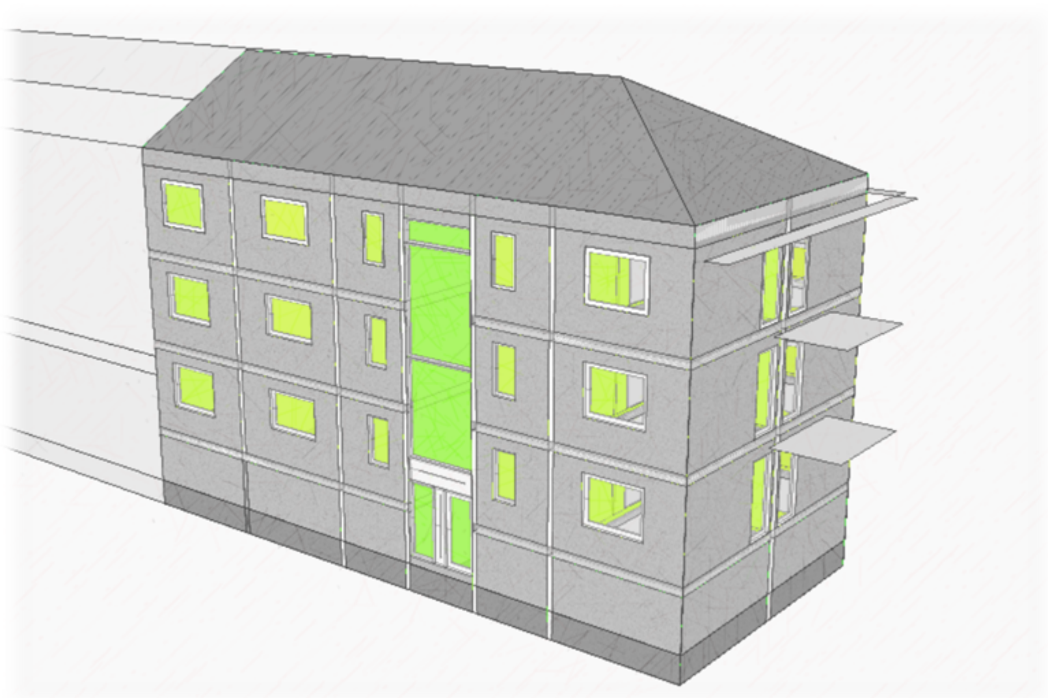
MASTER'S THESIS

Data-driven Assessment of energy use and HVAC components performance: A Danish residential building



MSc Building Energy Design

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Overleaf is used for typesetting the document. Bluebeam Revu is used for image and drawing editing. BE18, IDA ICE and Python 3.8/Spyder 5.0 are used for creating models.

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Abstract:

With the development of digitalization and its impact on domestic spaces, there is an increase in available data that describes the building performance and occurring processes in them. Integrated Smart Home systems usually control automatic temperature adjustment, light brightness levels, the position of the window openings or weather compensation. It provides insight into historical energy use and collects and stores information from installed sensors. As a result, there is an increase in data on actual outdoor and indoor boundary conditions which later can be used in creating the baseline models of buildings. It leads to a reduction of the Energy Performance Gap when compared with standard input models. Correspondingly, it allows for identifying best practices, establishing reference points for measuring and rewarding good performance, as well as increasing the general awareness of energy efficiency among building occupants which can result in behaviour changes.

Contents

0.1 Abbreviations

MSC:	Master's in Science
ECTS:	European Credit Transfer and Accumulation System
HVAC:	Heating, Ventilation and Air conditioning
DHW:	Domestic Hot Water
PG:	Performance Gap
EPG:	Energy Performance Gap
DK:	Denmark
AHU:	Air Handling Unit
HDD:	Heating Degree Days
CDD:	Cooling Degree Days
BE:	Building Energy (indicates software)
BR:	Building Regulations
PPD:	Predicted Percentage of Dissatisfied
DS:	Danish Standards
EN:	European standards
CEN:	European Committee for Standardization
BMS:	Building Management Systems
IEC:	Indoor Environmental Comfort
CO2:	Carbon dioxide
DMI:	Danish Meteorological Institute
ESBO:	Early-Stage Building Optimization
CAV:	Constant Air Velocity
VAV:	Variable Air Velocity
TH:	Til Højre (to the right)
TV:	Til Venstre (to the left)
ST:	Stue (ground floor)
MET:	Metabolic Equivalent of Task
DRY:	Danish Design Reference Year
KPI:	Key Performance Index
ASHRAE:	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
IWEC:	International Weather files for Energy Calculations
GHI:	Global Horizontal Irradiance
DNI:	Direct Normal Irradiance
DHI:	Diffused Horizontal Irradiance
AM:	Ante Meridiem
PM:	Post Meridiem
MPC:	Model Predictive Control
DH:	District Heating
SH:	Smart Home

Table 1: List of abbreviations

Preface

This report is produced as a part of the MSc Building Energy Design curriculum to complete the education at Aalborg University. This Master's Thesis is worth 30 ECTS (1 ECTS = 28 hours) which results in 840 hours of project time during the Autumn semester of 2022.

0.2 Readers guide

The document consists of two parts:

- Part I. Report. A core of the project.
- Part II. Appendix. Supplementary drawings, calculations, and imagery.

Report structure:	**Appendix structure:**
Example	*Example*
1	A
1.1	A.1
Figure 1.1	Figure A.1
Table 1.1	Table A.1

References of the used literature are described in the IEEE reference style.

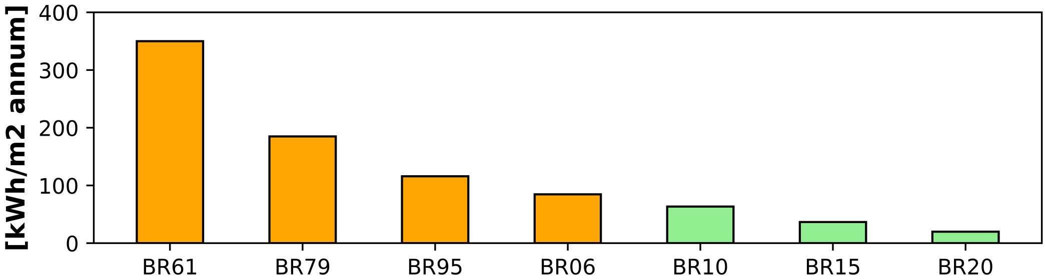
Aalborg University, January 11, 2023

Chapter 1

Introduction

Countries around the world face a key choice of boosting green transition to reduce global and local environmental impacts, as well as resource dependence from imports. It includes a shift to renewable energy, manufacturing of electric vehicles and construction of energy-efficient buildings [1]. In 2020, approximately 57 % of the European energy demand was covered by energy imports from which 98 % were petroleum products, natural gas, and solid fossil fuels [2]. Even though renewable energy source share doubled from 11 % in 2006 to 22 % in 2022, carbon reductions and energy import reliance decrease are not happening fast enough in the power sector [3]. To relief the energy demand, improve energy security and boost the share of renewables, the building sector, which accounts for 16 % of related emissions, needs to be optimized. It is considered a priority due to the sector's potential to be upgraded as the insulating materials and HVAC systems advanced through the last decades. This can be observed in the newly constructed buildings that follow current energy-use regulations. Although the majority of the standards are targeting new and future buildings, it is expected that 85-95 % of the European building stock that will exist in 2050 has already been built [4]. In the case of Denmark, dwellings built before 1960 already make up for 70 % of the entire stock and are considered high energy use compared with current standards. As a result, based on the literature presented above, buildings in Denmark account for 40 % share of total countries' energy use (space and Domestic Hot Water (DHW) heating account for approximately 25 % [5]) and 30 % of carbon emissions. The optimization potential is substantial and can be seen in Figure 1.1, where the change in energy demand of the single-family houses is presented. For this reason, it is vital to focus on energy improvement plans to retrofit old buildings in an optimal and structured manner [5], as well as establish a method of maintaining operational building stock to ensure intended efficiency.

Figure 1.1: Danish building codes from 1961 to present: Maximum allowed energy demand per year and m^2 heated floor space in a new 150 m^2 residential building [6]

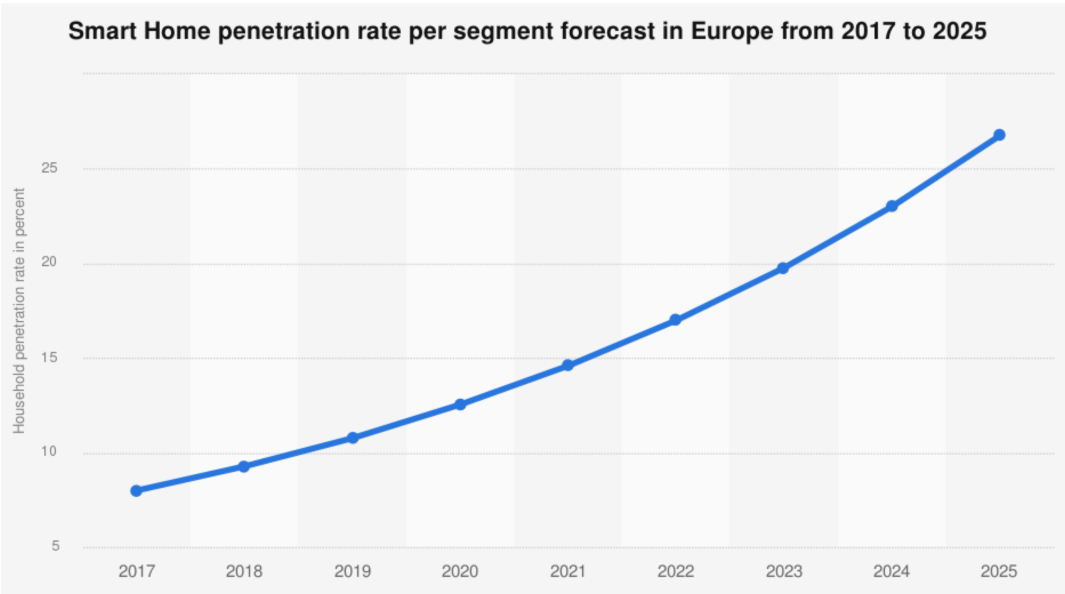


Nowadays building design and performance evaluation are usually based on a nationally accepted and standardized method. Denmark is not an exception. Building Regulations and supplementary software BE18 are primary directives in benchmarking energy performance. However, through various studies, currently used standard calculation procedures have been reported to display deviation when compared to the energy use during normal occupancy conditions. This mismatch in theoretical and actual energy performance is defined as *The Performance Gap*. The outcome of using standardized values can vary largely with some sources estimating 34 % [7] and others up to 80 % [8] increase or decrease in energy use during the operation. Such a magnitude of the performance gap makes it difficult to achieve model-based targets and benchmark the existing building stock. These discrepancies interfere with an understanding of the building systems by lacking objective and reliable information on energy use. It prevents effective management and implementation of improvements that can be utilized by prioritising poorly performing facilities, identifies best practices that can be replicated, establishes reference points for measuring and rewarding good performance, as well as increases general awareness of energy efficiency among building occupants that can result in behaviour changes.

Steady-state and dynamic white-box models are usually built to assess the performance of the designs and existing structures. Opposite to the black-box models, they have observable relationships between variables. In the building case, white-box models combine the properties and interactions between static structural parts, the dynamic HVAC systems and the external outdoor and indoor variables. As a result of its comprehensive nature of connections, the designers can understand how the model came to the results and seek further improvements. It guides the development of simulation tools and identifies the areas requiring research [9] to reduce the performance gap. One of the findings states the significant mismatch between standardised values used to assume user behaviour and actual values which occur in operating buildings [10]. Correspondingly, white-box models need to closely represent the actual behaviour of the external factors to result in a reliant baseline for comparison internally among the users and externally between similar type buildings [11]. Although the discrepancies between predicted and measured performance are unavoidable due to the complexity of the buildings and uncertainties in operation, describing its magnitude and underlying causes are useful for the development of the assessment framework, especially, of the residential multi-storey building stock.

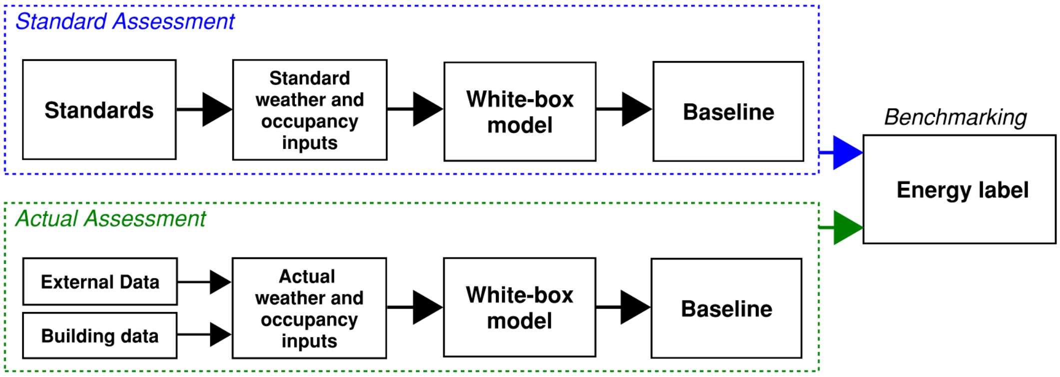
With the development of digitalization and its impact on domestic spaces, there is an increase in available data that describes the building performance and occurring processes in them. Integrated Smart Home (SH) systems are usually in control of automatic temperature adjustment, light brightness levels, the position of the window openings or weather compensation. It provides insight into historical energy use and most importantly collects and stores information from installed sensors.

Figure 1.2: Smart Home penetration in EU (2021 estimates) [12]



The SH penetration in Europe is presented in Figure 1.2. In the year 2022, it reaches 17 % and is expected to pass the 25 % mark by the year 2025 [12]. However, the share of SH users is larger in Western Europe with Denmark in the front. In 2019, 23 % of SH penetration was observed in Denmark compared with 10 % of Europe's average [13]. Due to the steady growth of building digitalization, there is an increase of data on actual outdoor and indoor boundary conditions which later can be used in building the baseline models. For this reason, studies that focus on the usage of newly obtained data are becoming increasingly relevant.

Figure 1.3: Process flow of the Standard and Actual assessments. Modified with permission from one of the authors' of the SATO Deliverable 3.1 [14]



One of the objectives of this project is to determine the performance gap between the standard and actual assessments of the case building using dynamic white-box models. The standard evaluation is based on the standard weather conditions, occupancy and key component parameters which are obtained from the national building energy design guidelines. It represents the currently used framework of the performance assessment and acts as a reference while quantifying the baseline improvements when introducing the actual inputs. The actual assessment measures the performance under real-life weather and occupancy conditions. This concept is based on the H2020 project [15] in SATO and Deliverable 3.1 (see Figure 1.3). It is a part of a larger objective that seeks to define which systems, energy components and appliances should be included in the assessment framework to efficiently monitor and manage buildings. This master's thesis focuses on one of the proposed KPIs such as heating energy use and aims to contribute to the development of larger assessment framework.

Even though many studies can be found that evaluate the performance gap in the building industry, the residential multi-storey building sector is still relevant to be investigated. One of the challenges is occupant authority over the building. Users in residential buildings tend to have more control over systems and envelope operation. It is less likely for predictive models to capture the dynamics and variance of occupants' behaviour, resulting in a usually larger energy performance gap [16]. The research publication which collected key sources regarding the occupant role in energy performance states that the median gap and standard deviation are larger in residential buildings (30 % $\mp$51 %) than in non-residential buildings (14 % $\mp$27 %). Additionally, multi-storey dwellings are more complex and have a larger number of thermal zones compared with single-family houses which further increases the performance gap, especially using steady-state models.

Table 1.1: Reference studies [17] [18] [15] [19] [20] [21]

General				Measurements		Results	
Building type	*Location*	*Built date*	**Original model inputs**	*Outdoor conditions*	*Indoor conditions*	*EPG in % before calibration*	*EPG in % after calibrations*
Residential	Aarhus DK	2017	Custom occupancy schedules	Air temperature sensors	Air temperature, humidity, ventilation air velocity, CO2, appliance usage	Heating: -2.43 %	-
Residential	DK	1999	Unknown	-	Clothing, frequency of thermostat adjustment, window opening	-	-
Non-residential	Odense DK	2015	Standard	Air temperature, wind speed, solar irradiation obtained from the local weather station	Air temperature, humidity, ventilation air velocity, CO2, appliance usage, illuminance, blinds position. Occupancy cameras	Regulatory performance vs. design certificates: 27 % to 122 %	Calibrated model vs. measured: -8.4 % to 6.9 %
Residential (multi-storey)	DK	1970 2011 renov.	Standard	Air temperature obtained from the local weather station	Air temperature	110 %	51 %
Residential (multi-storey)	DK	2020	Standard	-	Air temperature, DHW use and temperature, AHU air frow rate	9 %	-4 %
Residential (single-family)	DK	2017	Standard	-	DHW use, operative temperature, airflow rate, CO2, RH	89 %	-

For these reasons, this Danish residential apartment building case study is relevant at the current time of analysis. As a reference, studies with similar focus or buildings' location are presented in Table 1.1. It includes general information, output variables, input assumptions, logged measurements and a summary of the results.

To conclude, benchmarking tools generate summary statements and communicate information about the buildings' energy performance in a format that is both understandable and easy to use. Following this screening process, an energy renovation or user feedback proposals are selected considering a trade-off between energy savings, investment, operation costs and emission reductions. However, the use of standard practices when evaluating the existing buildings can lead to a performance gap between the predicted and actual, real-life energy use. As a result, the implementation of optimization measures is not utilized efficiently and limits the development potential. Additionally, the residential multi-storey buildings matching the case scenario attributed to a larger median energy performance gap than other types of buildings. Due to the inconsistent user behaviour, more studies are needed to be followed to develop a better understanding of occurring issues. For this reason, the residential multi-storey case building is benchmarked using steady-state, dynamic standard and data-driven white-box models and the results are assessed to find the impact of utilized data and causes of the remaining discrepancies.

1.1 Problem statement

The evaluation using outdoor boundary conditions is performed yearly on the whole building level resolution during the period between 2015 and 2022. The goal is to identify the relevance of using custom environment inputs and define the average improvement in bridging the performance gap. The assessment under the actual occupancy is evaluated on apartment-level resolution and is performed for the January-September months of 2022. It focuses on energy use for heating spaces and covers improvements in the performance gap under the acquired occupancy data. The variations of data properties such as time-series are investigated to present an optimal way of reducing the error. Also, the aim is to describe the underlying causes of the remaining performance gap and conclude what type of data is required to build a baseline when evaluating the performance of the existing buildings.

1.2 Research questions

The following set of research questions are investigated within this case study:

Aim of the project:

"How different data quality on outdoor and indoor boundary conditions affect the white-box model baseline for energy performance?"

Objectives:

- What climate data can be obtained from external sources and be utilized effectively in the conventional white-box modelling software?
- How the energy performance changes when actual outdoor and indoor boundary conditions are used in modelling?
- What are the remaining causes of a mismatch in the energy performance after the introduction of the obtained data?
- What is the rate of percentage change in total energy use working with different resolutions of data inputs?

Chapter 2

Methodology

This chapter establishes the boundaries that define the scope of the project, focus areas, and presents decisions which influence the choices.

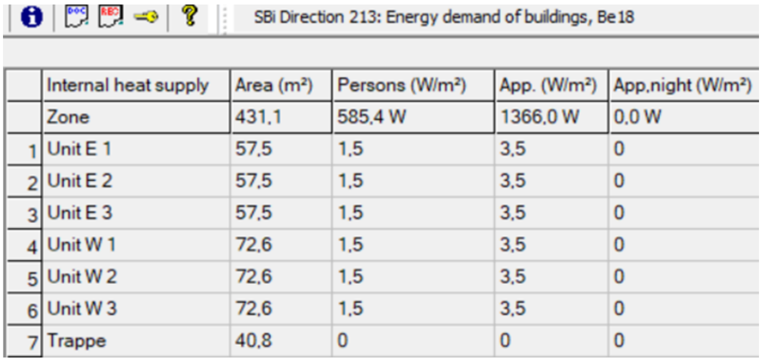
2.1 Steady-state modelling

There are many methods and models that can be used to analyse the energy use of buildings, however, there is no single one which is universally superior. It always depends on what one wants to calculate and what data is accessible. This chapter presents the background, advantages, disadvantages and application of the steady-state models.

A steady-state method is preferred due to its simplicity which requires less input data in comparison to the dynamic models. It can account for weather correction (Heating Degree Days (HDD) and Cooling Degree Days (CDD)), energy consumption with thermostat set points, the ratio of heat loss coefficient (external surfaces) and heating efficiency (heat pumps, boilers etc.) [22]. However, using simplified methods can lead to reduced accuracy due to the lack of customization provided by the steady-state model-based software. If a wide range of information is available about the structure, systems and users, the possibility to use those variables is limited.

An example of such limitations occurs when the internal heat supply is modelled in the steady-state software BE18 [23]. The only parameters which define the internal gains from the users and appliances are the zone area and expelled energy during the time period (see Figure 2.1). It is convenient when designing residential buildings as inhabitant number, behaviour and use of equipment are unknown. However, when evaluating the existing buildings and creating digital-twin models higher input resolution can be obtained. It can be set point temperature, number of occupants, type and efficiency of the equipment, domestic hot water use etc. This information cannot be effectively used in steady-state models due to input constraints.

Figure 2.1: BE18 software and example of available occupancy inputs


SBi Direction 213: Energy demand of buildings, Be18

	Internal heat supply	Area (m²)	Persons (W/m²)	App. (W/m²)	App.night (W/m²)
	Zone	431,1	585,4 W	1366,0 W	0,0 W
1	Unit E 1	57,5	1,5	3,5	0
2	Unit E 2	57,5	1,5	3,5	0
3	Unit E 3	57,5	1,5	3,5	0
4	Unit W 1	72,6	1,5	3,5	0
5	Unit W 2	72,6	1,5	3,5	0
6	Unit W 3	72,6	1,5	3,5	0
7	Trappe	40,8	0	0	0

At present, such detailed information is rarely acquired. A small number of building stock is equipped with sensors that track occupancy, equipment and use of natural ventilation. As a reference, Smart Home household penetration is expected to be approximately 18 % in 2022 in Europe [24] from which only a part of the homes will collect useful data for digital-twin design. For this reason, a steady-state method of designing and evaluating buildings is common, especially in the residential building sector.

2.2 Dynamic and Data-driven modelling

Even though building indoor processes are comparably stable to the other processes used in mechanical engineering, the fluctuations create an impact on the results when evaluations are performed over a long period of time such as daily, monthly or yearly periods. For this reason, dynamic models of the building can have many advantages when input criteria are fulfilled.

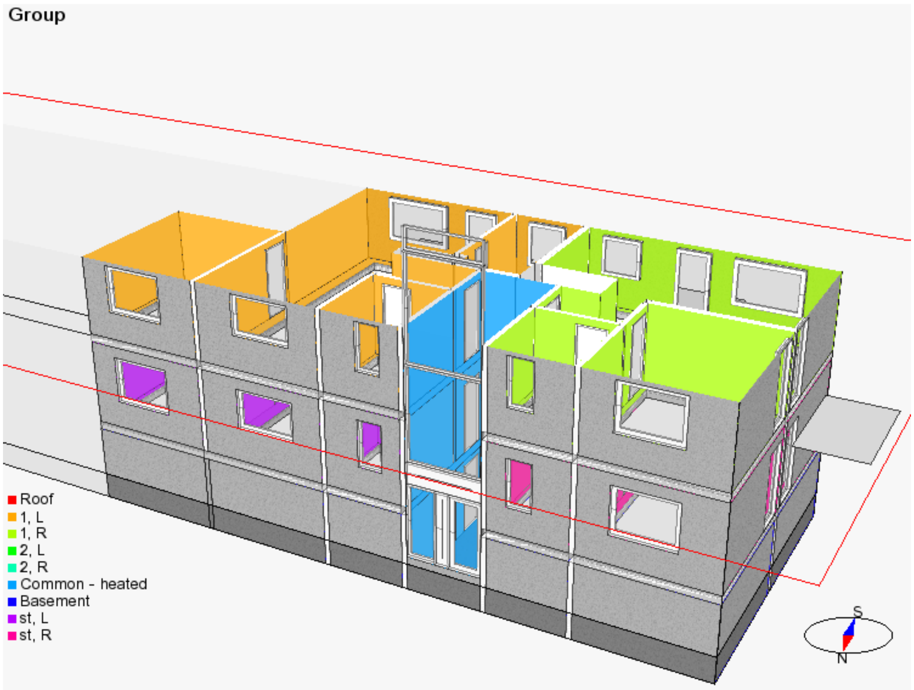
To begin, dynamic models without custom data inputs can partially resemble steady-state, especially when it comes to internal gains caused by users and equipment or in our case hot domestic water use. Factors which prevent use of dynamic models:

- Lack of detailed blueprints
- Requires more labour than steady state models assuming there are no previous computer models made (which is often the case in renovation projects)
- Changes during the construction period which are not noted
- Usually required resolution of the input data of 1-hour intervals. Hard to obtain it due to the small number of stock with SH systems

However, if a wide range of information is available, dynamic models can be superior due to their customization and the possibility to log various variables throughout the systems. Some other advantages include:

- A building can be split into different zones with individual variables
- Access to integrate dynamic occupancy and equipment schedules
- Increased complexity often reduces the EPG

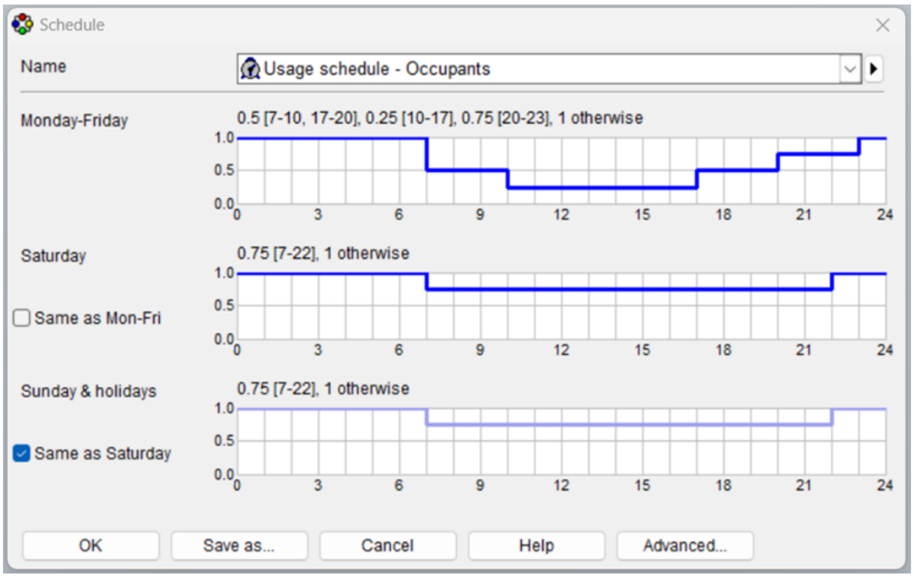
Figure 2.2: IDA ICE software: example of thermal zones



Following the previously mentioned example in the steady-state chapter (see Figure 2.1), internal heat supply input variables are compared. Dynamic modelling tool IDA ICE allows importing custom schedules of set points and occupancy. As shown in Figure 2.3, the template schedule can be created and customized for individual building zones. Additionally, activity level and clothing can be added to define internal heat supply and Predicted Percentage of Dissatisfied (PPD) more accurately.

Fundamentally, the goals define the preferred choice of modelling, while data accessibility dictates which modelling methods are available. Limitations can occur in both steady-state and dynamic models depending on the case project, thus desired output and acquired input values need to be examined conjointly to result in the optimal evaluation.

Figure 2.3: View of the occupancy schedule on the IDA ICE software [25]



2.3 Delimitation and limitations

In this residential apartment case, both steady-state and dynamic models are used to benchmark the building's performance. These model designs are made by using empirical data, obtained from reference documentation, and guidelines. The list of local and international manuals, as well as standards that are used as a basis for the case-building evaluation:

- Dansk standard (DS) 418 [26] – used for heat loss calculations. It covers the outdoor and indoor temperatures for steady-state models, U-value and linear loss calculation methods, as well as defines measurements for the estimation of transmission areas.

- Bygningsreglementer 2010 (BR10) [27] – used to assume unknown parameters of the building envelope components such as: U-value, G-values and transmittance of the windows.

- SBI-direction 213 [28] – used as a primary manual in developing steady-state models working with bygningsenergi 2018 (BE18) software. Unknown ventilation rates and domestic water use are assumed based on the manual guidelines.

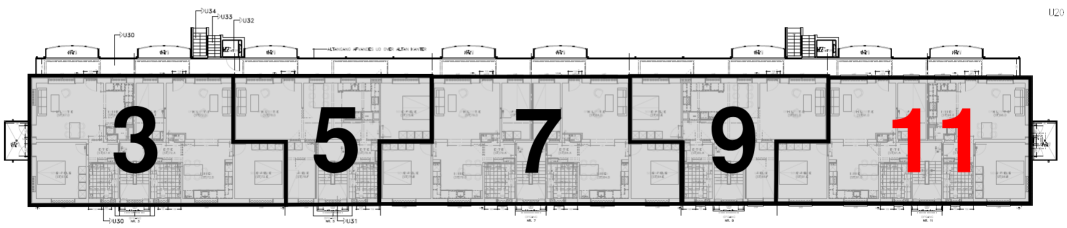
- DS/EN 16798 [29] - used in defining standard DHW and user behaviour inputs. It primarily covers operation time, indoor temperature set point and internal gains from the equipment and users.

All empirical data is obtained from the Building Management System (BMS), detailed drawings and reports. No on-site inspection or qualitative analysis are performed to validate the received documentation. It is assumed that all presented renovation solutions are implemented into the design and no changes were performed during the execution phase. The same approach is assigned to received data. It is assumed that logs are credible and data treatment which involved handling the errors was conducted prior. No analysis regarding data processing is included in this report and only interpretations of provided data use are described.

Due to the limited extent of detail possible to conduct during the given period, the project evaluation is narrowed down to the Heating, Ventilation and Cooling systems (HVAC). It includes an analysis of the building section which influences the performance of the HVAC systems such as: climate conditions, the structure of the envelope, HVAC system components and internal gains. Even though ventilation is a part of the evaluation, Indoor Environmental Comfort (IEC) is not covered. The volume flow of each zone is assumed from the provided renovation design documentation thus issues regarding moisture accumulation, Carbon Dioxide (CO_2) concentration, as well as global and local discomfort, are disregarded.

Additionally, the covered zone of the case building is reduced to one staircase (11^{th} entrance) and the apartments connecting to it (see Figure 2.4). The building has 5 separate HVAC systems which are assigned to each entrance. Due to the envelope and system layout similarities, only one HVAC system with its connecting thermal zones is analyzed.

Figure 2.4: Zone division based on staircases and connecting apartments. Number indicate entrance address number



Further points cover the validity and reliability of the data, also the limitation of acquiring certain resolution information:

- Lack of weather data to incorporate all the input values that influence the performance of the case building.

  The use of custom solar radiation data is not provided by DMI [30]. Mean radiation does not directly translate to the required climate input values of diffused and direct radiation. Also, limitations on the DMI data for a specific location for 2015-2022 data occur. Only 10 x 10-kilometre resolution is achieved, while solar radiation data is used from the station in Skagen. In addition, the last 24 hours of each year from 2015-2022 are not registered and the missing data set is replaced with the previous days' values.

- User behaviour is only obtained for the year 2022. Data regarding indoor temperature set points from January 19^{th} until August 31^{st} is used and excludes September, October and December months.

- A simplified ESBO (Early-Stage Building Optimization) system-building tool is used when designing HVAC systems in the IDA ICE model. Advanced mode is not used within this project. It is not a part of the case project complexity.

  In addition, lack of information regarding the floor heating and ceiling cooling sizing lead to the assumption of the sufficient designed capacity of the elements. It also prevents accurate inputs to describe the distribution systems. As a result, a detailed analysis of the losses due to the distribution is excluded.

- In addition, due to the existing mechanical ventilation and radiant cooling, natural ventilation is excluded which results in closed windows at all times. Not to get confused, infiltration is accounted for in the models.

The results and further developed conclusions are entirely based on the analyzed case building and do not directly translate to the other projects. To be aware, the buildings can greatly differ, and weighting factors of the analyzed parameters have various implications on results and require to be accounted for. When brands are referred to in this report, for example: software, manufacturers or service providers; they are used only for modelling, design or information-obtaining purposes and are not intentionally promoted.

Throughout the report, the comparisons between the simulated (measured) and actual (real) performance are presented as 'Percent Error':

$$Percent.Error = \left| \frac{measured - real}{real} \right| \cdot 100\% \tag{2.1}$$

Chapter 3

Case building

This study focuses on a low-energy residential multi-storey building, located in the Northern Denmark region, city of Frederikshavn (see Figure 3.1). It is a site in an urban, semi-sheltered area that is surrounded by equal or lower-height multi-storey and single-family houses. It is a 3-storey building with a basement and attic that has a total floor area of 2160 square meters (m^2). This project focuses on one of the 5 sections of the building (see Figure 3.2) which has 2 types of apartments with unique layouts.

Figure 3.1: Location of the building

General information	
Location	Denmark, Frederikshavn
Weather conditions	Standard: Denmark, Fredrikshavn - Skagen Custom: Frederikshavn 10 x 10 km (see appendix C)
Gross area	Total building: 2160 m^2 Simulated: 432 m^2
Internal height	2.55 m

3.1 Envelope

The building was erected in 1949/50 and consists of concrete basement walls, brick superstructure and timber frame cold attic. The thickness of load-bearing walls changes from 350 millimetres (mm) to 130 mm as the height of the building increase. After the renovation in 2012/13, the external layer of 220 mm of insulation was added to the basement and external walls providing a significant increase in thermal resistance. The insulation in the roof was present prior to the renovation, however, it was increased to 350 mm. It results in the U-value of 0.08 $W/(m^2 \cdot K)$ which fulfils the BR20 [31] requirements for the element. The windows are located on the south, east and north facades with an angle of 20 ° from south to east. They have integrated indoor blinds and external shading from the balconies on the south and east facades.

Construction (see appendix A)	
Floor	Basement to the ground: concrete. U-value = 4.37 $W/(m^2 \cdot K)$ Floor to the basement: Reinforced concrete with light insulation. U-value = 0.77 $W/(m^2 \cdot K)$
Walls	Outer: brick and external insulation. U-value = 0.15 $W/(m^2 \cdot K)$ Inner: brick. U value = 2.3 $W/(m^2 \cdot K)$. Basement: Concrete and insulation. U-value = 0.16 $W/(m^2 \cdot K)$
Ceiling	Basement: Reinforced concrete with light insulation. U-value = 0.77 $W/(m^2 \cdot K)$
Roof	Wood rafters and insulation: 0.08 $W/(m^2 \cdot K)$
Doors	External: U-value = 1.1 $W/(m^2 \cdot K)$, g-value = 0.7 , T-value = 0.7
Windows	U-value = 1.1 $W/(m^2 \cdot K)$, g-value = 0.7 , T-value = 0.7 Shading: multiplier for g-values = 0.71 South: area = 40.3 m^2 North: area = 43.83 m^2 East: area = 12.9 m^2
Thermal bridges	External window perimeter: = 0.01 $W/(m \cdot K)$ External door perimeter: = 0.01 $W/(m \cdot K)$ Roof / external walls: = 0.03 $W/(m \cdot K)$ External wall / external slab: = 0.27 $W/(m \cdot K)$ External slab / internal wall: = 0.27 $W/(m \cdot K)$
Air tightness	1.5 $l/(s \cdot m^2 floor)$ at 50 Pa

3.2 Heating, ventilation, and air conditioning

The occupied zones are heated by radiant floor heating with a maximum power of 99 W/m^2. The system capacity is designed to maintain indoor operative temperatures above the standard set point value of 20 °C. The brine temperature at the inlet is assumed to be between 35 °C to 40 °C with an estimated drop of 5 °C at the return. The heating demand is entirely covered by the water-to-water heat pumps which are placed in the basement. The borehole loop is used to extract or supply the underground heat energy depending on the heating or cooling mode. The ceiling cooling system is installed in the apartments located on the right side of the staircase (see Figure 3.2). The standard maximum cooling power of 99 W/m^2 is assumed which counteracts the extensive solar gains that cause indoor temperatures higher than 26 °C. The radiant ceiling cooling is connected to the heat exchanger which energy demands are covered by the borehole loop.

The air exchange requirements are covered by balanced mixing ventilation. Each apartment has Air Handling Unit (AHU) with a Constant Air Volume (CAV) flow of 90 m^3/h. Even though the recovery efficiency of 84 % is achieved, the backup heating coils are installed to ensure the minimum inlet air supply of 17 °C. Natural ventilation is possible, however, it is excluded from the simulations.

Systems	
Heating	Set points: standard 20 °C Floor heating: max power = 99 W/m^2, dT = 5 °C, PI control Heat pump: max power = 17 kW, COP = 3.6 Boreholes loop: length = 268 m
Cooling	Set point: standard 26 °C Ceilling cooling: max power = 99 W/m^2, dT = 5 °C, PI control
Ventilation	Individual AHU per apartment Set points: inlet air heating to the 17 °C Airflow = 90 m^3/h per apartment Recovery = 84 % Control: Constant Air Volume (CAV)
Venting	Windows closed at all times
Domestic hot water (DHW)	Hot water tank: V = 0.5 m^3, U-value = 0.3 $W/(m^2 \cdot K)$
Photovoltaics	A = 83 m^2, orientation = 20 ° (from south to the east), tilt = 21.7 ° Overall efficiency = 0.1

3.3 Internal load profiles

The occupancy and equipment loads are assigned for each room of the apartment which represent one thermal zone. Apartments on the right side, st, 1, 2 (th) have a floor area of 55 m^2 and have three separate spaces: kitchen/living room, bedroom and bathroom. On the left side, st, 1, 2 (tv) have a floor area of 73 m^2 and four separated spaces: kitchen/living room, master bedroom, bedroom and bathroom (see Figure 3.2). The apartments are connected to the staircase which provides access to the basement and the exit from the building. Occupancy and equipment loads are proportional to the area of the room but share the same user behaviour and equipment use schedule.

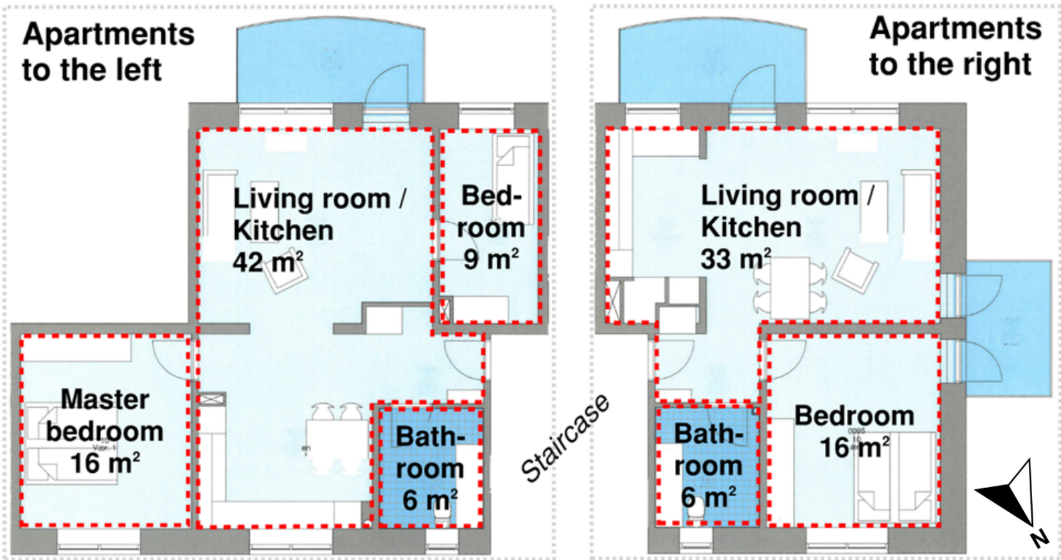


Figure 3.2: Example of two types of apartments

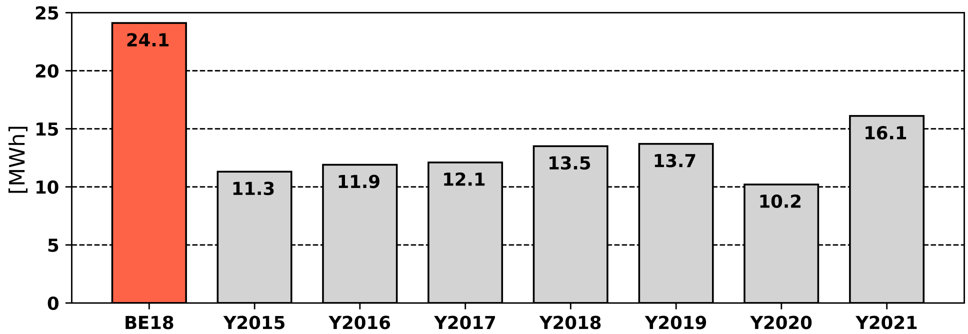
Internal loads (see appendix C)	
Thermal zones	Individual rooms and apartments (see Figure 3.2)
Occupancy	Apartment to the right: 2 users. Apartment to the left: 2.6 users. Activity level = 1 MET Schedule of the loads: Workdays: 0.5 [7-10, 17-20], 0.25 [10-17], 0.75 [20-23], 1 otherwise Weekends: 0.75 [7-22], 1 otherwise
Equipment	Apartment to the right: 2 units. Apartment to the left: 2.6 units. 82 *W* per unit. Schedule of the loads: All days: 0.75 [8-10, 18-23], 0.5 otherwise

Chapter 4

Results: Analysis of Steady-state models

The energy model using the latest BE18 software is designed for one of the building sections (see Figure 2.4). BE18 is a calculation software used to document if the building's energy performance complies with the energy framework of the Danish regulations. As a result, this design tool follows locally accepted guidelines. The BE18 model of the case building is a steady-state model with a DRY climate file and standard component as well as comfort values based on the SBi213 guidelines and BR10 requirements. BR10 is primarily used as a reference to assume the component performance if input data cannot be obtained. These regulations were active during the last renovation which was completed in 2012/2013. The objective of this section is to find the EPG of a widely used steady-state building energy performance evaluation tool by only following guidelines. Also, to assess the magnitude of EPG caused by simplified design interface when compared with dynamic, described in Chapter 2.

Figure 4.1: Energy use of the apartments for heating. Steady-state model (based on standard weather and occupancy inputs) and actual yearly performance.



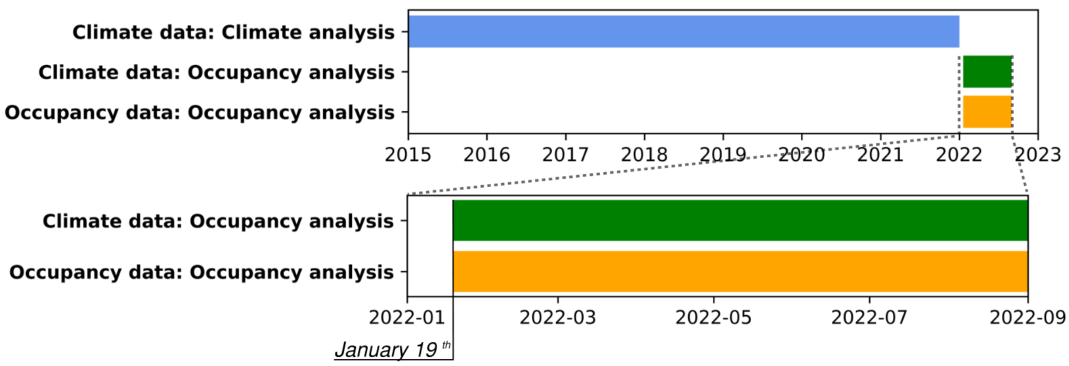
The calculated energy use requirement for the apartment heating by the software is presented in Figure 4.1. It is weighed against the actual heating use for the years 2015 – 2021. The simulated result is 59 % to 136 % higher than actual energy use. To compare, the standard dynamic model has an EPG of 6 % to 48 % (see Chapter 5). To conclude, when buildings are designed in steady-state white-box models (supporting reference example [21]), the performance gap can be more than twice higher than the actual performance. For this reason, case building is further assessed using a dynamic white-box model where zones are designed according to the local standards and assumptions of likely occurring set points in semi-heated areas.

Chapter 5

Results: Analysis of Dynamic models

The dynamic model use to define the baseline of the case building is presented in this chapter. It follows the conclusion of the Steady-state white-box model use when working with a multi-storey residential building that displays the complexity of heat transfer among thermal zones. The dynamic models take into consideration the geometry of each room, heat exchange through internal walls and air movement. It results in usually lower discrepancies and accounts for previously mentioned flaws of steady-state models. In addition, the standard climate and user behaviour inputs can be customised based on acquired data, which allows further improve the models and analyse the actual boundary condition influence on the energy performance gap. The Chapters 5.1 and 5.2 are based on the availability of actual data and are summarized in Figure 5.1

Figure 5.1: Timeline of used data and performed analysis. Climate analysis covers Chapter 5.1 while Occupancy analysis covers Chapter 5.2.



Energy use for apartment space heating is applied as a first Key Performance Indicator (KPI) when evaluating the output of the models. It excludes distribution losses, heating of the common spaces such as the staircase and is measured in megawatt hours per year (*MWh*). In this case scenario, a dynamic model with standard inputs is compared with the actual performance of the building between the years 2015 and 2021. Standard input values consist of weather data (see Table 5.1) of the nearest weather station available in the ASHRAE IWEC 2 [32] library and occupancy behaviour which is based on the local standards [29] (see Table 5.2, appendix C).

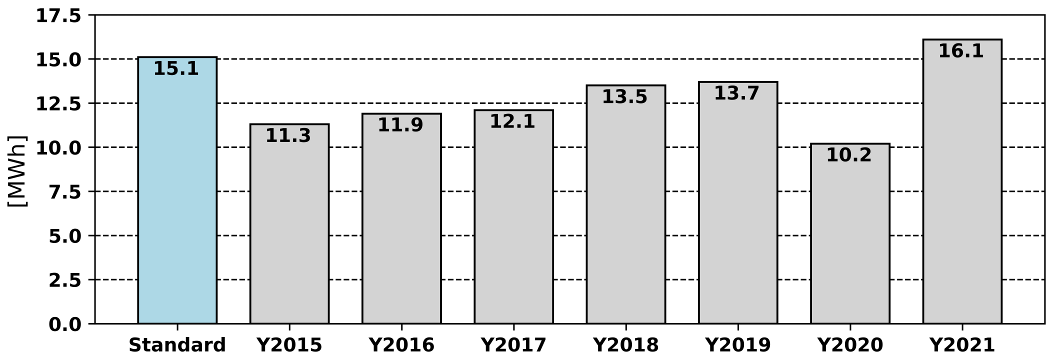
Time resolution	Mean dry temperature	Relative Humidity	Wind direction	Wind speed	Direct normal radiation	Diffused radiation
h	°C	%	°	m/s	W/m^2	W/m^2

Table 5.1: Variables and units of the weather file for IDA ICE simulation tool

Operation time	Internal gains	Minimum operational temperature	Maximum operational temperature	Domestic hot water use
h	W/m^2	°C	°C	l/m^2

Table 5.2: Variables and units of the occupancy for IDA ICE simulation tool

Figure 5.2: Energy use of the apartments for heating. Dynamic model (based on standard weather and occupancy inputs) and actual yearly performance.



As a reference, the dynamic model with standard inputs results in the combined apartment space heating of 15.1 *MWh* per year. In comparison, it is 4.9 *MWh* or 48 % higher than the lowest energy use year of 2020, and 1 *MWh* or 6 % lower than the highest energy use year of 2021 (see Figure 5.2). It indicates the maximum change of 58 % caused by the climate and occupants assuming the same integrity of the envelope and HVAC systems. Even though the predicted heating load of the dynamic model is located in between the under and outperforming years, the individual performance gap between the actual yearly output stresses the climate and occupant influence on the models' results. For this reason, further analysis of the boundary conditions is presented to find the causes of discrepancies and reduce the performance gap of the displayed standard baseline.

5.1 Standard and Actual climate

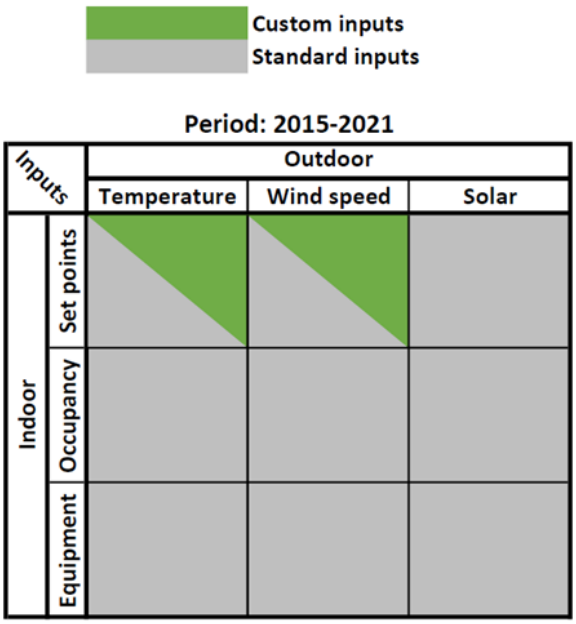
The dynamic standard weather files usually consist of variables presented in Table 5.1. In this analysis, inputs are grouped into three categories: temperature, wind speed and solar. Each category influences the energy balance in different ways. Changes in outdoor temperature primarily affect the losses caused by heat transfer through the envelope. The wind category includes wind speed and wind direction, and focuses on energy loss due to the infiltration. To simplify, relative outdoor humidity is included in the wind category as it does not impact energy balance. The last group is solar that covers direct normal radiation and diffused radiation. It affects passive internal gains caused by solar irradiation.

Additionally, each group presents different challenges on the feasibility to acquire data which further concretes the need of evaluating them separately. For instance, outdoor temperature sensors are the cheapest to acquire and install locally when compared to the cost of the anemometer or pyranometer used to log wind and solar properties. Also, all meteorologic stations as a priority track outdoor temperature and then follow with the additional parameters such as wind speed and direction. On the contrary, solar inputs create a challenge as usually global solar radiation is measured. It cannot be divided into diffused and direct radiation and requires to be logged separately on-site. For this reason, customization of solar input data is difficult to acquire. As a result, only temperature and wind categories are used in the case building scenario, while standard solar irradiation values are kept. The closest weather station provides only global solar irradiation that cannot be used directly in the white-box model and is utilized only as a reference. The summary of the actual and standard values used in climate input analysis is presented in Figure 5.3.

5.1.1 Outdoor temperature boundary conditions

Actual outdoor temperature is introduced, and the outcome is compared with standard model results and actual performance (see Figure 5.4). As a reference, HDD are graphed to indicate the thermal climate conditions of each year. It is often used as an indicator to quantify the demand for energy need to heat the building. In steady-state white-box models, the heating requirements are considered to be directly proportional to the number of HDD. In the case scenario, HDD is a temperature difference between the mean daily temperature and 17 °C base reference temperature which is used by the Danish Meteorological Institute. An additional

Figure 5.3: Inputs for the 2015-2021 weather analysis.



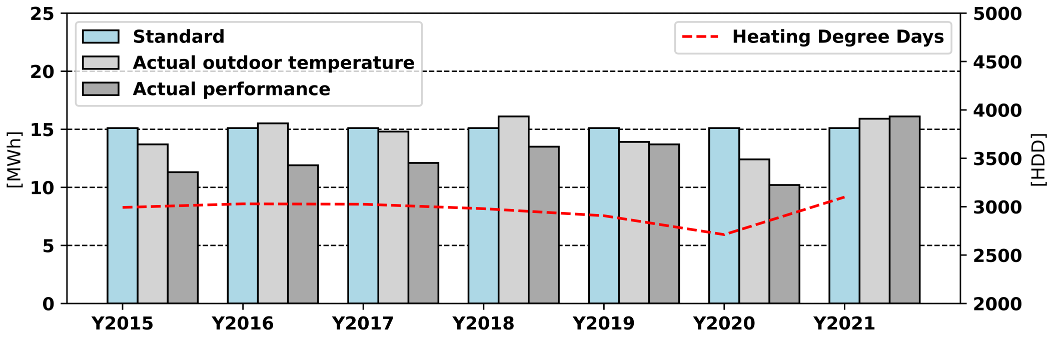
3 °C indoor temperature increase is assumed due to electrical equipment and radiation from the users which result in the minimum operating temperature defined in local standards [30].

Reflecting the results, the largest change of 2.7 MWh or 18 % in energy use is observed in 2020 (see Table 5.3). It also has 10 % less HDD in comparison to the standard climate boundary conditions. Contrary, an increase of 7 % in heating occurs in 2018 even though a similar number of HDD are reported. As none of the other climate inputs are changed, the results imply that not only the number but also the distribution of HDD throughout the year influence the results. HDD cannot be used as an isolated indicator to define the change in energy use for heating and is not directly proportional to the number of HDD in dynamic models.

Difference in	Y2015	Y2016	Y2017	Y2018	Y2019	Y2020	Y2021
Heating %	-9.27	2.65	-1.99	6.62	-7.95	-17.88	5.30
HDD %	-0.86	0.36	0.23	-1.29	-3.71	-10.17	2.68

Table 5.3: Change of energy use when actual dry bulb temperature is introduced.

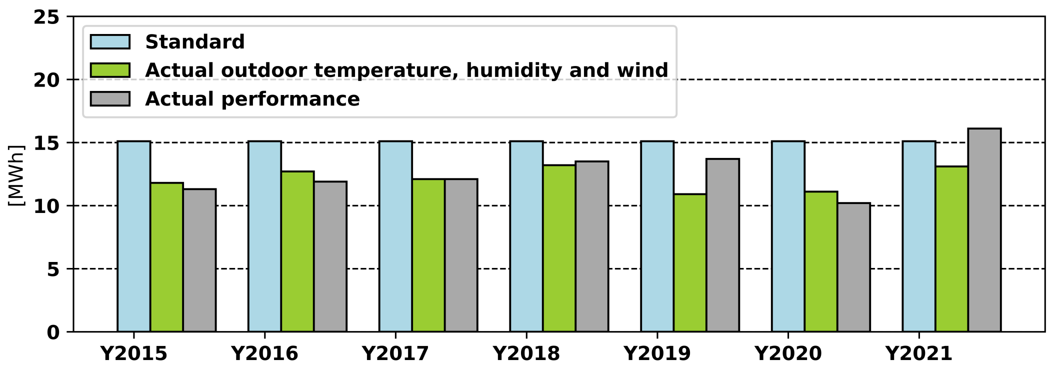
Figure 5.4: Energy use of the apartments for heating and Heating Degree Days. Dynamic standard model and custom model (includes inputs of actual dry bulb temperature and a standard occupancy) are shown.



5.1.2 Humidity, wind speed and wind direction boundary conditions

In the 2^{nd} scenario humidity, wind direction and wind velocity values are added. Increased wind speed is proportional to the pressure on the envelope and results in larger infiltration and is used as a reference to define changes in climate boundary conditions. When looking into the results, the losses decreased between 10 % and 22 % compared with the dynamic model and with the previous scenario climate condition (see Figure 5.5 and Table 5.4). As the relative humidity stays similar throughout the years of 2015 and 2021, the mean yearly wind speed fluctuated significantly and is the primary cause of the lower energy use in relation to the model with a standard climate input.

Figure 5.5: Energy use of the apartments for heating. Dynamic standard model and custom model (includes actual dry bulb temperature, humidity, wind direction and speed inputs, as well as a standard occupancy) are shown.

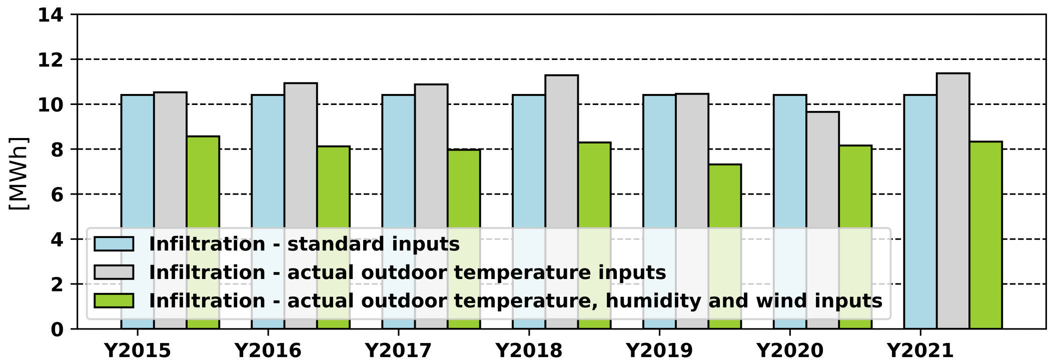


Difference in	Y2015	Y2016	Y2017	Y2018	Y2019	Y2020	Y2021
Temperature case %	-9.27	2.65	-1.99	6.62	-7.95	-17.88	5.30
Temperature and wind case %	-13.87	-18.06	-18.24	-18.01	-21.58	-10.48	-17.61
Average wind speed m/s	-6.67	-14.67	-12.00	-17.33	-16.00	-9.33	-20.00

Table 5.4: The change in percentage from the dynamic standard model when the 'actual temperature' and 'actual temperature and wind' climate data input scenarios are introduced. Also, a change in the average yearly wind speed of the 'actual temperature and wind' scenario is presented.

As presented in Figure 5.6, infiltration-caused heat losses are lower when average wind velocity decreased. For example, in the year 2019, a 16 % lower average wind speed and a 30 % decrease in heat losses through cracks are observed.

Figure 5.6: Energy loss due to infiltration in standard, 'actual outdoor temperature' and 'actual outdoor temperature and wind' scenario cases.



5.1.3 Summary

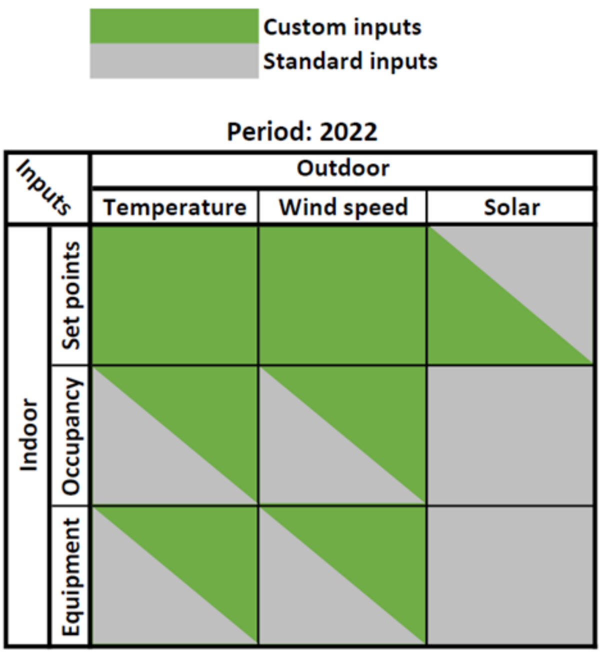
To finalize, use of both actual temperature and wind inputs have a high influence on the output results of the energy use for the space heating of the apartments. Even though the number of total HDD per year is similar in several scenarios (Standard, 2015 and 2017 cases), the variations of outdoor temperature follow the fluctuation of energy use by 11 %. It implies that performance cannot be solely judged by the accumulated HDD and more detail resolution needs to be applied when designing dynamic models. Also, climate variables of the wind scenario, especially wind velocity influence heat losses due to the infiltration and result in up to 20 % change in energy use.

5.2 Standard and Actual internal loads

Outdoor conditions can both increase and reduce energy use depending on the reference variable. During the heating season, lower outdoor temperature results in higher thermal losses, while an abundance of sunny days increases indoor gains. These factors of outdoor conditions are dependent on the building's location and can only be utilized by integrating passive design strategies. On the other hand, indoor inputs are primarily based on user behaviour. The desired indoor temperature, presence of the occupants, equipment use, and utilization of natural ventilation influence the performance of the existing buildings and result in an energy use change. Also, with low transmission losses through the envelope and efficient recovery of AHU, the design process of low-energy-use buildings is strongly reliant on the energy gains caused by the occupants and equipment. Consequently, the deviations of actual user behaviour compared to the standard one, have a larger impact on EPG when developing models for the case scenario type buildings.

5.2.1 Indoor temperature - set points

Figure 5.7: Inputs for the 2022 Indoor variable analysis.

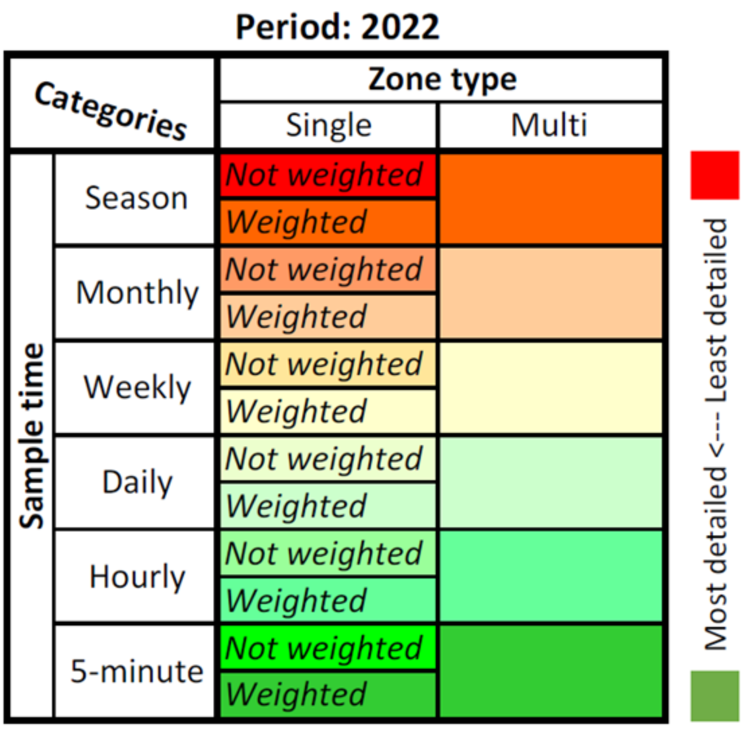


This chapter follows the data-driven model analysis by using the custom set point variations of the indoor temperature which are acquired from the case building. It is built as an addition to the custom weather analysis where 2022 climate data is used. Figure 5.7 presents custom and standard inputs used in performance evaluation influenced by user behaviour.

Regarding the outdoor conditions, custom temperature, wind speed and wind direction are used, while solar irradiation is standard (see Chapter 5.1 – weather data). Indoor inputs are divided into three sections of temperature, occupancy, and equipment. This chapter focuses on the evaluation of the supplied energy to the apartments when custom set point files are used. It is done due to acquired 5-minute resolution data in the period of January 19^{th} to August 31^{st}, 2022.

As case building has uncommonly high data resolution, the analysis of various time steps is performed to identify the error change. A number of sensors and storage, as well as treatment of logged data, follow the increase in the initial costs and maintenance. As a result, the evaluation can be used as a reference to identify the most optimal set-up choice regarding the desired precision.

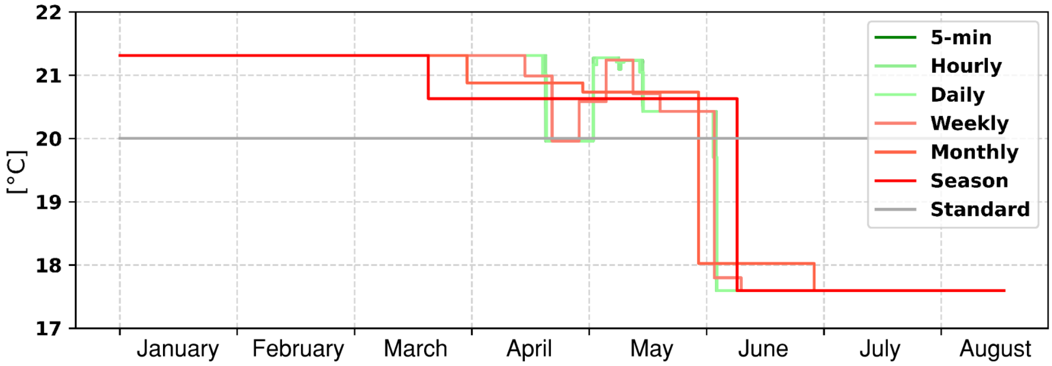
Figure 5.8: Resolution of the inputs for the 2022 indoor variable analysis



In total 18 variations are performed that are subdivided into the zones, which represent the number of used sensors, and sample time which indicates the time in between logged data points (see Figure 5.8).

The 5-minute logging interval is used as the highest resolution sample time is acquired from the BMS system used in the case building. The other data sets are derived by averaging the original set points. For example, monthly step time is the sum of all initial logs present during the time span and divided by the number of inputs (see Figure 5.8). It is based on the assumption that installed sensors store measured set points every 5 minutes and send averaged values to the BMS system monthly. The same principle is used to derive input data for hourly, daily, weekly and season set point files. The definition of season is: Winter 21.12.2022 – 20.03.2022; Spring 21.03.2022 – 20.06.2022; Summer 21.06.2022 – 22.09.202; Autumn 23.09.2022 – 20.12.2022.

Figure 5.9: Example of set point inputs. Single zone - weighted, apartment: 2^{nd} floor to the right



For example, monthly step time is the sum of all initial logs present during the time span and divided by the number of inputs (see Figure 5.9). It is based on the assumption that installed sensors store measured set points every 5 minutes and send averaged values to the BMS system monthly. The same principle is used to derive input data for hourly, daily, weekly and season set point files. The definition of season is: Winter 21.12.2022 – 20.03.2022; Spring 21.03.2022 – 20.06.2022; Summer 21.06.2022 – 22.09.202; Autumn 23.09.2022 – 20.12.2022.

<table>
<tr><th colspan="5">Apartment st th</th></tr>
<tr><th>Room</th><th>Parameter</th><th>Multi-storey</th><th>Single zone weighted</th><th>Single zone not weighted</th></tr>
<tr><td rowspan="3">Living room</td><td>Min</td><td rowspan="3">20.74</td><td rowspan="9">20.10</td><td rowspan="9">20.18</td></tr>
<tr><td>Max</td></tr>
<tr><td>Avg</td></tr>
<tr><td rowspan="3">Bedroom</td><td>Min</td><td rowspan="3">18.28</td></tr>
<tr><td>Max</td></tr>
<tr><td>Avg</td></tr>
<tr><td rowspan="3">Bathroom</td><td>Min</td><td rowspan="3">21.52</td></tr>
<tr><td>Max</td></tr>
<tr><td>Avg</td></tr>
</table>

Table 5.5: Summary of data-based indoor boundary conditions - set points of the heating

	5-min	Hourly	Daily	Weekly	Monthly	Season
Data points [-]	64512	5376	224	32	8	3
Error [%]	0.00	0.00	0.08	0.18	0.46	1.00

Table 5.6: Single zone - not weighted. Total logged data point per year and error of performance

Single zone - not weighted

The simulated models with the lowest resolution log of one set point per apartment during the previously described sample times. They represent the low maintenance case, where one value is obtained as an average of the installed sensors in the apartment (see equation 5.1). Room volume is not taken into consideration thus the models are defined as single zone "not weighted".

$$(T_{sensor.kitchen} + T_{sensor.bedroom} + ...) \div n_{number.of.sensors} = T_{Average.notweighted} \tag{5.1}$$

The difference in the performance of the supplied energy for heating to the apartments fluctuates not more than 1 % throughout the sample time range. Most importantly 5-minute and weekly logs result in an error of 0.2 % of the total supplied heat while having a different of 2016 times of delivered data size.

As shown in Table 5.6 the number of logged data points increases exponentially with each iteration of shorter sample time while the performance error does not exceed 1 %. As a reference, the use of custom outdoor temperatures changes the energy performance results by up to 18 % and wind inputs change it by up to 22 %, in the case building scenario.

Single zone - weighted

Following the zoning explanation in the previous chapter, the weighting factor of the spaces is introduced. The resulting single set-point value per apartment is an average of installed sensors, however, their influence is leveraged by the floor area of the room (see equation 5.2).

$$T_{sensor.kitchen} \times A_{kitchen} \div A_{apartment} + ... = T_{Average.weighted} \tag{5.2}$$

	5-min	Hourly	Daily	Weekly	Monthly	Season
Data points [-]	64512	5376	224	32	8	3
Error [%]	0.00	0.01	0.06	0.15	0.50	1.28

Table 5.7: Single zone - weighted. Total logged data point per year and error of performance

The performance error fluctuations throughout the sample time range are approximately 1 % (see Table 5.7) as in the not weighed case scenario, however, a difference of 2.6 % is observed between these two methods themselves.

Multi zone

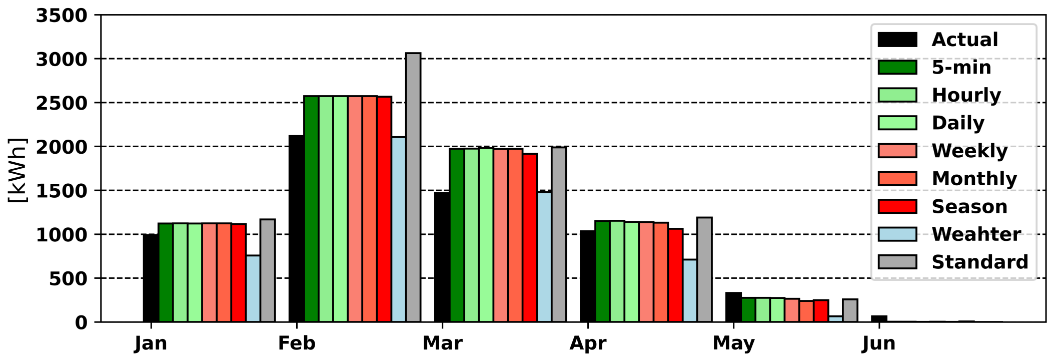
The models that use multi zones scenarios include and assign schedules to each room of the apartment. The averaging is performed only to create reduced resolution variation and does not require any weighting factors. For this reason, the multi zones model with a step time of 5 minutes utilizes all the provided set point data potential and is considered the closest to representing the actual scenario.

The performance error fluctuations for the total supplied heating energy throughout the sample time range of more than 2 % (see Table 5.8). Also, a difference of 4.5 % is observed between multi zones model results and single zone weighted models. The error further increases to 7 % when comparing the single zone not weighted models (see Figure 5.12).

	5-min	Hourly	Daily	Weekly	Monthly	Season
Data points [-]	193.536	16128	672	96	24	9
Error [%]	0.00	0.06	0.07	0.28	0.65	2.26

Table 5.8: Multi zone (3-room apartment example of data point count). Total logged data point per year and error of performance

Figure 5.10: Monthly energy supply to the apartments (Multi zone, 5-minute resolution). To note, Energy use in January covers only a part of the full month.

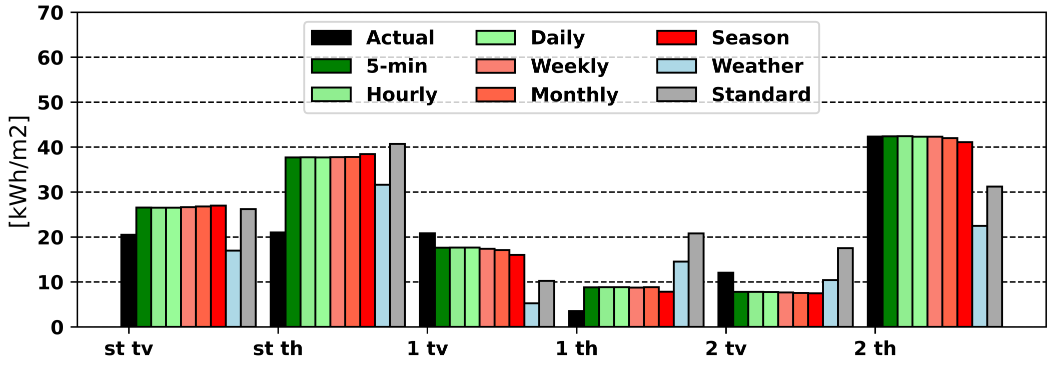


When the results of multi zones models are plotted as a total monthly supply of energy, the heating months between February and May follow a downward trend similar to the actual performance. The data-driven models result in lower EPG when compared with the standard weather and occupancy-based model (see

Figure 5.10). Not to forget, January includes only part of the month as limitations occur due to data availability (see Figure 5.1)

When the results are presented in total supplied energy to the individual apartment, no patterns occur, and randomness is observed. The only difference between the standard and actual set point models is the magnitude of the error. Custom set points reduce the extremes and bring the values closest to the actual ones.

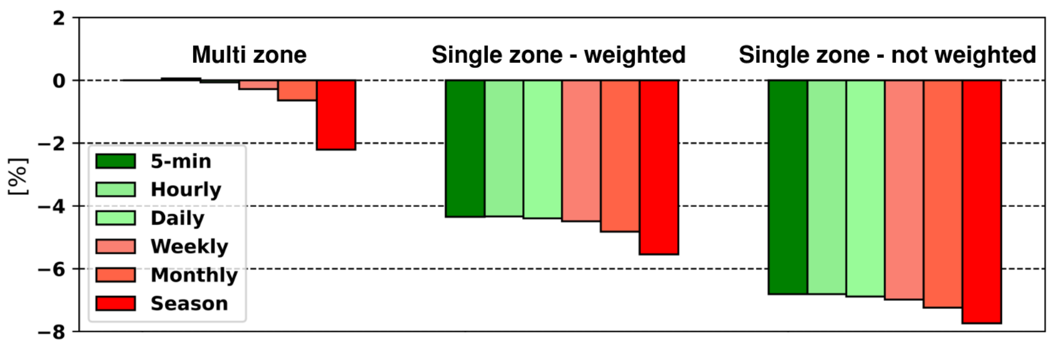
Figure 5.11: Energy supply to the individual apartments. Multi zone



When the actual climate and set points are included in the model design, the remaining error can be a result of internal gains due to occupant presence, equipment use, and natural ventilation. Further research is proposed to account for the remaining variables in the upcoming chapters.

5.2.2 Summary

Figure 5.12: Error of the custom set point models when compared with the multi zone 5-minute resolution model



The use of actual set points changed the EPG by 44 % from the original standard set points and actual weather model. It is the largest alteration compared with previously assessed changes in weather inputs. It further implies the importance of the use of real indoor boundary conditions when creating a baseline for the buildings. Additionally, the evaluations on data resolution show that variations in sample time and weighting factors between sensors influence the EPG. However, in relation to the most detailed scenario, the maximum increase in EPG stands below 8 % (see Figure 5.12). It is significantly lower than 44 % EPG of standard inputs and suggests that the use of low-resolution data logged once seasonally improves the design substantially.

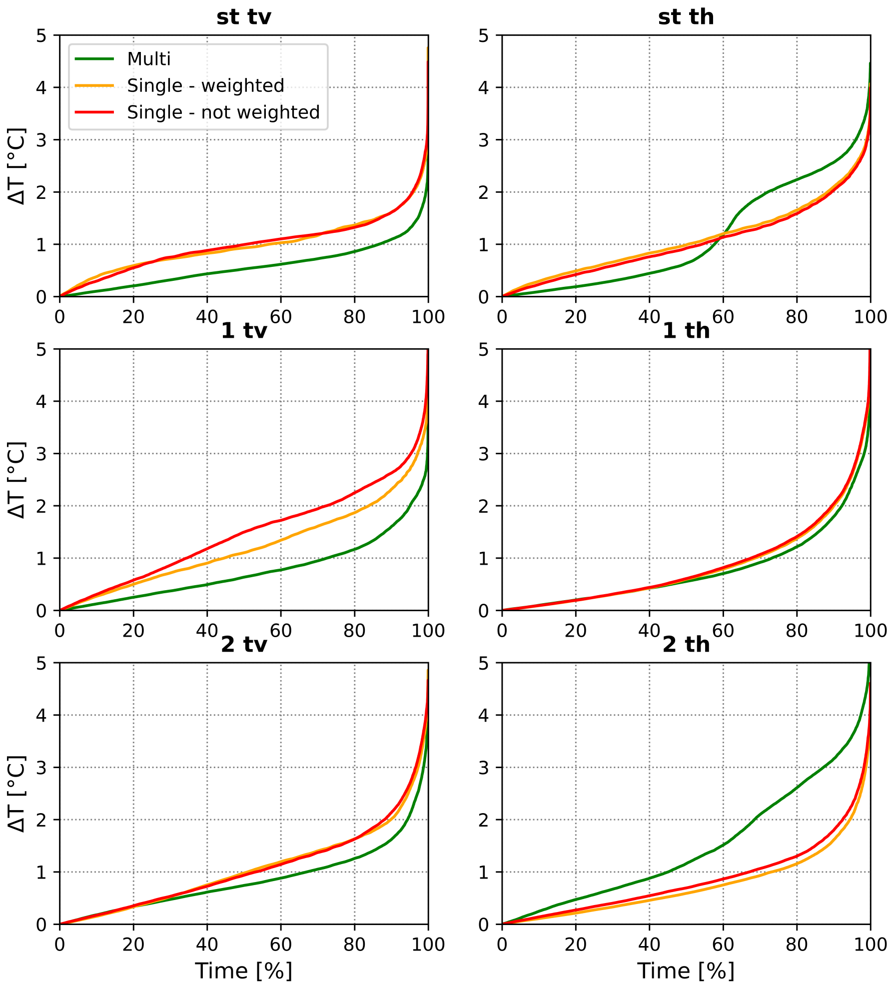
5.3 Causes of the remaining discrepancies

A limited amount of obtainable weather and occupancy data, inaccuracies in shape modelling and changes during the construction prevent building an ideal white-box model. In the case building scenario, an improvement from 26 % EPG to 17 % is achieved after correcting for available weather and occupancy boundary conditions. However, even though it is not possible to use all the information directly in the models, thematic analysis can guide the process of explaining the origin of the remaining mismatches. Looking into the pattern of the heating system behaviour, comparing outdoor and indoor boundary conditions, and defining inaccuracies in modelling, can help to adjust the models and stress the importance of further research on this topic. Also, the results from thematic analysis can be viewed and discussed freely which encourages talks on existing design faults, optimization, and the efficient techniques of renovation. The following objective of this chapter is to describe the underlying causes of the remaining performance gap and investigate the possible ways in which the white box models can be improved in the future.

5.3.1 Heating control set points and actual indoor temperature

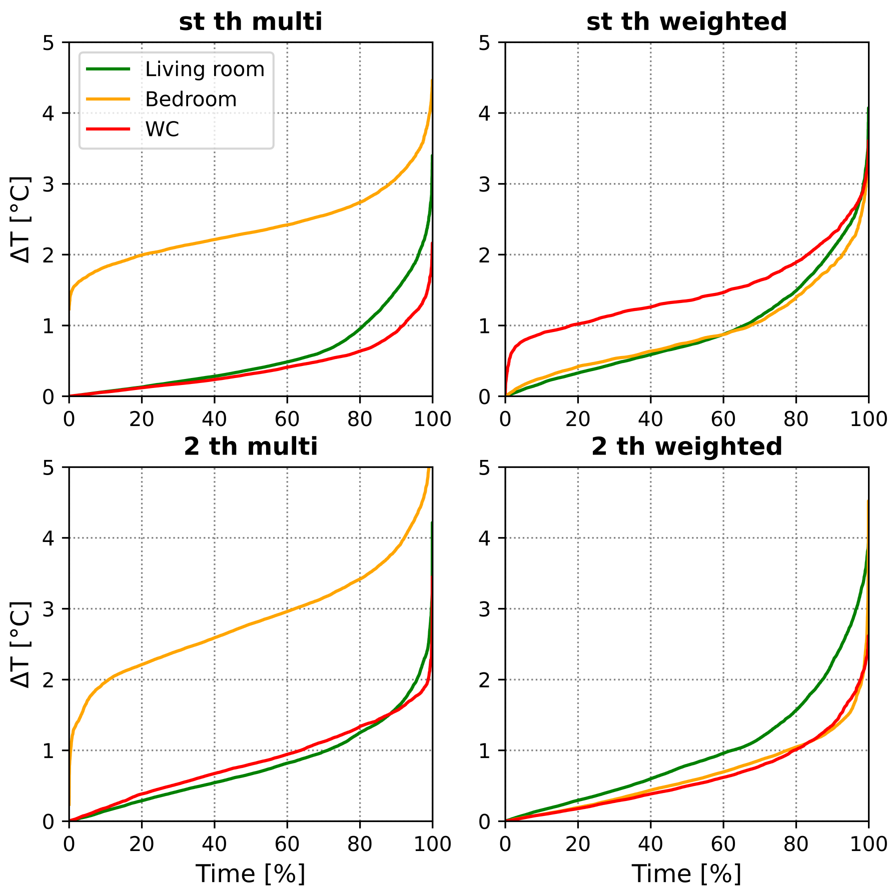
In Chapter 5.2, actual heating set points are used to account for indoor conditions. Three variations excluding the time-stamp resolution have been analyzed that result in EPG of 17 % multiple zones, 12 % single zone weighted and 9 % single zone not weighted. Theoretically, as a consequence of the input data describing each thermal zone of the apartments, the highest resolution multi zones scenario is expected to produce the best fitting of simulated and actual indoor temperatures. However, the assumptions are not ideal and do not always represent the actual behaviour of the systems. For example, air movement between rooms is difficult to predict due to the unknown state of indoor partitions. It can influence the indoor climate of the thermal zones and thus change the requirement of heating loads. To find which set point scenario should be used as a baseline, the difference between simulated and actual indoor temperatures is plotted (see Figure 5.13). The comparison covers the period from January until May which are primary heating months in the case building. The remaining months from May to the end of August are excluded to avoid discrepancies caused by overheating that are not evaluated in this study.

Figure 5.13: Temperature difference of actual and simulated models during the January to May months (5-minute resolution)



60 % of the time the output indoor temperature difference of the most fitting curve is equal to or lower than 1 °C. In four apartments out of six, the multi zones simulation has the lowest temperature difference among the scenarios. This match gap is noticeable in the apartment located on the left side. However, models with a single zone set point inputs cause similar or lower differences on the right-side apartment. As shown in Chapter 3 Figure 3.2, the volume and layout of the opposing apartments vary. To find the possible causes of why high-resolution input data results in higher temperature discrepancies compared with other weighting scenarios, a more detailed look into the individual zones are presented (see Figure 5.14).

Figure 5.14: Temperature difference of individual zones between actual and simulated models during the January to May months: st th, 2 th (5-minute resolution)



As shown in Figure 5.14, the leading mismatch between actual and simulated models output occurs in the Bedroom. Multi-zone scenario underestimates the convection between neighbouring rooms and results in indoor temperatures being strictly close to the input set points regardless of the temperatures in other thermal zones. However, actual indoor temperatures in the bedroom and living room are assumed to be similar due to air circulation. For this reason, the single-zone weighted scenario has lower temperature discrepancies as it takes into consideration interactions between zones.

5-minute resolution simulation results and actual indoor temperatures are summarized in Tables 5.15 and 5.16 for investigated apartments. The average temperature difference in the bedroom exceeds the other rooms, especially, the 2 TH apartment where an absolute difference of 2.7 °C is observed. The actual conditions of the bedrooms are closer to the connecting living room than set points. It is likely due to higher than simulated convection between two zones from which the living room is the dominant because of the larger volume. On the other hand, two other scenarios take into consideration the interaction between zones and result in indoor temperatures being closer to the actual ones.

Figure 5.15: Actual and simulated temperatures of 2 TH apartment

Actual, multi zone and single zone weighted temperatures									
ST TH	Living room			Bedroom			Bathroom		
	Actual	*Multi*	*Weighted*	*Actual*	*Multi*	*Weighted*	*Actual*	*Multi*	*Weighted*
Set points	20.7	20.7	20.1	18.3	18.3	20.1	21.5	21.5	20.1
Average	21.3	20.9	20.4	21.2	18.8	20.3	20.2	20.9	20.2
Minimum temp	20.1	20.3	19.8	20.0	18.2	20.0	20.2	20.9	19.7
Maximum temp	24.1	22.2	21.8	23.6	20.2	20.8	23.7	21.9	20.7

ST TH	Average temperature difference		
	Living room	*Bedroom*	*Bathroom*
Multi	-0.4	-2.4	0.7
Weighted	-0.9	-0.9	0

Figure 5.16: Actual and simulated temperatures of 2 TH apartment

Actual, multi zone and single zone weighted temperatures									
2 TH	Living room			Bedroom			Bathroom		
	Actual	*Multi*	*Weighted*	*Actual*	*Multi*	*Weighted*	*Actual*	*Multi*	*Weighted*
Set points	22.7	22.7	21.3	17.9	17.9	21.3	22.5	22.5	21.3
Average	22.5	22.7	21.7	21.3	18.5	21.4	21.7	22.5	21.3
Minimum temp	19.0	20.8	20.3	17.0	17.9	20.0	19.1	20.8	20.0
Maximum temp	26.2	25.2	24.1	24.8	19.8	22.1	23.9	22.9	22.0

2 TH	Average temperature difference		
	Living room	*Bedroom*	*Bathroom*
Multi	0.2	-2.8	0.8
Weighted	0.79	0.1	-0.4

The standards of designing models do not describe air change rate variations between the neighbouring rooms. The default assumption in the dynamic model is accepted as "doors always closed" and only the fixed area of the gap is defined. This assumption is used throughout all the dynamic simulations, and it results in the previously described temperature mismatch. However, if the opposite, "doors always opened" setting is used, the rooms in the same apartment function as one thermal zone and the highest heating set point overwrites the remaining set points. Consequently, all weighting methods are inapplicable and lead to larger deviations.

Air exchange between rooms is dependent on the internal partition position. It is controlled by the users and therefore can be classified as a variable of occupancy behaviour. The actual state of the doors is likely between the assumed "always closed" and "always opened" that, as other indoor user behaviour parameters can be standard or data-driven.

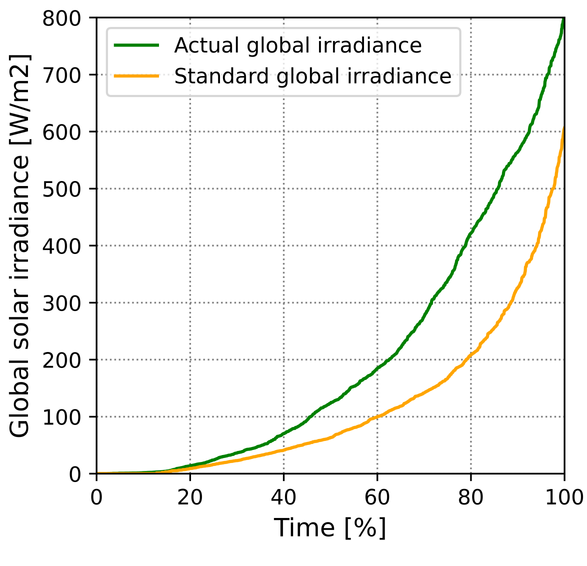
5.3.2 Solar irradiation and indoor temperature

In Chapter 5.1, actual outdoor boundary conditions are used to reduce EPG. Outdoor temperature, humidity, wind direction and wind speed inputs are replaced by the actual values, however, direct normal and diffused radiations are kept as standard. Instead, actual global solar irradiation is obtained that cannot be used in the white-box model design. Nevertheless, the standard diffused and direct solar radiation values can be combined which results in standard global solar irradiation. Having actual and standard Global solar irradiation allows us to compare the solar loads that explain the cause of the remaining energy performance gap.

$$GHI = DNI * cos(\alpha) * DHI$$

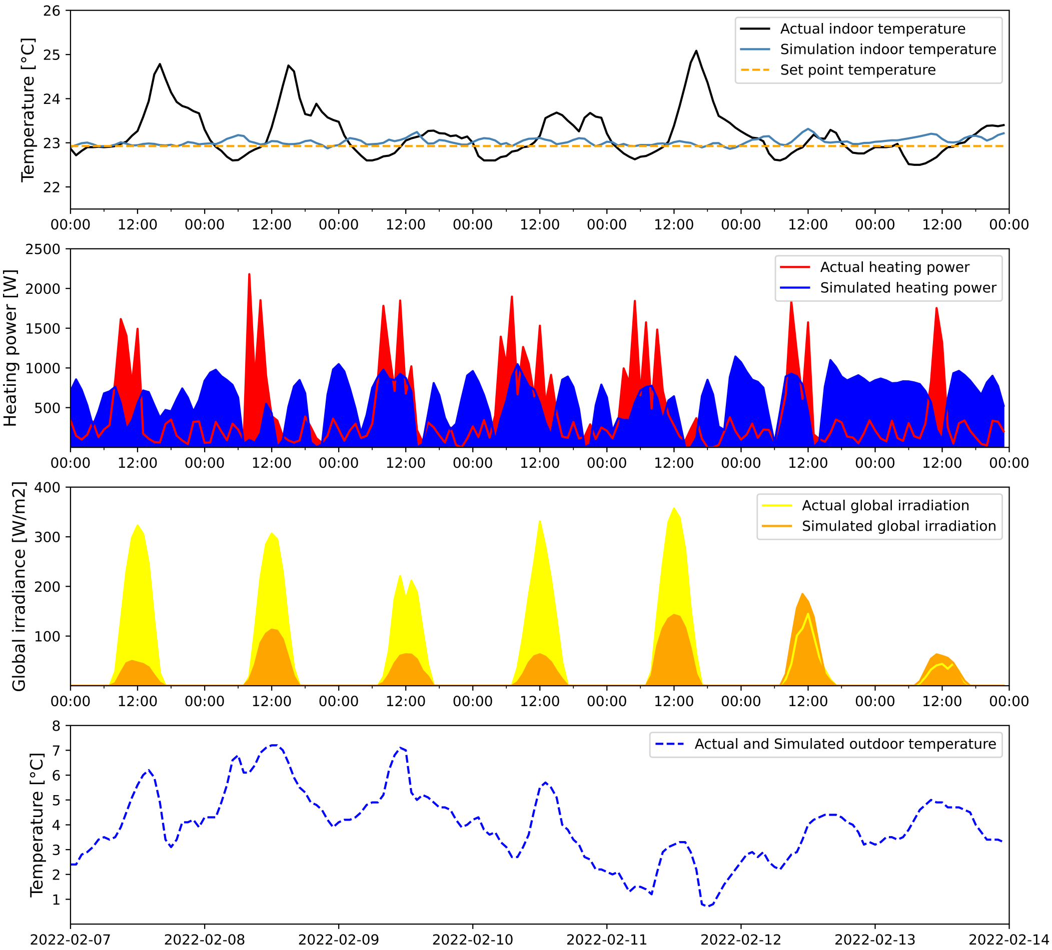
GHI - Global Horizontal Irradiance $[W/m^2]$
DNI - Direct Normal Irradiance $[W/m^2]$
A - solar zenith angle $[°]$
DHI - Diffused Horizontal Irradiance $[W/m^2]$

Figure 5.17: Actual and Simulated global solar irradiation boundary conditions during primary simulated heating months (January to May)



Actual and standard global irradiation during the heating months between January and May are compared (see Figure F.1). A higher actual global irradiance than assumed implies that internal gains are higher and energy use for heating is respectively lower.

Figure 5.18: Internal and external boundary conditions of 1 TV, living room. February 7-14, 2022



The analysis is performed for one of the apartments for 3 week period (see appendix F) and an example week is presented in Figure F.1. It describes actual and simulated model outdoor and indoor boundary conditions, as well as output from the heating system. It illustrates qualitative data that entails searching across a data set to identify, analyze, and report repeated patterns. For example, possibly higher actual occupancy loads can be seen between the 12^{th} and 14^{th} (weekend). Even though the indoor temperature profile and solar loads are similar, a simulated model requires more energy to maintain the same indoor temperature. It is only an assumption because higher energy use can be also caused by human design errors or changes present during the construction which are not included when creating a white-box model.

Chapter 6

Discussion

This chapter focuses on the obtained results in numerical and thematic analysis, the limitations, improvements, and possible future research.

The project focuses on the creation of an energy use baseline in multi-storey residential buildings. Steady-state and dynamic white-box models are built to simulate the output and compare it with the actual performance. The white-box model includes detailed three-dimensional geometry of the building and a simplified HVAC system and initially is based on the standard inputs of occupancy, heating set points and Danish Reference Year weather conditions. The white-box model can be gradually improved towards the digital-twin model. The improvements include changes to the outdoor and indoor conditions, such as the use of actual weather data, heating set points, number of occupants etc. The boundary conditions are the critical inputs of the energy and mass balance calculations, that describe the physics in the white-box models. However, the software interface, lack of information regarding the envelope, sensor accuracy, overestimated KPIs of the components etc. limit the potential of the analysis and increase the uncertainty of the results.

The first limitation that cannot be accounted for is the precision of the geometry and thermal performance of the structure. For example, the conflicting information of 200 *mm* and 220 *mm* wall re-insulation thickness is noted in the building design documentation and detailed construction drawings. Also, the envelope tightness is unknown thus assumptions are made. As described in Chapter 5.1, infiltration has a significant influence on energy use for heating and changes in air leakage can alter the importance of using actual wind conditions. However, the lack of information on window performance is an essential limitation. The insulating properties and ratio of transmitted solar energy are estimated following the building regulations for 2010. Choices of window performance characteristics are an essential part of passive energy optimization strategies, and the lack of precision reduces the reliability of the models.

The following limitations are caused by climate boundary conditions. As described in Chapters 3 and 5.1, the data is obtained from the nearest weather station within a 10 by 10 *km* area. Outdoor temperatures and wind speed can vary due to location and surrounding structures and, as a result, influence model output. Also, DNI and DHI are not measured at the selected station and numerical evaluation is replaced by less credible thematic analysis. Additionally, assumptions are made when converting standard DNI and DHI to GHI that is compared with actual solar irradiation.

Furthermore, obtained occupancy data and software input requirements resulted in approximations. The heating set points are logged starting from the 19^{th} of January 2022 and continue further into the year. The missing January indoor boundary conditions are assumed to be equal to the first recorded data points of the thermal zones. The same estimation is done for 2 week period before the starting point of the simulation which is used to stabilize the system by taking into consideration the thermal inertia of the components. These assumptions reduce the result validity of the heating energy use during January month which is used in EPG identification for total and individual apartment baseline. In addition, standard inputs are used for occupancy and equipment thermal loads. It prevents numerical analysis and quantifying the EPG change that likely causes the remaining discrepancies.

Lastly, the objective that covers the *rate of percentage change in total energy use working with different resolutions of data inputs* is limited by the accessible information on the financial aspect of the data storage. A one-dimensional approach is taken in this study when assessing the importance of time stamps of the measured indoor boundary conditions. Only the change in EPG is quantified when different resolution is used and highly valuable financial aspects of data storage and treatment are neglected. It results in a simplified objective that covers only a small part of the initially targeted goal.

6.1 Future work

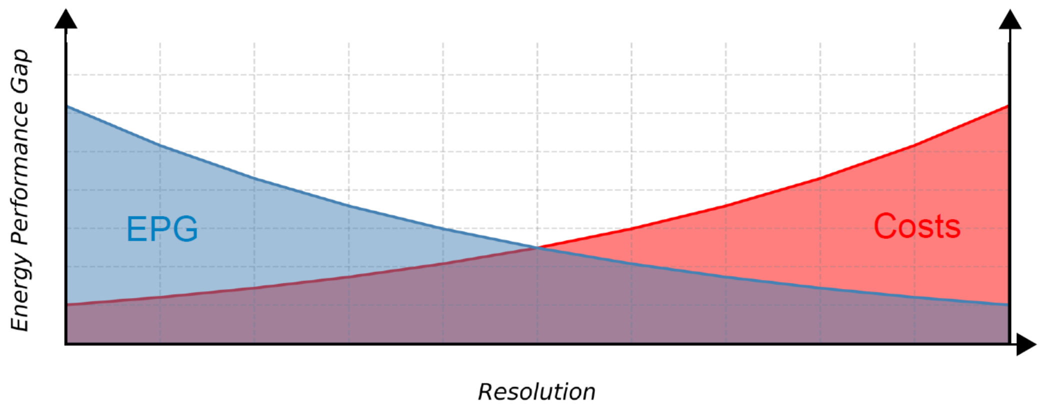
The Master Thesis covers only a small part of the research theme and does not utilize the created model to its full potential. Further paragraphs present the importance and possible paths for future research.

Most importantly, the additional assessment of results can be performed by using the designed IDA ICE white-box model. Due to time constraints, this project primarily focuses on energy use for heating apartments. Even though the results include data on cooling loads, distribution losses and various KPIs of the HVAC components, no qualitative or thematic analysis is performed. This indicated a further potential of continuing with an already built model and comparing actual with a simulated performance at different detail levels. For example, the COP of the heat pump is already accessible in steady-state and dynamic models, as well as actual performance measurements are logged. The minimum, maximum and seasonal performance can be identified and compared with the characteristics provided by the producer.

Equally, it is important to continue the research with various types of multi-storey residential buildings to create a more robust pool of samples. Only one scenario is covered when answering the raised research questions in this project. The same objectives can have significantly different results when different types, shapes, structures or occupancy loads are modelled. For example, high variations in EPG are noticed in previously presented studies (see Table 1.1). Deviations from 2 % to 110 % are observed before calibrations and 4 % to 51 % after. However, only one scenario evaluates EPG before and after calibration in a similar energy performance building as in this project. It indicated a lack of study cases to validate the proposed baseline methods and establish an optimal modelling approach

Additionally, the project is limited to two software: BE18 for steady-state white-box models and IDA ICE for dynamic white-box models. Different modelling tools can produce another outcome due to the various weighting factors, interface and compatible time stamp resolutions. For this reason, it can be relevant to replicate the study based on the software preferable in other countries.

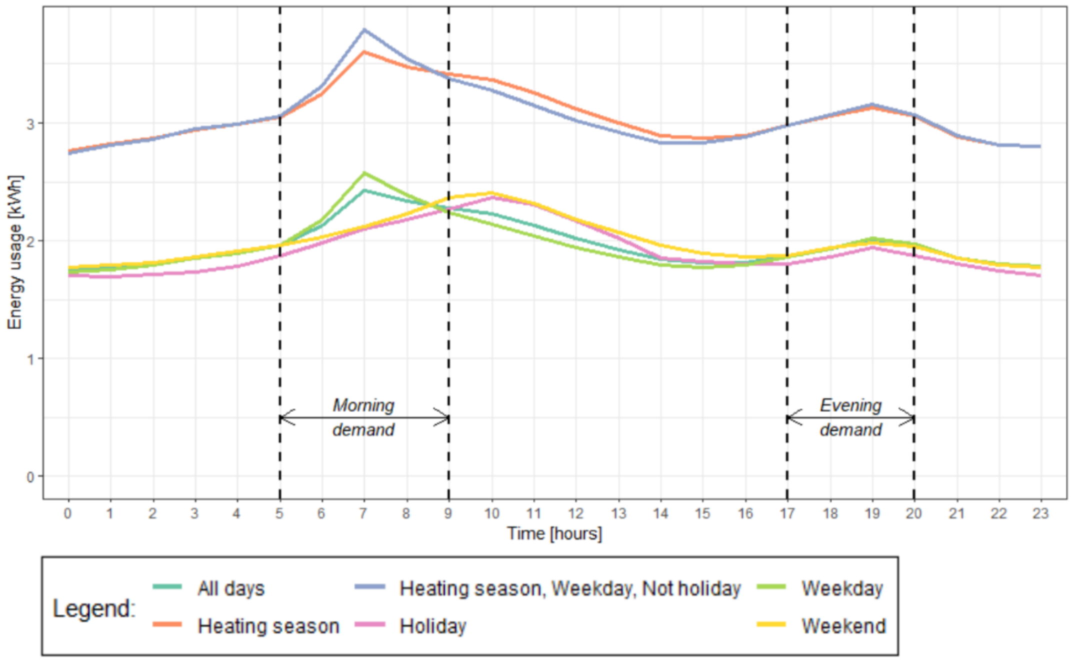
Figure 6.1: Example of Energy Performance Gap and Cost to resolution change



Finally, the previously mentioned potential to further interpret the importance of the sample resolution is suggested. Due to the increase in digitalization and use of the indoor climate monitoring tools, the field of data science regarding building stock evaluation is increasing in value. If the data point costs are quantified in this project, the cost-to-performance proportion can be plotted (see Figure 6.1). It is a step forward in finding a method to choose the optimal setup of the monitoring tools to baseline the performance of the buildings.

Example on the future work: power peaks of the heating system
One of the objectives of SATO project is to define which systems, energy components and appliances should be included in the assessment framework to efficiently monitor and operate buildings. Identification of the EPG is the first step towards the development of reliable methods for optimization of the building energy use, fault detection and diagnosis. An example of plausible optimization can be seen in the Actual heating load pattern (see Figure F.1).

Figure 6.2: Example of average daily space and DHW heating load profile. The image is taken from the study conducted in Denmark [33] (Supporting study that focuses on the District Heating plant peak loads: Turin, Italy [34])



In the actual scenario, a combination of high heating power between 6-12 AM and larger solar loads during the daytime lead to a 1-2 °C temperature increase. Minimum heating is required until the temperature falls back to the set point. The actual temperature usually hits the set point between 12 PM - 6 AM when the heating power starts increasing again and peaks after 6 AM. As shown in Figure 6.2), most of the energy used in the cities matches the case buildings' heating profile. Heating during peak hours is disadvantageous for the client due to increased prices and the energy provider as higher than average capacity supply systems need to be installed to cover peak loads. Even though the total heating energy demand is lower in the actual case scenario, the financial result can be similar or even unfavourable compared with an evenly distributed heating pattern. The same question is raised when evaluating the benefits of implementing night set-back. Night set-back is a mode that reduces the heating set point during the night period while the users are asleep. It does not compromise thermal comfort as the lower temperatures are acceptable and usually preferable [35] [36]. Even though this control strategy reduces the energy use for heating, it results in high heating power during peak demand hours. Based on the case building performance and energy price fluctuations the set-back control can reduce or increase the costs regardless of the lower energy demand.

In the showcased apartment scenario (see Figure F.1), the indoor temperatures are notably higher than the heating set point during the 12 AM to 12 PM hours and similar until 6 AM. This temperature rise is likely caused by solar gains and occurring heating delays due to the use of floor heating. If a digital-twin model with a lower EPG would be used as a part of the Model Predictive Control (MPC) system, the delays could be accounted for and distributed heating pattern achieved. It would potentially result in reduced heating costs and balanced loads on the grid.

Chapter 7

Conclusion

The evaluation of the Danish multi-storey residential building is performed in connection to EPG identification to establish the energy use baseline of space heating. The objectives of this project focus on quantifying the discrepancies between the dynamic model output when standard and actual boundary conditions are used. It covers the investigation of available data, its utilization and its impact on performance. Additionally, the rate of percentage change in energy use is presented and concludes on the importance of sampling time in creating a baseline. To finalize, the thematic analysis is conducted to explain the remaining mismatch of the energy use for space heating and identify the data that could improve the model and further reduce the EPG.

Energy use for apartment space heating is a main KPI when evaluating the output of the models. Starting with the climate analysis, standard input values are based on the weather data of the nearest weather station available in the ASHRAE IWEC 2. The data-driven climate conditions include the outdoor temperature, wind direction and wind speed sampled from the nearest weather station available in the DMI database. The solar data is excluded from the quantitative evaluation due to the unfeasible utilization of Global Solar Irradiation when working with the IDA ICE modelling software. The yearly energy use values are benchmarked during the period between 2015 and 2022. Overall, the use of both actual temperature and wind speed has a high influence on the output results of the energy use for the space heating of the apartments. The implementation of actual outdoor temperature followed the fluctuation of energy use by 11 % while the introduction of wind parameters affected heat losses due to the infiltration and resulted in performance changes of up to 20 %. Progressing into the indoor boundary conditions, the standard and actual heating set point values are introduced. The standard inputs are based on the DS16798 occupancy description while the data-driven model uses the actual set points logged on-site. The use of actual heating set points changed the EPG by 44 % from the standard occupancy – actual weather model. It is the largest alteration compared with previous assessments and it supports the assumption that low-energy use buildings are greatly dependent on occupant behaviour and less on the outdoor boundary conditions.

Additionally, the rate of percentage change in total energy use working with different resolutions of data is quantified by modifying previously covered actual set point inputs. The comparison between timestamps of 5 minutes, hourly, daily, weekly, monthly and seasonal (3-month) intervals are performed. Also, three weighting factors are applied for each interval: multi-zone – one room represents one thermal zone thus individual set point inputs are used; single zone weighted – apartment represents one thermal zone and one set point input is used which is weighed taking into consideration volume of the rooms; single zone not weighted – apartment represents one thermal zone and one set point input is used which does not take into consideration the volume of the rooms (see Chapter 5.2). The evaluations on data resolution show that variations in sample time and weighting factors between sensors influence the EPG. However, in relation to the most detailed, 5-minutes scenario, the maximum increase in EPG stands below 8 %. To put into perspective, it is significantly lower than 44 % EPG of standard inputs and suggests that even the use of low-resolution data has a substantial effect on creating a baseline.

The resulting data-driven model of previously described inputs results in overestimated EPG of 17 %. To further explain the discrepancies, the comparison is performed between standard and actual Global Solar Irradiation or GHI. The distribution of GHI during the primary heating months between January and May shows an approximately 25 % higher actual solar irradiation than standard. It indicated higher actual solar gains and, as a result, lower energy use for space heating. It supports the assumption that the use of actual solar irradiation further reduces the EPG.

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Appendix A

Case building description

A.0.1 Detailed drawings

Figure A.1: Example of detailed ground floor plan drawing

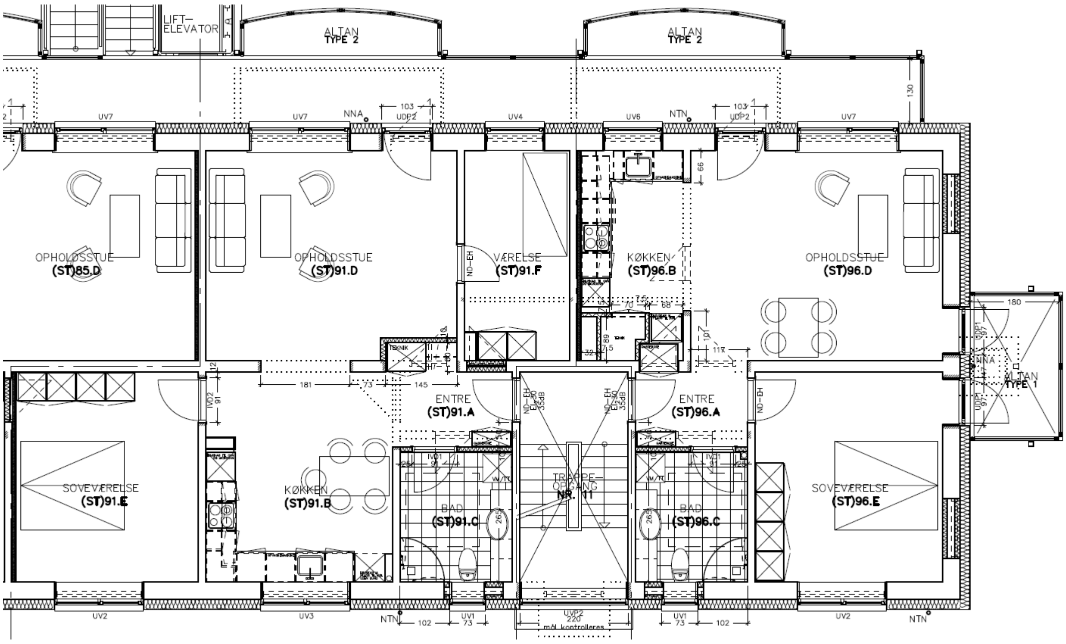
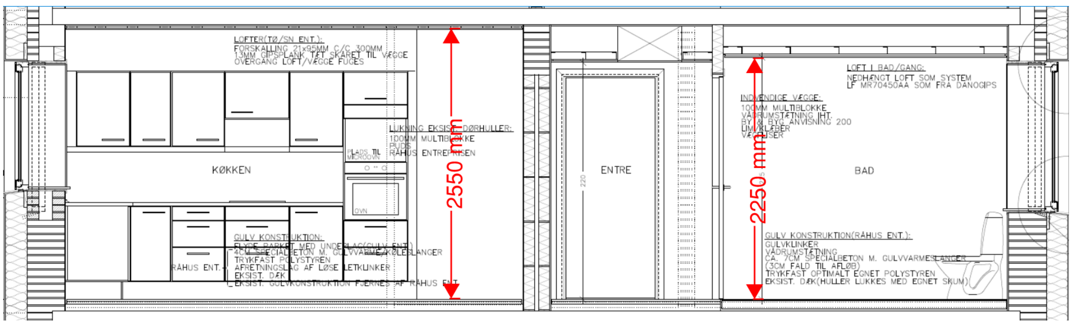


Figure A.2: Example of detailed 1st floor cross-section drawing



A.0.2 U-values

Figure A.3: External wall U-value

can be filled

Assembly No.:	Building Assembly Description
1	**External wall**

		Section 1		Section 2			Section 3						t_{in} [C°] :	20.00
No.:	Name	λ [W/mK]	% (0-100]	Name	λ [W/mK]	% (0-100]	Name	λ [W/mK]	% (0-100]	λ_{total} [W/mK]	d [m]	R [m²K/W]	Δt [K]	t [C°]
	Internal heat surface											0.130	0.61	19.39
1.	Brick	0.580	100							0.580	0.380	0.655	3.10	16.29
2.	Insulation 37	0.037	100							0.037	0.220	5.946	28.10	-11.81
3.	Cover													
4.														
5.														
6.														
7.														
8.														
9														
	External heat surface resistance											0.040	0.19	-11.81
												0	t_{out} [C°]:	-12.00
										Total values:	0.600	6.771		

Correction factors: [W/m²K]			
	U_g	0	Air-cracks
	U_f	0	Ties and similar fixations
	U_r	0	Precipitation on "upside down"

U-value:	0.148	[W/m²K]

Figure A.4: Roof U-value

can be filled

Assembly No.:	Building Assembly Description
2	**Roof**

		Section 1		Section 2			Section 3						t_{in} [C°] :	20.00
No.:	Name	λ [W/mK]	% (0-100]	Name	λ [W/mK]	% (0-100]	Name	λ [W/mK]	% (0-100]	λ_{total} [W/mK]	d [m]	R [m²K/W]	Δt [K]	t [C°]
	Internal heat surface											0.100	0.25	19.75
1.	Insulation 37	0.037	100							0.037	0.350	9.459	23.91	-4.16
2.	Insulation 37	0.037	85	Timber	0.160	15				0.055	0.150	2.705	6.84	-11.00
3.	Plywood	0.160	100							0.160	0.025	0.156	0.39	-11.39
4.	Rood cover (DS418 6.5)											0.200	0.51	-11.90
5.														
6.														
7.														
8.														
9														
	External heat surface resistance											0.040	0.10	-11.90
												0	t_{out} [C°]:	-12.00
										Total values:	0.525	12.661		

Correction factors: [W/m²K]			
	U_g	0	Air-cracks
	U_f	0	Ties and similar fixations
	U_r	0	Precipitation on "upside down" r

U-value:	0.079	[W/m²K]

Figure A.5: Floor to the basement U-value

	can be filled

Assembly No.:	Building Assembly Description
3	**Floor to the basement**

No.:	Section 1 Name	λ [W/mK]	% (0-100)	Section 2 Name	λ [W/mK]	% (0-100)	Section 3 Name	λ [W/mK]	% (0-100)	λ_{total} [W/mK]	d [m]	R [m²K/W]	Δt [K]	t [C°]
	Internal heat surface											0.170	0.55	19.45
1.	Parket	1.200	100							1.200	0.005	0.004	0.01	19.44
2.	Special beton	1.600	100							1.600	0.040	0.025	0.08	19.36
3.	EPS80	0.038	100							0.038	0.060	1.579	5.07	14.29
4.	Reinforced concrete dæk	2.400	100							2.400	0.150	0.063	0.20	14.09
5.	Rockorbit isolering	0.034	100							0.034	0.095	2.794	8.97	5.13
6.														
7.														
8.														
9														
	External heat surface resistance											0.040	0.13	5.13
												0	t_{out} [C°]:	5.00
										Total values:	0.350	4.675		

t_{in} [C°]: 20.00

Correction factors: [W/m²K]			
	U_g	0.000	Air-cracks
	U_f	0.007	Ties and similar fixations
	U_r	0.000	Precipitation on "upside down"

U-value: **0.221** **[W/m²K]**

U_g	level	Value	Description
	0	0	No air-cracks across the insulation layer
	1	0.01	Possibility for air-cracks actross the oinsulation layer No air circulation on the warm side of the insulation layer
	2	0.04	Possibility for air-cracks actross the oinsulation layer Possibility for air circulation on the warm side of the insulation layer
	R_i	2.700	Heat flow resistance of the insulation layer [m²K/W]

$$\Delta U_g = \Delta U'' \left(\frac{R_i}{R_T}\right)$$

Figure A.6: Floor to the ground (staircase) U-value

	can be filled

Assembly No.:	Building Assembly Description
4	**Floor to the ground (staircase)**

No.:	Section 1 Name	λ [W/mK]	% (0-100)	Section 2 Name	λ [W/mK]	% (0-100)	Section 3 Name	λ [W/mK]	% (0-100)	λ_{total} [W/mK]	d [m]	R [m²K/W]	Δt [K]	t [C°]
	Internal heat surface											0.170	21.62	-1.62
1.	Reinforced concrete	2.400	100							2.400	0.100	0.042	5.30	-6.91
2.														
3.														
4.														
5.														
6.														
7.														
8.														
9														
	External heat surface resistance											0.040	5.09	-6.91
												0	t_{out} [C°]:	-12.00
										Total values:	0.100	0.252		

t_{in} [C°]: 20.00

Correction factors: [W/m²K]			
	U_g	0	Air-cracks
	U_f	0	Ties and similar fixations
	U_r	0	Precipitation on "upside down"

U-value: **3.974** **[W/m²K]**

U_g	level	Value	Description
	0	0	No air-cracks across the insulation layer
	1	0.01	Possibility for air-cracks actross the oinsulation layer No air circulation on the warm side of the insulation layer
	2	0.04	Possibility for air-cracks actross the oinsulation layer Possibility for air circulation on the warm side of the insulation layer
	R_i	2.700	Heat flow resistance of the insulation layer [m²K/W]

$$\Delta U_g = \Delta U'' \left(\frac{R_i}{R_T}\right)$$

Figure A.7: Floor to the ground U-value

can be filled

Assembly No.:	Building Assembly Description
5	**Floor to the ground**

No.:	Section 1 Name	Section 1 λ [W/mK]	Section 1 % (0-100)	Section 2 Name	Section 2 λ [W/mK]	Section 2 % (0-100)	Section 3 Name	Section 3 λ [W/mK]	Section 3 % (0-100)	λ_{total} [W/mK]	d [m]	R [m²K/W]	Δt [K]	t [C°]
	Internal heat surface											0.140	5.61	14.39
1.	Reinforced concrete	1.800	100							1.800	0.350	0.194	7.79	6.60
2.														
3.														
4.														
5.														
6.														
7.														
8.														
9														
	External heat surface resistance											0.040	1.60	6.60
												0		
										Total values:	0.350	0.374		

t_{in} [C°]:	20.00
t_{out} [C°]:	5.00

Correction factors: [W/m²K]			
	U_g	0	Air-cracks
	U_f	0	Ties and similar fixations
	U_r	0	Precipitation on "upside down"

U-value:	2.671	[W/m²K]

	level	Value	Description
U_g	0	0	No air-cracks across the insulation layer
	1	0.01	Possibility for air-cracks actross the oinsulation layer No air circulation on the warm side of the insulation layer
	2	0.04	Possibility for air-cracks actross the oinsulation layer Possibility for air circulation on the warm side of the insulation layer
	R_i	2.700	Heat flow resistance of the insulation layer [m²K/W]

$$\Delta U_g = \Delta U'' \left(\frac{R_i}{R_T}\right)$$

Appendix B

Steady-state standard model

Figure B.1: BE18 - input values

Højbo, Frederikshavn boligforening	
The building	
Building type	Multy-story house
Rotation	22,0 deg
Area of heated floor	431,1 m²
Area heated basement	0,0 m²
Area existing / other usage	0,0 m²
Heated gross area incl. basement	431,1 m²
Heat capacity	120,0 Wh/K m²
Normal usage time	168 hours/week
Usage time, start at - end at, time	0 - 24
Calculation rules	
Calculation rules	BR: Actual conditions
Suplement to energy frame	0,0 kWh/m² år
Heat supply and cooling	
Basic heat supply	Electricity
Heat distribution plant	Yes
Electric panels	No
Wood stoves, gas radiators etc.	No
Solar heating plant	No
Heat pumps	Yes
Solar cells	Yes
Wind mills	No
Mechanical cooling	Yes

Room temperatures, set points	
Heating	20,0 °C
Wanted	23,0 °C
Natural ventilation	24,0 °C
Mechanical cooling	25,0 °C
Heating store	15,0 °C
Dimensioning temperatures	
Room temp.	20,0 °C
Outdoor temp.	-12,0 °C
Room temp. store	15,0 °C

External walls, roofs and floors					
Building component	Area (mÂ²)	U (W/mÂ²K)	b	Dim.Inside (C)	Dim.Outside (C)
External walls	314,0	0,16	1,000		
Roof	175,0	0,08	1,000	20	-12
Floor to the basement (floor heating)	165,0	0,22	1,000	30	
Floor to the ground (staircase)	12,7	3,97	0,700	15	10
Walls to the basement (staircase)	24,4	2,67	0,700	15	5

External walls, roofs and floors					
Roof openings (take a look)	0,0	0,00	1,000		
Ialt	691,1	-	-	-	-

Foundations etc.					
Building component	l (m)	Loss (W/mK)	b	Dim.Inside (C)	Dim.Outside (C)
Foundation - staircase (no need - too high ground floor U-value	0,0	0,00	1,000		
Loss to the basement (6.13.3 - mid case) - external walls	42,0	0,27	1,000		
Loss to the basement (6.13.3 - mid case) - internal walls	72,3	0,27	0,700		
Windows regular (top, sides and bottom) U-(99)1.02 (Box frame)	153,0	0,01	1,000		
Doors (bottom)	12,0	0,01	1,000		
Doors (top and sides)	65,0	0,01	1,000		
Staircase glazing (top and sides	22,8	0,01	1,000		
Staircase glazing bottom (arguable - can be 0)	2,2	0,01	1,000		
Balconies (no linear loss due to external super structure)	0,0	0,00	1,000		
Roof (no loss)	0,0	0,00	1,000		
Ialt	369,3	-	-	-	-

Windows and outer doors													
Building component	Number	Orient	Inclination	Area (mÂ^2)	U (W/mÂ^{2}K)	b	Ff (-)	g (-)	Shading	Fc (-)	Dim.Inside (C)	Dim.Outside (C)	Ext
UV1 [N]	6	N	90,0	1,0	1,10	1,000	0,70	0,64	UV1 [N]	-0,80			0
UV2 [N]	6	N	90,0	2,5	1,10	1,000	0,70	0,64	UV2 [N]	-0,80			0
UV3 [N]	3	N	90,0	2,2	1,10	1,000	0,70	0,64	UV3 [N]	-0,80			0
UVP2 [N]	1	N	90,0	6,2	1,10	1,000	0,90	0,64	UVP2&3+UDP3 [N]	1,00			0
UVP3 [N]	1	N	90,0	8,1	1,10	1,000	0,90	0,64	UVP2&3+UDP3 [N]	1,00			0
UDP3 [N]	1	N	90,0	6,2	1,10	1,000	0,50	0,64	UVP2&3+UDP3 [N]	1,00			0
UDP1 [W] top	2	W	90,0	2,1	1,10	1,000	0,70	0,64	West top [W]	-0,80			0
UDP1 [W] mid and bottom	4	W	90,0	2,1	1,10	1,000	0,70	0,64	West mid and bottom [W]	-0,80			0
UV5 [S] top	2		90,0	2,9	1,10	1,000	0,70	0,64	UV5 [S] top	-0,80			0
UDP2 [S] top	2		90,0	2,5	1,10	1,000	0,70	0,64	UDP2 [S] top	-0,80			0
UV6 [S] top	1		90,0	1,4	1,10	1,000	0,70	0,64	UV6 [S] top	-0,80			0
UV4 [S] top	1		90,0	1,7	1,10	1,000	0,70	0,64	UV4 [S] top	-0,80			0
UV5 [S] mid left	1		90,0	2,9	1,10	1,000	0,70	0,64	UV5 [S] mid left	-0,80			0
UV5 [S] mid right	1		90,0	2,9	1,10	1,000	0,70	0,64	UV5 [S] mid right	-0,80			0

Windows and outer doors													
UV4 [S] mid	1		90,0	1,7	1,10	1,000	0,70	0,64	UV4 [S] mid	-0,80			0
UDP2 [S] mid and bottom	4		90,0	2,3	1,10	1,000	0,70	0,64	UDP2 [S] mid and bottom	-0,80			0
UV6 [S] mid and bottom	2		90,0	1,4	1,10	1,000	0,70	0,64	UV6 [S] mid and bottom	-0,80			0
UV7 [S] bottom left	1		90,0	2,9	1,10	1,000	0,70	0,64	UV7 [S] bottom left	-0,80			0
UV7 [S] bottom right	1		90,0	2,9	1,10	1,000	0,70	0,64	UV7 [S] bottom right	-0,80			0
UV4 [S] bottom	1		90,0	1,7	1,10	1,000	0,70	0,64	UV4 [S] bottom	-0,80			0
Ialt	42	-	-	101,7	-	-	-	-	-	-	-	-	

Shading					
Description	Horizon (Â°)	Eaves (Â°)	Left (Â°)	Right (Â°)	Window opening (%)
West top [W]	0	26	0	0	13
West mid and bottom [W]	0	53	0	0	13
UV5 [S] top	0	31	0	0	9
UDP2 [S] top	0	25	0	0	13
UV6 [S] top	0	31	0	0	11
UV4 [S] top	0	31	0	0	11
UV5 [S] mid left	0	10	0	0	9
UV5 [S] mid right	0	58	0	0	9
UV4 [S] mid	0	10	0	0	11
UDP2 [S] mid and bottom	0	53	0	0	13
UV6 [S] mid and bottom	0	58	0	0	11
UV7 [S] bottom left	0	6	0	0	9
UV7 [S] bottom right	0	58	0	0	9
UV4 [S] bottom	0	6	0	0	11
UV1 [N]	0	0	0	0	9
UV2 [N]	0	0	0	0	9
UV3 [N]	0	0	0	0	11
UVP2&3+UDP3 [N]	0	0	0	0	6

Unheated room: Basement		
Gross area	0,0 m^2	
Ventilation	0,0 l/s m^2	
b	0,00	
Transmission loss from building		
Building component	Area (mÂ^2)	U (W/mÂ^{2}K)
Transmission loss to surroundings		
Building component	Area (mÂ^2)	U (W/mÂ^{2}K)

Summer comfort	
Floor area	20,0 m^2
Ventilation, winther	0,3 l/s m^2
Ventilation, summer, 9-16	0,9 l/s m^2
Ventilation, summer, 17-24	0,9 l/s m^2

Summer comfort	
Ventilation, summer, 0-8	0,6 l/s m^2

Ventilation													
Zone	Area (mÂ^2)	Fo, -	qm (l/s mÂ^2), Winter	n vgv (-)	ti (Â°C)	El-HC	qn (l/s mÂ^2), Winter	qi,n (l/s mÂ^2), Winter	SEL (kJ/mÂ^3)	qm,s (l/s mÂ^2), Summer	qn,s (l/s mÂ^2), Summer	qm,n (l/s mÂ^2), Night	qn,n (l/s mÂ^2), Night
Sovevaelse E	48,9	1,00	0,44	0,80	18,0	Yes	0,13	0,00	1,8	0,44	0,30	0,00	0,00
Opholdsstue + kokken + entre E	105,6	1,00	0,44	0,80	18,0	Yes	0,13	0,00	1,8	0,44	0,30	0,00	0,00
Bad E	18,0	1,00	0,44	0,80	18,0	Yes	0,13	0,00	1,8	0,44	0,30	0,00	0,00
Opholdsstue + kokken + entre W	124,2	1,00	0,34	0,80	18,0	Yes	0,13	0,00	1,8	0,44	0,30	0,00	0,00
Sovevaelse W	47,7	1,00	0,34	0,80	18,0	Yes	0,13	0,00	1,8	0,44	0,30	0,00	0,00
Vaelse W	27,6	1,00	0,34	0,80	18,0	Yes	0,13	0,00	1,8	0,44	0,30	0,00	0,00
Bad W	18,3	1,00	0,34	0,80	18,0	Yes	0,13	0,00	1,8	0,44	0,30	0,00	0,00
Trappe	40,8	1,00	0,00	0,00	0,0	No	0,30	0,00	0,0	0,00	0,30	0,00	0,00

Internal heat supply				
Zone	Area (mÂ^2)	Persons (W/mÂ^2)	App. (W/mÂ^2)	App,night (W/mÂ^2)
Unit E 1	58	1,5	3,5	0,0
Unit E 2	58	1,5	3,5	0,0
Unit E 3	58	1,5	3,5	0,0
Unit W 1	73	1,5	3,5	0,0
Unit W 2	73	1,5	3,5	0,0
Unit W 3	73	1,5	3,5	0,0
Trappe	41	0,0	0,0	0,0

Lighting											
Zone	Area (mÂ^2)	General (W/mÂ^2)	General (W/mÂ^2)	Lighting (lux)	DF (%)	Control (U, M, A, K)	Fo (-)	Work (W/mÂ^2)	Other (W/mÂ^2)	Stand-by (W/mÂ^2)	Night (W/mÂ^2)
Opholdsstue + kokken E	0,0	2,0	10,0	200	1,00	M	1,00	2,0	0,0	0,0	0,0
Sovevaelse E	0,0	2,0	10,0	200	1,00	M	1,00	2,0	0,0	0,0	0,0
Bad E and W	0,0	2,0	13,0	200	1,00	M	1,00	2,0	0,0	0,0	0,0
Opholdsstue W	0,0	2,0	10,0	200	1,00	M	1,00	2,0	0,0	0,0	0,0
Kokken W	0,0	2,0	10,0	200	1,00	M	1,00	2,0	0,0	0,0	0,0
Sovevaelse W	0,0	2,0	10,0	200	1,00	M	1,00	2,0	0,0	0,0	0,0
Vaelse W	0,0	2,0	13,0	200	1,00	M	1,00	2,0	0,0	0,0	0,0
Entre	0,0	2,0	13,0	50	1,00	M	1,00	2,0	0,0	0,0	0,0
Trappe	0,0	2,0	10,0	50	1,00	M	1,00	2,0	0,0	0,0	0,0

Other el. consumption	
Outdoor lighting	0,0 W
Spec. apparatus, during service	0,0 W
Spec. apparatus, always	0,0 W

Basement car parkings etc.											
Zone	Area (mÂ^2)	General (W/mÂ^2)	General (W/mÂ^2)	Lighting (lux)	DF (%)	Control (U, M, A, K)	Fo (-)	Work (W/mÂ^2)	Other (W/mÂ^2)	Stand-by (W/mÂ^2)	Night (W/mÂ^2)

Mechanical cooling	
Description	Mekanisk køling
Share of floor area	0,36
El-demand	0,50 kWh-el/kWh-cool
Heat-demand	0,00 kWh-heat/kWh-cool
Load factor	1,2
Heat capacity phase shift (cooling)	0 Wh/m²
Increase factor	1,50
Documentation	

Heat distribution plant					
Composition and temperature					
Supply pipe temperature	45,0 °C				
Return pipe temperature	30,0 °C				
Type of plant	2-string		Anlægstype		
Pumps					
Pump type	Description	Number	Pnom	Fp	
Time-controlled service during heating season	Room heating	1	40,0 W	0,40	
Heating pipes					
Pipe lengths in supply and return	l (m)	Loss (W/mK)	b	Outdoor comp (J/N)	Unused summer (J/N)
Varme frem	8,9	0,17	0,700	N	N
Varme retur	14,6	0,17	0,700	N	N

Domestic hot water			
Description	Domestic hot water		
Hot-water consumption, average for the building	100,0 litre/year per mÂ² of floor area		
Domestic hot water temp.	55,0 °C		
Hot-water tank			
Description	New hot-water tank		
Number of hot-water containers	1,0		
Tank volume	500,0 liter		
Supply temperature from central heating	45,0 °C		
El. heating of DHW	Always		
Solar heat tank with heating coil	No		
Heat loss from hot-water tank	0,0 W/K		
Temp. factor for setup room	0,7		
Charging pump			
Effect	0,0 W		
Controled	No		
Charge effect	0,0 kW		
Heat loss from connector pipe to DHW tank			
Length	Loss	b	Description
5,1 m	0,2 W/K	0,70	

Cirkulating pump for DHW	
Description	PumpCirc
Number	1,0
Effect	40,0 W
Number	0,0
Effect	0,0 W
Reduction factor	0,40 [-]
El. tracing of discharge water pipe	No

Domestic hot water discharge pipes			
Pipe lengths in supply and return	l (m)	Loss (W/mK)	b
Brugsvand circulation	7,3	0,21	0,700

Water heaters	
Electric water heater	
Description	Electric water heater
Share of DHW in separate el. water heaters	0,5
Heat loss from hot-water tank	0,0 W/K
Temp. factor for setup room	0,70
Gas water heater	
Description	Gas water heater
Share of DHW in separate gas water heaters	0,0
Heat loss from hot-water tank	0,0 W/K
Efficiency	0,5
Pilot flame	50,0 W
Temp. factor for setup room	1,00

District heat exchanger	
Description	New district heating exchanger
Nominal effect	0,0 kW
Heat loss	0,0 W/K
DHW heating through exchanger	No
Exchanger temperature, min	60,0 °C
Temp. factor for setup room	1,00
Automatics, stand-by	5,0 W

Other room heating	
Direct el for room heating	
Description	Suplemental direct room heating
Share of floor area	0,0
Wood stoves, gas radiators etc.	
Description	
Share of floor area	0,0
Efficiency	0,4

Wood stoves, gas radiators etc.	
Air flow requirement	0,1 m^3/s

Solar heating plant		
Description	New solar heating plant	
Type	Domestic hot water	
Solar collector		
Area 0,0 mÂ^2	Start 0,8	-
Coefficient of heat loss a1 3,5 W/mÂ^{2}K	Coefficient of heat loss a2 0,0 W/mÂ^{2}K	Anglefactor 0,9
Orientation S	Slope 0,0 Â°	-
Horizon 10,0 Â°	Left 0,0 Â°	Right 0,0 Â°
Solar collector pipe		
Length 0,0 m	Heat loss 0,00 W/mK	Circuit 0,8
Electricity		
Pump in solar collector circuit 50,0 W	Automatics, stand-by 5,0 W	

Heat pumps		
Description	Generic	
Type	Combined	
Share of heating requirement	1,0	
El. driven heat pump		
-	Room heating	DHW
Nominal effect	16,1 kW	16,1 kW
Nominal COP	3,60	3,60
Rel. COP at 50% load	1,00	0,00
Test temperatures		
-	Room heating	DHW
Cold side	7,0 °C	7,0 °C
Warm side	45,0 °C	45,0 °C
Type		
-	Room heating	DHW
Cold side	Earth hose	Earth hose
Warm side	Heating plant	-
Additional		
-	Room heating	DHW
Special auxiliary tool	0,0 W	0,0 W
Automatics, stand-by	0,0 W	0,0 W
Heat pumps connected with ventilation		
-	Room heating	DHW
Temp. Efficiency for HRV before heat pump	0,00	0,00
Dim. air supply temperature	0,0 °C	-
Air flow requirement	0,00 m^3/s	0,00 m^3/s
Data for other source		
-	Room heating	DHW
Temp. dif. exchanger cold side	0,00 °C	0,00 °C

Data for other source	
Source temp., jan, feb..., Â°C	0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0

Solar cells		
Description	Generic	
Solar cells		
Area 83,0 mÂ²	Orientation S	Slope 21,7 Â°
Horizon 0,0 Â°	Left 0,0 Â°	Right 0,0 Â°
Additional		
Peak power 0,105 kW/mÂ²	Efficiency 0,80	

Figure B.2: BE18 - results

SBi	Beregningskerne 10.19.7.22												
Be18 results: Højbo, Frederikshavn boligforening													
Energy requirement													
MWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Heating	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
El. 2018	1,90	1,58	1,52	0,22	-0,28	-0,17	-0,02	-0,12	-0,14	0,39	1,39	1,90	8,17
El. low energy	1,90	1,58	1,52	0,22	-0,28	-0,17	-0,02	-0,12	-0,14	0,39	1,39	1,90	8,17
Excess temperature in rooms	0,00	0,00	0,00	0,00	0,00	0,00	0,43	0,08	0,00	0,00	0,00	0,00	0,51
Total energy requirement													
MWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Existing building	3,61	3,00	2,89	0,43	-0,53	-0,31	0,39	-0,16	-0,27	0,73	2,63	3,62	16,04
kWh/m²	8,4	7,0	6,7	1,0	-1,2	-0,7	0,9	-0,4	-0,6	1,7	6,1	8,4	37,2
BR 2018	3,61	3,00	2,89	0,43	-0,53	-0,31	0,39	-0,16	-0,27	0,73	2,63	3,62	16,04
kWh/m²	8,4	7,0	6,7	1,0	-1,2	-0,7	0,9	-0,4	-0,6	1,7	6,1	8,4	37,2
Low energy	3,61	3,00	2,89	0,43	-0,53	-0,31	0,39	-0,16	-0,27	0,73	2,63	3,62	16,04
kWh/m²	8,4	7,0	6,7	1,0	-1,2	-0,7	0,9	-0,4	-0,6	1,7	6,1	8,4	37,2
Room heating, Heating requirement													
MWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
In rooms	4,31	3,74	4,07	1,66	0,04	0,00	0,00	0,00	0,06	1,29	3,35	4,35	22,87
Heat coil	0,25	0,23	0,29	0,08	0,00	0,00	0,00	0,00	0,00	0,01	0,17	0,25	1,28
Pipe loss	0,09	0,08	0,10	0,08	0,07	0,06	0,06	0,06	0,06	0,07	0,08	0,09	0,90
Total	4,66	4,05	4,46	1,81	0,11	0,06	0,06	0,06	0,12	1,37	3,60	4,69	25,05
Total, kWh/m²	10,8	9,4	10,3	4,2	0,3	0,1	0,1	0,1	0,3	3,2	8,4	10,9	58,1
Room heating, Fulfilment of heat requirement													
MWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Boiler/district heating	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Solar heating plant	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Heat pump	4,41	3,82	4,17	1,74	0,11	0,06	0,06	0,06	0,12	1,37	3,43	4,44	23,77
El. heating of rooms	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
El-VF in ventilation plant	0,25	0,23	0,29	0,08	0,00	0,00	0,00	0,00	0,00	0,01	0,17	0,25	1,28
Wood stoves etc.	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Total	4,66	4,05	4,46	1,81	0,11	0,06	0,06	0,06	0,12	1,37	3,60	4,69	25,05
Net heating requirement in rooms													
MWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year

Heat loss	5,98	5,47	6,40	3,95	2,78	1,91	0,93	0,90	1,82	3,29	5,01	5,98	44,42
Incident solar radiation	0,18	0,39	0,84	0,86	1,85	1,95	2,10	1,45	0,58	0,53	0,23	0,15	11,11
Internal supplement	1,45	1,31	1,45	1,41	1,45	1,41	1,45	1,45	1,41	1,45	1,41	1,45	17,10
From pipes and water container	0,03	0,03	0,04	0,03	0,03	0,02	0,02	0,02	0,02	0,03	0,03	0,03	0,34
Total supplement	1,67	1,73	2,33	2,30	3,33	3,38	3,57	2,92	2,01	2,01	1,67	1,63	28,54
Relative supplement	0,28	0,32	0,36	0,58	1,20	1,77	3,86	3,26	1,10	0,61	0,33	0,27	
Utilization factor	1,00	1,00	1,00	1,00	0,80	0,56	0,26	0,31	0,85	1,00	1,00	1,00	0,81
Part of month with heating	1,00	1,00	1,00	1,00	0,36	0,00	0,00	0,00	0,51	1,00	1,00	1,00	
Heating requirement	4,31	3,74	4,07	1,66	0,04	0,00	0,00	0,00	0,06	1,29	3,35	4,35	22,87
Heating in ventilating heat surface	0,25	0,23	0,29	0,08	0,00	0,00	0,00	0,00	0,00	0,01	0,17	0,25	1,28
Net. room heating	4,57	3,97	4,36	1,74	0,04	0,00	0,00	0,00	0,06	1,30	3,52	4,60	24,15
Total, kWh/m^2	10,6	9,2	10,1	4,0	0,1	0,0	0,0	0,0	0,1	3,0	8,2	10,7	56,0

Appendix C

Dynamic state standard model

Figure C.1: 3D model (IDA ICE) - facade north

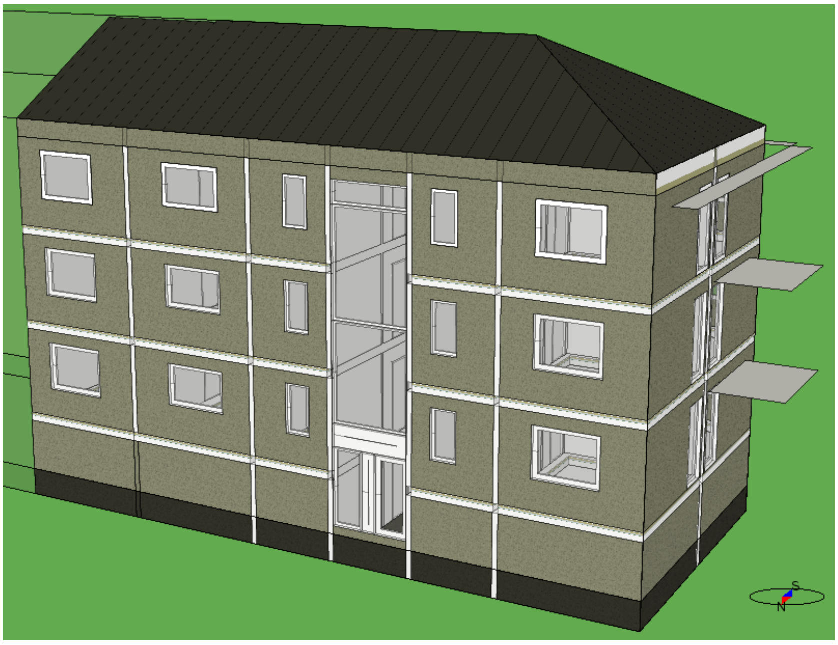
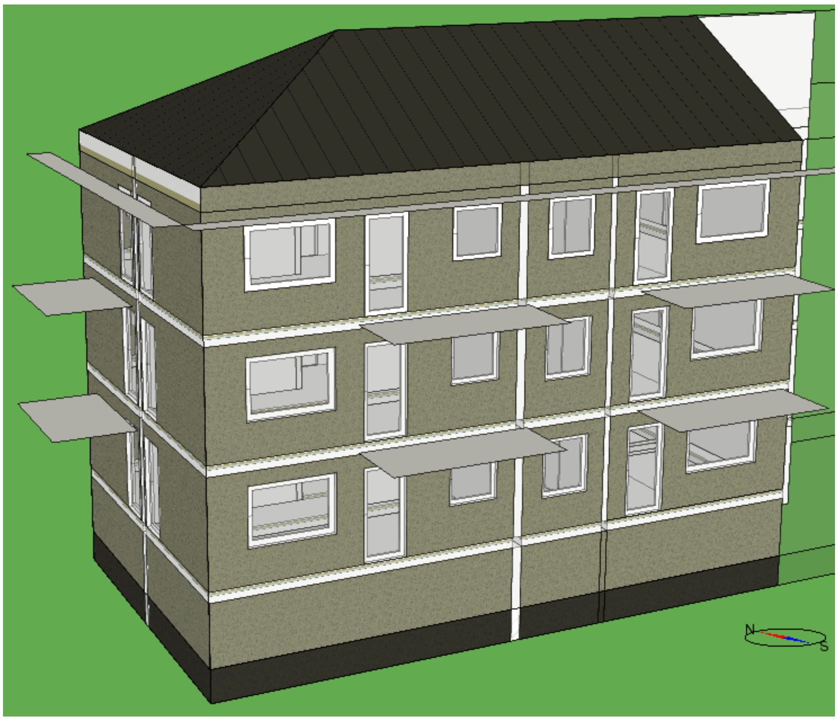


Figure C.2: 3D model (IDA ICE) - facade south



C.0.1 Thermal zones

Figure C.3: Thermal zones - basement level

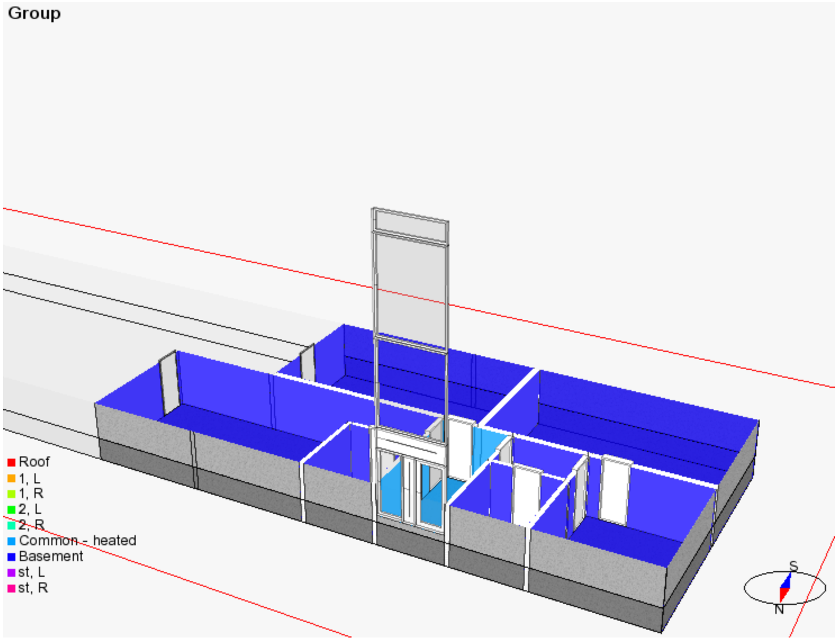


Figure C.4: Thermal zones - ground-floor level

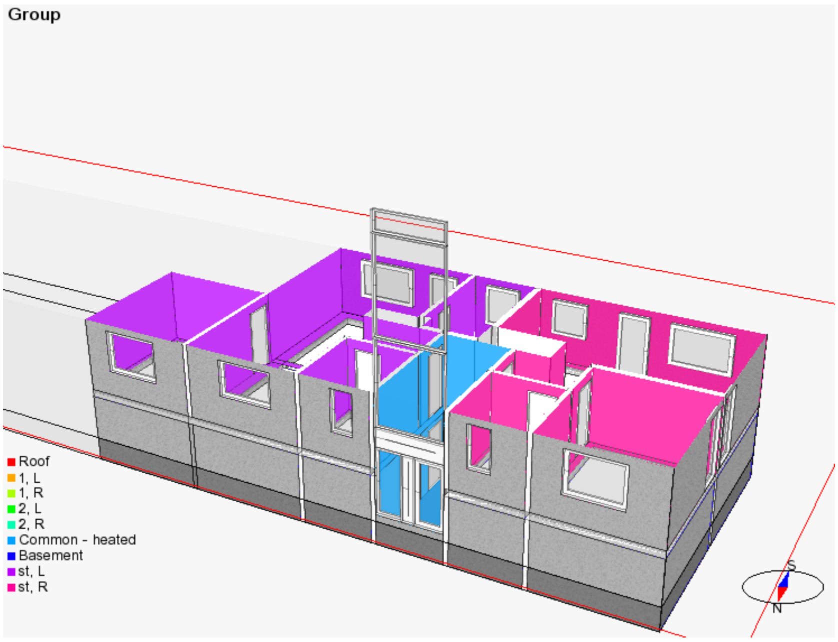


Figure C.5: Thermal zones - 1st floor level

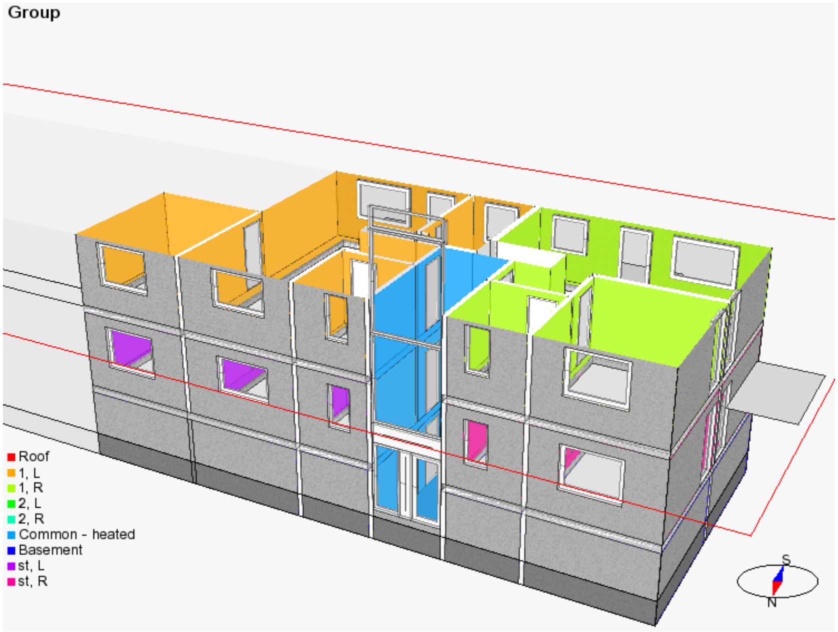
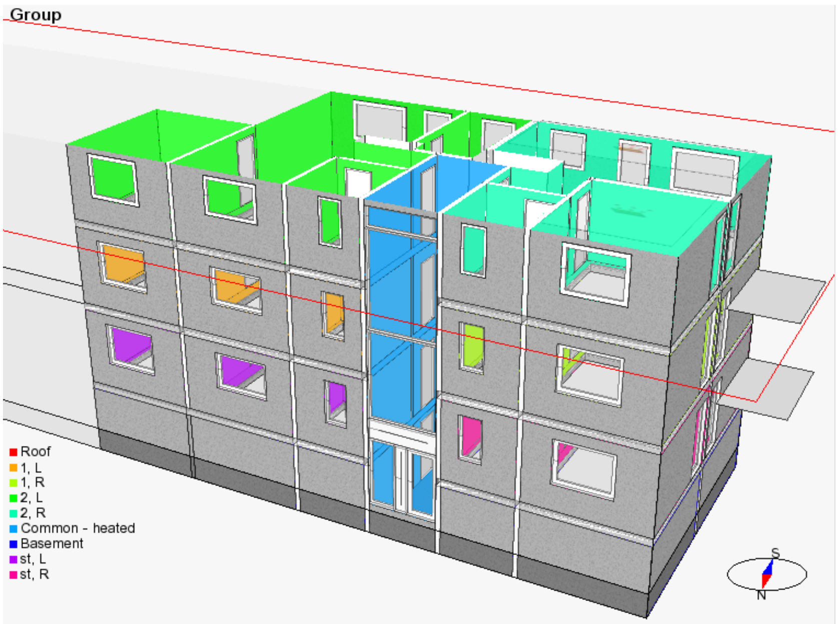


Figure C.6: Thermal zones - 2nd floor level



C.0.2 Standard geometry, climate and occupancy inputs

Figure C.7: IDA ICE standard inputs

EQUA SIMULATION TECHNOLOGY GROUP

Input data Report

Project		**Building**	
Højbo Frederikshavn		Model floor area	432.0 m^2
Customer		Model volume	1628.9 m^3
Created by	Benas Jokubauskis	Model ground area	148.8 m^2
Location	Fredrikshavn (Skagen)_060410 (ASHRAE 2013)	Model envelope area	754.9 m^2
Climate file	DNK_SKAGEN_060410(IW2)	Window/Envelope	13.4 %
Case	Højbo Frederikshavn - AHU check - 24 h	Average U-value	1.6 $W/(m^2\ K)$
Simulated	17/10/2022 12.43.53	Envelope area per Volume	0.4635 m^2/m^3

DHW use	**L/m2 floor area and year**	**Total, [l/s]**
	100.000	0.002

Occupant schedules in zones (click to expand/contract)

Lighting schedules in zones (click to expand/contract)

Equipment schedules in zones (click to expand/contract)

Controller setpoints in zones (click to expand/contract)

Setpoints Max/Min	**Percentage of zones with these setpoints (% of total zone area).**
26.00/20.00	57.12
25.00/16.00	42.88

Wind driven infiltration airflow rate	1009.212 l/s at 50.000 Pa

Building envelope	Area [m^2]	U [W/(m^2 K)]	U*A [W/K]	% of total
Walls above ground	**300.19**	**0.15**	**44.31**	**3.67**
External wall Højbo	300.19	0.15	44.31	3.67
Walls below ground	**33.54**	**0.10**	**3.32**	**0.27**
External basement wall Højbo	33.54	0.10	3.32	0.27
Roof	**170.93**	**5.88**	**1005.00**	**83.20**
Roof steel cladding	170.93	5.88	1005.00	83.20
Floor towards ground	**148.80**	**0.19**	**28.32**	**2.34**
Concrete floor against ground Højbo	148.80	0.19	28.32	2.34
Floor towards amb. air	**0.00**	**0.00**	**0.00**	**0.00**
Windows	**101.48**	**1.10**	**111.63**	**9.24**
Custom glazing	101.48	1.10	111.63	9.24
Doors	**0.00**	**0.00**	**0.00**	**0.00**
Thermal bridges			**15.31**	**1.27**
Total	**754.93**	**1.60**	**1207.88**	**100.00**

Thermal bridges	Area or Length	Avg. Heat conductivity	Total [W/K]
External wall / internal slab	318.58 m	0.000 W/(m K)	0.000
External wall / internal wall	161.25 m	0.000 W/(m K)	0.000
External wall / external wall	20.90 m	0.000 W/(m K)	0.000
External windows perimeter	280.06 m	0.010 W/(m K)	2.801
External doors perimeter	0.00 m	0.000 W/(K m)	0.000
Roof / external walls	42.89 m	0.030 W/(m K)	1.287
External slab / external walls	41.56 m	0.270 W/(m K)	11.220
Balcony floor / external walls	0.00 m	0.000 W/(K m)	0.000
External slab / Internal walls	0.00 m	0.000 W/(K m)	0.000
Roof / Internal walls	14.04 m	0.000 W/(m K)	0.000
External walls, inner corner	0.00 m	0.000 W/(m K)	0.000
Roof / external walls, inner corner	0.00 m	0.000 W/(K m)	0.000
External slab / external walls, inner corner	0.00 m	0.000 W/(K m)	0.000
Total envelope (incl. roof and ground)	745.90 m^2	0.000 W/(m^2 K)	0.000
Extra losses	-	-	-0.000
Sum	-	-	15.308

Windows	Area [m^2]	U Glass [W/(m^2 K)]	U Frame [W/(m^2 K)]	U Total [W/(m^2 K)]	U*A [W/K]	Shading factor g
NNE	48.26	1.10	1.10	1.10	53.08	0.70
SSW	40.30	1.10	1.10	1.10	44.33	0.70
WNW	12.92	1.10	1.10	1.10	14.21	0.70
Total	101.48	1.10	1.10	1.10	111.63	0.70

Air handling unit	Pressure head supply/exhaust [Pa/Pa]	Fan efficiency supply/exhaust [-/-]	System SFP [kW/(m^3/s)]	Heat exchanger temp. ratio/min exhaust temp. [-/C]
AHU St R	450.00/450.00	0.60/0.60	0.75/0.75	0.84/1.00
AHU St L	450.00/450.00	0.60/0.60	0.75/0.75	0.84/1.00
AHU 1 R	450.00/450.00	0.60/0.60	0.75/0.75	0.84/1.00
AHU 1 L	450.00/450.00	0.60/0.60	0.75/0.75	0.84/1.00
AHU 2 R	450.00/450.00	0.60/0.60	0.75/0.75	0.84/1.00
AHU 2 L	450.00/450.00	0.60/0.60	0.75/0.75	0.84/1.00

Figure C.8: IDA ICE standard climate file description

Climate file

IDA Indoor Climate and Energy 4.802 License: ICE40X:ICE40X:ED255
Object: Climate file
Description:
Date: 2022-01-01 - 2022-12-31
Saved: 02/11/2022 13.47.42

	Variables						
	Dry-bulb temperature, Deg-C	Rel humidity of air, %	Direct normal rad, W/m2	Diffuse rad on hor surf, W/m2	Wind speed, x-component, m/s	Wind speed, y-component, m/s	Cloudness, %
January	3.1	87.8	26.2	11.4	0.5	1.7	67.7
February	2.9	86.4	34.8	24.3	3.5	4.9	69.0
March	3.7	81.4	51.4	52.1	1.4	1.1	65.3
April	5.9	88.2	65.5	83.9	-2.7	-0.3	55.4
May	10.1	85.4	98.8	114.9	-0.9	-1.2	48.8
June	14.2	84.5	117.5	126.6	1.2	1.3	47.7
July	16.3	87.7	90.4	126.9	3.3	0.4	50.0
August	17.1	82.8	85.1	102.0	3.8	1.5	54.1
September	14.1	82.7	71.0	70.8	5.0	1.7	54.8
October	9.6	87.4	47.3	34.3	2.6	4.7	62.1
November	5.1	85.9	33.9	15.7	-0.2	-0.9	61.7
December	3.8	91.1	25.3	8.1	3.0	1.5	58.5
mean	8.9	85.9	62.4	64.4	1.7	1.3	57.9
mean*8760.0 h	77647.0	752892.0	546574.0	564516.0	14864.3	11741.9	506940.0
min	2.9	81.4	25.3	8.1	-2.7	-1.2	47.7
max	17.1	91.1	117.5	126.9	5.0	4.9	69.0

Figure C.9: IDA ICE standard occupancy file description based on DS16798

Residential, apartment

Parameters and set points

	Parameter	**Value**	**Unit**
Operation time	Hour at day, START	0	hour
	Hour at day, END	24	hour
	Breaks, inside range	0	hours
	days/week	7	days
	hours/day	24	hours
	hours/year	8760	hours
Internal gains	Occupants	28,3	m2/pers
	Occupants (Total)	4,2	W/m^2
	Occupants (Dry)	2,8	W/m^2
	Appliances	3	W/m^2
	Lighting		
	Moisture production	2,12	g/(m2, h)
	CO_2 production	0,66	l/(m2, h)
Set points	Min T,op in unoccupied hours	16	°C
	Max T,op in unoccupied hours	32	°C
	Min T,op	20	°C
	Max T,op	26	°C
	Ventilation rate (min.)	0,5	$l/(s\,m^2)$
	Ventilation rate for CO_2 emission	0,28	$l/(s\,m^2)$
	Max CO_2 concentration (above outdoor)	500	ppm
	Min. relative humidity	25	%
	Max. relative humidity	60	%
	Lighting, illuminance in working areas	0	lux
Other	Domestic hot water use	100	l/(m2 year)

Usage schedule

	Energy calculation					
	Weekdays			Weekends		
h	Occupants	Appliances	Lighting	Occupants	Appliances	Lighting
1	1	0,5	0	1	0,5	0
2	1	0,5	0	1	0,5	0
3	1	0,5	0	1	0,5	0
4	1	0,5	0	1	0,5	0
5	1	0,5	0	1	0,5	0
6	1	0,5	0	1	0,5	0
7	0,5	0,5	0,15	0,8	0,5	0,15
8	0,5	0,7	0,15	0,8	0,7	0,15
9	0,5	0,7	0,15	0,8	0,7	0,15
10	0,1	0,5	0,15	0,8	0,5	0,15
11	0,1	0,5	0,05	0,8	0,5	0,05
12	0,1	0,6	0,05	0,8	0,6	0,05
13	0,1	0,6	0,05	0,8	0,6	0,05
14	0,2	0,6	0,05	0,8	0,6	0,05
15	0,2	0,6	0,05	0,8	0,6	0,05
16	0,2	0,5	0,05	0,8	0,5	0,05
17	0,5	0,5	0,2	0,8	0,5	0,2
18	0,5	0,7	0,2	0,8	0,7	0,2
19	0,5	0,7	0,2	0,8	0,7	0,2
20	0,8	0,8	0,2	0,8	0,8	0,2
21	0,8	0,8	0,2	0,8	0,8	0,2
22	0,8	0,8	0,2	0,8	0,8	0,2
23	1	0,6	0,15	1	0,6	0,15
24	1	0,6	0,15	1	0,6	0,15

Appendix D

Dynamic state climate models

D.0.1 Actual climate inputs and simulation results

Figure D.1: 2015 climate file description with custom outdoor temperature, humidity, wind direction and wind speed inputs

Climate file

IDA Indoor Climate and Energy 4.802 License: ICE40X:ICE40X:ED255
Object: Climate file
Description:
Date: 2022-01-01 - 2022-12-31
Saved: 09/11/2022 08.24.19

	Variables					
	Dry-bulb temperature, Deg-C	Rel humidity of air, %	Direction of wind, Deg	Speed of meteorological wind, m/s	Direct normal rad, W/m2	Diffuse rad on hor surf, W/m2
January	3.0	89.1	212.5	7.8	26.2	11.4
February	2.1	90.4	199.3	7.6	34.8	24.3
March	4.2	85.4	189.9	6.4	51.4	52.1
April	6.5	78.6	239.0	6.3	65.5	83.9
May	9.0	81.6	219.9	6.7	98.8	114.9
June	12.3	78.8	244.7	6.5	117.5	126.6
July	14.9	81.0	223.4	6.3	90.4	126.9
August	16.8	78.9	170.0	6.0	85.1	102.0
September	13.6	82.0	183.1	7.2	71.0	70.8
October	9.7	82.2	156.2	7.4	47.3	34.3
November	7.2	86.8	212.7	6.9	33.9	15.7
December	6.3	86.8	211.4	8.7	25.3	8.1
mean	8.9	83.4	205.1	7.0	62.4	64.4
mean*8760.0 h	77579.5	730796.1	1796372.5	61168.9	546574.0	564516.0
min	2.1	78.6	156.2	6.0	25.3	8.1
max	16.8	90.4	244.7	8.7	117.5	126.9

Figure D.2: 2015 model results with actual climate inputs

SIMULATION TECHNOLOGY GROUP		**Systems Energy**	
Project		**Building**	
Højbo Frederikshavn		Model floor area	432.0 m^2
Customer		Model volume	1628.9 m^3
Created by	Benas Jokubauskis	Model ground area	148.8 m^2
Location	Fredrikshavn (Skagen)_060410 (ASHRAE 2013)	Model envelope area	754.9 m^2
Climate file	CW2015	Window/Envelope	13.4 %
Case	Højbo Frederikshavn - DW2015	Average U-value	1.6 W/(m^2 K)
Simulated	09/11/2022 10.05.32	Envelope area per Volume	0.4635 m^2/m^3

Used energy

kWh (sensible and latent)

Month	Zone heating	Zone cooling	AHU heating	AHU cooling	Dom. hot water
1	2680.9	0.0	0.0	0.0	622.9
2	2485.2	0.0	0.8	0.0	562.6
3	1520.5	0.0	0.0	0.0	626.0
4	733.4	0.0	0.0	0.0	607.2
5	192.2	0.0	0.0	0.0	628.3
6	37.1	5.6	0.0	0.0	608.1
7	0.0	18.7	0.0	0.0	628.4
8	0.0	81.5	0.0	0.0	628.4
9	0.0	1.7	0.0	0.0	608.1
10	441.7	0.0	-0.0	0.0	628.2
11	1482.1	0.0	0.0	0.0	606.5
12	2193.7	0.0	-0.0	0.0	624.9
Total	11766.8	107.6	0.8	0.0	7379.6

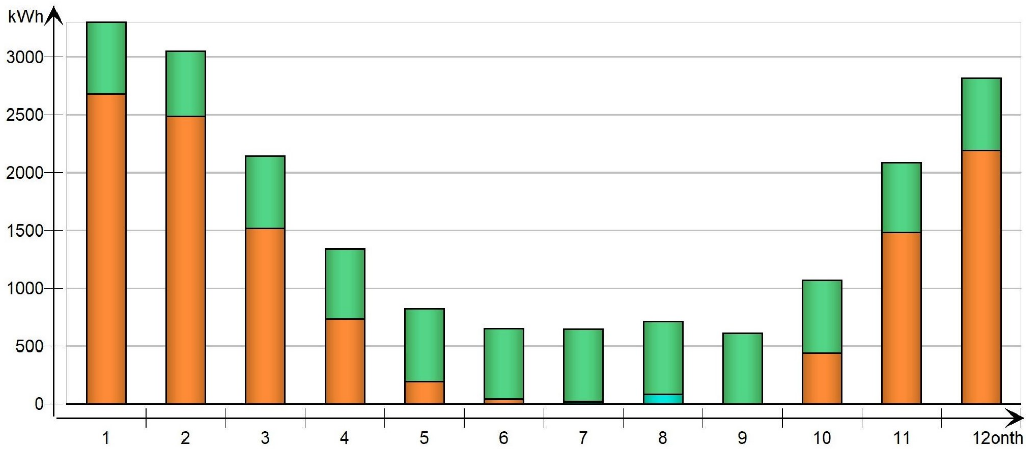


Figure D.3: 2016 climate file description with custom outdoor temperature, humidity, wind direction and wind speed inputs

Climate file

IDA Indoor Climate and Energy 4.802 License: ICE40X:ICE40X:ED255
Object: Climate file
Description:
Date: 2022-01-01 - 2022-12-31
Saved: 09/11/2022 08.34.30

	Variables					
	Dry-bulb temperature, Deg-C	Rel humidity of air, %	Direction of wind, Deg	Speed of meteorological wind, m/s	Direct normal rad, W/m2	Diffuse rad on hor surf, W/m2
January	0.1	85.5	164.8	7.7	26.2	11.4
February	2.0	82.7	211.1	6.6	34.8	24.3
March	3.4	88.3	193.5	5.6	51.4	52.1
April	6.2	77.6	182.2	5.9	65.5	83.9
May	11.8	76.8	160.5	5.4	98.8	114.9
June	15.6	78.8	164.6	5.2	117.5	126.6
July	16.1	82.8	225.0	5.5	90.4	126.9
August	15.7	81.1	219.8	6.5	85.1	102.0
September	16.1	80.4	192.4	5.2	71.0	70.8
October	8.8	80.6	116.8	7.9	47.3	34.3
November	4.5	84.3	178.2	7.6	33.9	15.7
December	4.9	86.5	232.6	7.2	25.3	8.1
mean	8.8	82.1	186.7	6.4	62.4	64.4
mean*8760.0 h	77104.1	719494.1	1635243.5	55733.6	546574.0	564516.0
min	0.1	76.8	116.8	5.2	25.3	8.1
max	16.1	88.3	232.6	7.9	117.5	126.9

Figure D.4: 2016 model results with actual climate inputs

SIMULATION TECHNOLOGY GROUP		**Systems Energy**	
Project		**Building**	
Højbo Frederikshavn		Model floor area	432.0 m^2
Customer		Model volume	1628.9 m^3
Created by	Benas Jokubauskis	Model ground area	148.8 m^2
Location	Fredrikshavn (Skagen)_060410 (ASHRAE 2013)	Model envelope area	754.9 m^2
Climate file	CW2016	Window/Envelope	13.4 %
Case	Højbo Frederikshavn - DW2016	Average U-value	1.6 W/(m^2 K)
Simulated	09/11/2022 10.32.53	Envelope area per Volume	0.4635 m^2/m^3

Used energy

kWh (sensible and latent)

Month	Zone heating	Zone cooling	AHU heating	AHU cooling	Dom. hot water
1	2972.6	0.0	37.8	0.0	621.6
2	2283.0	0.0	0.4	0.0	564.1
3	1578.9	0.0	0.0	0.0	626.2
4	719.9	0.0	0.0	0.0	607.5
5	114.5	2.2	0.0	0.0	628.3
6	0.0	78.0	0.0	0.0	608.1
7	0.0	88.4	0.0	0.0	628.4
8	0.0	29.8	0.0	0.0	628.4
9	0.0	31.4	0.0	0.0	608.1
10	726.4	0.0	-0.0	0.0	627.9
11	2133.7	0.0	-0.0	0.0	605.2
12	2188.8	0.0	-0.0	0.0	624.9
Total	12717.7	229.9	38.2	0.0	7378.7

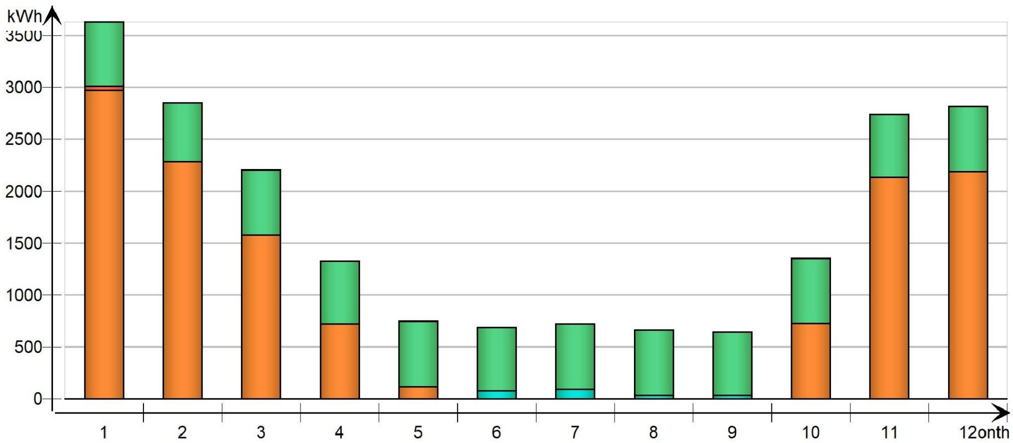


Figure D.5: 2017 climate file description with custom outdoor temperature, humidity, wind direction and wind speed inputs

Climate file

IDA Indoor Climate and Energy 4.802 License: ICE40X:ICE40X:ED255
Object: Climate file
Description:
Date: 2022-01-01 - 2022-12-31
Saved: 09/11/2022 08.43.23

	Variables					
	Dry-bulb temperature, Deg-C	Rel humidity of air, %	Direction of wind, Deg	Speed of meteorological wind, m/s	Direct normal rad, W/m2	Diffuse rad on hor surf, W/m2
January	1.9	86.2	200.9	6.2	26.2	11.4
February	1.5	86.0	174.7	7.4	34.8	24.3
March	3.9	87.5	220.0	6.6	51.4	52.1
April	6.1	77.9	228.5	7.2	65.5	83.9
May	11.0	79.4	173.0	5.5	98.8	114.9
June	14.3	81.9	208.4	7.0	117.5	126.6
July	15.4	82.0	196.7	5.8	90.4	126.9
August	15.8	81.2	213.4	5.6	85.1	102.0
September	13.6	84.3	134.1	5.6	71.0	70.8
October	10.7	82.2	216.6	8.1	47.3	34.3
November	5.8	83.8	212.7	6.7	33.9	15.7
December	4.0	88.9	219.3	7.5	25.3	8.1
mean	8.7	83.4	200.1	6.6	62.4	64.4
mean*8760.0 h	76329.3	730893.6	1752983.5	57721.0	546574.0	564516.0
min	1.5	77.9	134.1	5.5	25.3	8.1
max	15.8	88.9	228.5	8.1	117.5	126.9

Figure D.6: 2017 model results with actual climate inputs

EQUA SIMULATION TECHNOLOGY GROUP		**Systems Energy**	
Project		**Building**	
Højbo Frederikshavn		Model floor area	432.0 m^2
Customer		Model volume	1628.9 m^3
Created by	Benas Jokubauskis	Model ground area	148.8 m^2
Location	Fredrikshavn (Skagen)_060410 (ASHRAE 2013)	Model envelope area	754.9 m^2
Climate file	CW2017	Window/Envelope	13.4 %
Case	Højbo Frederikshavn - DW2017	Average U-value	1.6 W/(m^2 K)
Simulated	09/11/2022 11.01.33	Envelope area per Volume	0.4635 m^2/m^3

Used energy

kWh (sensible and latent)

Month	Zone heating	Zone cooling	AHU heating	AHU cooling	Dom. hot water
1	2600.2	0.0	21.0	0.0	624.1
2	2388.6	0.0	3.6	0.0	563.9
3	1617.4	0.0	0.0	0.0	626.5
4	863.9	0.0	0.0	0.0	607.4
5	85.8	0.7	0.0	0.0	628.4
6	0.0	14.4	0.0	0.0	608.1
7	0.0	51.7	0.0	0.0	628.4
8	0.0	32.5	0.0	0.0	628.4
9	0.0	2.1	0.0	0.0	608.1
10	405.8	0.0	-0.0	0.0	628.2
11	1664.4	0.0	-0.0	0.0	606.1
12	2462.5	0.0	-0.0	0.0	624.8
Total	12088.7	101.4	24.6	0.0	7382.4

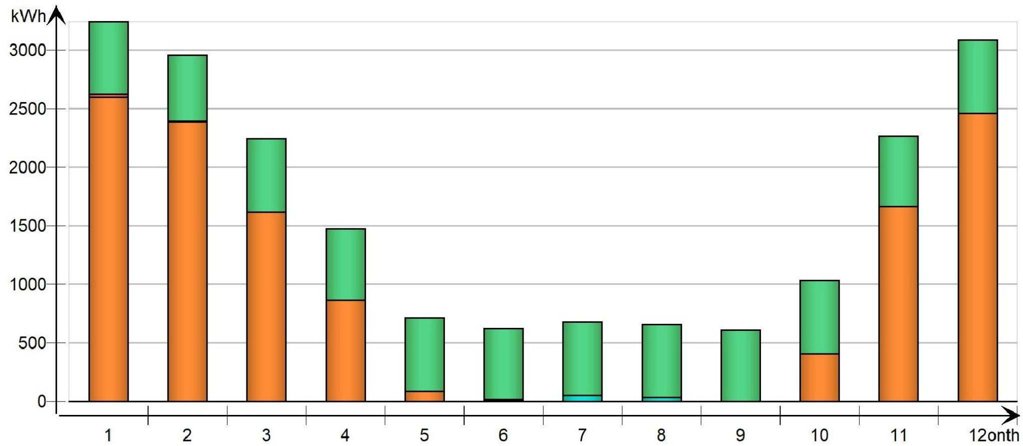


Figure D.7: 2018 climate file description with custom outdoor temperature, humidity, wind direction and wind speed inputs

Climate file

IDA Indoor Climate and Energy 4.802 License: ICE40X:ICE40X:ED255
Object: Climate file
Description:
Date: 2022-01-01 - 2022-12-31
Saved: 09/11/2022 09.22.44

	Variables					
	Dry-bulb temperature, Deg-C	Rel humidity of air, %	Direction of wind, Deg	Speed of meteorological wind, m/s	Direct normal rad, W/m2	Diffuse rad on hor surf, W/m2
January	2.6	88.7	165.8	7.1	26.2	11.4
February	-0.9	82.6	145.8	7.0	34.8	24.3
March	-0.5	83.2	125.0	6.7	51.4	52.1
April	6.8	83.4	174.6	6.1	65.5	83.9
May	14.9	75.6	149.4	4.3	98.8	114.9
June	16.6	75.0	209.2	5.3	117.5	126.6
July	19.3	77.4	213.1	5.1	90.4	126.9
August	17.0	83.5	212.6	5.6	85.1	102.0
September	14.0	83.6	220.5	7.5	71.0	70.8
October	9.9	87.0	209.9	7.1	47.3	34.3
November	6.2	90.6	143.4	6.1	33.9	15.7
December	4.0	87.5	189.5	6.7	25.3	8.1
mean	9.2	83.2	180.1	6.2	62.4	64.4
mean*8760.0 h	80813.2	728670.3	1577714.5	54348.8	546574.0	564516.0
min	-0.9	75.0	125.0	4.3	25.3	8.1
max	19.3	90.6	220.5	7.5	117.5	126.9

Figure D.8: 2018 model results with actual climate inputs

EQUA SIMULATION TECHNOLOGY GROUP		**Systems Energy**	
Project		**Building**	
Højbo Frederikshavn		Model floor area	432.0 m^2
Customer		Model volume	1628.9 m^3
Created by	Benas Jokubauskis	Model ground area	148.8 m^2
Location	Fredrikshavn (Skagen)_060410 (ASHRAE 2013)	Model envelope area	754.9 m^2
Climate file	CW2018	Window/Envelope	13.4 %
Case	Højbo Frederikshavn - DW2018	Average U-value	1.6 W/(m^2 K)
Simulated	09/11/2022 11.34.19	Envelope area per Volume	0.4635 m^2/m^3

Used energy

kWh (sensible and latent)

Month	Zone heating	Zone cooling	AHU heating	AHU cooling	Dom. hot water
1	2489.2	0.0	0.0	0.0	624.7
2	2994.5	0.0	67.7	0.0	561.5
3	2435.5	0.0	31.2	0.0	624.6
4	795.2	0.0	0.0	0.0	607.4
5	81.0	102.1	0.0	0.0	628.4
6	0.0	163.5	0.0	0.0	608.1
7	0.0	326.2	0.0	0.0	628.4
8	0.0	111.1	0.0	0.0	628.4
9	23.1	13.1	0.0	0.0	608.1
10	640.9	0.0	-0.0	0.0	627.8
11	1521.7	0.0	-0.0	0.0	606.2
12	2185.7	0.0	-0.0	0.0	625.7
Total	13166.7	716.0	98.9	0.0	7379.3

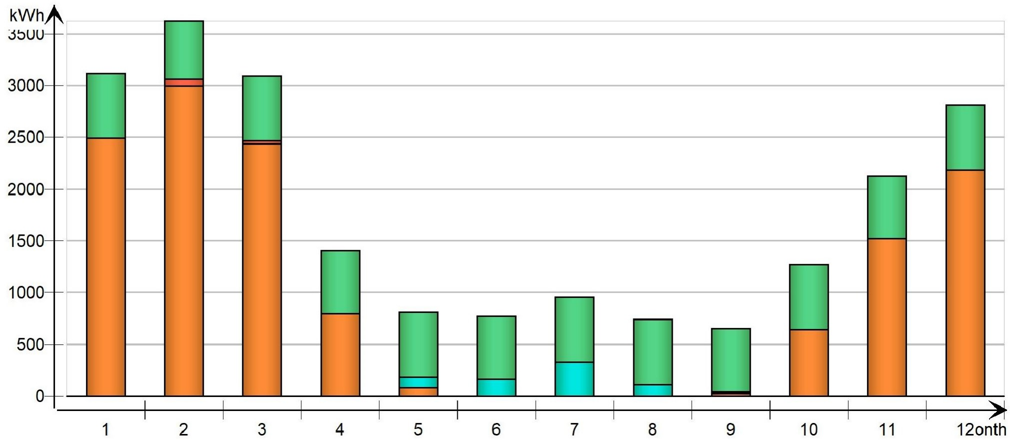


Figure D.9: 2019 climate file description with custom outdoor temperature, humidity, wind direction and wind speed inputs

Climate file

IDA Indoor Climate and Energy 4.802 License: ICE40X:ICE40X:ED255
Object: Climate file
Description:
Date: 2022-01-01 - 2022-12-31
Saved: 09/11/2022 09.22.10

	Variables					
	Dry-bulb temperature, Deg-C	Rel humidity of air, %	Direction of wind, Deg	Speed of meteorological wind, m/s	Direct normal rad, W/m2	Diffuse rad on hor surf, W/m2
January	2.0	83.1	203.6	6.9	26.2	11.4
February	4.0	88.5	224.5	6.8	34.8	24.3
March	4.8	84.3	234.9	7.1	51.4	52.1
April	8.0	68.0	119.4	5.2	65.5	83.9
May	9.7	77.6	209.9	6.4	98.8	114.9
June	15.3	82.4	189.6	5.6	117.5	126.6
July	16.6	82.0	212.9	5.7	90.4	126.9
August	16.7	83.9	205.8	5.3	85.1	102.0
September	13.2	82.0	209.2	7.1	71.0	70.8
October	9.0	84.2	188.7	5.5	47.3	34.3
November	5.7	89.2	124.9	6.4	33.9	15.7
December	4.7	88.9	207.7	6.9	25.3	8.1
mean	9.2	82.8	194.4	6.2	62.4	64.4
mean*8760.0 h	80234.7	725576.4	1702745.0	54749.0	546574.0	564516.0
min	2.0	68.0	119.4	5.2	25.3	8.1
max	16.7	89.2	234.9	7.1	117.5	126.9

Figure D.10: 2019 model results with actual climate inputs

SIMULATION TECHNOLOGY GROUP		**Systems Energy**	
Project		**Building**	
Højbo Frederikshavn		Model floor area	432.0 m^2
Customer		Model volume	1628.9 m^3
Created by	Benas Jokubauskis	Model ground area	148.8 m^2
Location	Fredrikshavn (Skagen)_060410 (ASHRAE 2013)	Model envelope area	754.9 m^2
Climate file	CW2019	Window/Envelope	13.4 %
Case	Højbo Frederikshavn - DW2019	Average U-value	1.6 W/(m^2 K)
Simulated	09/11/2022 12.06.41	Envelope area per Volume	0.4635 m^2/m^3

Used energy

kWh (sensible and latent)

Month	Zone heating	Zone cooling	AHU heating	AHU cooling	Dom. hot water
1	2591.0	0.0	1.0	0.0	624.2
2	1949.2	0.0	0.0	0.0	565.1
3	1544.4	0.0	0.0	0.0	626.9
4	565.9	0.0	0.0	0.0	607.7
5	121.2	0.7	0.0	0.0	628.4
6	0.0	63.4	0.0	0.0	608.1
7	0.0	170.9	0.0	0.0	628.4
8	0.0	76.8	0.0	0.0	628.4
9	9.9	2.1	0.0	0.0	608.1
10	451.1	0.0	-0.0	0.0	628.1
11	1577.9	0.0	-0.0	0.0	606.3
12	2181.3	0.0	-0.0	0.0	625.0
Total	10991.9	314.0	1.0	0.0	7384.7

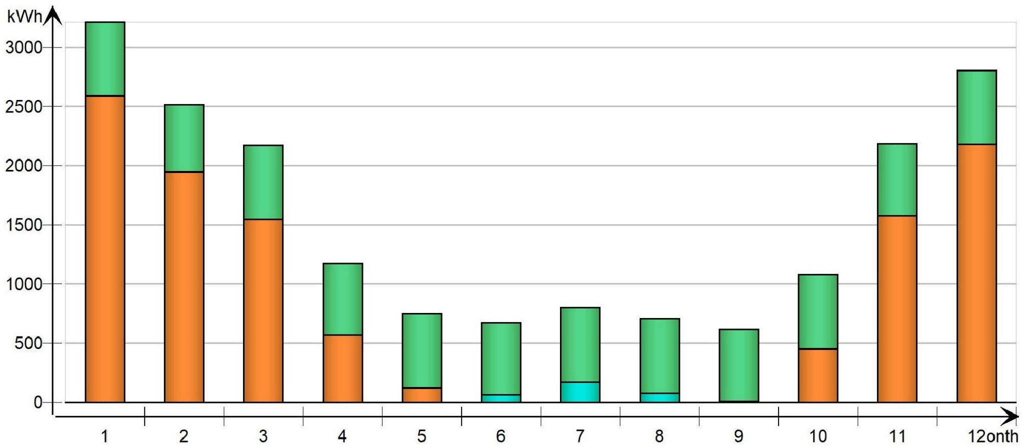


Figure D.11: 2020 climate file description with custom outdoor temperature, humidity, wind direction and wind speed inputs

Climate file

IDA Indoor Climate and Energy 4.802 License: ICE40X:ICE40X:ED255
Object: Climate file
Description:
Date: 2022-01-01 - 2022-12-31
Saved: 09/11/2022 09.33.43

	Variables					
	Dry-bulb temperature, Deg-C	Rel humidity of air, %	Direction of wind, Deg	Speed of meteorological wind, m/s	Direct normal rad, W/m2	Diffuse rad on hor surf, W/m2
January	5.4	88.7	225.7	8.2	26.2	11.4
February	4.3	85.2	217.1	8.4	34.8	24.3
March	4.2	78.2	182.4	7.3	51.4	52.1
April	7.1	72.7	218.5	6.4	65.5	83.9
May	9.3	75.3	235.4	6.1	98.8	114.9
June	16.6	75.9	163.5	4.9	117.5	126.6
July	14.6	81.5	240.0	6.7	90.4	126.9
August	17.6	81.3	186.2	4.7	85.1	102.0
September	14.0	83.9	189.1	6.0	71.0	70.8
October	10.5	86.7	176.7	6.7	47.3	34.3
November	8.3	89.9	208.1	7.2	33.9	15.7
December	4.9	92.1	152.7	8.5	25.3	8.1
mean	9.8	82.6	199.5	6.8	62.4	64.4
mean*8760.0 h	85539.9	723824.5	1747886.5	59164.3	546574.0	564516.0
min	4.2	72.7	152.7	4.7	25.3	8.1
max	17.6	92.1	240.0	8.5	117.5	126.9

Figure D.12: 2020 model results with actual climate inputs

EQUA SIMULATION TECHNOLOGY GROUP		Systems Energy	
Project		**Building**	
Højbo Frederikshavn		Model floor area	432.0 m^2
Customer		Model volume	1628.9 m^3
Created by	Benas Jokubauskis	Model ground area	148.8 m^2
Location	Fredrikshavn (Skagen)_060410 (ASHRAE 2013)	Model envelope area	754.9 m^2
Climate file	CW2020	Window/Envelope	13.4 %
Case	Højbo Frederikshavn - DW2020	Average U-value	1.6 W/(m^2 K)
Simulated	09/11/2022 12.36.32	Envelope area per Volume	0.4635 m^2/m^3

Used energy

kWh (sensible and latent)

Month	Zone heating	Zone cooling	AHU heating	AHU cooling	Dom. hot water
1	2295.2	0.0	0.0	0.0	625.5
2	2113.1	0.0	0.0	0.0	563.0
3	1782.1	0.0	0.0	0.0	625.5
4	720.8	0.0	0.0	0.0	607.6
5	184.9	0.0	0.0	0.0	628.3
6	0.0	170.0	0.0	0.0	608.1
7	0.0	19.6	0.0	0.0	628.4
8	0.0	162.7	0.0	0.0	628.4
9	0.0	2.5	0.0	0.0	608.1
10	432.3	0.0	-0.0	0.0	628.0
11	1220.3	0.0	-0.0	0.0	606.9
12	2316.0	0.0	0.0	0.0	624.2
Total	11064.7	354.8	0.0	0.0	7382.0

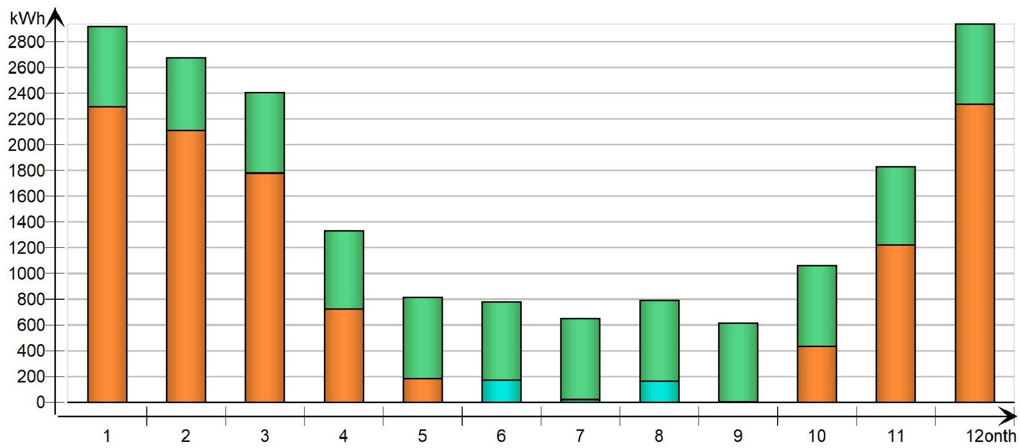


Figure D.13: 2021 climate file description with custom outdoor temperature, humidity, wind direction and wind speed inputs

Climate file

IDA Indoor Climate and Energy 4.802 License: ICE40X:ICE40X:ED255
Object: Climate file
Description:
Date: 2022-01-01 - 2022-12-31
Saved: 07/11/2022 14.28.33

	Variables					
	Dry-bulb temperature, Deg-C	Rel humidity of air, %	Direction of wind, Deg	Speed of meteorological wind, m/s	Direct normal rad, W/m2	Diffuse rad on hor surf, W/m2
January	0.6	89.1	147.9	5.9	26.2	11.4
February	-0.4	87.4	148.4	6.9	34.8	24.3
March	3.9	84.8	221.9	6.4	51.4	52.1
April	5.6	69.0	188.8	5.7	65.5	83.9
May	9.5	85.7	189.1	5.3	98.8	114.9
June	15.2	81.5	212.1	5.0	117.5	126.6
July	18.8	81.3	176.7	4.8	90.4	126.9
August	16.1	78.5	184.5	5.8	85.1	102.0
September	14.4	82.5	175.0	5.5	71.0	70.8
October	10.9	83.6	214.0	6.8	47.3	34.3
November	6.8	86.9	194.6	6.8	33.9	15.7
December	2.2	87.7	177.0	7.3	25.3	8.1
mean	8.7	83.2	186.1	6.0	62.4	64.4
mean*8760.0 h	76054.1	728652.0	1630011.5	52653.2	546574.0	564516.0
min	-0.4	69.0	147.9	4.8	25.3	8.1
max	18.8	89.1	221.9	7.3	117.5	126.9

Figure D.14: 2021 model results with actual climate inputs

EQUA SIMULATION TECHNOLOGY GROUP		**Systems Energy**	
Project		**Building**	
Højbo Frederikshavn		Model floor area	432.0 m^2
Customer		Model volume	1628.9 m^3
Created by	Benas Jokubauskis	Model ground area	148.8 m^2
Location	Fredrikshavn (Skagen)_060410 (ASHRAE 2013)	Model envelope area	754.9 m^2
Climate file	custom 2	Window/Envelope	13.4 %
Case	Højbo Frederikshavn - DW2021	Average U-value	1.6 W/(m^2 K)
Simulated	07/11/2022 15.09.09	Envelope area per Volume	0.4635 m^2/m^3

Used energy

kWh (sensible and latent)

Month	Zone heating	Zone cooling	AHU heating	AHU cooling	Dom. hot water
1	2953.1	0.0	2.9	0.0	623.2
2	2926.3	0.0	84.1	0.0	561.9
3	1656.1	0.0	0.0	0.0	626.3
4	900.4	0.0	0.0	0.0	607.1
5	164.0	0.0	0.0	0.0	628.3
6	0.0	57.8	0.0	0.0	608.1
7	0.0	304.6	0.0	0.0	628.4
8	0.0	51.0	0.0	0.0	628.4
9	0.0	14.0	0.0	0.0	608.1
10	319.3	0.0	-0.0	0.0	628.3
11	1440.9	0.0	-0.0	0.0	606.1
12	2700.3	0.0	3.1	0.0	622.9
Total	13060.5	427.4	90.1	0.0	7377.1

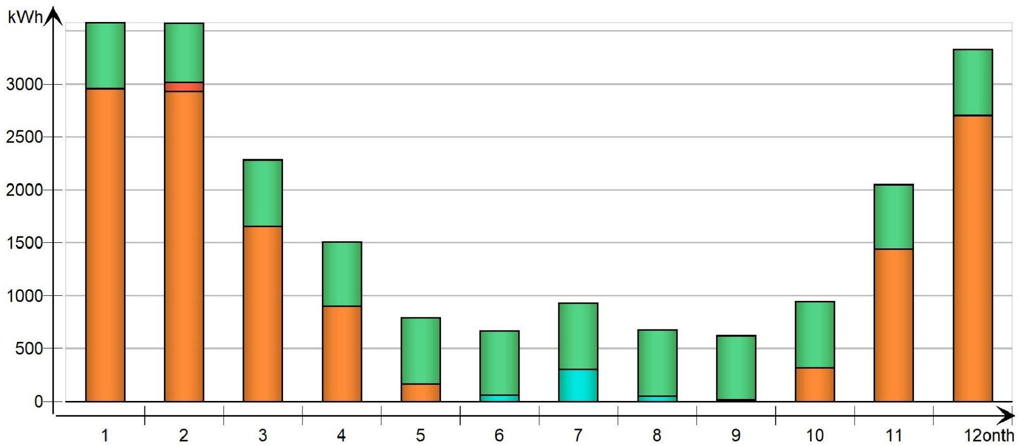


Figure D.15: 2022 climate file description with custom outdoor temperature, humidity, wind direction and wind speed inputs

Climate file

IDA Indoor Climate and Energy 4.802 License: ICE40X:ICE40X:ED255
Object: Climate file
Description:
Date: 2022-01-01 - 2022-08-01
Saved: 14/11/2022 08.46.57

	Variables					
	Dry-bulb temperature, Deg-C	Rel humidity of air, %	Direction of wind, Deg	Speed of meteorological wind, m/s	Direct normal rad, W/m2	Diffuse rad on hor surf, W/m2
January	4.1	83.6	240.0	7.9	26.2	11.4
February	3.6	84.3	238.5	7.4	34.8	24.3
March	3.6	78.9	189.9	5.8	51.4	52.1
April	6.4	72.7	163.1	5.3	65.5	83.9
May	11.0	76.0	215.2	6.0	98.8	114.9
June	14.8	81.3	214.5	5.5	117.5	126.6
July	16.5	78.9	231.0	5.6	90.4	126.9
August	16.3	78.5	253.4	6.4	159.7	130.0
mean	8.7	79.4	213.2	6.2	69.9	77.9
mean*5111.0 h	44293.9	405569.4	1089877.0	31650.3	357440.0	397977.0
min	3.6	72.7	163.1	5.3	26.2	11.4
max	16.5	84.3	253.4	7.9	159.7	130.0

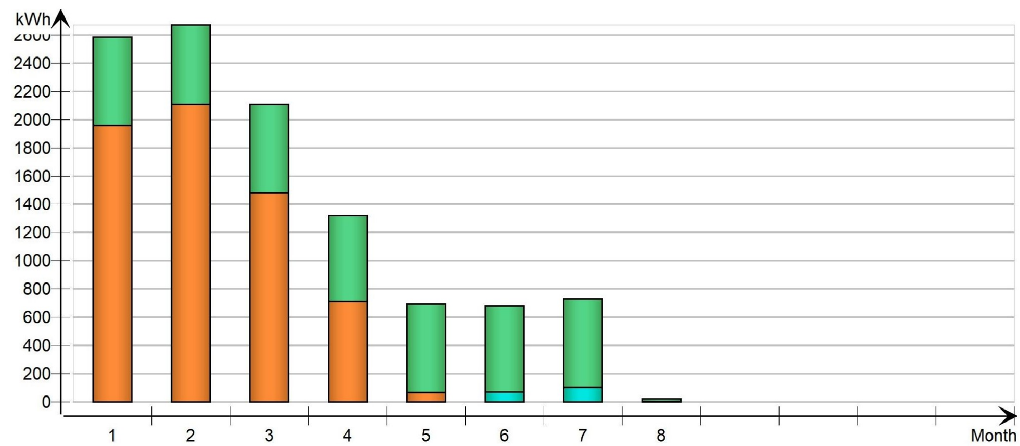
Figure D.16: 2022 model results with actual climate inputs

EQUA SIMULATION TECHNOLOGY GROUP		**Systems Energy**	
Project		**Building**	
Højbo Frederikshavn		Model floor area	432.0 m^2
Customer		Model volume	1628.9 m^3
Created by	Benas Jokubauskis	Model ground area	148.8 m^2
Location	Fredrikshavn (Skagen)_060410 (ASHRAE 2013)	Model envelope area	754.9 m^2
Climate file	custom 2	Window/Envelope	13.4 %
Case	Højbo Frederikshavn - DW2022	Average U-value	1.6 W/(m^2 K)
Simulated	24/11/2022 20.48.22	Envelope area per Volume	0.4635 m^2/m^3

Used energy

kWh (sensible and latent)

Month	Zone heating	Zone cooling	AHU heating	AHU cooling	Dom. hot water
1	1956.9	0.0	0.0	0.0	625.6
2	2106.4	0.0	0.0	0.0	563.6
3	1480.3	0.0	0.0	0.0	626.3
4	710.8	0.0	0.0	0.0	607.4
5	65.3	0.0	0.0	0.0	628.4
6	0.0	70.4	0.0	0.0	608.1
7	0.0	103.1	0.0	0.0	628.4
8	0.0	2.8	0.0	0.0	19.4
Total	6319.7	176.3	0.0	0.0	4307.2



D.0.2 Heating and Cooling Degree Days for years 2015-2022

2015		
Month	HDD	CDD
Jan	-434.6	0
Feb	-416.9	0
Mar	-396	0
Apr	-313.3	0
May	-248	0
Jun	-142.6	0
Jul	-68	4.1
Aug	-20.8	15.5
Sep	-102.9	0
Oct	-225.8	0
Nov	-293.1	0
Dec	-330.1	0
Total	2992.1	19.6

2016		
Month	HDD	CDD
Jan	-524.2	0
Feb	-418.8	0
Mar	-420.9	0
Apr	-323.3	0
May	-162.7	0
Jun	-51.8	10.1
Jul	-41.7	15.3
Aug	-44.7	5.2
Sep	-38.9	11.6
Oct	-252.5	0
Nov	-375.3	0
Dec	-374.4	0
Total	3029.2	42.2

2017		
Month	HDD	CDD
Jan	-466.5	0
Feb	-435	0
Mar	-406.5	0
Apr	-327.1	0
May	-184.7	0
Jun	-81.4	0.1
Jul	-50.7	0.9
Aug	-38.5	1.7
Sep	-103	0
Oct	-192.8	0
Nov	-334.8	0
Dec	-404	0
Total	3025	2.7

2018		
Month	HDD	CDD
Jan	-447	0
Feb	-500.9	0
Mar	-540.8	0
Apr	-306.1	0
May	-81.6	14.8
Jun	-37.4	27
Jul	-3	73.9
Aug	-27.8	26.9
Sep	-90.8	2.6
Oct	-219.5	0
Nov	-322.9	0
Dec	-401.6	0
Total	2979.4	145

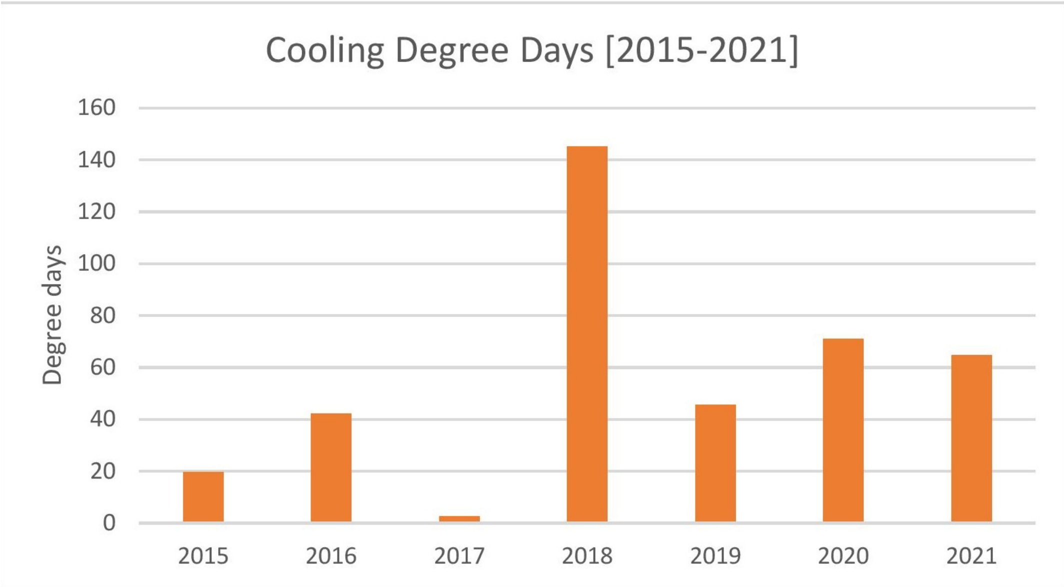
2019		
Month	HDD	CDD
Jan	-463.6	0
Feb	-365	0
Mar	-378.3	0
Apr	-271.4	0
May	-228	0
Jun	-53.9	2.3
Jul	-41.4	29
Aug	-22.5	14.2
Sep	-112.9	0
Oct	-248	0
Nov	-339.8	0
Dec	-381.3	0
Total	2906.1	45.5

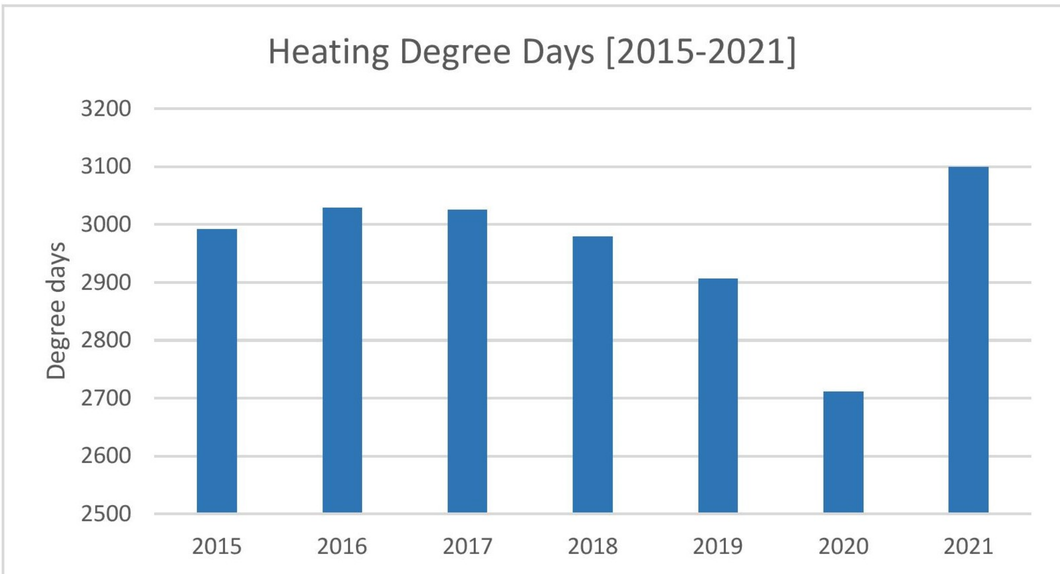
2020		
Month	HDD	CDD
Jan	-358.8	0
Feb	-354.7	0
Mar	-395.9	0
Apr	-298	0
May	-239.4	0
Jun	-39.7	27.5
Jul	-75.6	0.2
Aug	-25.9	43.2
Sep	-89.6	0
Oct	-199.8	0
Nov	-259.9	0
Dec	-373.9	0
Total	2711.2	70.9

2021		
Month	HDD	CDD
Jan	-508.1	0
Feb	-486.5	0
Mar	-404.9	0
Apr	-342.7	0
May	-232.4	0
Jun	-56.6	2.3
Jul	-1.2	56.5
Aug	-32	3.1
Sep	-80.1	2.9
Oct	-188.8	0
Nov	-306.4	0
Dec	-459.5	0
Total	3099.2	64.8

2022 until Nov		
Month	HDD	CDD
Jan	-399.6	0
Feb	-375.5	0
Mar	-414.1	0
Apr	-318.4	0
May	-184.6	0
Jun	-73.1	7.2
Jul	-29.8	13.8
Aug	-21.2	35.3
Sep	-102.9	0
Oct	-169.6	0
Nov	0	0
Dec	0	0
Total	2088.8	56.3

2015-2021		
Year	HDD	CDD
2015	2992.1	19.6
2016	3029.2	42.2
2017	3025	2.7
2018	2979.4	145
2019	2906.1	45.5
2020	2711.2	70.9
2021	3099.2	64.8


Cooling Degree Days [2015-2021]
Degree days
160
140
120
100
80
60
40
20
0
2015
2016
2017
2018
2019
2020
2021


Heating Degree Days [2015-2021]
Degree days
3200
3100
3000
2900
2800
2700
2600
2500
2015
2016
2017
2018
2019
2020
2021

Appendix E

Dynamic state set point models

Apartment st th				
Room	**Parameter**	**Multi-storey**	**Single zone weighted**	**Single zone not weighted**
Living room	Min	20.74	20.10	20.18
	Max			
	Avg			
Bedroom	Min	18.28		
	Max			
	Avg			
Bathroom	Min	21.52		
	Max			
	Avg			

Table E.1: Summary of data-based indoor boundary conditions - set points of the heating

Apartment st tv				
Room	**Parameter**	**Multi-storey**	**Single zone weighted**	**Single zone not weighted**
Living room	Min	21.16	20.83	21.10
	Max	22.52	21.63	21.44
	Avg	21.79	21.19	21.25
Bedroom	Min	19.00	20.83	21.10
	Max		21.63	21.44
	Avg		21.19	21.25
Bathroom	Min	23.06	20.83	21.10
	Max		21.63	21.44
	Avg		21.19	21.25
Room (second bedroom)	Min	21.17	20.83	21.10
	Max		21.63	21.44
	Avg		21.19	21.25

Table E.2: Summary of data-based indoor boundary conditions - set points of the heating

Apartment 1 th				
Room	**Parameter**	**Multi-storey**	**Single zone weighted**	**Single zone not weighted**
Living room	Min	17.24	17.10	17.10
	Max	19.57	19.63	19.67
	Avg	18.51	18.42	18.44
Bedroom	Min	16.75	17.10	17.10
	Max	19.72	19.63	19.67
	Avg	18.36	18.42	18.44
Bathroom	Min	17.32	17.10	17.10
	Max	19.73	19.63	19.67
	Avg	18.59	18.42	18.44

Table E.3: Summary of data-based indoor boundary conditions - set points of the heating

Apartment 1 tv				
Room	**Parameter**	**Multi-storey**	**Single zone weighted**	**Single zone not weighted**
Living room	Min	17.24	17.36	17.44
	Max	23.11	21.22	20.35
	Avg	21.33	19.91	19.24
Bedroom	Min	17.54	17.36	17.44
	Max		21.22	20.35
	Avg		19.91	19.24
Bathroom	Min	17.50	17.36	17.44
	Max	24.76	21.22	20.35
	Avg	20.87	19.91	19.24
Room (second bedroom)	Min	17.50	17.36	17.44
	Max		21.22	20.35
	Avg		19.91	19.24

Table E.4: Summary of data-based indoor boundary conditions - set points of the heating

Apartment 2 th				
Room	**Parameter**	**Multi-storey**	**Single zone weighted**	**Single zone not weighted**
Living room	Min	17.57	17.59	17.48
	Max	22.75	21.31	21.12
	Avg	20.85	19.87	19.68
Bedroom	Min	17.87	17.59	17.48
	Max		21.31	21.12
	Avg		19.87	19.68
Bathroom	Min	16.99	17.59	17.48
	Max	22.87	21.31	21.12
	Avg	20.55	19.87	19.68

Table E.5: Summary of data-based indoor boundary conditions - set points of the heating

Apartment 2 tv				
Room	**Parameter**	**Multi-storey**	**Single zone weighted**	**Single zone not weighted**
Living room	Min	17.38	17.45	17.45
	Max	20.72	20.30	20.32
	Avg	19.12	18.92	18.96
Bedroom	Min	17.74	17.45	17.45
	Max	18.61	20.30	20.32
	Avg	18.38	18.92	18.96
Bathroom	Min	17.29	17.45	17.45
	Max	21.17	20.30	20.32
	Avg	19.78	18.92	18.96
Room (second bedroom)	Min	17.42	17.45	17.45
	Max	20.78	20.30	20.32
	Avg	18.77	18.92	18.96

Table E.6: Summary of data-based indoor boundary conditions - set points of the heating

Appendix F

Causes of discrepancies

Figure F.1: Internal and external boundary conditions of 1 TV, living room. February 7-14, 2022

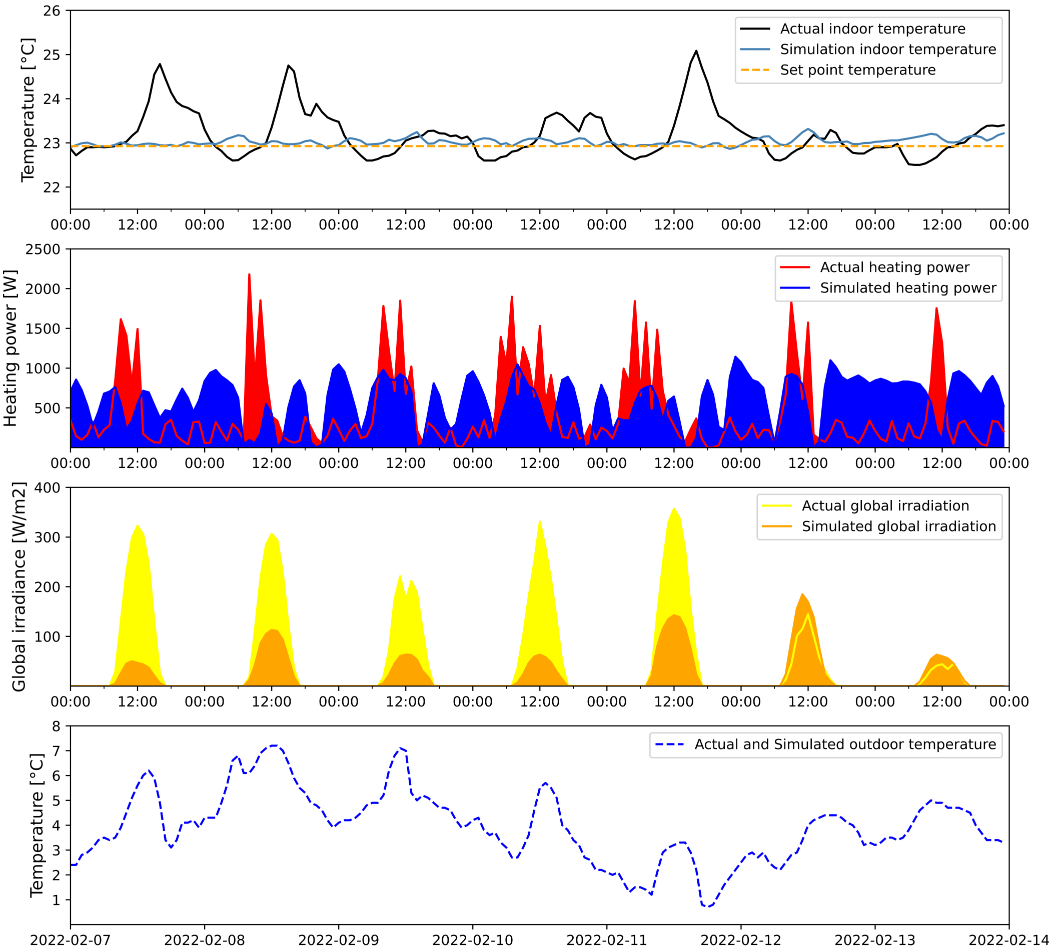


Figure F.2: Internal and external boundary conditions of 1 TV, living room. March 7-14, 2022

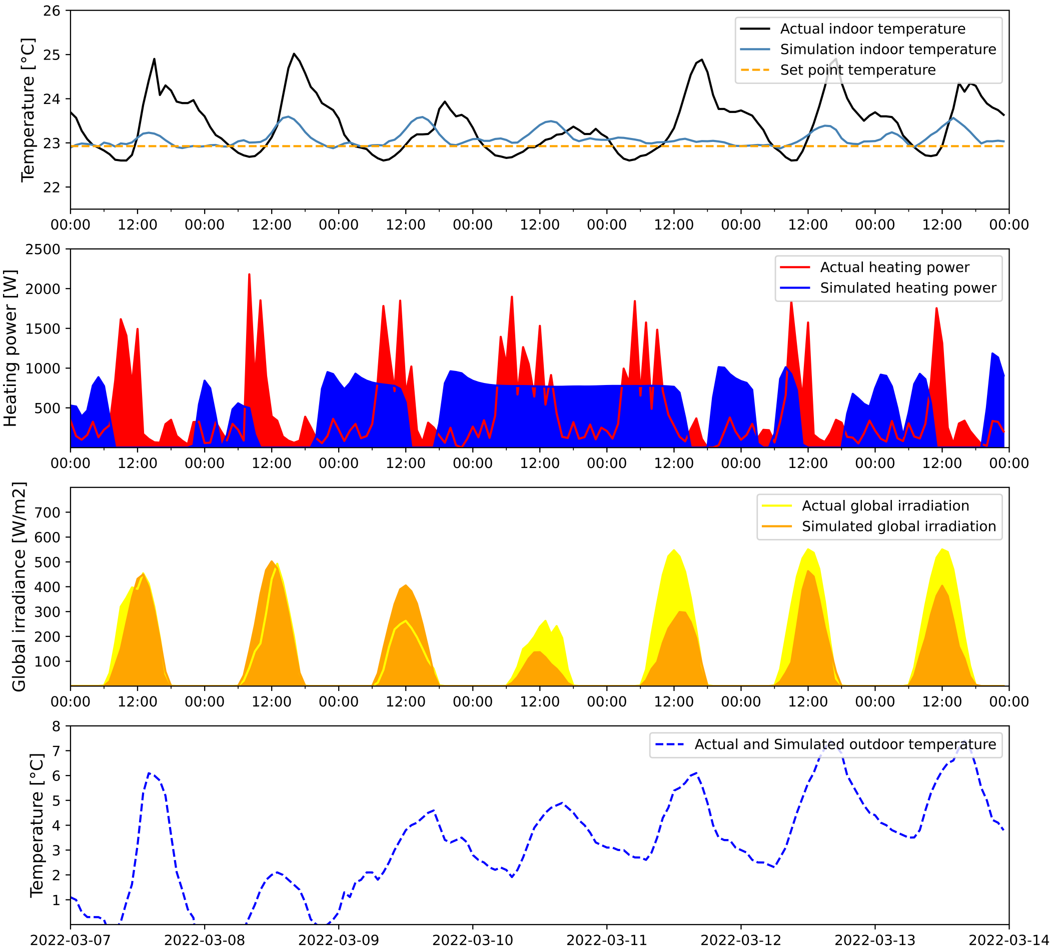
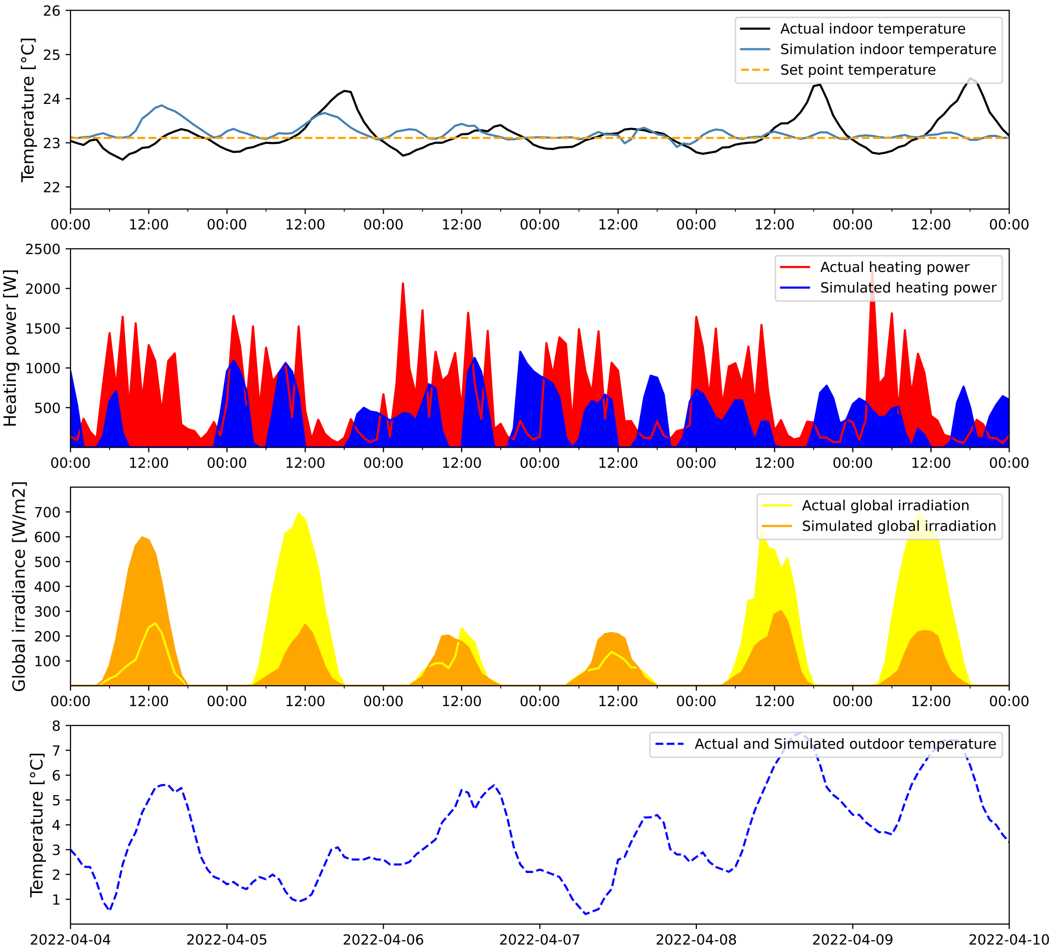


Figure F.3: Internal and external boundary conditions of 1 TV, living room. April 4-11, 2022



Appendix G

Additional documentation

G.0.1 Thesis contract

DEPARTMENT OF THE BUILT ENVIRONMENT
AALBORG UNIVERSITY

Specialekontrakt – Institut for Byggeri, by og miljø

Application for Thesis Contract – Department of the Built Environment

Kontrakt (Kandidat eller Diplomingeniør)/ Type of thesis (Master or Bachelor of Engineering):

Master thesis of Science in Technology

Studerende/Student

Navn/Name: Benas Jokubauskis

Studienummer/Student number: 20210018

Email: bjokub21@student.aau.dk

Uddannelse/Programme: Building Energy Design, Master of Science in Technology

Vejledere/Project Supervisors

Navn/Name: Anna Marszal-Pomianowska Underskrift/Signature: Anna Marszal-Pomianowska Digitally signed by Anna Marszal-Pomianowska Date: 2022.09.30 09:53:27 +02'00'

Navn/Name: Kamilla Heimar Andersen Underskrift/Signature: Kamilla Heimar Andersen Digitally signed by Kamilla Heimar Andersen Date: 2022.09.22 10:29:35 +02'00'

Virksomhedskontakt (hvis relevant) /Company Contact Person (if relevant).

Navn/Name: - Underskrift/Signature: -

Email: -

Speciale/afgangsprojekt/Thesis/Project

Titel på speciale eller afgangsprojekt/Project Title: Data-driven Assessment of energy use and HVAC components performance: A Danish residential building

Startdato/Starting: 1 September

Deadline: 1 to 10 January

ECTS: 30

DEPARTMENT OF THE BUILT ENVIRONMENT
AALBORG UNIVERSITY

Projektbeskrivelse/Project Description:

The use of standard weather file air temperatures, resident occupant behavior, and average COP of the HVAC system elements can all lead to a performance gap between the predicted and actual, real-life energy use of the buildings. Additionally, on-site changes while constructing, and installing, , wear and tear of the components, and occurrence of faults further increase this difference. For this reason, the residential case building is evaluated by the commonly used steady-state, dynamic and data-driven system identification methods to find the performance gap between the whole building and individual selected systems (which can later be compared with the stated manufacturer's KPIs & COP).

Plan for vejledning og laboratoriearbejde/Plan for Thesis Supervision and Lab Work:

Not relevant for the project

Godkendt af Studieleder/Approved by Head of Studies

Dato/Date: 7/10-22

Underskrift/Signature: Lene Faber Ussing

G.0.2 Abstract - Cisbat 2023

Title suggestion:

The energy performance gap: How much does the influence of model input parameters in dynamic white-box models really matter?

1. Aim of research (max 200 words)

There is a known energy performance gap between the design and the actual energy use in buildings. Many areas have been shown to cause this gap, including unrealistic model inputs on occupant presence and behavior, the adopted energy management heuristics, faults occurring in building systems, or benchmarks comparing building performance. Nevertheless, efforts have been made to bridge this gap. However, each building is unique and requires tailored design inputs. Hence there is still a lack of knowledge on the influence of parameters affecting the models for building benchmarks, especially in residential buildings.

Moreover, the market has reached a turning point where it must advance beyond simply certifying the energy performance of buildings with standard design input parameters. This study aims to address the latter by quantifying the discrepancies between two defined assessment types; standard and actual evaluation of building performance compared to measured energy use. Furthermore, this study is part of the bigger picture contributing to defining which systems, energy components, and appliances should be included in a developed framework assessment to monitor and manage buildings more efficiently.

2. Scientific methodology (max 200 words)

Two defined assessments have been introduced in this study. The standard assessment is based on standardized weather files, occupant presence, and other building system parameters. It represents the currently used methodology of the Danish Energy Performance certification. On the contrary, the actual assessment is based on real-life weather- and occupant conditions.

These two assessments were modeled in the white-box building performance simulation (BPS) tool, "IDA ICE". The latter was compared to a total of 1-year measurements of heating energy use in the case study, a multi-storey building renovated in 2013 in the North of Denmark. Furthermore, each assessment has been evaluated for its relevant input parameter sensitivity (variations of inputs in the weather file, occupant presence, heating setpoints, window opening, and other internal input boundary conditions). The actual occupant presence was determined through a measurement campaign in January 2023 in the case study, while the heating setpoints and window openings data were extracted through the building management system.

3. Results obtained (max 200 words)

The comparison of the two assessment types against the historical data showed a rate of percentage change of 17 % (actual assessment) and 26 % (standard assessment) performance gap. Both comparisons were mainly caused by discrepancies in the occupant behavior (heating setpoints, window opening, and actual presence) and weather conditions. Furthermore, variations and aggregation of the heating setpoints and zone multipliers were performed to investigate the effects of simplifying these BPS models, which were significant. The sensitivity analysis showed that the occupant behavior (heating setpoints) was the most sensitive parameter to model changes. Occupants in residential buildings often have a larger control of their indoor environment than in office buildings. Especially in cold climates with the need for heating, occupant behavior (heating setpoints) has been shown to influence the performance gap greatly.

This study shows that modeling a baseline for design needs considerations of actual conditions to provide robustness and accurate predictions of, e.g., the building energy use in operation.