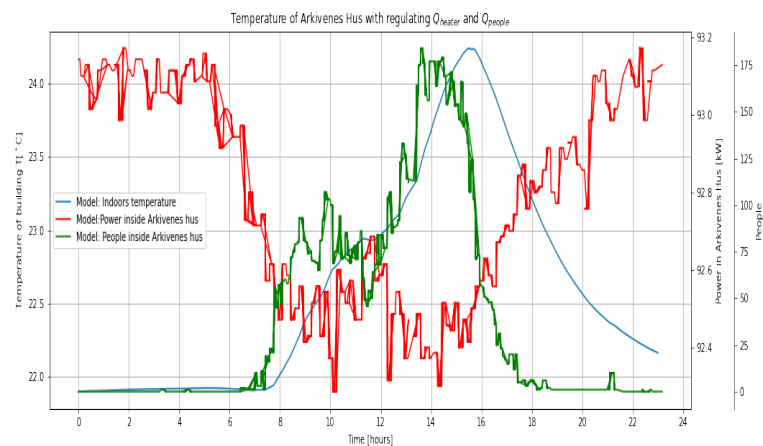


Figure 5.34: Comparing indoor temperature with the measured power and people data of simulation

In figure 5.34 we can see what explains the temperature increase. From last simulation (figure 5.32) we saw the heater (\dot{Q}_{heater}) made the air temperature stable. It makes sense that the added heat from people increases the temperature. The max added heat in watts from people is 14720 watts, Not too far away from the max added heat from \dot{Q}_{heater} , which were 93171 watts. The new simulated temperature looks more like the measured temperature of *Arkivenes hus*, we should compare them.

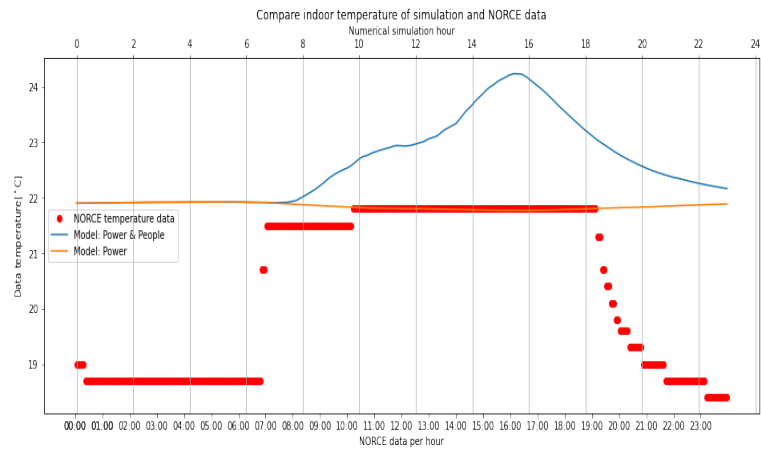


Figure 5.35: Comparing indoor temperature results, measured data versus our model

Visually we can see an improvement in the temperature pattern. However, the temperature is higher than the measured one. By decreasing the heat, can we get better representation?

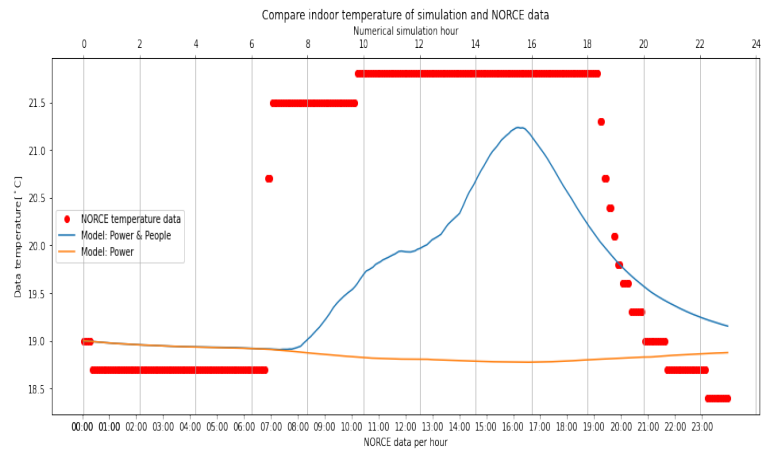


Figure 5.36: New temperature comparison, decreased heat and new initial temperature point

Now the power has decreased to a fraction of 80, and we used a new initial point in our simulation. 19°C. We can see how the simulated temperature mimics the measured temperature a lot better now. It would make sense that the power from \dot{Q}_{heater} helps to stabilize the temperature around a comfortable temperature ($\approx 20^\circ\text{C}$). Nevertheless, unanticipated events, such as a good increase of people, can warm up a room.

5.4.3 Combining power and outdoor temperature data

The outdoor temperature T_∞ has at this stage just been a constant -2.2°C . What will happen if we introduce the measured data from outside *Arkivenes hus*? We have seen in chapter 5.3.2 that the outside temperature had an essential role in the previous test building unit. How will it fair when scaled up?

Before presenting the results, the heater is still scaled-down 1/80, and the initial starting point is 19°C. We have a regulating heater (as usual), no heat from people, and at last a regulating outside temperature.

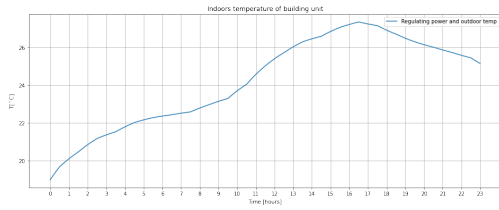


Figure 5.37:
Indoor temperature with power and outdoor temperature data

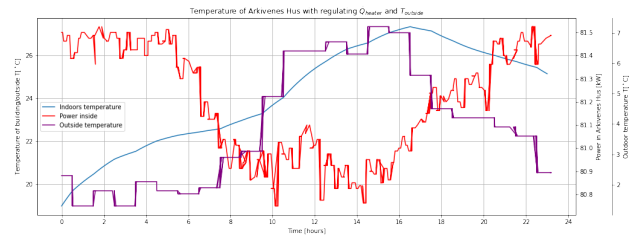


Figure 5.38: Comparing indoor temperature with the measured power and outdoor temperature data of simulation

With a dynamically changing outdoor temperature, we can also see an increase in the simulated indoor temperature. The outdoor temperature varies from 1.3°C to 7.2°C. With the outdoor temperature data, the indoor temperature starts increasing at once instead of waiting. It also has a higher increase in indoor temperature. Why does our model have a higher increase when exposed to the measured regulating outdoor temperature than with people heating the building?

The answer could be *specifically* because of the higher outdoor temperature. *Thermal conduction* happens in all of these cases. This phenomenon is explaining the movement of heat from an object to another with a different temperature. When the temperature difference between these objects is more considerable, the heat required to heat the air inside *Arkivenes hus* also needs to be higher. However, when the temperature difference lowers, as it does throughout the day, less heat is required to keep the building from cooling, and it can use more to heat the room. Like buildings have a higher energy consumption in the winter than summer. Thus, *Thermal conduction* explains why we have a more significant indoor temperature increase with measured outdoor temperature instead of the heat radiation from people.

We should compare the temperatures for better visualization.

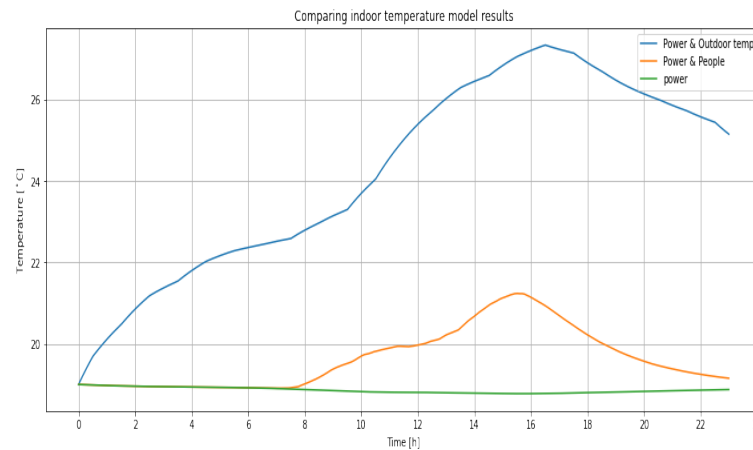


Figure 5.39: Compare indoor temperature with either regulating \dot{Q}_{people} or T_{∞}

Despite the reason for the indoor temperature difference between regulating \dot{Q}_{people} or T_{∞} , could it be changed with changing the airflow to a higher value?

Next simulation we increased the airspeed by 3.5 to $\dot{V}_{in} = \dot{V}_{out} = 4812.5 \frac{m^3}{s} * A_{floor}$

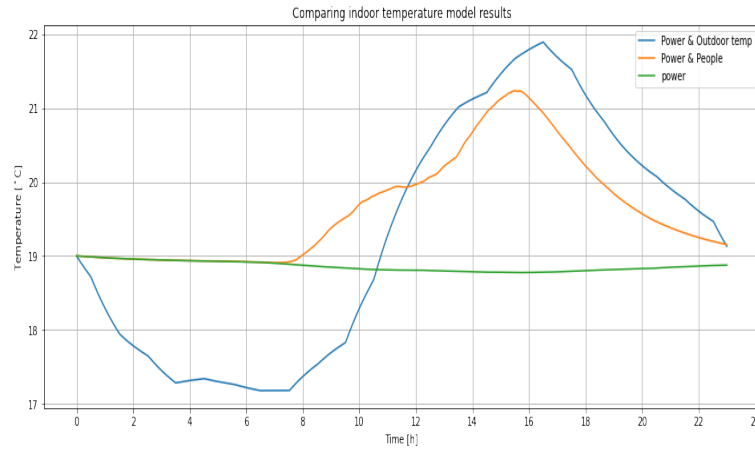


Figure 5.40: Compare indoor temperature with either regulating \dot{Q}_{people} or T_{∞} with new ventilation speed

Because the increased ventilation speed is constant, we see how the whole temperature has been affected. How does this stand up against the measured indoor temperature?

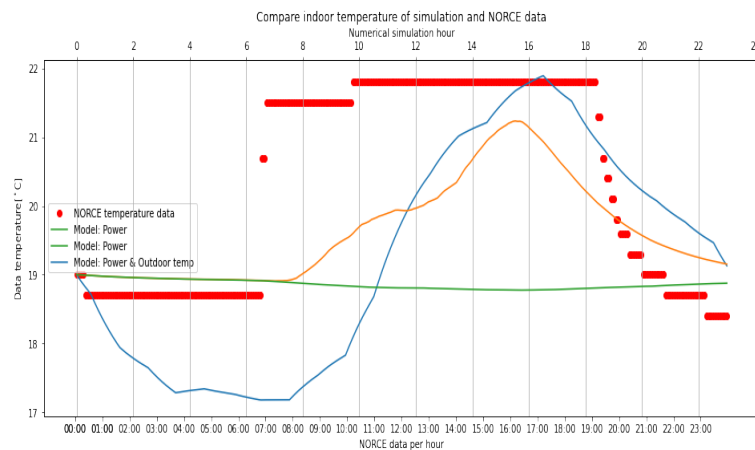


Figure 5.41: Comparing indoor temperature results, measured data versus our model

Now we can see the temperature reaching the *desired* temperature as the measured data at around 17:00. It defiantly helped to increase the ventilation speed. However, we can see the ventilation speed should not be at a constant throughout the whole day. The next part will focus on the airflow data measured from *Arkivenes hus*.

5.4.4 Combining power and airflow data

In the previous chapter, we saw how the airflow could help with regulating the air temperature of *Arkivenes hus*. Now by still scaling down the value of Q_{heater} by $1/80$, $T_{\infty} = -2.2^{\circ}\text{C}$, an initial starting point of 19°C we can use the measured air-flow data from *Arkivenes hus*.

There has been an issue with the model if \dot{V}_{in} and \dot{V}_{out} both are zero, the model breaks. The airflow value is, for this reason, assuming to be of a low value. $0.7 \frac{\text{m}^3}{\text{s}}$ per m^2 . This is a deficient value compared to the average of $1375 \frac{\text{m}^3}{\text{s}}$ per m^2 .

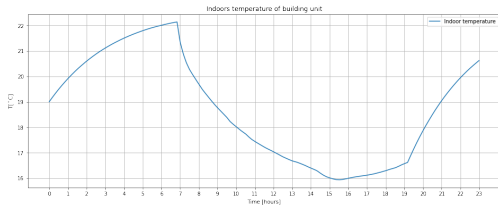


Figure 5.42:

Indoor temperature with regulating

$$\dot{V}_{in}/\dot{V}_{out}$$

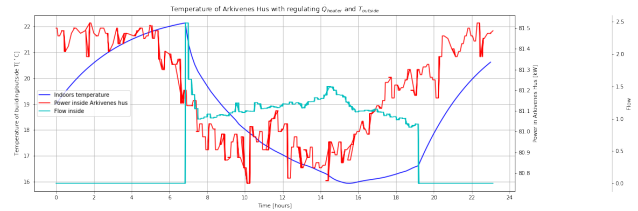


Figure 5.43:

Comparing temperature with regulating power

$$\text{and } \dot{V}_{in}/\dot{V}_{out}$$

The results prove yet again that a decrease in airflow increases the temperature of the room, which can be seen in figure 5.43 before 7:00. At this time, the airflow gets a considerable increase towards $5633 \frac{\text{m}^3}{\text{s}}$ per m^2 before reducing and stabilizing its flow rate. The temperature breaks perfectly when the airflow drops, proving that the airflow is a valuable asset of temperature control in our model.

5.4.5 Comparing measured data and simulated data

There should be a quick comparison of the measured data and the simulated data. We should see how much of the measured data our model is using in our simulations.

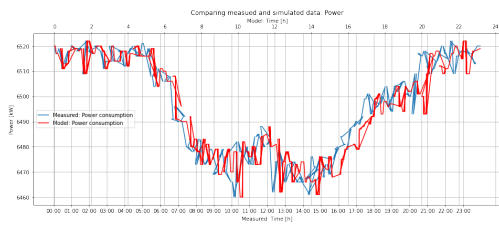


Figure 5.44:
Comparing simulated heater; \dot{Q}_{heater}
and measured heat

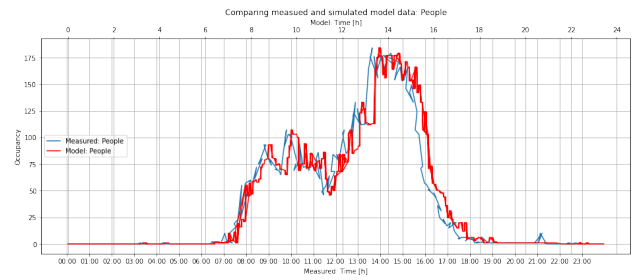


Figure 5.45:
Comparing simulated occupancy; \dot{Q}_{people} and
measured occupancy

From all comparisons, we can see a slight delay in each comparison. We can see how the visualization and not the simulation. Despite this fact, we can see how the simulated data has the same pattern and values as the measured data it tries to mimic.

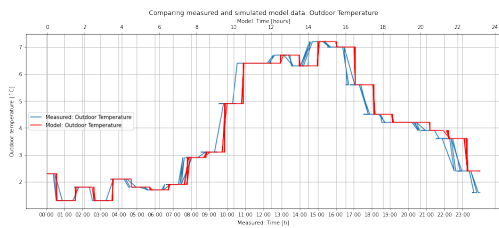


Figure 5.46:
Comparing simulated outdoor
temperature; T_{∞} and measured
outdoor temperature

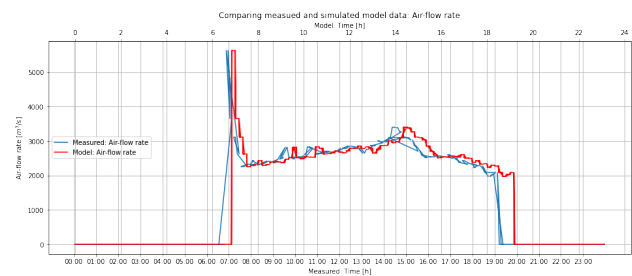


Figure 5.47:
Comparing simulated air-flow rate; $\dot{V}_{in}/\dot{V}_{out}$ and
measured air-flow rate

In conclusion, we can see how well our model uses the measured data from *Arkivenes hus*. Up until this point, the measured data has just been used one at a time, except this *power* data, which has been used each time, due to this is the reason our model can have a stable indoor temperature.

What happens if we combine the different results? Can our model simulation look more like the measured data? This hypothesis should be analyzed further.

5.5 Further temperature simulations of Arkivenes Hus

5.5.1 Combining the three data sets simulations

The next try would be to combine more data with seeing if we can get closer to the measured indoor temperature. Our simulations will be as followed:

1. Combining power, occupancy and outside temperature data
2. Combining power, airflow rate and outside temperature data
3. Combining power, airflow rate, and occupancy data

The power data is still being used on each simulation since it stabilizes the simulated indoor temperature to a preferred degree. Table 5.6 shows the variables and their assumed values when not using the measured data from *Arkivenes hus*.

Variable	Value
T_{∞}	-2.2 [°C]
\dot{V}_{in} and \dot{V}_{out}	1375 [m^3/s per m^2]
\dot{Q}_{people}	0

Table 5.6: Assumed constant values when not using measured data

The following figure represents each of the three simulations described in the list previously listed in this chapter.

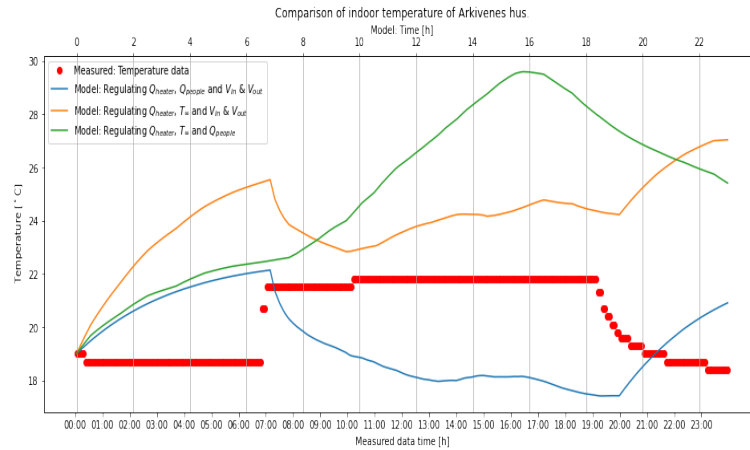


Figure 5.48: Three different simulation with three different combining data sets

Both the blue and orange simulation has a pattern similar to the airflow results in chapter 5.4.4. This pattern happened because the airflow rate value is insignificant and the heater uses the most power in this period. We then have a temperature increase that would not be necessary because the building is not in use at this period.

The green graph could be more promising. It is close to the last results as in chapter 5.4.3, however here with a smaller temperature peak. With the same conclusion, a decrease in power or increase in airflow rate could lower the temperature to a comparable temperature pattern as the measured data.

In figure 5.49 we can see how the simulated temperature has stabilized in the early hour. However, the temperature does not increase as much as the measured one. Still, it reaches a peak before

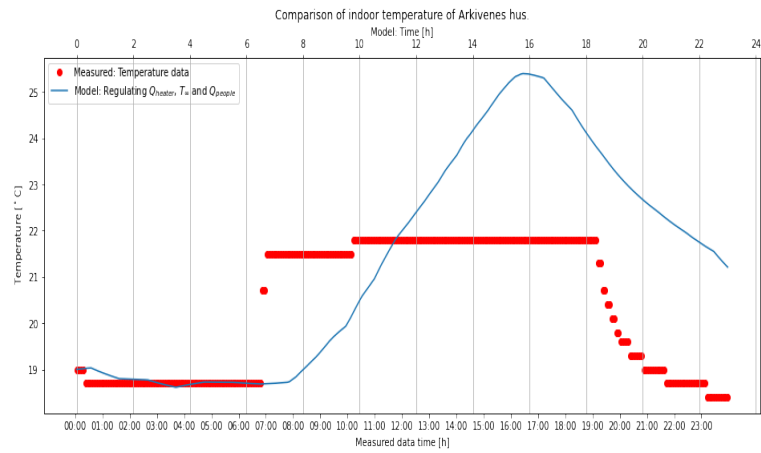


Figure 5.49: Comparing measured and simulated indoor temperature with updated \dot{Q}_{heater}

declining. Here the data set for \dot{Q}_{heater} has been lowered with 1/100, which would assume that *just* 1 percent of the power measured in *Arkivenes hus* is used for heating the building. Is this a reasonable assumption?

Despite this, we can see that the simulated indoor temperature maybe should be even because it reaches a little more than 25°C. This is most likely because of the increase of temperature explained by people and/or the outdoor temperature.

5.5.2 Disabling power

Previously we have assumed that \dot{Q}_{heater} has been the primary source of heat for the building because of the high watt and how it has behaved in previous simulations (stabilized the temperature). We can do a simulation where each of the three variables is time-dependent and uses the provided data sets, while the heater \dot{Q}_{heater} is equal to zero.

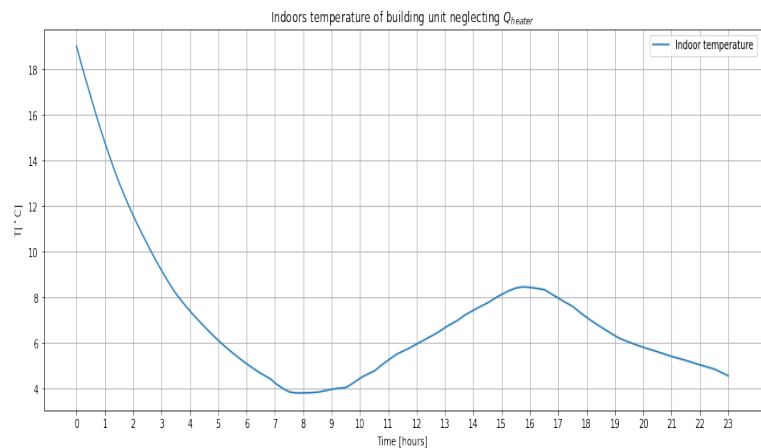


Figure 5.50: Comparing measured and simulation indoor temperature with updated \dot{Q}_{heater}

Figure 5.50 proves this hypothesis. We can see the temperature falling from the initial point and fluctuating between 4°C and 8°C. The combined heat from outside temperature, people, and ventilation is not enough to heat the building.

5.5.3 Combining all data sets from Arkivenes hus

Last simulation with $\dot{Q}_{heater}=0$ had no significant results. What happens if we now introduce the regulating \dot{Q}_{heater} ? With all four measured data affecting our simulation, the preferred result would be a simulation that is close to the measured indoor temperature data. However, initial assumption would be that the low airflow values will have a huge impact on the temperature at the early and late hours of the simulation.

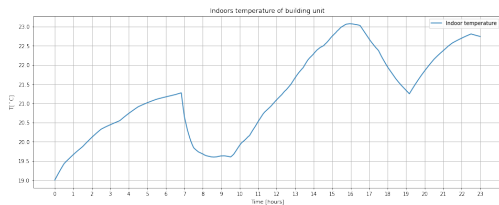


Figure 5.51:

Simulated indoor temperature in
Arkivenes Hus

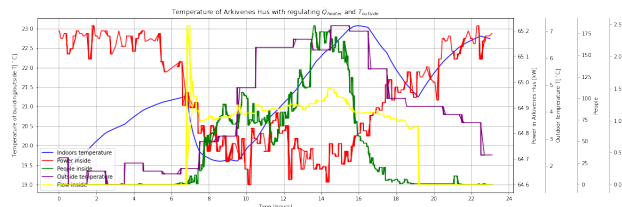


Figure 5.52:

Comparing the data with the indoor temperature

Looking at the results from the last simulation, we can initially conclude that our hypothesis was correct. The issue is with the low airflow.

Lower airflow means the outdoor temperature is not effectively introduced to the system and can not help cool the building down. When the airflow raises, we can see how the temperature drops. The reason for the temperature decrease is that now the outdoor temperature is introduced at a better flow rate, which helps with cooling the building down. The second temperature rise is, as seen in most of the previous simulations, caused by the increase of both people and outdoor temperature. When the outdoor temperature is decreasing again we can see how the indoor temperature gets affected. Nevertheless, when the airflow rate is decrease, the temperature rises again.

The fluctuation of indoor temperature is not ideal in a working day environment.

5.5.4 Solar energy

In [16] and as previously mentioned, the average solar irradiation is around $100 W/m^2$, maybe this can have an effect on the indoor temperature. Table 5.5 mentions the area of both windows and doors is $1996 m^2$.

The next simulation is assuming that the whole area for both windows and doors in *Arkivenes Hus* has the same potential for gaining heat from solar irradiation. The reason for this assumption is because the data from *Smi Energi and Miljø AS* does not mention how much of the area is just windows. The known variables \dot{Q}_{heater} , \dot{Q}_{people} , T_{∞} and $\dot{V}_{in} + \dot{V}_{out}$ has been given the measured data and will have the same behaviour as in chapter 5.5.2. The simulation will run with four different percentages of the total area of both windows and doors to mimic a scenario where just a percentage of the window area is struck by solar energy to the whole area is hit by solar energy. In other words, the four percentages are 1%, 25%, 50%, and 100% of the windows/door area. The sun will be introduced to the model from 10:00 until 14:00 to not "disturbing" the whole simulation.

In a real-life scenario, this would not be accurate. The simulation in this section of the thesis is merely an attempt to see how the indoors temperature behaves when exposed to solar radiation and not an attempt on a real-life scenario.

According to the website *timeanddate.no*, [21], there was partially clouded on the fifth of March 2021, the same time the data provided from NORCE were measured. However, we can simulate a scenario to see how much the windows play a part in *Arkivenes Hus*' indoor temperature.

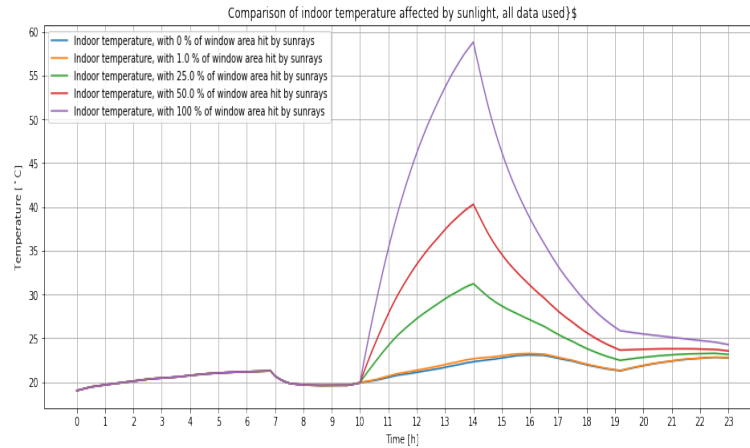


Figure 5.53: Comparing indoor temperature with different \dot{Q}_{solar} values

The results show an increase in indoor temperature even at 1% of the windows been hit by solar energy.

5.5.5 Summary and discussion of the temperature control simulation

In this chapter we have tried to replicate the temperature pattern of *Arkivenes hus* by manipulating the data gathered from the same building and using it on our heating model. The initial simulation were with the power data alone (\dot{Q}_{power}), this was data gathered from the same building and described the amount of watt used by the building. How much of the watt were used to heat and regulate the indoor temperature of air at *Arkivenes hus*?

The initial simulation of *Arkivenes hus* were with the power data regulating \dot{Q}_{heater} alone. The first simulation had no restriction on the power data itself, we had to do a simulation to verify with our model if the whole amount of power measured from *Arkivenes hus* really were for heating the building, and nothing else. The answer were no, we had to scale the power down.

After scaling the power data down, we started to get a more sensible indoor air temperature in the building. The scaled down power data gave us a stable temperature. The next natural step were to implement the other three data sets from *Arkivenes hus*. By implementing the outdoor temperature ($T_{outside}$), heat from people (\dot{Q}_{people}) and the air flow rate (\dot{V}_{in} & \dot{V}_{out}) first one by one, then combining them either two by two or everything together, then we could simulate the behaviour and compare with the measured indoor temperature (T_b) of the building. Some data sets had a better impact than other, and some had worse.

The results showed a combination of power, outdoor temperature and heat from people had the best looking results, with a pattern that resembled the *real* temperature of the room. The air flow rate data had some issues. When the ventilation were off, at night, the temperature of the building rose because that's when the heater were at highest power. This was an issue with our model, since is relied on air flow transporting the colder outdoor temperature inside to cool the system.

Each of the simulations done in this chapter has taught us something. From how the temperature can increase and decrease when the data-driven variables rise or falls. Our model has given evidence on how one could integrate a more energy-efficient temperature control depending on factors such as a high outdoor temperature or save energy if the building hosts an event where an abnormal amount of people will be inside the building.

5.6 Energy efficiency simulation of Arkivenes Hus

Chapter 5.5 imitates the air temperature inside of *Arkivenes hus* with the help of the measured data of the building. Another way of using the data provided from *Arkivenes hus* is to check if our model has the same energy consumption that the measured data has. To start this kind of simulation, we have to make some assumptions.

First, the temperature inside, here we introduce the temperature set points again. When looking at figure 5.27, we see how the measured temperature is throughout the day. The temperature is 18.7°C from 00:00 to 07:00, after 07:00 it rises to 21.5°C until 11:00, then it reaches 21.7°C. Afterward, at around 19:00, it falls towards 18.5°C. We then assume some temperature set points in approximately the same time frames. Seen in table 5.7.

A system checks if the indoor temperature is either lower or higher than the set temperature to achieve the desired indoor temperature. If the indoor temperature is lower than the set temperature, the heater will turn on, and if the indoor temperature measured by the system is higher than the set temperature, the heater will turn off. The value of the heater will be logged for each time step in the simulation. Afterward, the indoor temperature will be averaged for each simulated hour.

Time frame	Temperature [°C]
00:00 to 06:00	18.7
06:00 to 10:00	21.5
10:00 to 18:00	21.8
18:00 to 24:00	18.7

Table 5.7: Assumed set temperatures for the on/off heater control

The \dot{Q}_{heater} variable will have a value of 6500kW to mimic the actual power data set. By averaging each hour, we will get a good approximation of the power used to heat the building.

The energy efficiency simulations will be conducted with first no data sets implemented. Then with the measured outdoor temperature from *Arkivenes hus* data sets, the people data set will be used afterward. In the end, we will be introducing the airflow to a simulation. All three simulation is separate and will not affect one another.

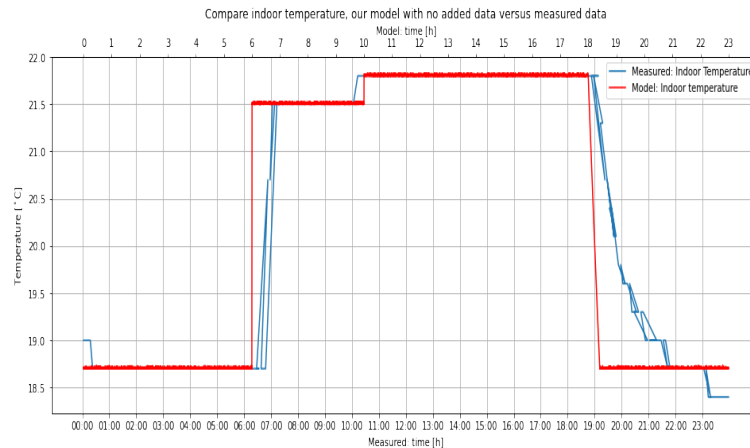


Figure 5.54: Comparing measured and our models indoor temperature

Figure 5.54 shows the compared temperatures. Our models mimicked, temperature seen in (red

result) has a faster increase and decrease, but this has been ignored because for the most part, the indoor temperature are similar to one another.

5.6.1 Energy efficiency without data sets

The purpose to have a simulation with just the constant values is to check if our model is working as intended. This means that values are kept as a constant. The values are as following:

- $T_{\infty} = -2.2^{\circ}\text{C}$,
- $\dot{Q}_{people} = 0$,
- $\dot{V}_{in} = \dot{V}_{out} = 1375\text{m}^3/\text{s}$ per m^2 .

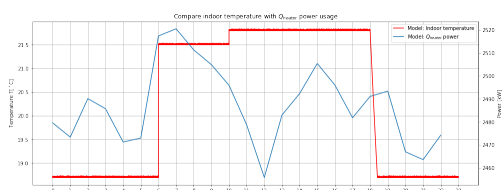


Figure 5.55: Comparing indoor temperature with \dot{Q}_{heater} results, no data provided

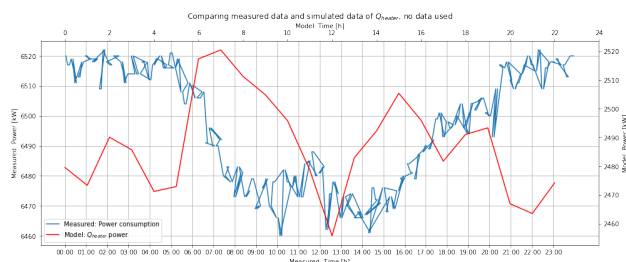


Figure 5.56: Comparing simulated \dot{Q}_{heater} results with no data provided and measured power

With all variables as constants, we can see how power used by \dot{Q}_{heater} is fluctuating with a difference of 60kW with no actual pattern. Not at all similar to the measured power data we are trying to recreate.

5.6.2 Energy efficiency with one integrated data set

What happens if we integrate and use the measured data set of T_{∞} , \dot{Q}_{people} and $\dot{V}_{in} + \dot{V}_{out}$ separately? Will the data sets help our model to have a resemblance of the measured power data?

Integrating outside temperature T_{∞} and people \dot{Q}_{people} separately

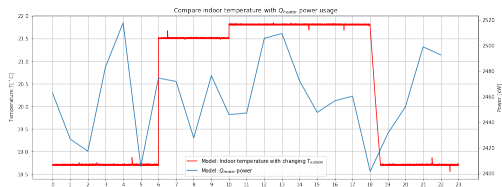


Figure 5.57: Comparing indoor temperature with \dot{Q}_{heater} results, outdoor temperature data provided

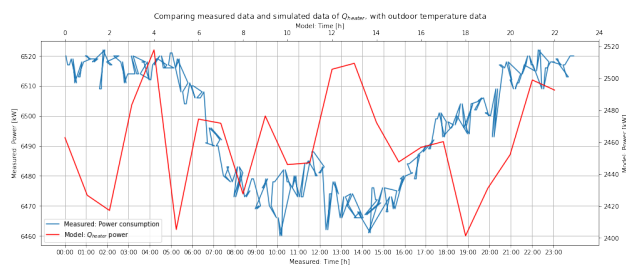


Figure 5.58: Comparing simulated \dot{Q}_{heater} results with outside temperature data provided and measured power

When just integrating either the people inside or the outdoor temperature, we can see the simulations of them both do not resemble the measured data from *Arkivenes hus*. The reason might be

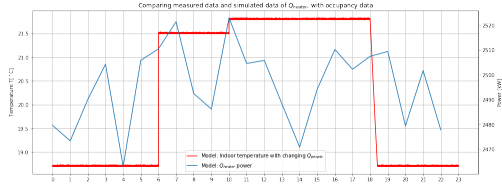


Figure 5.59: Comparing indoor temperature with \dot{Q}_{heater} results, occupancy data provided

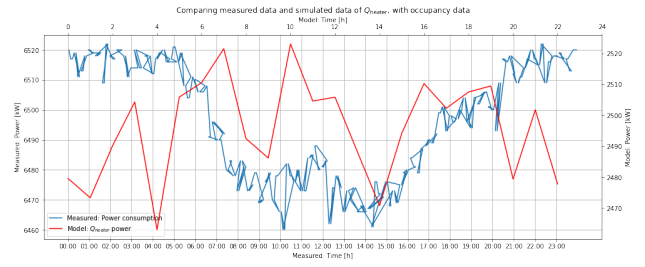


Figure 5.60: Comparing simulated \dot{Q}_{heater} results with occupancy data provided and measured power

because the high power value is not affected by the heat provided from \dot{Q}_{people} or that the difference in outdoor temperature T_{∞} and the indoor temperature is not enough to disrupt the heater.

Integrating airflow rate data $\dot{V}_{in} + \dot{V}_{out}$ separately

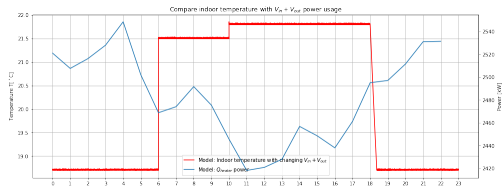


Figure 5.61: Comparing indoor temperature with \dot{Q}_{heater} results, airflow rate data provided

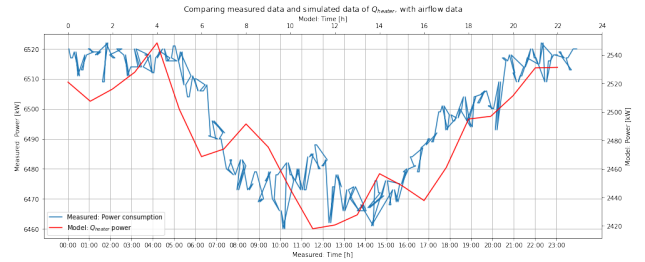


Figure 5.62: Comparing simulated \dot{Q}_{heater} results with airflow rate data provided and measured power

Much more exciting results happen when the airflow rate is integrated into our model separately. Now the value of \dot{Q}_{power} resembles the measured power data. It seems that the airflow rate has a more significant impact on the indoor temperature than the other two factors. What will happen if we integrate the other data sets with the airflow rate? How will this affect power consumption?

In table 5.8 we can see the average value for \dot{Q}_{heater} for each simulation and compare it to the measured power data average value.

Simulation	Average power used [kW]
With no data	2487.18
With Outdoor temperature	2460.17
With people	2495.74
With airflow	2483.27
Measured power average	6496.34

Table 5.8: Average power used by \dot{Q}_{heater} for each simulation and measured data

We can see that the average power is not that different from each other. However, the average simulated power results are lower compared to the power data measured in *Arkivenes hus*.

5.6.3 Using all data sets

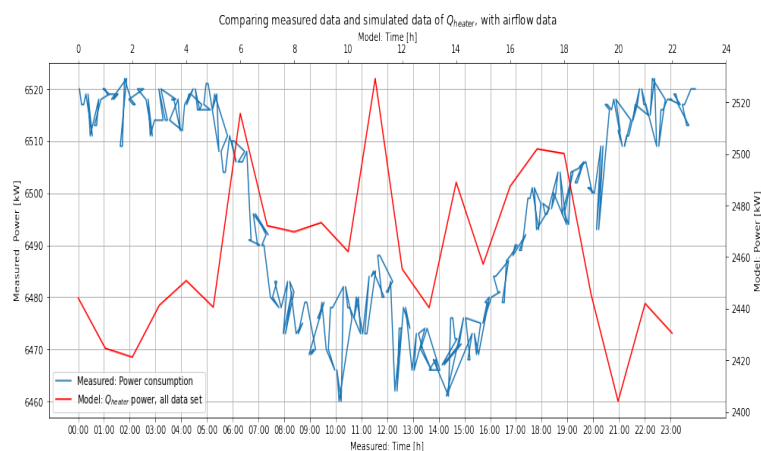


Figure 5.63: Comparing simulated \dot{Q}_{heater} results with all data provided and measured power

When introducing the outside temperature and the heat from people, we see that the simulated power results go wrong again. One could argue that the simulated data since it is the average for each hour, could be too few data points to get a good visualization of the results. We can test this question by increasing the data points on the simulated results by 1000.

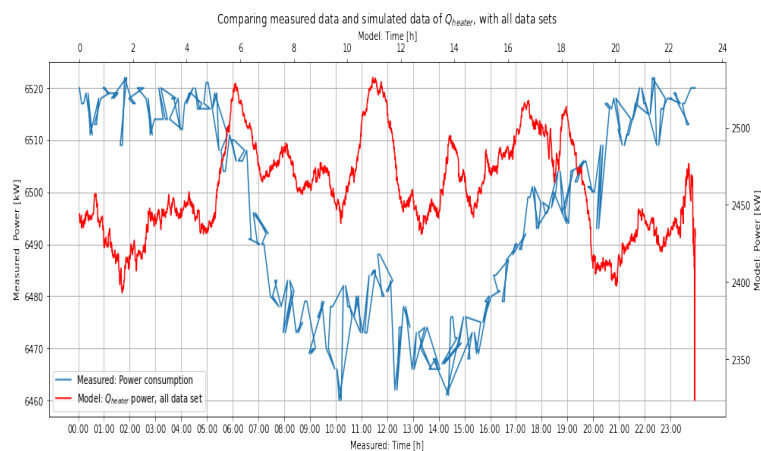


Figure 5.64: Comparing simulated \dot{Q}_{heater} results with all data provided and measured power with more points

The results stay the same with an increase instead of a decrease in the middle of the day.

5.6.4 Summary and discussion of energy efficiency simulation

In this chapter we have simulated the energy usage of *Arkivenes hus* by controlling the temperature itself. By having a on/off controllable heater we have managed to simulate how a heat system potentially could work in regulating the air temperature inside of a building (A real life controllable system is most likely not an on/off type of system, they however use a variable heater control that can go in increments from 0% to 100% in steps.)

By counting up and finding the average total heat dissipated from the variable \dot{Q}_{heater} per hour (or less) we found the average watt used per hour and could compare it to the data from sensors on *Arkivenes hus*. From here we added data gathered from sensors around *Arkivenes hus* to see how they would affect the power regulated from the heating system (\dot{Q}_{heater}). The data was the outside temperature, the amount of people inside the building and the air flow rate from *Arkivenes hus*.

The initial three simulations had just one of the measured data each. Here we found out that the airflow alone gave the best result from the three simulations, because it mimicked the measured power data the best. By adding all data together we found no significant results. The average power used stayed approximately the same for each of the simulations. However, the pattern on how the power was dissipated was different.

Chapter 6

Summary and Conclusion

6.1 Summary

This thesis can be separated into two parts:

1. The first part made a mathematical model and tested the behavior with a fictional building unit specifically designed for the simulation model. See chapters 5.1 to 5.3.
2. The second we compared this model to see if the model could be used to analyze the temperature and energy efficiency of a physical building provided with the necessary data. See chapter 5.4 through 5.6.

6.1.1 Summary of the first part: Testing and verifying

In the first part, two different scenarios were presented. The first part was to simulate the behavior of a fictive building unit where its parameters were inspired by the article " [16]". Here we created two separate experiments to learn more about the building unit's behavior. The primary task was to simulate how the indoor air temperature rises and falls when a heater element controls the indoor temperature. However, here we also introduced the *analytical* model to verify the model's behavior and were introducing more equations to make the simulation more accurate. The results in 5.1 show how both the numerical and analytical results work as intended

In the second part of the fictive building unit, we created a simulation of how the model might be used in a real-world scenario. With different temperatures and airflow rates throughout the day. This task was primarily used to test different events and variables of the simulations, which can be seen in the bullet list below:

- Varying Outdoor temperature
- Occupancy
- Varying Airflow rate
- Different amount of sunlight exposure on windows

By simulating the same building unit with the different events, one by one, we learned how the indoor temperature of the building unit was behaving accordingly. Like the outdoor temperature, some variables could raise the indoor temperature if the outdoor temperature was higher than the indoor temperature. Others, like the airflow rate, could help lower the indoor temperature if the speed increased. The results can be seen in chapter 5.2 and 5.3.

6.1.2 Summary of the second part: Arkivenes hus

When the model had been tested and its behaviors more understood, we could start on the second part. In this part, we had received data gathered from sensors in *Arkivenes hus*. Here we conducted two different simulation types with the help of the given data:

- Power data [kW]
- Outdoor temperature data
- Airflow rate data [m^3/s]
- Occupancy data

As mentioned, the simulations done on *Arkivenes hus* were first to see if our model could reproduce the indoor air temperature of the building by using the measured data sets above. We could see the air temperature inside *Arkivenes hus* change when implementing the different data sets into the model's variables, either each on their own or combine them. We could also see how an increasing outdoor temperature could affect a building's environment if the heating system runs on its own. Moreover, because our model has no integrated ventilation system that heats the air before pushing it into the building, we could see the airflow having a significant effect on obstructing and assisting the heater in keeping the temperature inside comfortable. The people, which can be seen as a volatile factor, also could quickly make a room or building more uncomfortable with its heat irradiation. The people factor can not, for the most part, be easily prevented with a regulating heating system. However, this can be a thought for in the future.

Lastly, we used our model to try to simulate the power use of *Arkivenes hus*. Here our model uses the measured data differently. We try to simulate the power data and not the temperature data. By having the same type of on/off the heating system as in chapter 5.2, we initially simulated *Arkivenes hus* with the same principles as the fictive building unit. Here we added the measured data sets to see how they affected the power consumption of the building. The results were that the power data average values were similar in all cases. However, how the power was used throughout the simulation time was different. As the last simulation type, we include the other data sets, outdoor temperature, airflow rate, and occupancy, and with a constant value on \dot{Q}_{heater} as either 6500kW or 0, to simulate an on/off heater.

6.2 Future work

For future work, some factors of our implementations should be revisited.

The first remark is the behavior of the model in chapter 5.1.2, the quick rise from 20°C to 50°C, and more importantly, the fast descent from 50°C all the way through -2.2°C should be analyzed further to see if some improvements can be found.

Some coefficients should also be looked at, the coefficients in question are ρ_b (listing 4.6) T_{in} (6.1). The boundary equation, mainly the furniture equations, should also be revised. T_{in} (6.1) is described as "integrated ventilation heat recovery system" in article [16]. Air flowing through the integrated ventilation heat recovery system would be higher compared to the temperature outside. It is possible to estimate this using an energy efficiency coefficient η and assuming equal density and specific heat capacity in the two counter-current airflow streams(in and out). Equation (6.1) is constructed for modelling the inflow temperature of air. By using equation (6.1), we can calculate the thermal properties of the inlet air. This equation could further help our model with the temperature simulations.

$$T_{in} = \frac{\eta \dot{V}_{out} \rho_b c_{p,b} (T_b - T_{\infty})}{\dot{V} \rho_{in} C_{p,in}} + T_{\infty} \quad (6.1)$$

In the article [16], they state the furniture is a *vital* part of the building model. This could be revised to see if a better implementation can prove this statement more thoroughly.

In chapter 5.5.4 we had some results from simulation of *Arkivenes Hus* regarding sunlight. Some future work could be researching other means of reducing the indoor temperature to set temperature due to sunlight.

As stated in chapter 5.4 to simulate the heat loss from elements, we opt-in using (3.14) to (3.19) instead of the more complex ones due to the lack of information about the layers inside the elements. This can be looked at to make the heat loss from such a large building more optimized.

When creating the model, a new version of the *odeint* function was found. The *scipy.integrate.solve_ivp* is said to be the new standard of solving ODE's with *scipy*. This can be used instead of the old standard. Perhaps a test involving the performance difference of the two?

6.3 What I have learnt

I was going into this master thesis with no actual knowledge of thermodynamics. By writing this paper, I have learned a great deal about the fascinating branch. It has been interesting to learn how a few laws are tying everything around us together.

Learning about combining ODE's and DAE's on a grander scale has also been fascinating. Before I wrote this thesis, I wondered how we could work with ODE's on a grander scale. I felt that in this thesis, I had learned much on how I can tie concepts like this together.,

The concept of good visualization of results and data has been a fun task by learning how a good presentation of the simulation data has been vital for this thesis.

6.4 Conclusion

This thesis shows how a building unit's heat dynamics react when initiated with different scenarios or data. It is adaptable and will react as anticipated. This model shows an implementation method of a fundamental thermodynamic system. It is possible to extend and adapt this model when presented with new methods of calculating or new data to solve temperature or energy efficiency questions.

This model can provide insight into the thermodynamics of a definite system. For example, to create a simple environment with various temperatures, humidity, heat transfer, or conductivity coefficients, to mention a few environment-related variables. The user will learn how their simulation model would react to a thermodynamic system.

The model, however, was not without concerns. When weighing the results with the article "[16]" (figure 5.4) we could see how different the temperature curves were. The issues could be due to slightly different calculations or coefficients used by the article [16]. If these values were known, the results would be more similar.

Although we are satisfied with the simulation results done on *Arkivenes hus*, we have another issue with heat loss in these simulations. Here we only use the more "basic" type of heat loss functions, calculating the overall heat loss from outdoor to indoor temperature for the boundary elements instead of calculating the heat loss for each element's layer. With more knowledge on how *Arkivenes hus* is constructed, like what is inside of the walls or how thick they are, then we could produce a more complex temperature or energy efficiency simulation.

We can conclude that our model can give some degree of suggestions on improvement when used on various buildings. If a user had the necessary data required for this model to run, the user would get results from the simulation usable for recommendations and improvements on the user's energy usage or temperature questions.

Chapter 7

Unit Terminology

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

Table 7.1: Unit terminology

Appendix A

Programming Environment

To test the model a python script were created. Tools used were Anaconda [3], Visual Studio Code[11].

A.1 Python Environment

This project, as a lot of others requires the need of third party packages. To make sure only the correct packages is used by the project, we can set up a personal environment for this project. Anaconda has a feature to easily create a environment.

A.1.1 Conda

Conda is a package and environment management tool implemented in the Anaconda software. This tool allows you to install the Python packages as well as create and manage multiple environment, containing different packages. One of the major advantages for using Conda is the dependency management. Conda will look at each package to check that all packages installed is compatible.

A.1.2 Conda Environment Setup

To create our environment we use the command in listing A.1. Here we install the packages Numpy [4], Pandas [20], Matplotlib [7] and Scikit-Learn [14] under the environment name *Thesis*. We also install pip and Jupyter Notebook in case a package isn't available on the Anaconda Cloud and Jupyter to view

```
1 conda create -n thesis python pip numpy numba pandas matplotlib scikit-learn ...  
   scipy jupyter
```

Listing A.1: Conda command to create new environment

Appendix B

Programming Code

B.1 Python model class

Code used can be found on GitHub repository: "[18]".

Appendix C



Arkivenes Hus

iPark eiendom AS

Arkivenes hus

Energinotat

Prosjektnr. 14-0743

Tittel Energinotat Arkivenes hus	
Utførende organisasjon smi energi & miljø as Postboks 8034, 4068 Stavanger Prof. O. Hanssensvei 7A, 4021 Stavanger Tlf: 51 87 44 90 E-post: post@smigruppen.no Webside: www.smigruppen.no	Oppdragsgiver iPark eiendom as Postboks 8034 4068 Stavanger Kontakt: Rune Augenstein E-post: ra@smedvig.no Tlf: 992 12 414
Prosjektansvarlig, utførende organisasjon Jan Tang jat@niras.dk + 47 458 01 652	
Prosjektmedarbeidere Pål Bårdsen, Åsta Vaaland Veen (smi energi & miljø as)	
Sammendrag Arkivenes hus skal bygges med høye miljø og energiambisjoner. Energisimuleringer er utført med ytelser tilpasset gjeldende bygningsmodell. Med ytelsene listet i tabell 1, oppfyller bygget krav til energi i hht. Teknisk forskrift (TEK). Med disse ytelsene havner også bygget innenfor energiklasse A, forutsatt energiforsyning som spesifisert i energimerkesimuleringer fra GK. Med solavskjerming på solutsatte fasader vil man for de fleste områder få en akseptabel inne temperatur Sonen innenfor glassatrie er et utfordrende område med hensyn på inne klima. Det er listet flere mulige tiltak for å opprettholde komfortkrav Tiltak for å redusere varmetap fra horisontal glassflate i atrietak bør vurderes. Arealet vil ha problem med høy temperatur om sommeren og lav temperatur om vinteren. Det anbefales en U-verdi i skille mellom arkiver og kontorer bedre enn 0,5/0,7W/m ² K Inneklimasimuleringer bør gjennomføres for utsatte arealer for å sikre at kontorarealer ikke har problemer med kaldras eller strålingstap fra store vindusflater.	
Prosjektnr 14-0743	
Dato 22.06.2015	Utgave 02
Utført av Åsta Vaaland Veen	Signatur <i>Åsta Vaaland Veen</i>
Kvalitetssikrer Pål Bårdsen	Signatur <i>Pål Bårdsen</i>

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1 Generelt

Arkivenes hus er et nybygg på Ullandhaug med 4 kontoretasjer over bakken og 3 etasjer arkiver i underetasjer og huser arkivfunksjoner for flere offentlige etater.

Man har med bygget høye energi og miljøambisjoner, bla med BREAM-NOR excellent sertifisering og krav til energiklasse A.

Bygget skal oppføres med struktur i stål og betong, men med utenpåliggende lett klimaskjerm. Bygget skal ha utvendig solavskjerming i form av mikroperforert screen på solutsatte fasader.

Denne rapporten omhandler optimalisering av byggets energieffektivitet. Det tas ikke stilling til energiforsyningsløsning, utover at det i simuleringene er lagt inn forsyning fra varmpumpe og gasskjele som forutsatt av GK i energimerkesimuleringer.

2 Inndata

Alle arealer er hentet fra BIM modell datert 26. februar 2015.03.16, bortsett fra vindusarealer som er oppdatert med data fra IFC-fil datert 08.06.2015.

Foreløpige ytelser for bygningskomponenter er vurdert ut fra byggemål i BIM modell

Data på ventilasjonsanlegg er mottatt fra GK 10.06.2015.

Driftstider og internlast er benyttet verdier i NS3031 for kontorbygg, med unntak for arkivplan hvor det ikke er beregnet tappevann. Bygningskropp og teknisk utstyr er lagt inn i en simuleringsmodell i energisimuleringsprogrammet Simien versjon 5.502.

Det settes opp en basismodell (Simulering A) for å kunne vurdere om bygningen oppfyller krav til byggverk i forhold til energibruk i teknisk forskrift. Flere ytelser i modellen er valgt bedre enn minimumsverdier i TEK 10 der dette er vanlig praksis eller krav fra byggherre er strengere enn minimumskrav i teknisk forskrift.

Følgende inndata og ytelser er benyttet i simuleringene:

Bygningsdel	Ytelse	Areal [m ²]	Kommentar
Oppvarmet del av BRA	-	12904	Hele bygget inkludert arkiv
Oppvarmet luftvolum	-	47267	
Yttervegger [W/m ² K]	0,17	3486	Tilsvare ca. 25cm isolasjon
Kjellervegger (under bakken)[W/m ² K]	0,15	1878	Utvendig isolert 200mm mot kulvert med b verdi på 0,7W/m ² K.
Tak [W/m ² K]	0,13	3090	Tilsvare ca. 300mm isolasjon
Gulv mot grunn (arkiv) [W/m ² K]	0,18	2269	Minstekrav i TEK
Skille arkiv og kontorer [W/m ² K]	0,5/0,7	2150	Tilsvare ca. 50mm isolasjon i skille. U-verdi 0,5 W/m ² K nedover og 0,7W/m ² K oppover.
Vinduer og dører yttervegg[W/m ² K]	0,8	1996	Minstekrav Smedvig. Horisontale glassflater: (422m ² , U=1,0 W/m ² K) Vertikale glassflater/vinduer: (1574 m ² , U _{gj} =0,75 W/m ² K)
Andel vinduer og dører [%]		15,5	Inkludert kjeller, 30 % i kontordel**
Lekkasjetall	0,5	-	N50 [1/t]
Nominell kuldebroverdi	0,05	-	Utenpåhengt vegg med lave kuldebroer
Varmevirkningsgrad ventilasjon [%]	87	-	Data GK 10.06.2015. (Årsgjennomsnitt med luftmengder vinter)
SFP ventilasjon [kW/m ³ /s]	1,5	-	Data GK 10.06.2015
Effektbehov belysning kontorer [W/m ²]	4		Minstekrav byggherre og NS3701
Effektbehov belysning Arkiv [W/m ²]	2		4W/m ² benyttes i TEK evaluering i henhold til NS 3031
Effektbehov teknisk utstyr kontorer [W/m ²]	8		Satt lavere enn standard for å ikke underestimere framtidig varmebehov (NS3031 standardverdi 11 W/m ²)
Effektbehov teknisk utstyr Arkiver[W/m ²]	2		11W/m ² benyttes i TEK evaluering i henhold til NS 3031
Personlast kontorer [W/m ²]	4		Standardverdi NS3031
Personlast magasin [W/m ²]	0,5		4W/m ² benyttes i TEK evaluering i henhold til NS 3031
Tappevann kontorer [W/m ²]	0,8		Standardverdi NS3031
Tappevann magasin [W/m ²]	0		

Tabell 1 Inndata basismodell

**Vindusareal i kontordel utgjør 30 % av oppvarmet areal. Dette er høyt, men kompenseres av U-verdi på 0,8 for vinduer. 0,8*0,3=0,24 og oppfyller krav i TEK for kontordelen alene.

Energimodellen tar hensyn til skjerming fra vegetasjon og mulige framtidige bygninger, og modellen muliggjør simulering ved ekstremforhold sommer og vinter samt verifikasjon mot forskrifter.

Midlere kuldebroverdi.

Standardverdi kuldebroverdi for betongbygg er 0,09W/mK og for et trestenderbygg 0,05W/m/K. Arkivenes bygg er et betongbygg med en påhengt fasade og tak som utvendig isolert kompakttak. Denne byggemåten hindrer at det blir kuldebroer mellom betongkonstruksjonen og fasadeløsningen siden disse er adskilte.

Fasadekonstruksjonene vil kunne sammenliknes med en god trestendervegg og kuldebroverdi for trestenderbygg vil være riktigere enn verdi for betongbygg. Med fokus på kuldebro rundt vinduer vil sannsynligvis kuldebro for bygget være lavere enn dette, men uten spesifikke beregninger kan det ikke brukes en lavere verdi enn 0,05W/mK.

3 Energisimuleringer

3.1 Simulering basismodell (Simulering A)

Modellen som er satt opp har mange ytelser som er til dels betydelig bedre enn krav i TEK10. Det gjennomføres først en årssimulering hvor netto energibehov og årsbudsjett med lokalt klima. Driftsstrategi varme og ventilasjon er lagt så nær forventet drift som mulig.

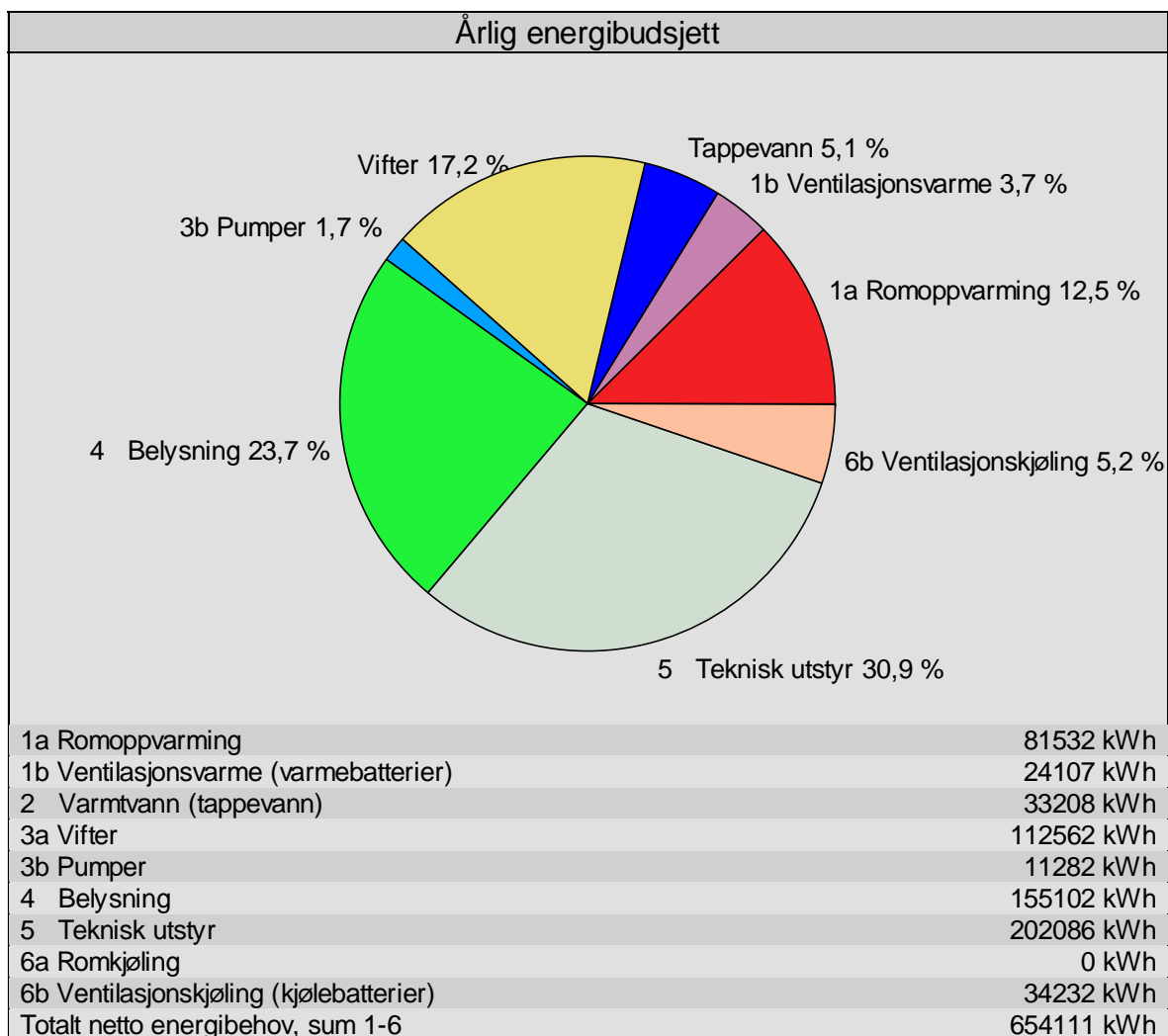
Det er for magasinene simulert med lavere energibehov til teknisk utstyr og personlast enn i NS3031, og verdiene antas å ligge nærmere virkeligheten enn standardverdier fra NS3031. Dette er beskrevet i inndatatabell

Årssimulering

Netto energibehov fra basissimulering for hele bygget:

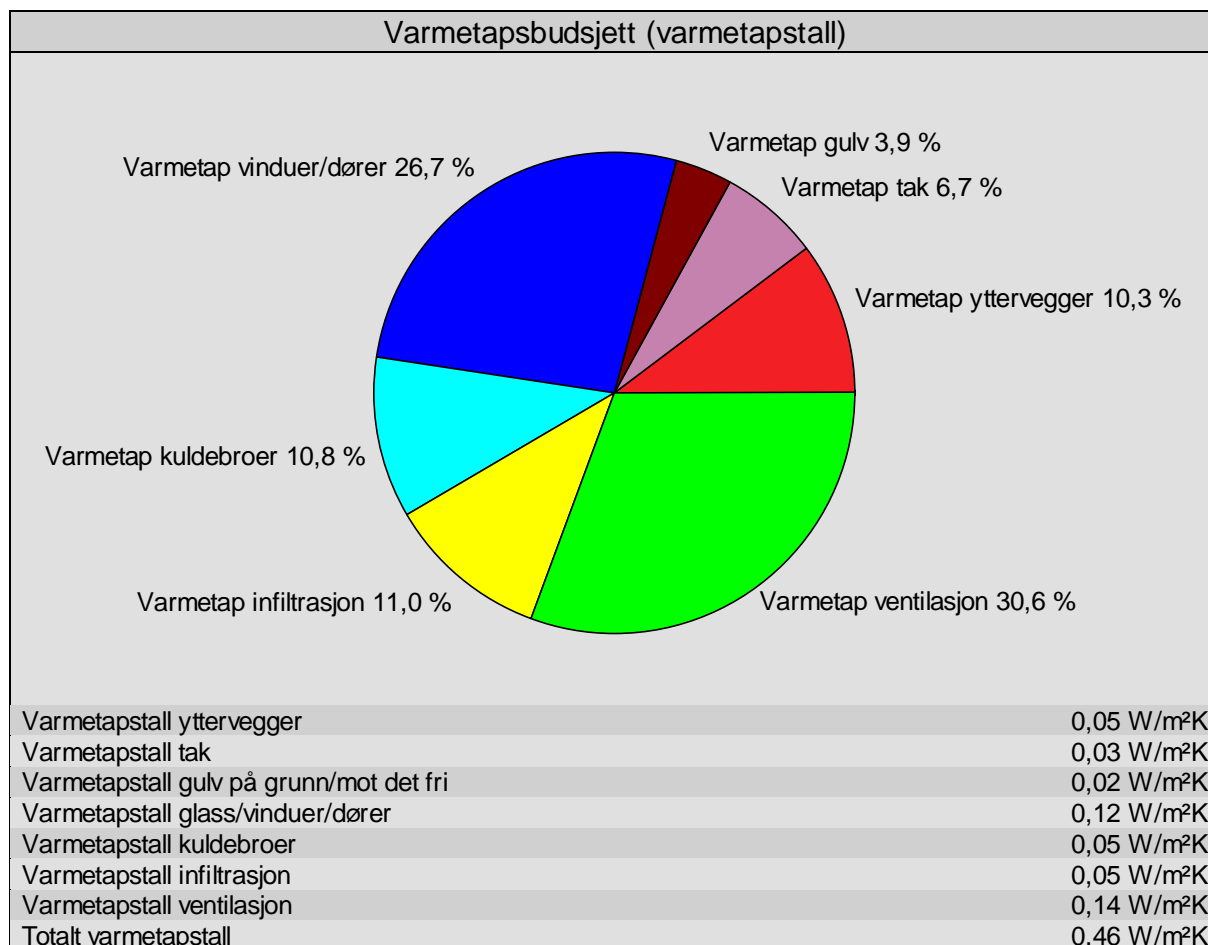
Energipost	Energibudsjett	
	Energibehov	Spesifikt energibehov
1a Romoppvarming	81532 kWh	6,3 kWh/m ²
1b Ventilasjonsvarme (varmebatterier)	24107 kWh	1,9 kWh/m ²
2 Varmtvann (tappevann)	33208 kWh	2,6 kWh/m ²
3a Vifter	112562 kWh	8,7 kWh/m ²
3b Pumper	11282 kWh	0,9 kWh/m ²
4 Belysning	155102 kWh	12,0 kWh/m ²
5 Teknisk utstyr	202086 kWh	15,7 kWh/m ²
6a Romkjøling	0 kWh	0,0 kWh/m ²
6b Ventilasjonskjøling (kjølebatterier)	34232 kWh	2,7 kWh/m ²
Totalt netto energibehov, sum 1-6	654111 kWh	50,7 kWh/m ²

Av energibehovet til bygget er kun 16 % av energien oppvarming. Resterende er elektrisk behov til viftedrift, pumper, belysning og teknisk utstyr, samt noe kjøling. Bygget har et kjølebehov på ca5% av energibehovet.



Her ser man tydelig fordelingen mellom elektrisk og oppvarmingsbehovet.

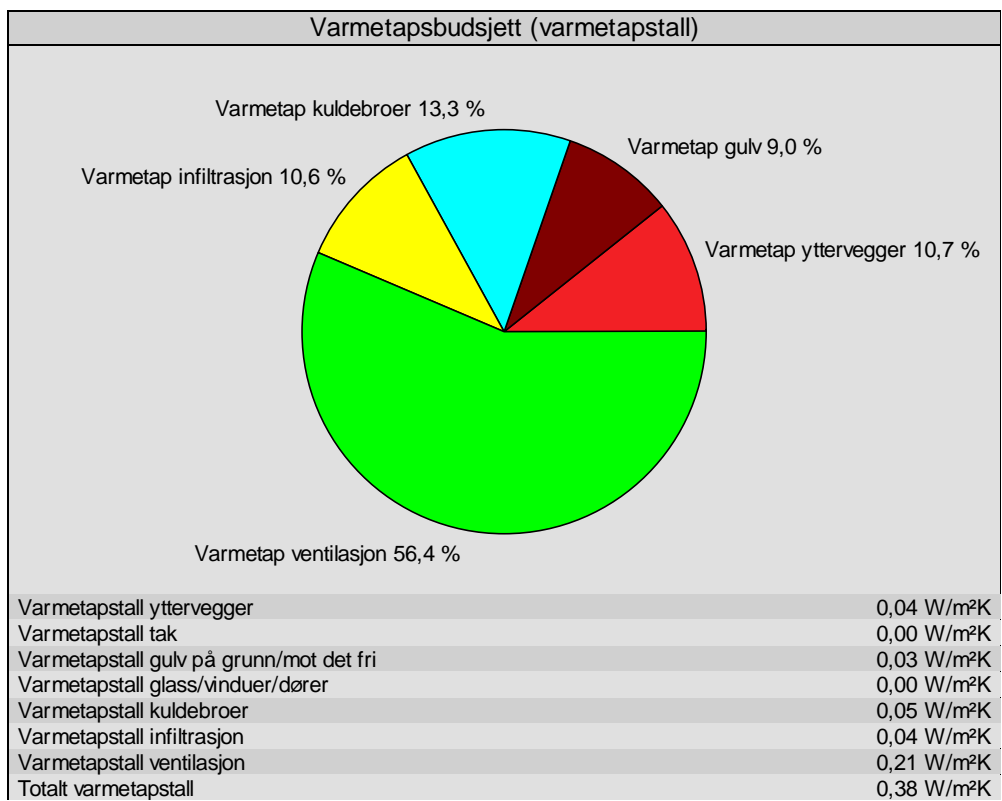
Postene rom og ventilasjonsoppvarming utgjør summen av varmetap ut av bygget. Bygget har lavt varmetap. Postene teknisk utstyr og belysning utgjør over 50 % av byggets energibehov, selv med energieffektiv belysning og redusert teknisk utstyr i arkivene. Beregningene er utført med nærmest mulig reelle driftsforhold. Med standardiserte laster og driftstider vil bildet se annerledes ut.



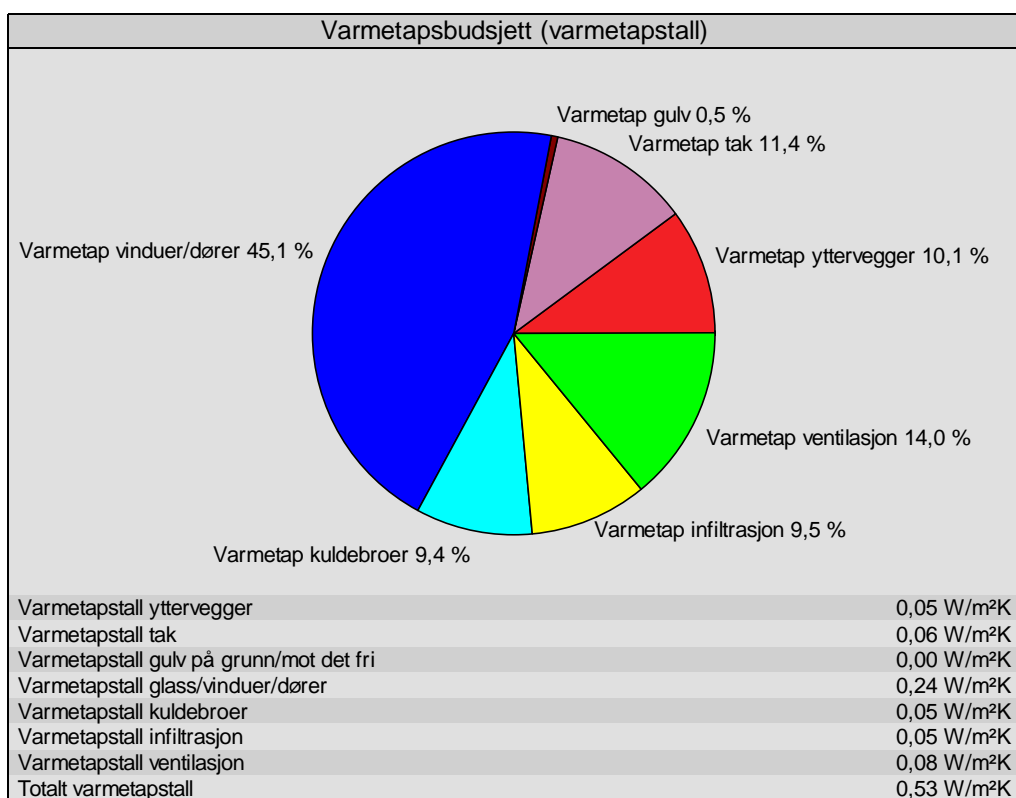
Totalt varmetapstall er på 0,46 hvor 0,14 er varmetap i ventilasjon.

Bygget har i praksis to områder med helt forskjellig driftsmønster med arkiver i underetasjene og kontorer over bakken. Fordeling kontorer og arkiv er ca. 50 %.

Settes figurene for varmetapstall for arkiver og kontordel ved siden av hverandre framgår det tydelig at disse er svært forskjellige.



Varmetapstall Arkiver



Varmetapstall kontordel

Totalt varmetapstall for magasiner er kun 0,38 hvor ventilasjon (grønt) står for over 50 % av dette. Totalt varmetapstall for kontordelen er 0,53 hvor ventilasjon står for kun 14 % av dette.

I magasinene er varmetapene svært lave. Reelle luftmengder kan være lavere enn verdiene som er benyttet i simuleringen.

Energibudsjett

Energibudsjett kontorer

Energipost	Energibudsjett	
	Energibehov	Spesifikt energibehov
1a Romoppvarming	76721 kWh	11,6 kWh/m ²
1b Ventilasjonsvarme (varmebatterier)	1331 kWh	0,2 kWh/m ²
2 Varmtvann (tappevann)	33208 kWh	5,0 kWh/m ²
3a Vifter	42288 kWh	6,4 kWh/m ²
3b Pumper	8866 kWh	1,3 kWh/m ²
4 Belysning	83023 kWh	12,5 kWh/m ²
5 Teknisk utstyr	166046 kWh	25,1 kWh/m ²
6a Romkjøling	0 kWh	0,0 kWh/m ²
6b Ventilasjonskjøling (kjølebatterier)	16539 kWh	2,5 kWh/m ²
Totalt netto energibehov, sum 1-6	428022 kWh	64,6 kWh/m ²

Energibudsjett magasiner

Energipost	Energibudsjett	
	Energibehov	Spesifikt energibehov
1a Romoppvarming	904 kWh	0,1 kWh/m ²
1b Ventilasjonsvarme (varmebatterier)	21750 kWh	3,5 kWh/m ²
2 Varmtvann (tappevann)	0 kWh	0,0 kWh/m ²
3a Vifter	70663 kWh	11,3 kWh/m ²
3b Pumper	2262 kWh	0,4 kWh/m ²
4 Belysning	72079 kWh	11,5 kWh/m ²
5 Teknisk utstyr	36040 kWh	5,7 kWh/m ²
6a Romkjøling	0 kWh	0,0 kWh/m ²
6b Ventilasjonskjøling (kjølebatterier)	17740 kWh	2,8 kWh/m ²
Totalt netto energibehov, sum 1-6	221439 kWh	35,3 kWh/m ²

Arkivdelen trekker ned energibehovene betydelig i forhold til kontordelen.

Faktiske behov i arkiver kan det forventes et enda lavere energibehov til bla ventilasjon og belysning.

For kontordelen har enkeltsoner som atrie og kantineområdet betydelig høyere energibehov enn resterende soner. Dette vil bli omhandlet i senere avsnitt.

3.2 Validering mot TEK10

Et nybygg skal oppfylle krav til energiltak (§14.3-1) eller varmetapsramme (§14.3-4). Energiltak lister flere predefinerte minimumsverdier som må være oppfylt om man velger dette, ellers må bygget ha et netto energibehov som er mindre enn 150kWt/m² i Oslo klima. Driftstider, internlast etc. som er endret for årssimulering vil bli overstyrt og beregnet med standardverdier ihht. NS3031. Validering mot TEK gjennomføres i Simien. Resultatet er vist i tabellen under

Resultater av evalueringen	
Evalueringsav	Beskrivelse
Energiltak	Bygningen tilfredsstillere kravene til energiltak i paragraf §14-3 (1)
Varmetapsramme	Bygningen tilfredsstillere omfordeling energiltak (varmetapstall) ihht. §14-3 (3)
Energiramme	Bygningen tilfredsstillere energirammen ihht. §14-4
Minstekrav	Bygningen tilfredsstillere minstekravene i §14-5
Luftmengder ventilasjon	Luftmengdene tilfredsstillere minstekrav gitt i NS3031:2010 (tabell A.6)
Energiforsyning	Bygningen tilfredsstillere krav til energiforsyning i §14-7
Samlet evaluering	Bygningen tilfredsstillere byggeforskriftenes energikrav

Bygget oppfyller energikrav i TEK10 både gjennom tiltaksmodell og energiramme.

3.3 Passivhusevaluering

Det er utført passivhusevaluering av bygget i SIMIEN. Bygget oppfyller ikke minstekrav til kuldebroverdier, og oppfyller derav heller ikke krav til energiytelse for passivhus.

Dersom normalisert kuldebroverdi kan reduseres fra 0,05 til dokumentert 0,03, vil bygget tilfredsstillere alle krav til passivhus dersom hele bygget evalueres i bygningskategori kontorbygg. Ved evaluering av hele bygget mot bygningskategori kutlurbygg, vil bygget ikke kunne oppfylle krav til passivhusstandard. Ved evaluering hver for seg, vil kontorbygget ikke kunne oppnå passivhusstandard

Resultater av evalueringen	
Evalueringsav	Beskrivelse
Evalueringsav mot NS 3701	
Varmetapsramme	Bygningen tilfredsstillere kravet for varmetapstall
Energiytelse	Bygningen tilfredsstillere krav til energiytelse
Minstekrav	Bygningen tilfredsstillere ikke minstekrav til enkeltkomponenter
Luftmengder ventilasjon	Luftmengdene tilfredsstillere minstekrav gitt i NS3701 (tabell A.2)
Samlet evaluering	Bygningen tilfredsstillere ikke alle krav til passivhus

Passivhusevaluering av hele bygget som kontorbygg, uten forbedret kuldebroverdi

3.4 Energimerkesimulering

Bygget består av en kontordel og en magasindel. .

Kontordelen er et kontorbygg, med internlaste som dette, mens arkivene vil passe best i kategori lagerbygning. Andre bygningskategori som eks kulturbygg passer mindre bra da minimumsventilasjonsluftmengde er betydelig høyere og internlast svært mye lavere for denne kategorien, og tilsvarende vil gjelde for universitet/høgskolebygg.

Byggherren har et krav om energimerke A for bygget.

Denne rapporten vurderer ikke energiforsyning til bygget, men ut fra forutsetninger beskrevet av GK med en energiforsyning basert på lavtemperert varmepumpe med ytelse tilsvarende Ullandhaug Energi med gass til spisslast, vil bygget kunne oppnå energimerke A. Det er utført energimerkesimuleringer for ulike scenarier. Scenariene listet i tabellen under

Inkluderte areal	Kategori	Energimerke
Kontor	kontorbygg	A
Magasin	Lagerbygg	A
Kontor og magasin	kontorbygg	A
Kontor og magasin	kulturbygg	A

4 Inneklimasimuleringer

4.1 Sommersimuleringer

Bygget har et stort vindusareal i kontordel. Det er forutsatt solavskjerming på alle solutsatte fasader.

Bygget har store glassarealer mot sør slik at det må verifiseres at innnetemperaturen i lokalene ikke blir for høy. Modellen er delt opp i 8 soner for områder som hører sammen i forhold til belastninger. Operativ temperatur ikke overstige 26 grader i mer enn 50 timer i løpet av et år. Sommersimuleringer har som formål å undersøke om og hvordan dette kravet kan oppfylles i del ulike sonene

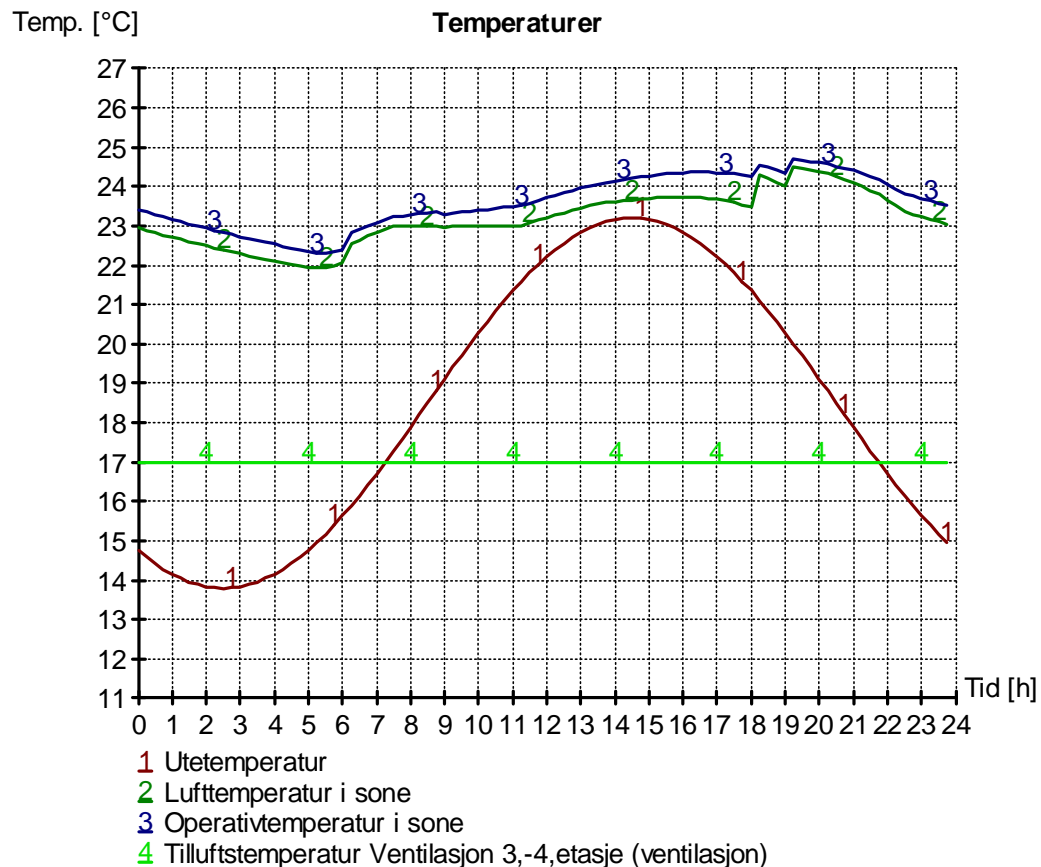
Det er for alle sonene forutsatt komfortkjøling på ventilasjon som ved behov kan redusere tilluftstemperaturen til 17°C. Det forutsettes automatisk solavskjerming som aktiveres med en solflux på 100W/m². Simuleringene forutsetter 5 påfølgende varme dager.

Arkivene ligger under bakkenivå og vil være minimalt påvirket av solbelastning utover ventilasjonsluft og vil ikke vurderes inngående.

Sør- og vestfasader vil ha høyest solbelastning, men midt på sommeren vil også området innenfor glassatriet ha høy belastning.

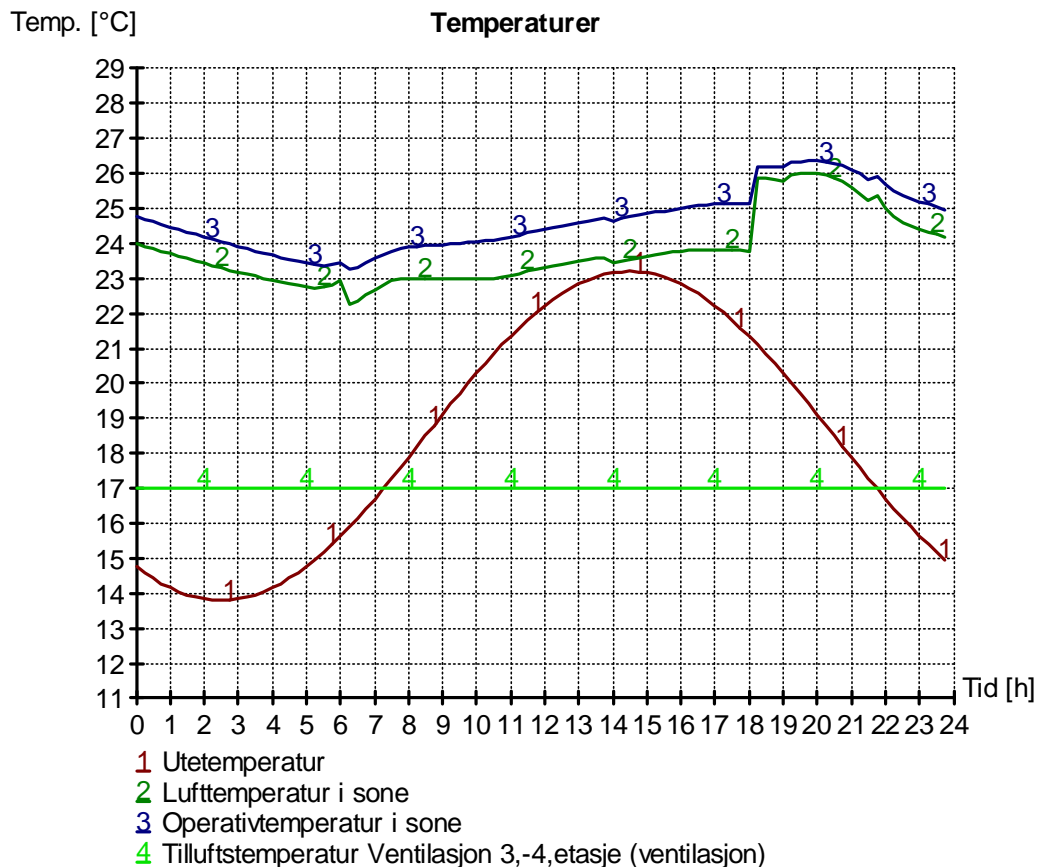
Simulering av de mest utsatte sonene:

Temperaturutvikling i Sone 3-4 etasje sidefløy:



Maksimal operativ temperatur i arbeidstiden vil være <25°C. Når ventilasjonen stoppes kl. 18.00 er det liten økning i temperaturen, dvs. solavskjermingen reduserer solbelastningen til rommene slik at innetemperaturen vil være innenfor ønsket temperaturområde hele døgnet.

Temperaturutvikling i Sone 3-4 etasje vestfløy:



Operativ temperatur vil være høyere for den vestvendte fasaden enn for den sørvendte fasaden, men i hele arbeidstiden vil temperaturen i lokalene være <25°C. Når ventilasjon stoppes kl. 18.00 får man et temperatursprang. Dette kan man unngå ved å forlenge driftstiden på ventilasjonsanleggene når det er høye utetemperaturer.

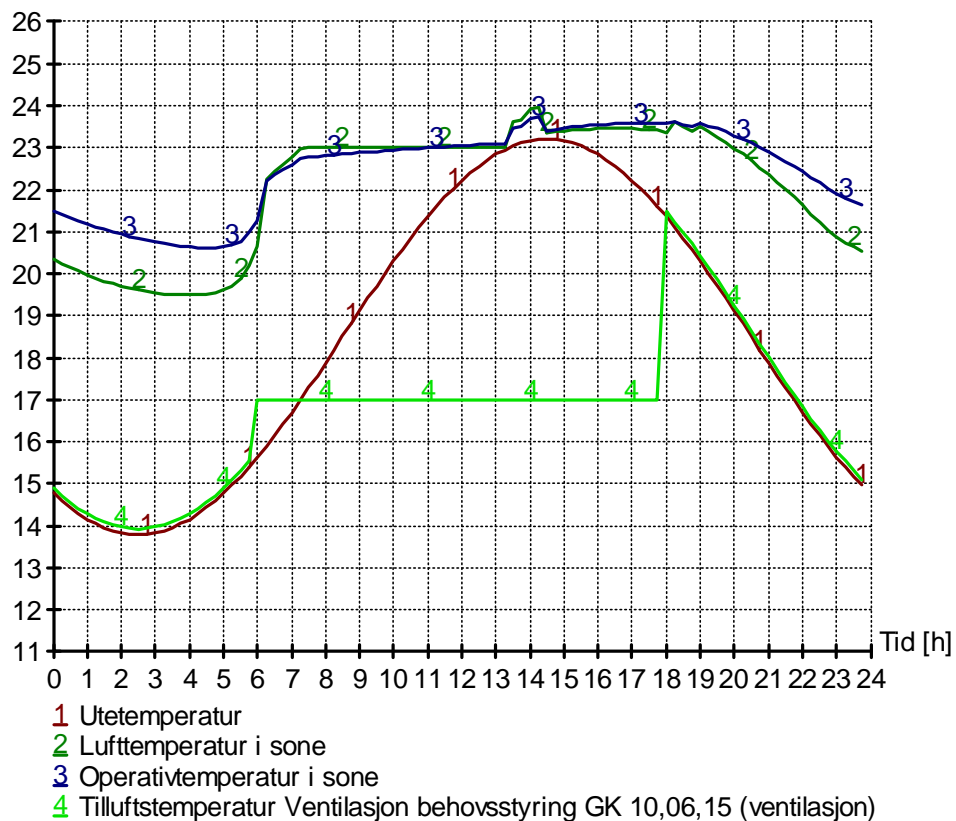
Årsaken til at temperaturen blir høyere på vestfasaden er at fasaden har større andel vinduer enn sørfasaden. Sørfasaden vil kunne akkumulere mer i tunge materialer, men denne effekten avtar utover ettermiddagen. Temperaturene vil være en middeltemperatur i sonen. Da sonene i energimodellen er relativt små og lokalene ventileres med omrøringsventilasjon kan det antas at romtemperaturen i sonene vil være omtrent som simulert.

Det er benyttet en tilluftstemperatur på 17°C som er standardverdi i NS3031 i bygg med kjøling. Det vil etter simuleringene ikke være behov for å redusere denne ytterligere, men ved høyere internlast eller annen drift enn standard vil man kunne ha behov for å redusere tilluftstemperaturen ytterligere.

Temperaturutvikling i glassgård kantinesone:

Temp. [°C]

Temperaturer



Operativ temperatur i sonen vil være under 24°C. Dette med en minimums tilluftstemperatur på 17°C. Simuleringen forutsetter standard varmelaster fra NS3031.

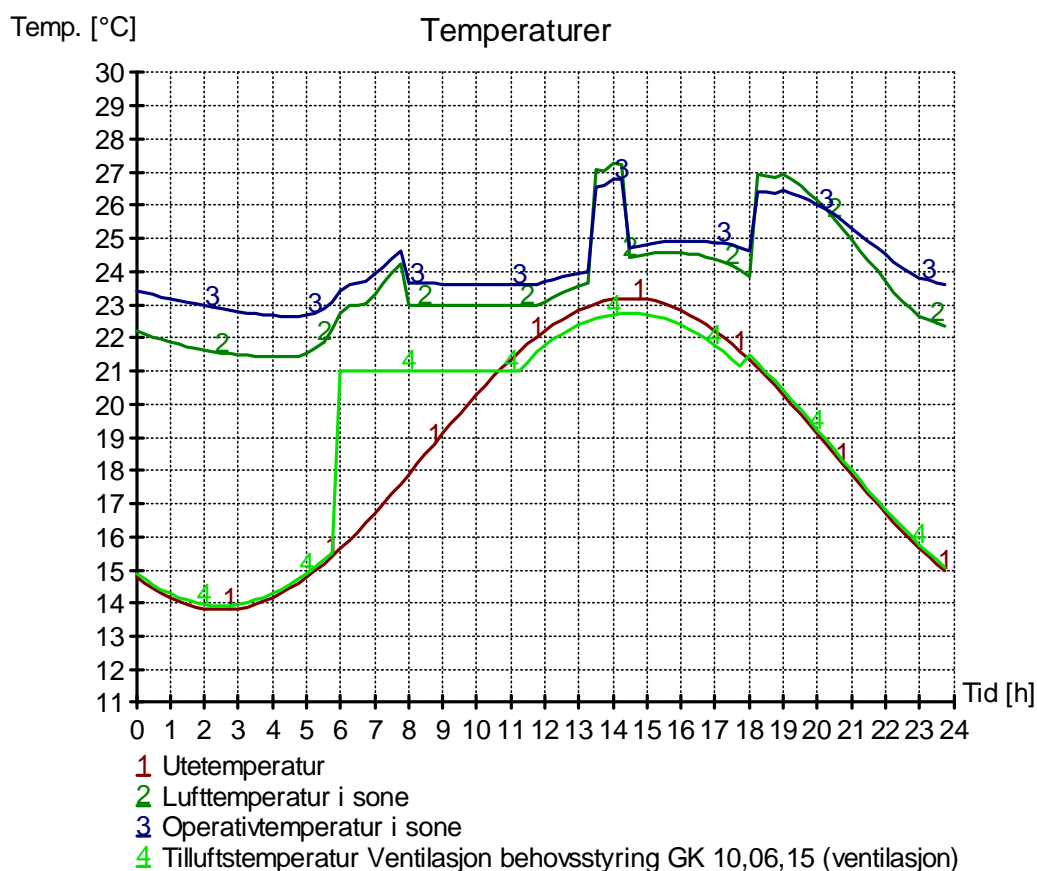
Det er forutsatt at det ikke er kjøling på ventilasjonsluft utover driftstiden på bygget.

I praksis vil kantinesonen ha betydelig høyere belastning i lunchtid, men ha en lavere internlast til teknisk utstyr og belysning. Totalbelastning ikke være høyere enn simuleringen viser.

temperaturutvikling i nordvendt glassatrie

Nordvendt glassatrie er identifisert som et utfordrende område med hensyn på termisk komfort.

I inneklimasimulering for nordvendt glassatrie er det forutsatt maksimal luftmengde 27.000 m³/h, med temperatur 21 grader (overstrømming fra andre arealer). Det er forutsatt mulighet for frikjøling med 10m³/h*m² utenfor driftstid. Fast solfaktor i glass er satt til 0,5, og tilskudd fra teknisk utstyr er satt til 0 W/m².



Temperaturen i sonen vil bli for høy med en operativ opp mot 27°C kl. 14.00. På temperaturgrafene vises temperaturtopper på morgenen når sola står i øst, og på ettermiddagen når sola står i vest. SIMIEN gir ikke noe bilde på hvordan temperaturofordelingen er i atriet. Typisk vil temperaturen være høyest øverst i atriet, og her skal det være gangsoner i flere etasjer, og vinduer fra kontorarealer og ut mot sonen helt opp mot toppen av atriet.

Med en luftmengde på oppmot 50.000m³/h trukket av via atriet, vil maksimal operativ temperatur komme ned mot 26 grader.

Det er flere måter å redusere romtemperaturen. Det er utført simuleringer med innvendig og utvendig solavskjerming, aerogelglass og naturlig ventilasjon med inndata og resultater listet i tabellen under

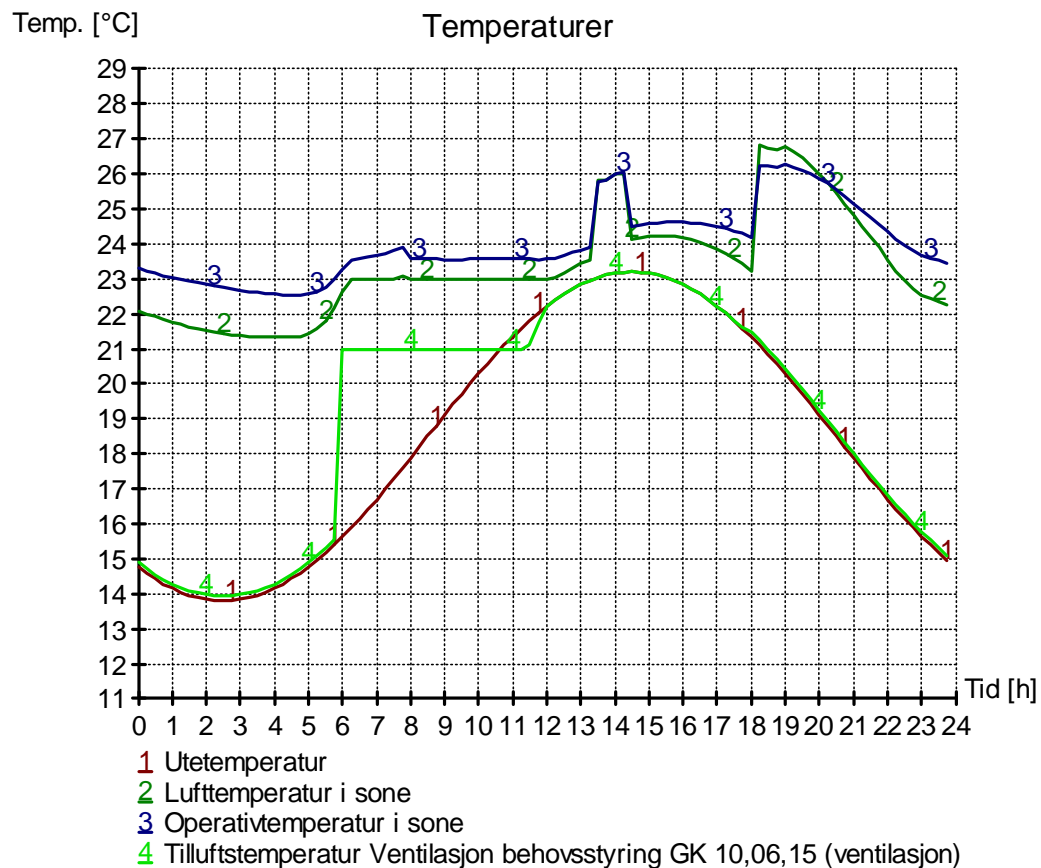
Alle de foreslåtte tiltakene under vil kunne bidra til at temperaturen i sonen holdes under 26 grader.

Teknisk forskrift §14-5 (3)b, stiller krav til Total solfaktor for glass/vindu (gt) skal være mindre enn 0,15 på solbelastet fasade, med mindre det kan dokumenteres at bygningen ikke har kjølebehov. Total solfaktor 0,15 kan kun oppfylles med utvendig solavskjerming eller innvendig solavskjerming kombinert med svært mørke glass. Så lenge ventilasjonen i glassatriet baseres på avtrekksluft fra andre soner, og det ikke tilføres kjølt luft til sonen, kan det argumenteres med at sonen ikke har kjølebehov, slik at komfortkrav kan løses på andre måter enn med total solfaktor 0,15.

Tiltak	T _{max} [°C]	T _{op max} [°C]
Basismodell	27,3	26,8
Med luftmengde 50.000 m ³ /h	26,8	26,3
Med innvendig solskjerming Solfaktor 0.35 aktivert, 0.5 ikke aktivert	26,0	25,7
Med utvendig solskjerming Solfaktor 0.04 aktivert, 0.5 ikke aktivert	24,1	23,9
Med utvendig solskjerming og solfaktor 0.75 i glass Solfaktor 0.04 aktivert, 0.75 aktivert	25,2	24,9
Med 1500m ³ /h naturlig ventilasjon	26,5	25,9
Med aerogelglass i glassatrie og utv. avskjerming fasadeglass Aerogel fast solfaktor 0.3 , U-verdi 0.3 Fasadeglass Solfaktor 0.04 aktivert, 0.5 ikke aktivert	25,2	24,8

Temperaturutvikling i nordvendt glassatrie med luftmengde 50.000m³/h

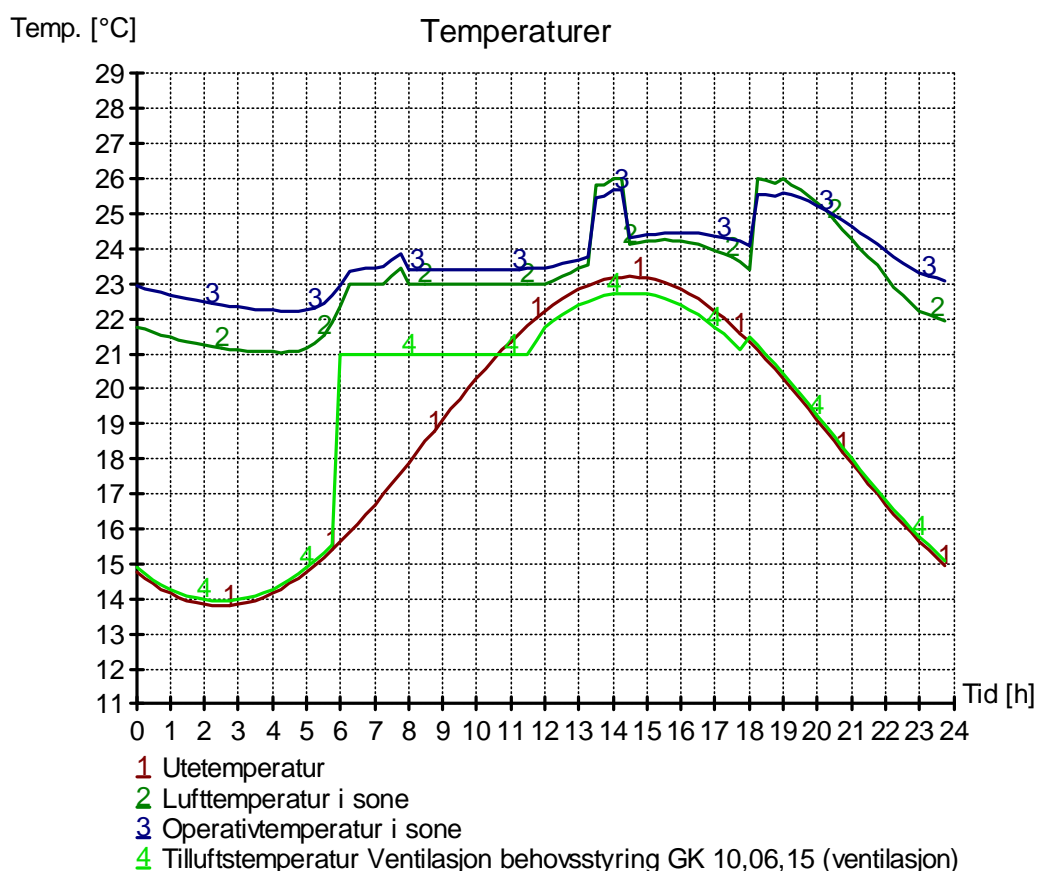
Simuleringen er utført med luftmengde 50.000m³/h avtrekk i sonen. Makismal operativ temperatur blir 26,3 grader, men holder seg under 26 grader i arbeidstiden



Temperaturutvikling i nordvendt glassatrie med innvendig solavskjerming

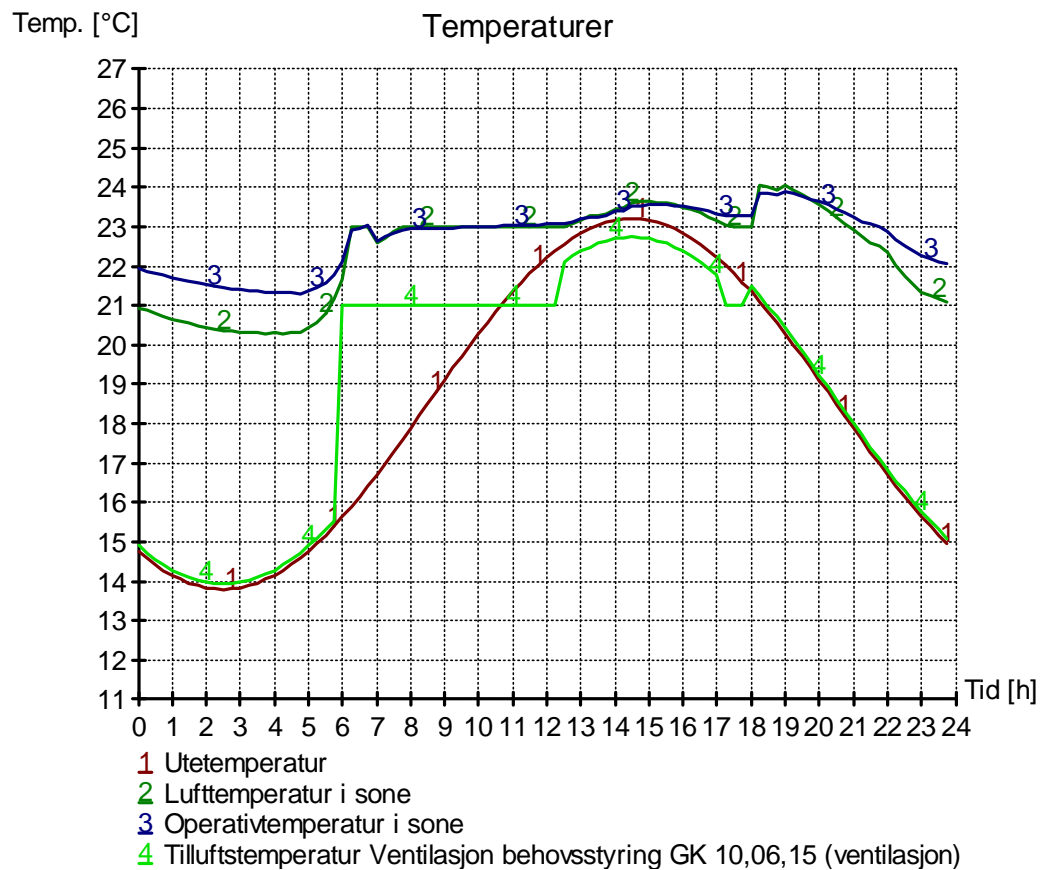
Simuleringen er utført med solfaktor 0.35 aktivert og 0.5 når ikke aktivert. Toppene fra basisimuleringen er de samme, men er noe dempet. Operativ temperatur er opp i mot 26 grader på det høyeste.

Innvendig solavskjerming gir typisk ikke mer enn 30% forbedring av solfaktor i forhold til fast solavskjerming i glasset. Altså må det stilles strengere krav til solfaktor i glassene for å komme i mål, noe som gir mindre dagslys. Det finnes innvendige solskjermingsløsninger som kan gi bedre solfaktor, eksempelvis reflekterende duk, men dette kan være et relativt kostbart alternativ.



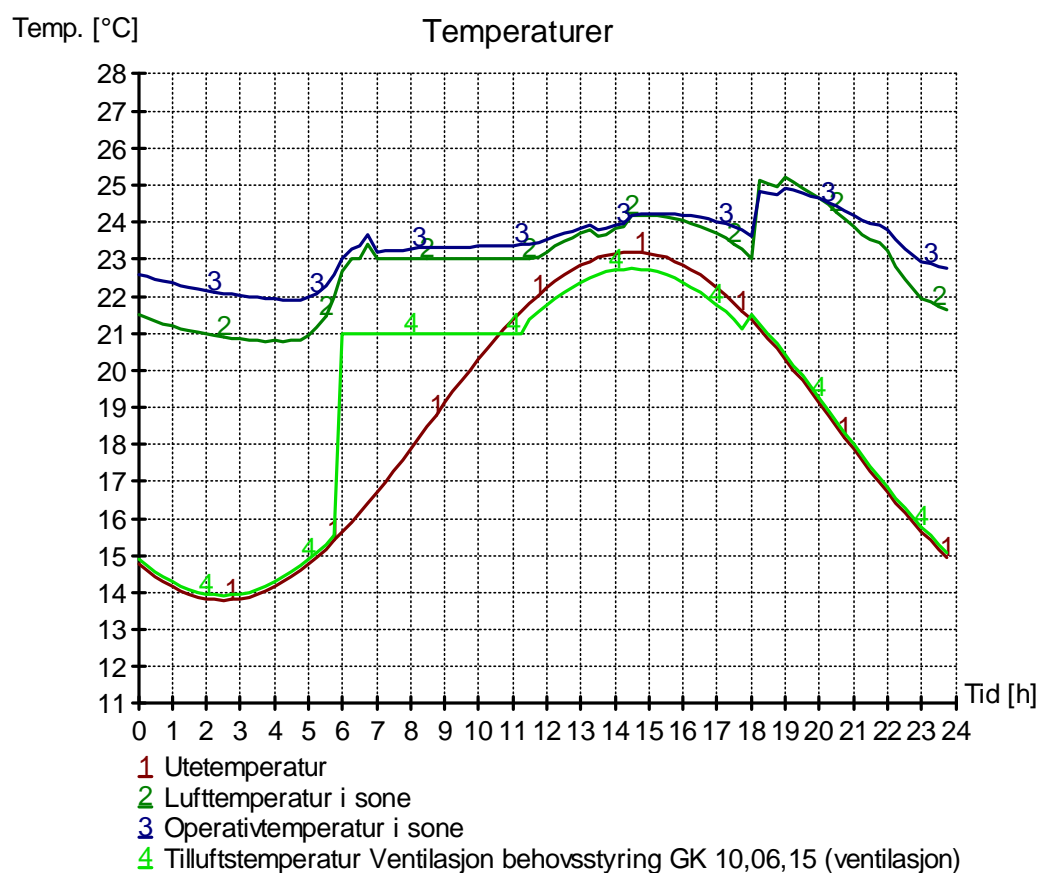
Temperaturutvikling i nordvendt glassatrie med utvendig solavskjerming

Simuleringen er utført med solfaktor 0.04 når aktivert og 0.5 når ikke aktivert. Toppene fra basisimuleringen er nesten helt glattet ut. Operativ temperatur er ikke over 24,4 grader.



Temperaturutvikling i nordvendt glassatrie med utvendig solavskjerming og solfaktor 0,75

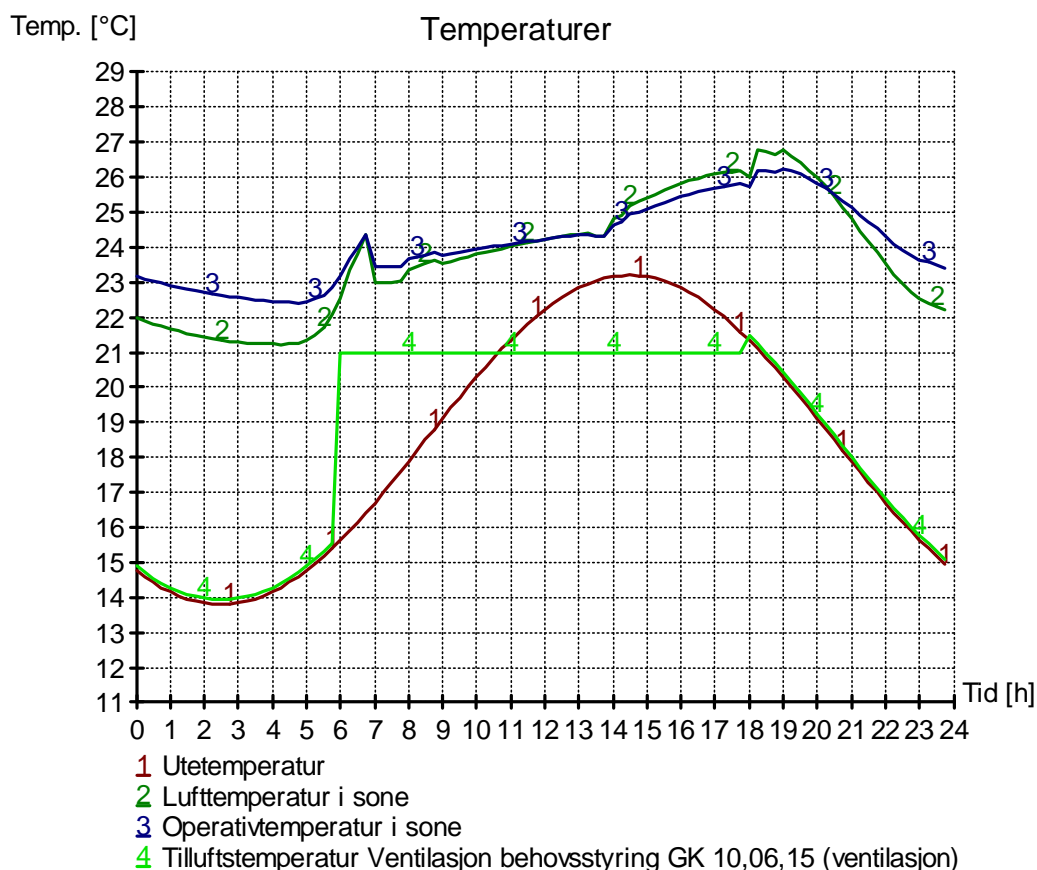
Simuleringen er utført med solfaktor 0.04 når aktivert og 0.75 når ikke aktivert. Toppene fra basisimuleringen er nesten helt glattet ut. Operativ temperatur er ikke over 24,9 grader. Altså gir utvendig solavskjerming fleksibilitet til å velge glass med høyt innslipp av dagslys.



Temperaturutvikling i nordvendt glassatrie med 1500m³/h naturlig ventilasjon

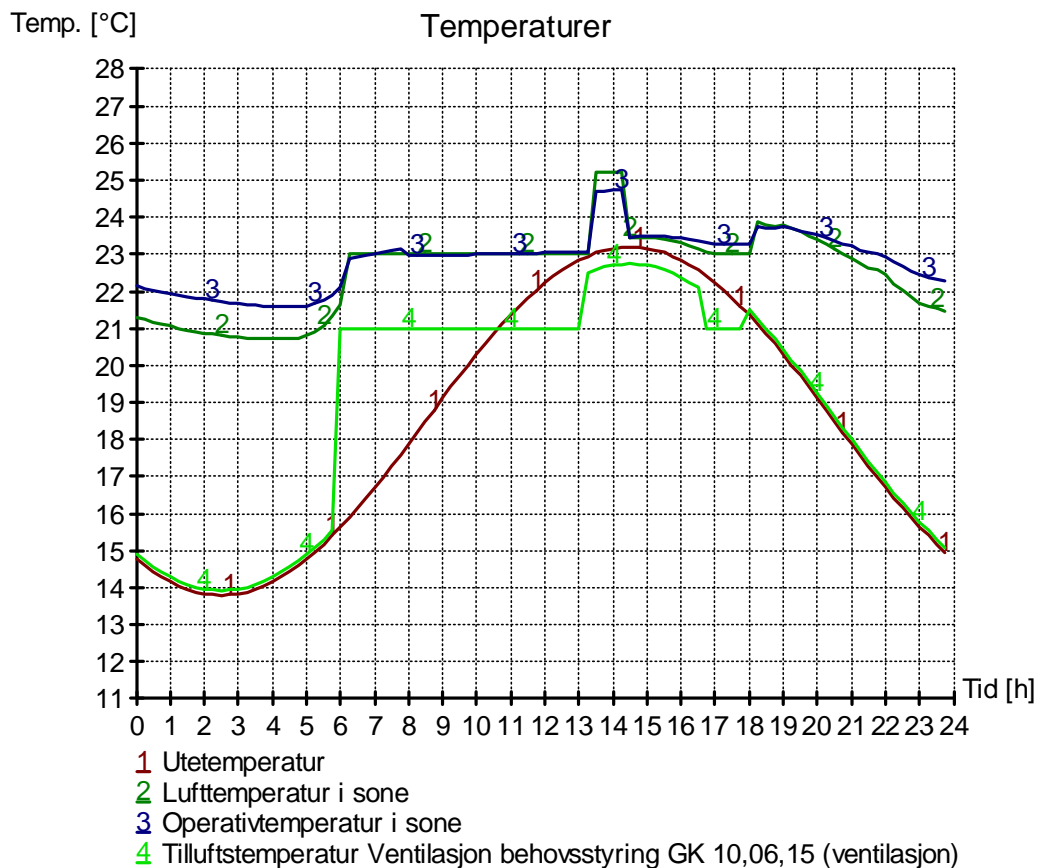
Simuleringen er utført med fast solfaktor i vinduer på 0,5. Toppene fra basisimuleringen er nesten helt glattet ut. Operativ temperatur er ikke over 26,3 grader. Temperaturtoppen kommer dessuten etter arbeidstid.

Det forutsettes at balansert ventilasjon kjører luftmengde 27000 m³/h gjennom sonen, samtidig som det åpnes for naturlig ventilasjon. nødvendig areal for 1500 m³/h naturlig ventilasjon vil være 2,5-3m² dersom man skal minimere trykkfall og utnytte naturlige drivkrefter. Det må da være tilgjengelig areal på denne størrelsen i 1. etasje av bygget som kan åpnes etter behov. Avtrekket fra naturlig ventilasjon kan prinsipielt løses på to måter. Uten hjelpevifte, med tilsvarende areal takluker i atriet, eller gjennom avtrekksrister inn til teknisk rom knyttet til hjelpevifter eller gjennom aggregat (NB! Å øke tilluftmengde gjennom atriet med 1500m³/h vil ikke gi samme effekt. Da denne har høyere temperatur, må luftmengde økes mer)



Temperaturutvikling i nordvendt glassatrie med aeroglass i atriene

Simuleringen er utført med fast solfaktor i atrieglass på 0,3 og U-verdi 0,3 W/m²K. Det er forutsatt utvendig solavskjerming på de andre vinduene inn mot sonen. Temperaturtopp operativ temperatur på 24,8 grader.



4.2 Vintersimuleringer

For å finne nødvendige oppvarmingsbehov gjennomføres vintersimulering av bygget.

Bygget har store vindusareal i kontordel og varmetap fra disse vil kunne medføre kaldras ved vinduer. Dette omhandles ikke denne rapporten.

Modellen er delt opp i 8 soner for områder som hører sammen i forhold til belastninger.

Det er for alle sonene forutsatt tilluftstemperatur konstant på 19°C. I praksis bør denne reguleres ut fra utetemperatur og økes mot settpunktet til rommene når utetemperaturen synker.

Det forutsettes automatisk solavskjerming som aktiveres med en solflux på 100W/m².

Maksimal effekt til romoppvarming er satt til 25W/m².

Luftmengde i driftstiden er ihht. minimumsverdi i TEK på 7m³/m².

Dette vil være høyt ved dimensjonerende utetemperaturer slik at det legges inn en redusert luftmengde ved utetemperaturer lavere enn -10°C på 5m³/m², en verdi som med behovsstyring i praksis gjerne kan være enda lavere.

Simuleringene forutsetter 3 påfølgende kalde vinterdager i januar måned. (Dimensjonerende utetemperaturer 3 påfølgende dager)

Arkivene under bakkenivå inngår i simuleringene.

Vintersimulering av bygg gir følgende effektbehov:

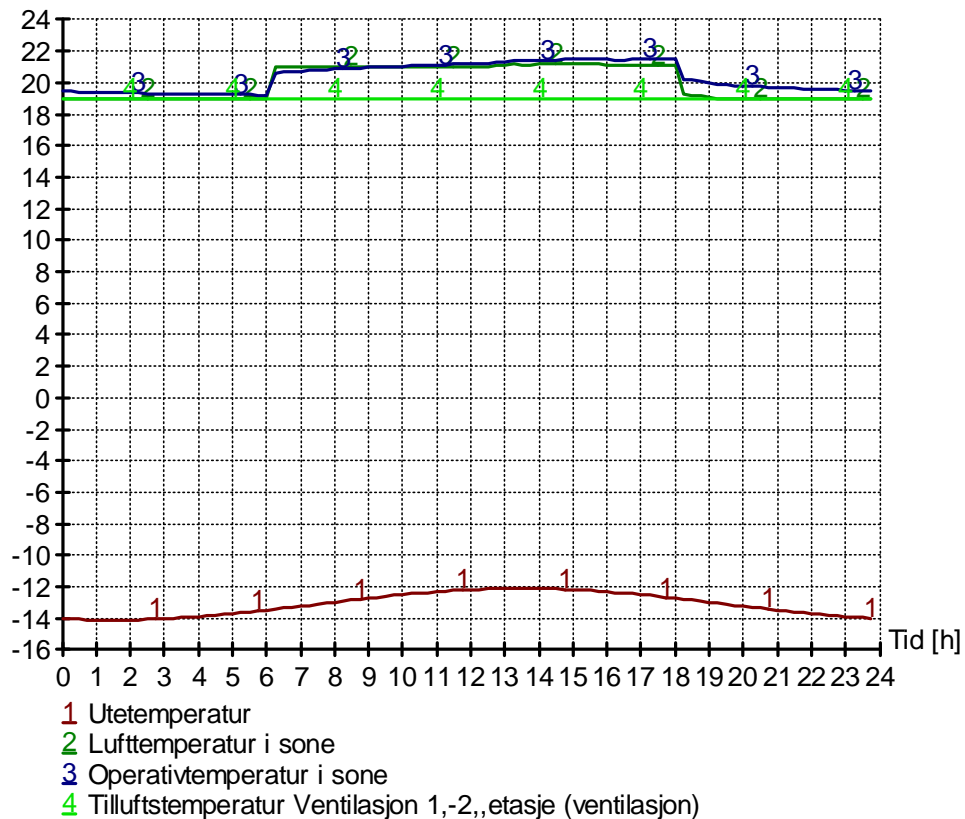
Beskrivelse	Dimensjonerende verdier	
	Verdi	Tidspunkt
Maks. samtidig effekt varmebatterier:	74,3 kW / 5,8 W/m ²	06:00
Totalt installert effekt varmebatterier	324,4 kW / 25,1 W/m ²	06:00
Maks. samtidig effekt romoppvarming:	100,1 kW / 7,8 W/m ²	06:00
Totalt installert effekt romoppvarming	322,6 kW / 25,0 W/m ²	06:00
Min. romlufttemperatur:	14,7 °C	06:00
Min. operativ temperatur:	15,8 °C	06:00
Maksimal CO2 konsentrasjon (arkiv plan U1, U2, U3)	675 PPM	21:00

Settpunkt i simuleringer er 21°C for alle lokaler uten arkivene som er i henhold til NS3031 og en nattsinking til 19°C utenom driftstid, I praksis vil man gjerne ønske en noe høyere romtemperatur i kontorlokaler med stillesittende arbeide. Dette kan sikres enten med lokal romoppvarming, eller en forsiktig økning av tilluftstemperatur og redusert nattsinking. Det er et prosjektkrav at man skal kunne styre temperatur innenfor egen sone. Løsning som velges må ivareta dette.

Temperaturutvikling nordvendte kontorer 1-2 etasje

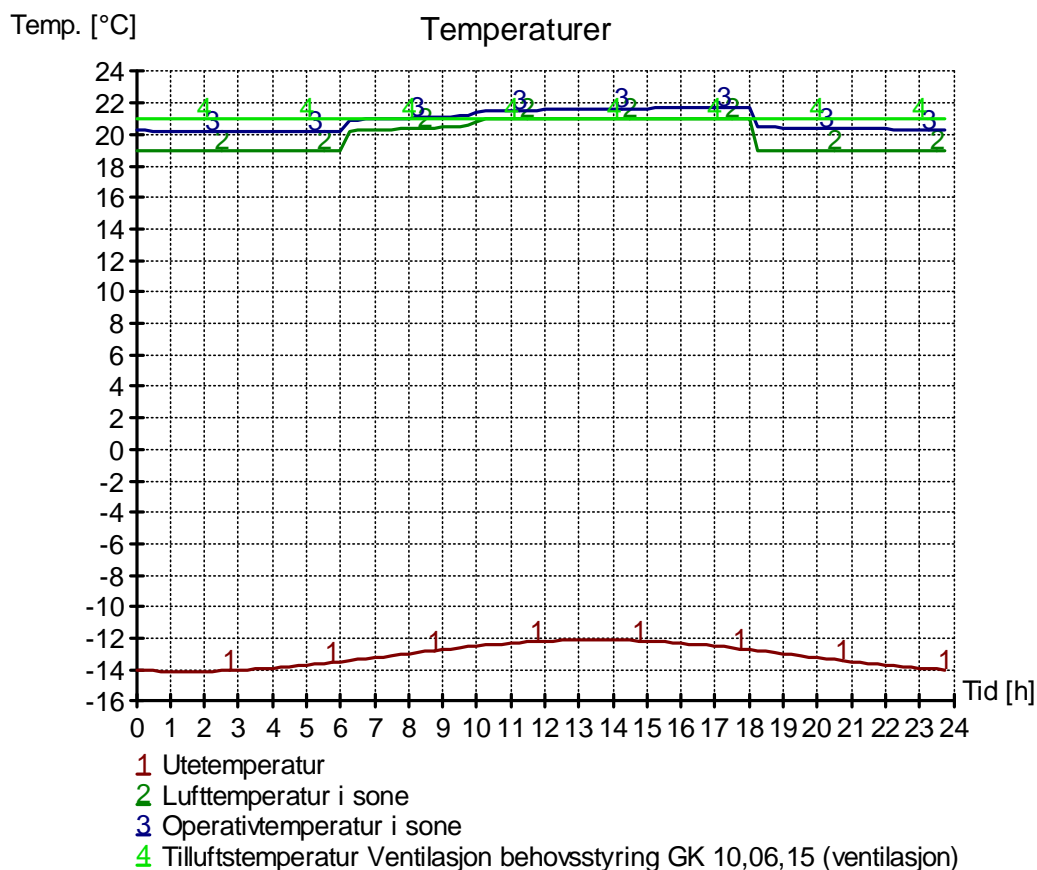
Temp. [°C]

Temperaturer



I arbeidstiden er operativ temperatur på settpunkt. Med nattsinking på temperaturen i lokalene er det viktig at romoppvarmingen har kapasitet til å heve temperaturen tilstrekkelig raskt når det kommer personer i lokalene.

Temperaturutvikling nordvendt glassatrie.



Selv et varmeanlegg med 30W/m² på ventilasjon og 25W på romoppvarming er ikke tilstrekkelig til å holde romtemperaturen til ønsket nivå. Her er det store glassarealet i tak årsaken til dette. Energibudsjettet for denne sonen viser tydelig at denne skiller seg fra de andre sonene ved at varmetapene er store.

Energipost	Energibudsjett	
	Energibehov	Spesifikt energibehov
1a Romoppvarming	36099 kWh	116,1 kWh/m ²
1b Ventilasjonsvarme (varmebatterier)	1018 kWh	3,3 kWh/m ²
2 Varmtvann (tappevann)	1559 kWh	5,0 kWh/m ²
3a Vifter	7828 kWh	25,2 kWh/m ²
3b Pumper	1328 kWh	4,3 kWh/m ²
4 Belysning	1948 kWh	6,3 kWh/m ²
5 Teknisk utstyr	0 kWh	0,0 kWh/m ²
6a Romkjøling	0 kWh	0,0 kWh/m ²
6b Ventilasjonskjøling (kjølebatterier)	564 kWh	1,8 kWh/m ²
Totalt netto energibehov, sum 1-6	50343 kWh	161,9 kWh/m ²

Arealet på sonen er relativt lite slik at totalt utgjør økningen i energibehov for sonen ca. 4 %, men kun 0,2 % av totalen for hele bygget.

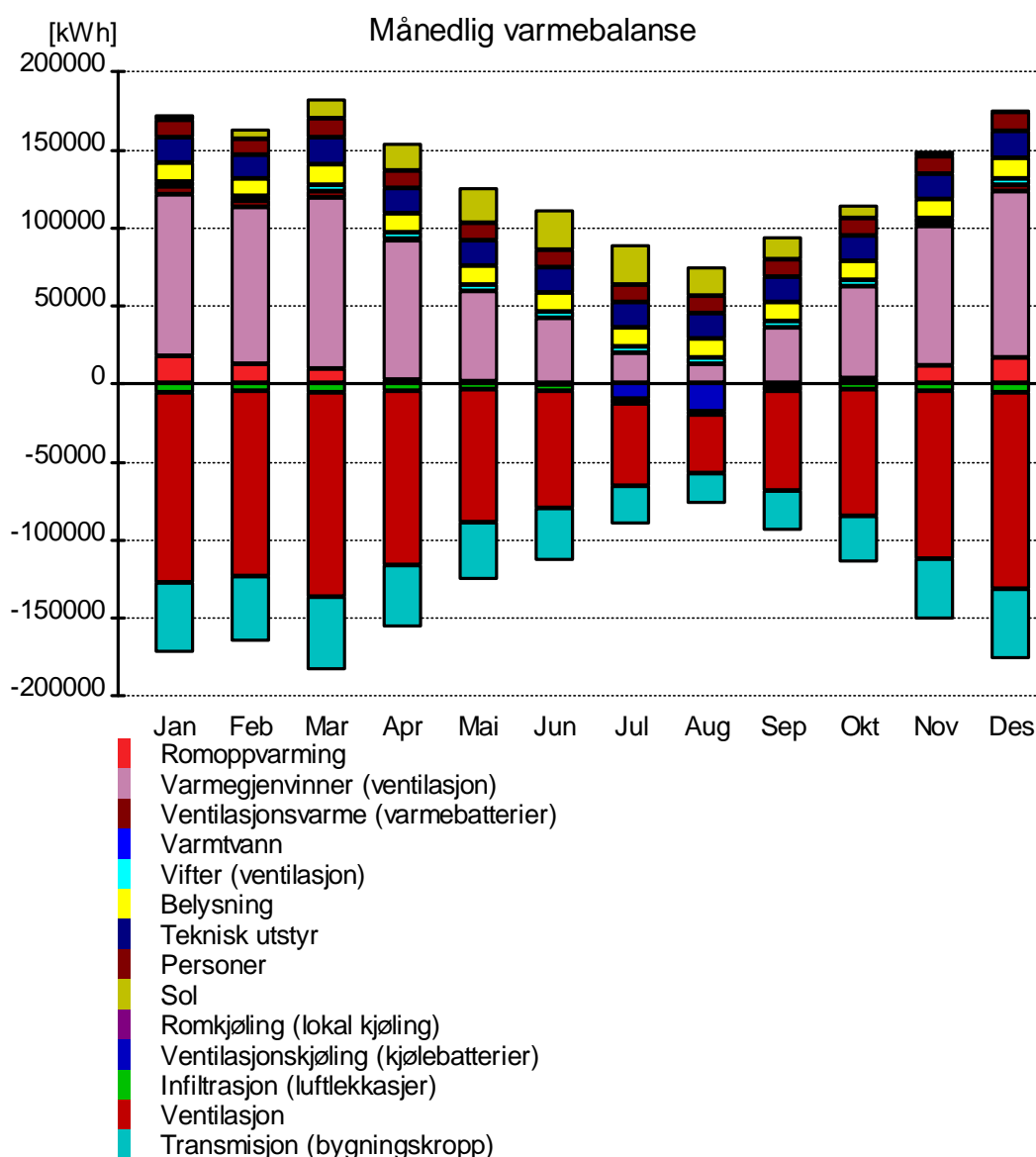
Midlere U-verdi på alle vinduer er satt til 0,8W/m², men i vinter- og sommersimuleringer er U-verdi på vinklede glassflater satt til 1,0W/m².

5 Effektbehov til varme og kjøling

Effektbehov til oppvarming finnes ut fra årssimulering med utgangspunkt i basissimuleringen, da ingen av tiltakene vil ha særlig påvirkning på vurdering av effektbehovene.

Fordeling mellom ventilasjonsoppvarming og romoppvarming vil avhenge av temperaturstyring på ventilasjon, og bør såfremt legges en stor del via ventilasjonen slik at tilluftstemperatur økes opp mot settpunkt for rom (men ikke over) Dette gir raskere responstid på systemet og man sikrer at varmegjenvinner utnyttes optimalt.

Månedlig netto varmebalanse fordeler seg over året med større andel soltilskudd om sommeren



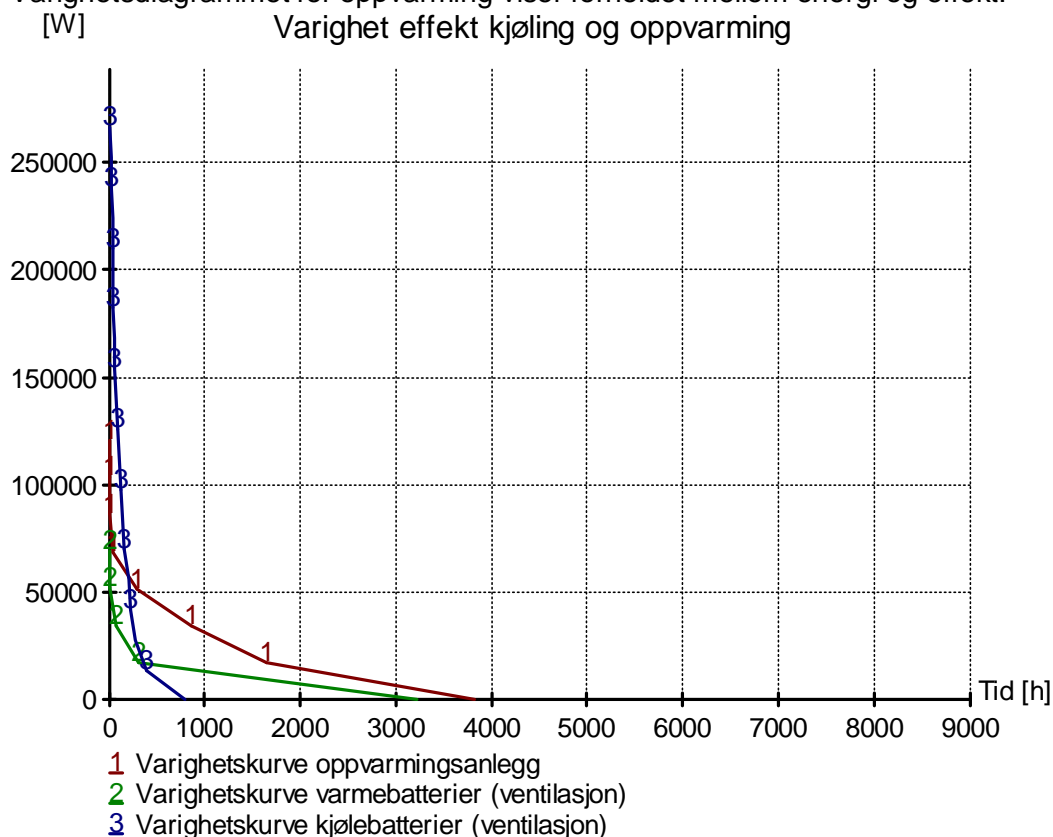
Oppvarmingssystemet skal dekke kun en liten del av energibehovene, og det er kun behov i en liten del av året.

Teknisk utstyr, belysning, personer og sol står for en god del av oppvarmingen utover det som varmegjenvinneren dekker, og utgjør på vinteren.

Teknisk utstyr ligger i energimodellen inne med en varmelast på $11\text{W}/\text{m}^2$ som er verdier fra NS3031. Dette er med dagens tekniske utstyr (Datamaskiner/printere etc) noe høyt i forhold til reelle verdier, og med mer energieffektivt utstyr kan man på sikt oppleve at oppvarmingsbehovene i lokalene øker –og kjølebehovene reduseres på grunn av dette.

I lokaler som kantine, korridorer etc vil det være minimalt med teknisk utstyr. Dette må tas hensyn til ved utforming av varmeanlegget i bygget. Detaljerte inneklimasimuleringer vil kunne vise dette.

Varighetsdiagrammet for oppvarming viser forholdet mellom energi og effekt:



Simuleringen viser et maksimalt effektbehov til kjøling på ca. 280kW, mens det er vanskeligere å lese effektbehovene til oppvarming av figuren.

Tabellen under viser effekt og energidekning med forskjellige effekter.

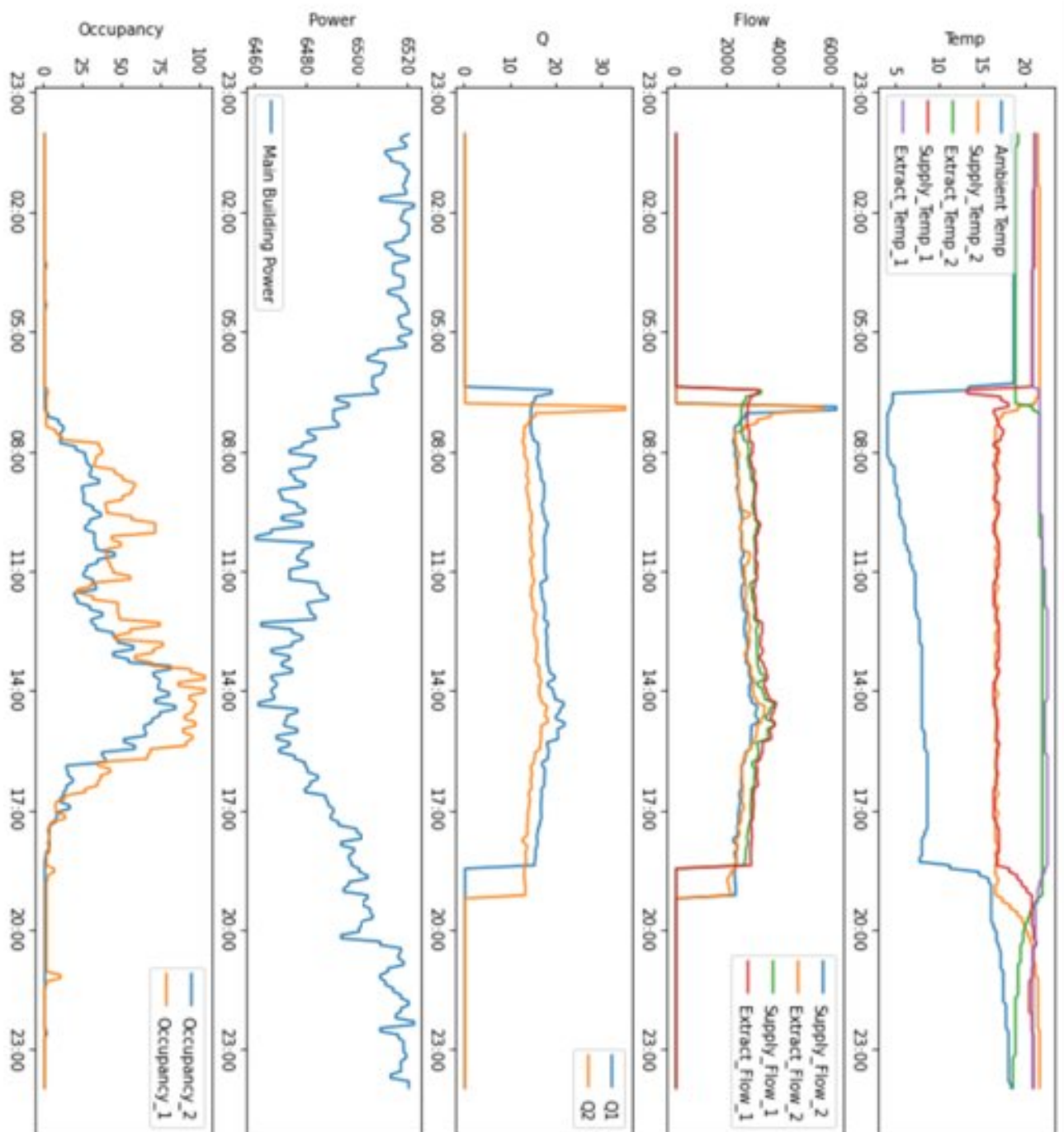
Beregningen viser at 70 % effektdekning dekker hele oppvarmingsbehovet. Dette betyr at det er få timer i løpet av et år man er over denne effekten.

Effekt (dekning)	Dekningsgrad effekt/energi oppvarming	Dekningsgrad energibruk
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 %
Nødvendig effekt til oppvarming av tappevann er ikke inkludert		-

Spisseeffekten til oppvarming vil være ca. 180kW inkludert tappevann. Da spissene er svært høye vil man i praksis kunne glatte dette med noe akkumulering, men dette avhenger av system, styring og fordeling. Tappevann utgjør kun en liten del av total effekt.

Appendix D

NORCE sensor data



Appendix E

NORCE power data

	time	value
22723	00:02:51	6520
22727	00:22:51	6521
22728	00:17:52	6521
22729	00:37:51	6517
22730	00:07:51	6520
22731	00:12:51	6520
22732	00:27:51	6521
22733	00:32:51	6521
22734	00:57:51	6514
22735	00:42:51	6517
22736	00:47:51	6515
22737	00:52:51	6515
22738	01:02:52	6514
22739	01:22:51	6522
22740	01:17:51	6522
22741	01:07:51	6518
22742	01:12:51	6518
22743	01:27:51	6519
22744	01:42:52	6515
22745	01:32:51	6519
22746	01:47:51	6522
22747	01:37:51	6515
22748	01:57:51	6517
22749	01:52:51	6522
22750	02:17:51	6520
22751	02:12:51	6518
22752	02:02:51	6517
22753	02:07:51	6518
22754	02:37:51	6515
22755	02:22:51	6520
22756	02:27:51	6519
22757	02:32:51	6519
22758	02:42:51	6515
22759	02:57:51	6520
22760	02:47:51	6521
22761	03:02:51	6520
22762	03:17:51	6512
22763	03:07:51	6521
22764	03:12:51	6521
22765	02:52:51	6521
22766	03:22:51	6512
22767	03:37:51	6517
22768	03:27:51	6518
22769	03:32:51	6518
22770	03:42:52	6517
22771	03:57:51	6519

22772	03:52:51	6522
22773	04:02:51	6519
22774	03:47:52	6522
22775	04:17:51	6522
22776	04:07:51	6518
22777	04:22:51	6522
22778	04:12:51	6518
22779	04:42:51	6510
22780	04:27:51	6522
22781	04:47:51	6520
22782	05:02:51	6523
22783	04:52:51	6520
22784	04:57:51	6523
22785	05:12:51	6520
22786	05:07:51	6520
22787	05:17:51	6518
22788	05:22:51	6518
22789	05:27:51	6512
22790	05:32:51	6512
22791	04:32:51	6522
22792	04:37:51	6510
22793	05:42:51	6506
22794	05:37:51	6506
22795	05:47:52	6510
22796	06:07:51	6509
22797	06:02:51	6507
22798	06:12:51	6509
22799	05:52:52	6510
22800	05:57:51	6507
22801	06:32:51	6504
22802	06:17:51	6508
22803	06:27:51	6504
22804	06:22:51	6508
22805	06:37:51	6486
22806	06:52:51	6493
22807	06:47:51	6493
22808	06:42:51	6486
22809	06:57:51	6488
22810	07:17:51	6480
22811	07:02:51	6488
22812	07:07:52	6494
22813	07:12:51	6494
22814	07:37:51	6478
22815	07:27:52	6486
22816	07:32:51	6486
22817	07:22:52	6480
22818	07:42:51	6478

22819	07:57:51	6474
22820	08:02:51	6474
22821	07:47:51	6484
22822	07:52:51	6484
22823	08:07:51	6479
22824	08:27:51	6479
22825	08:12:52	6479
22826	08:22:51	6480
22827	08:17:51	6480
22828	08:32:52	6479
22829	08:47:51	6478
22830	08:37:51	6466
22831	08:42:51	6466
22832	08:52:52	6478
22833	09:12:51	6467
22834	09:02:52	6472
22835	09:07:51	6467
22836	08:57:51	6472
22837	09:32:51	6467
22838	09:17:51	6472
22839	09:22:51	6472
22840	09:27:51	6467
22841	09:42:51	6461
22842	09:37:51	6461
22843	09:57:51	6478
22844	09:52:51	6476
22845	09:47:51	6476
22846	10:02:51	6478
22847	10:22:51	6470
22848	10:07:51	6473
22849	10:17:51	6470
22850	10:12:51	6473
22851	10:27:51	6487
22852	10:42:51	6474
22853	10:32:51	6487
22854	10:37:51	6474
22855	10:47:51	6470
22856	11:02:51	6481
22857	10:57:51	6481
22858	11:17:51	6473
22859	10:52:51	6470
22860	11:12:51	6482
22861	11:22:51	6473
22862	11:07:51	6482
22863	11:27:52	6477
22864	11:47:51	6481
22865	11:37:51	6480

22866	11:42:51	6480
22867	11:32:51	6477
22868	12:07:51	6471
22869	11:52:51	6481
22870	11:57:51	6479
22871	12:02:51	6479
22872	12:27:51	6486
22873	12:17:51	6480
22874	12:22:51	6480
22875	12:12:51	6471
22876	12:47:52	6483
22877	12:32:51	6486
22878	12:37:51	6480
22879	12:42:51	6480
22880	13:07:51	6483
22881	12:57:51	6479
22882	13:02:51	6479
22883	12:52:51	6483
22884	13:12:51	6483
22885	13:32:51	6475
22886	13:17:51	6483
22887	13:22:51	6483
22888	13:37:51	6481
22889	13:42:51	6481
22890	13:27:51	6475
22891	14:02:51	6487
22892	13:47:51	6482
22893	13:52:51	6482
22894	13:57:51	6487
22895	14:22:51	6489
22896	14:12:51	6484
22897	14:17:51	6489
22898	14:07:51	6484
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22904	15:07:51	6493
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22906	14:57:51	6487
22907	15:12:52	6493
22908	15:02:51	6487
22909	15:27:51	6482
22910	15:22:51	6493
22911	15:17:51	6493
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22915	15:47:51	6494
22916	15:52:51	6494
22917	15:42:51	6487
22918	16:02:51	6489
22919	16:22:52	6492
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22933	17:07:51	6496
22934	17:12:51	6496
22935	17:42:51	6496
22936	17:37:51	6496
22937	17:27:51	6493
22938	17:32:51	6493
22939	17:47:51	6496
22940	18:02:51	6506
22941	17:52:51	6496
22942	17:57:51	6506
22943	18:07:51	6497
22944	18:17:51	6502
22945	18:12:52	6497
22946	18:37:52	6507
22947	18:22:51	6502
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22949	18:32:51	6504
22950	18:57:51	6499
22951	18:52:52	6496
22952	19:12:51	6504
22953	19:22:51	6505
22954	19:27:51	6504
22955	19:37:51	6506
22956	19:52:51	6503
22957	20:07:51	6501
22958	18:42:52	6507
22959	18:47:51	6496

22960	19:02:51	6499
22961	19:07:51	6504
22962	19:17:51	6505
22963	19:32:51	6504
22964	19:42:51	6506
22965	19:47:51	6503
22966	19:57:51	6507
22967	20:02:51	6507
22968	20:12:51	6501
22969	20:32:51	6518
22970	20:27:51	6518
22971	20:17:51	6508
22972	20:22:51	6508
22973	20:37:51	6522
22974	20:42:51	6522
22975	21:07:51	6520
22976	20:52:52	6513
22977	20:47:51	6513
22978	20:57:51	6516
22979	21:02:51	6516
22980	21:27:51	6516
22981	21:17:51	6515
22982	21:22:51	6515
22983	21:12:51	6520
22984	21:32:51	6516
22985	21:52:51	6517
22986	21:47:51	6517
22987	22:07:51	6520
22988	22:22:51	6517
22989	21:37:51	6520
22990	21:42:51	6520
22991	22:02:51	6519
22992	22:12:51	6520
22993	22:17:51	6517
22994	21:57:52	6519
22995	22:27:51	6521
22996	22:47:51	6516
22997	22:42:51	6518
22998	22:32:51	6521
22999	23:07:51	6519
23000	22:37:51	6518
23001	23:02:51	6518
23002	22:52:51	6516
23003	22:57:51	6518
23004	23:27:51	6516
23005	23:12:51	6519
23006	23:17:51	6523

23007	23:22:51	6523
23008	23:47:51	6517
23009	23:42:51	6519
23010	23:32:51	6516
23011	23:37:51	6519
23012	23:52:51	6517
23014	23:57:52	6519

Appendix F

NORCE people data

	time	value
2138	00:02:51	
2140	00:07:51	0
2141	00:22:51	0
2142	00:12:51	0
2143	00:17:52	0
2144	00:32:51	0
2145	00:27:51	0
2146	00:37:51	0
2147	00:47:51	0
2148	00:42:51	0
2149	01:02:52	0
2150	00:52:51	0
2151	00:57:51	0
2152	01:12:51	0
2153	01:07:51	0
2154	01:17:51	0
2155	01:27:51	0
2156	01:22:51	0
2157	01:42:52	0
2158	01:32:51	0
2159	01:37:51	0
2160	01:47:51	1
2161	01:52:51	1
2162	01:57:51	0
2163	02:07:51	0
2164	02:02:51	0
2165	02:12:51	0
2166	02:22:51	0
2167	02:17:51	0
2168	02:37:51	0
2169	02:27:51	0
2170	02:32:51	0
2171	02:47:51	0
2172	02:42:51	0
2173	02:52:51	0
2174	02:57:51	0
2175	03:07:51	0
2176	03:02:51	0
2177	03:12:51	0
2178	03:22:51	0
2179	03:17:51	0
2180	03:37:51	0
2181	03:27:51	0
2182	03:32:51	0
2183	03:52:51	0
2184	03:42:52	0

2185	03:47:52	0
2186	04:02:51	0
2187	03:57:51	0
2188	04:17:51	0
2189	04:07:51	0
2190	04:12:51	0
2191	04:32:51	0
2192	04:22:51	0
2193	04:27:51	0
2194	04:37:51	0
2195	04:42:51	0
2196	04:47:51	0
2197	04:52:51	0
2198	04:57:51	0
2199	05:12:51	0
2200	05:02:51	0
2201	05:07:51	0
2202	05:22:51	1
2203	05:17:51	1
2204	05:27:51	0
2205	05:37:51	0
2206	05:32:51	0
2207	05:52:52	0
2208	05:42:51	0
2209	05:47:52	0
2210	06:07:51	0
2211	05:57:51	0
2212	06:02:51	0
2213	06:17:51	0
2214	06:12:51	0
2215	06:22:51	0
2216	06:27:51	3
2217	06:37:51	2
2218	06:32:51	5
2219	06:42:51	3
2220	06:52:51	3
2221	06:47:51	2
2222	07:07:52	10
2223	06:57:51	10
2224	07:02:51	14
2225	07:12:51	10
2226	07:27:52	24
2227	07:17:51	14
2228	07:22:52	13
2229	07:32:51	23
2230	07:47:51	18
2231	07:37:51	23

2232	07:42:51	37
2233	07:57:51	38
2234	07:52:51	38
2235	08:02:51	44
2236	08:12:52	45
2237	08:07:51	49
2238	08:17:51	55
2239	08:27:51	56
2240	08:22:51	61
2241	08:42:51	57
2242	08:32:52	62
2243	08:37:51	98
2244	08:52:52	80
2245	08:47:51	88
2246	08:57:51	63
2247	09:02:52	83
2248	09:12:51	80
2249	09:07:51	102
2250	09:17:51	73
2251	09:27:51	106
2252	09:22:51	66
2253	09:42:51	72
2254	09:32:51	91
2255	09:37:51	71
2256	09:52:51	86
2257	09:47:51	86
2258	09:57:51	73
2259	10:07:51	88
2260	10:02:51	73
2261	10:22:51	75
2262	10:12:51	83
2263	10:17:51	58
2264	10:37:51	62
2265	10:27:51	80
2266	10:32:51	70
2267	10:42:51	64
2268	10:47:51	66
2269	10:52:51	66
2270	10:57:51	61
2271	11:07:51	67
2272	11:02:51	71
2273	11:12:51	57
2274	11:22:51	68
2275	11:17:51	68
2276	11:37:51	46
2277	11:27:52	47
2278	11:32:51	58

2279	11:47:51	55
2280	11:42:51	57
2281	11:52:51	55
2282	11:57:51	81
2283	12:12:51	71
2284	12:02:51	74
2285	12:07:51	78
2286	12:22:51	63
2287	12:17:51	63
2288	12:27:51	66
2289	12:32:51	71
2290	12:42:51	80
2291	12:37:51	80
2292	12:47:52	66
2293	12:52:51	67
2294	13:02:51	73
2295	12:57:51	67
2296	13:07:51	68
2297	13:17:51	70
2298	13:12:51	68
2299	13:32:51	67
2300	13:22:51	70
2301	13:27:51	67
2302	13:42:51	60
2303	13:37:51	67
2304	13:47:51	66
2305	13:57:51	63
2306	13:52:51	57
2307	14:12:51	65
2308	14:02:51	61
2309	14:07:51	74
2310	14:22:51	67
2311	14:17:51	69
2312	14:27:51	76
2313	14:32:51	76
2314	14:42:51	58
2315	14:37:51	69
2316	14:47:51	69
2317	14:57:51	59
2318	14:52:51	62
2319	15:02:51	57
2320	15:12:52	68
2321	15:07:51	42
2322	15:27:51	47
2323	15:17:51	35
2324	15:22:51	35
2325	15:37:51	22

2326	15:32:51	34
2327	15:42:51	21
2328	15:47:51	20
2329	15:57:51	31
2330	15:52:51	18
2331	16:02:51	24
2332	16:12:51	18
2333	16:07:51	18
2334	16:27:52	15
2335	16:17:51	14
2336	16:22:52	14
2337	16:42:51	13
2338	16:32:51	14
2339	16:37:51	12
2340	16:52:51	9
2341	16:47:51	8
2342	16:57:51	7
2343	17:07:51	7
2344	17:02:51	5
2345	17:22:51	5
2346	17:12:51	6
2347	17:17:51	5
2348	17:32:51	5
2349	17:27:51	5
2350	17:37:51	9
2351	17:47:51	2
2352	17:42:51	9
2353	17:52:51	2
2354	18:02:51	2
2355	17:57:51	2
2356	18:07:51	2
2357	18:12:52	2
2358	18:17:51	2
2359	18:27:51	2
2360	18:22:51	2
2361	18:42:52	2
2362	18:32:51	2
2363	18:37:52	2
2364	18:57:51	2
2365	18:47:51	4
2366	18:52:52	4
2367	19:02:51	2
2368	19:07:51	1
2369	19:12:51	1
2370	19:17:51	0
2371	19:22:51	0
2372	19:37:51	0

2373	19:27:51	0
2374	19:32:51	0
2375	19:47:51	0
2376	19:42:51	0
2377	19:52:51	0
2378	20:02:51	0
2379	19:57:51	0
2380	20:17:51	0
2381	20:07:51	0
2382	20:12:51	0
2383	20:27:51	0
2384	20:22:51	0
2385	20:32:51	0
2386	20:37:51	0
2387	20:42:51	0
2388	20:47:51	0
2389	20:52:52	0
2390	21:02:51	0
2391	20:57:51	0
2392	21:07:51	0
2393	21:17:51	0
2394	21:12:51	0
2395	21:32:51	0
2396	21:22:51	0
2397	21:27:51	0
2398	21:42:51	0
2399	21:37:51	0
2400	21:47:51	0
2401	21:57:52	0
2402	21:52:51	0
2403	22:12:51	0
2404	22:02:51	0
2405	22:07:51	0
2406	22:22:51	0
2407	22:17:51	0
2408	22:27:51	0
2409	22:32:51	0
2410	22:42:51	0
2411	22:37:51	0
2412	22:47:51	0
2413	22:57:51	0
2414	22:52:51	0
2415	23:12:51	0
2416	23:02:51	0
2417	23:07:51	0
2418	23:27:51	0
2419	23:17:51	0

2420	23:22:51	0
2421	23:32:51	0
2422	23:37:51	0
2423	23:52:51	0
2424	23:42:51	0
2425	23:47:51	
2427	23:57:52	0

Appendix G

NORCE outdoor temperature data

	time	value
2136	00:07:51	1.6
2138	00:12:51	1.6
2140	00:27:51	1.6
2141	00:02:51	1.6
2142	00:22:51	1.6
2143	00:17:52	1.6
2144	00:47:51	1.3
2145	00:32:51	1.3
2146	00:42:51	1.3
2147	01:07:51	1.3
2148	00:37:51	1.3
2149	01:12:51	1.3
2150	01:02:52	1.3
2151	00:52:51	1.3
2152	00:57:51	1.3
2153	01:17:51	1.3
2154	01:32:51	0.8
2155	01:27:51	1.3
2156	01:22:51	1.3
2157	01:37:51	0.8
2158	01:52:51	0.8
2159	01:57:51	0.8
2160	02:02:51	0.8
2161	01:42:52	0.8
2162	01:47:51	0.8
2163	02:22:51	0.8
2164	02:12:51	0.8
2165	02:17:51	0.8
2166	02:07:51	0.8
2167	02:42:51	0.6
2168	02:47:51	0.6
2169	02:27:51	0.8
2170	02:32:51	0.6
2171	02:37:51	0.6
2172	02:52:51	0.6
2173	03:07:51	0.6
2174	03:02:51	0.6
2175	03:12:51	0.6
2176	02:57:51	0.6
2177	03:27:51	0.6
2178	03:32:51	0.6
2179	03:37:51	0.6
2180	03:22:51	0.6
2181	03:17:51	0.6
2182	03:57:51	0.6
2183	03:42:52	0.6

2184	03:47:52	0.6
2185	04:07:51	0.6
2186	03:52:51	0.6
2187	04:12:51	0.6
2188	04:22:51	0.6
2189	04:17:51	0.6
2190	04:02:51	0.6
2191	04:27:51	0.6
2192	04:42:51	0.5
2193	04:47:51	0.5
2194	04:52:51	0.5
2195	04:57:51	0.5
2196	05:02:51	0.5
2197	05:07:51	0.5
2198	05:12:51	0.5
2199	04:37:51	0.5
2200	04:32:51	0.5
2201	05:22:51	0.5
2202	05:17:51	0.5
2203	05:42:51	0.4
2204	05:27:51	0.5
2205	05:37:51	0.4
2206	05:47:52	0.4
2207	05:57:51	0.4
2208	05:52:52	0.4
2209	05:32:51	0.4
2210	06:17:51	0.4
2211	06:02:51	0.4
2212	06:07:51	0.4
2213	06:12:51	0.4
2214	06:22:51	0.4
2215	06:37:51	0.9
2216	06:32:51	0.9
2217	06:27:51	0.4
2218	06:42:51	0.9
2219	06:47:51	0.9
2220	06:52:51	0.9
2221	07:12:51	0.9
2222	07:07:52	0.9
2223	06:57:51	0.9
2224	07:02:51	0.9
2225	07:32:51	1.9
2226	07:17:51	0.9
2227	07:22:52	0.9
2228	07:27:52	0.9
2229	07:52:51	1.9
2230	07:47:51	1.9

2231	07:37:51	1.9
2232	07:42:51	1.9
2233	08:12:52	1.9
2234	07:57:51	1.9
2235	08:02:51	1.9
2236	08:07:51	1.9
2237	08:17:51	1.9
2238	08:32:52	2.8
2239	08:27:51	1.9
2240	08:22:51	1.9
2241	08:37:51	2.8
2242	08:42:51	2.8
2243	08:52:52	2.8
2244	08:47:51	2.8
2245	08:57:51	2.8
2246	09:02:52	2.8
2247	09:22:51	2.8
2248	09:12:51	2.8
2249	09:17:51	2.8
2250	09:07:51	2.8
2251	09:42:51	3.3
2252	09:27:51	2.8
2253	09:32:51	3.3
2254	09:37:51	3.3
2255	10:02:51	3.3
2256	09:52:51	3.3
2257	09:57:51	3.3
2258	09:47:51	3.3
2259	10:07:51	3.3
2260	10:27:51	3.3
2261	10:12:51	3.3
2262	10:17:51	3.3
2263	10:32:51	4
2264	10:37:51	4
2265	10:22:51	3.3
2266	10:42:51	4
2267	11:02:51	4
2268	10:57:51	4
2269	10:47:51	4
2270	10:52:51	4
2271	11:22:51	4
2272	11:17:51	4
2273	11:07:51	4
2274	11:12:51	4
2275	11:42:51	4.5
2276	11:27:52	4
2277	11:32:51	4.5

2278	11:47:51	4.5
2279	11:37:51	4.5
2280	12:07:51	4.5
2281	11:57:51	4.5
2282	11:52:51	4.5
2283	12:02:51	4.5
2284	12:12:51	4.5
2285	12:27:51	4.5
2286	12:22:51	4.5
2287	12:17:51	4.5
2288	12:32:51	4.8
2289	12:37:51	4.8
2290	12:57:51	4.8
2291	12:52:51	4.8
2292	12:42:51	4.8
2293	12:47:52	4.8
2294	13:17:51	4.8
2295	13:02:51	4.8
2296	13:07:51	4.8
2297	13:12:51	4.8
2298	13:37:51	5.2
2299	13:32:51	5.2
2300	13:22:51	4.8
2301	13:27:51	4.8
2302	13:42:51	5.2
2303	13:57:51	5.2
2304	13:47:51	5.2
2305	14:02:51	5.2
2306	13:52:51	5.2
2307	14:22:51	5.2
2308	14:12:51	5.2
2309	14:07:51	5.2
2310	14:17:51	5.2
2311	14:27:51	5.2
2312	14:32:51	4.8
2313	14:52:51	4.8
2314	14:42:51	4.8
2315	14:47:51	4.8
2316	14:37:51	4.8
2317	15:12:52	4.8
2318	14:57:51	4.8
2319	15:02:51	4.8
2320	15:17:51	4.8
2321	15:07:51	4.8
2322	15:37:51	4.1
2323	15:27:51	4.8
2324	15:47:51	4.1

2325	15:57:51	4.1
2326	15:22:51	4.8
2327	15:32:51	4.1
2328	15:52:51	4.1
2329	15:42:51	4.1
2330	16:02:51	4.1
2331	16:17:51	4.1
2332	16:07:51	4.1
2333	16:22:52	4.1
2334	16:27:52	4.1
2335	16:12:51	4.1
2336	16:37:51	2.6
2337	16:32:51	2.6
2338	16:42:51	2.6
2339	17:02:51	2.6
2340	16:52:51	2.6
2341	16:57:51	2.6
2342	16:47:51	2.6
2343	17:22:51	2.6
2344	17:07:51	2.6
2345	17:12:51	2.6
2346	17:17:51	2.6
2347	17:42:51	1.5
2348	17:27:51	2.6
2349	17:32:51	1.5
2350	17:37:51	1.5
2351	18:02:51	1.5
2352	17:52:51	1.5
2353	17:57:51	1.5
2354	17:47:51	1.5
2355	18:22:51	1.5
2356	18:07:51	1.5
2357	18:27:51	1.5
2358	18:12:52	1.5
2359	18:17:51	1.5
2360	18:32:51	1.6
2361	18:47:51	1.6
2362	18:37:52	1.6
2363	18:42:52	1.6
2364	19:07:51	1.6
2365	19:12:51	1.6
2366	19:17:51	1.6
2367	19:22:51	1.6
2368	19:27:51	1.6
2369	19:32:51	1.3
2370	19:37:51	1.3
2371	18:52:52	1.6

2372	18:57:51	1.6
2373	19:47:51	1.3
2374	19:42:51	1.3
2375	19:52:51	1.3
2376	19:02:51	1.6
2377	20:07:51	1.3
2378	19:57:51	1.3
2379	20:12:51	1.3
2380	20:02:51	1.3
2381	20:22:51	1.3
2382	20:27:51	1.3
2383	20:17:51	1.3
2384	20:37:51	1
2385	20:32:51	1
2386	20:42:51	1
2387	20:47:51	1
2388	21:02:51	1
2389	20:52:52	1
2390	20:57:51	1
2391	21:22:51	1
2392	21:17:51	1
2393	21:07:51	1
2394	21:12:51	1
2395	21:27:51	1
2396	21:42:51	0.7
2397	21:37:51	0.7
2398	21:32:51	0.7
2399	21:47:51	0.7
2400	21:52:51	0.7
2401	22:12:51	0.7
2402	22:02:51	0.7
2403	22:07:51	0.7
2404	21:57:52	0.7
2405	22:32:51	0.2
2406	22:17:51	0.7
2407	22:37:51	0.2
2408	22:22:51	0.7
2409	22:27:51	0.7
2410	22:57:51	0.2
2411	22:42:51	0.2
2412	22:47:51	0.2
2413	22:52:51	0.2
2414	23:17:51	0.2
2415	23:12:51	0.2
2416	23:02:51	0.2
2417	23:07:51	0.2
2418	23:37:51	0

2419	23:22:51	0.2
2420	23:27:51	0.2
2421	23:32:51	0
2422	23:42:51	0
2423	23:47:51	0
2425	23:57:52	0
2426	23:52:51	0

Appendix H

NORCE flow data

	time	value
2140	00:02:51	0
2141	00:07:51	0
2142	00:27:51	0
2143	00:17:52	0
2144	00:22:51	0
2145	00:12:51	0
2146	00:47:51	0
2147	00:32:51	0
2148	00:37:51	0
2149	00:52:51	0
2150	00:42:51	0
2151	01:12:51	0
2152	01:02:52	0
2153	00:57:51	0
2154	01:07:51	0
2155	01:17:51	0
2156	01:32:51	0
2157	01:27:51	0
2158	01:22:51	0
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