Final Report

Heating Optimisation in Studio Apartments
Based on Modular Construction

Funded by the Bjarne Saxhofs Fond

Lundtofte Student Residences at DTU Lyngby Campus

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Abstract

This report documents a research project funded by the Bjarne Saxhofs Fond investigating heating optimisation in modular student housing at Lundtoftevej 162, DTU Lyngby Campus. The project addressed two parallel tracks: domestic hot water (DHW) system optimisation and space heating analysis through grey-box thermal modelling.

For the DHW system, a validated digital shadow model was developed in Dymola to simulate the dual-tank accumulative storage system. Systematic investigation of control parameters demonstrated that district heating return temperatures can be reduced from approximately 45°C to below 25°C—a reduction of nearly 20°C—through three software-only changes: reducing charging pump flow from 0.50 kg/s to 0.10 kg/s, increasing the stop difference parameter from −18 K to −39 K, and eliminating post-run time. However, field implementation revealed that reduced flow rates accelerate heat exchanger fouling in hard water areas with high district heating supply temperatures, necessitating infrastructure upgrades (mixing shunt or water treatment) before sustainable deployment.

For space heating, a grey-box thermal model was developed using CO_2 decay analysis to empirically determine apartment-specific ventilation rates. The calibrated model aims to predict daily heating consumption and detect operational anomalies, particularly excess consumption correlated with window-opening events. Analysis revealed that ventilation dominates heat loss in these highly insulated apartments, with an estimated 40% supply/exhaust imbalance driving significant mechanically induced infiltration through the building envelope.

Qualitative interviews with technically expert residents revealed an "expert struggle paradox": even occupants with doctoral-level training in building energy systems cannot optimally operate their heating and ventilation systems. This finding reframes the challenge from user education to system design, supporting the development of automated feedback systems that provide real-time guidance based on measured performance rather than relying on occupant expertise.

The project was significantly impacted by persistent data infrastructure failures from the heat cost allocation provider, requiring strategic pivots from planned sensor-based analysis to simulation-based methodologies. Despite these challenges, the project delivered validated methodologies for both DHW optimisation and space heating overconsumption detection, with clear pathways to implementation pending infrastructure upgrades.

Keywords: district heating, domestic hot water, return temperature optimisation, grey-box modelling, CO_2 decay analysis, occupant behaviour, modular construction, digital shadow

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background

The transition to a sustainable energy system requires significant reductions in the supply and return temperatures of district heating networks. Lower supply and return temperatures improve heat production efficiency, reduce distribution losses, and enable the integration of renewable and waste heat sources that operate at lower temperature levels. Buildings are central to this transition: in Europe, they account for approximately 40% of final energy consumption, with space heating and domestic hot water representing the largest share. Achieving ambitious climate goals therefore requires not only efficient building envelopes but also optimised operation of heating installations.

Modern residential buildings constructed using modular methods present both an opportunity and a challenge in this context. Modular construction—characterised by highly automated, offsite manufacturing of repeatable volume modules—has expanded rapidly in Denmark due to housing shortages, skilled labour constraints, and the potential for faster construction schedules with reduced material waste. However, newly constructed buildings are frequently prone to higher-than-expected energy consumption and suboptimal thermal comfort, often due to poor commissioning, misaligned control strategies, and a disconnect between design assumptions and actual occupant behaviour.

The Danish government's requirement for remotely read sub-meters for electricity, heating, and water creates a valuable but underutilised data resource. Billing companies such as Ista, Brunata, and Techem have leveraged their existing IT infrastructure to offer affordable wireless sensors and cloud-based data access. This infrastructure provides an unprecedented opportunity to characterise heat flows in new buildings and develop data-driven methods for heating system optimisation—methods that could be replicated across the growing stock of modular residential buildings.

1.2 Problem Statement

In 2020, Boligfonden DTU and PensionDanmark completed a development of 491 DGNB-gold-certified accommodations at Lundtoftevej 162 in Kongens Lyngby, constructed by ScandiByg using modular volume modules. Early indications suggested that the district heating return temperatures from the domestic hot water (DHW) system were significantly higher than necessary—a common problem in new buildings that undermines the goals of fourth-generation district heating networks.

Furthermore, the highly insulated building envelope, while minimising transmission losses, makes the apartments particularly sensitive to internal heat gains and occupant behaviour. Traditional static assumptions about ventilation rates and heating control cannot adequately characterise the thermal dynamics of such buildings. There was a clear need for analytical methods that could move beyond these assumptions, diagnose real-world operational inefficiencies, and guide targeted interventions.

The building was instrumented with wireless Lansen sensors and connected to gateways, creating the potential for high-resolution monitoring of indoor climate, heating consumption, and system operation.

1.3 Project Objectives

This project, funded by Bjarne Saxhofs Fond, aimed to leverage the unused data resources at Lundtoftevej 162 to develop and verify methods for heating system optimisation applicable to low-rise studio apartments based on modular construction. As specified in the original funding application, the project was organised around five key objectives relating to at least 80 student apartments:

1. **Qualitatively analyse** the experiences and behaviours of occupants and building operators concerning the heating systems and thermal comfort.
2. **Characterise all heat flows** using thermal models with statistically estimated parameters based on data from cloud-connected sensors and meters.
3. **Detect and diagnose faults** and poor operation of heating installations, leading to improved operations and repairs.
4. **Optimise regulation** of space heating systems to prevent excessive heating consumption while maintaining thermal comfort.
5. **Document the technical requirements, methods, and expected impact** for low-temperature operation of the heating system.

These objectives were distributed across four work packages: WP1 (Management, Dissemination and Reporting), WP2 (Qualitative Analysis of User Experiences with Heating Systems), WP3 (Development and Validation of Thermal Grey-box Models), and WP4 (Fault Detection and Optimised Space-Heating Regulation).

1.4 Scope and Limitations

The project focused on Building H at Lundtoftevej 162, comprising mostly studio apartments served by a shared DHW system with two accumulative storage tanks and individual space heating via radiators in main rooms and floor heating in bathrooms. Mechanical ventilation with heat recovery is provided by rooftop air handling units that supply ventilation air to both common areas and individual apartments.

The intended data sources included Lansen wireless carbon dioxide, temperature and humidity sensors in at least 80 apartments, heat cost allocators on radiators, window contact sensors, controller data from the ventilation units via Neogrid gateways, and heat meter readings from the DHW system and air heating coils. The project planned to use data from two full heating seasons (2021–22 and 2022–23) to develop, validate, and test optimisation methods.

As detailed in Chapter 3, persistent data quality and availability issues from the heat cost allocation provider, combined with building system faults discovered during the project, necessitated strategic pivots in research focus. The project nonetheless achieved substantial progress on methodological development across both the DHW and space heating domains.

1.5 Report Structure

This report documents the work completed under the Bjarne Saxhofs Fond project:

- **Chapter 2** describes the case study building and its technical systems.
- **Chapter 3** addresses the data infrastructure challenges and strategic pivots that shaped the project's trajectory.
- **Chapter 4** presents findings from qualitative interviews with residents (WP2).
- **Chapter 5** details the DHW system analysis, including digital shadow development and optimisation of return temperature control.
- **Chapter 6** presents the thermal grey-box modelling methodology for space heating analysis (WP3/WP4).
- **Chapter 7** synthesises the key findings and provides recommendations.
- **Chapter 8** concludes with an assessment of objectives achieved and a path forward for completing the remaining work.

Chapter 2

Case Study

This chapter describes the building and technical systems that formed the basis for the project's research activities.

2.1 Building Overview

The student residences at Lundtoftevej 162 are located directly north of DTU Campus in Kongens Lyngby, Denmark (55.79°N, 12.52°E). The property comprises 491 accommodations distributed across eight separate buildings (A–H):

- 416 one-room studio apartments with private kitchenettes and bathrooms
- 31 single rooms with private bathrooms and shared kitchens
- 44 two-bedroom apartments (corner units combining two modules, containing a main room, two bedrooms, and bathroom)

Figure 2.1: Location of Lundtoftevej 162 student residences north of DTU Campus, Kongens Lyngby, Denmark.

The buildings were completed in 2020 by ScandiByg, Denmark's largest modular construction company, in partnership with PensionDanmark and Boligfonden DTU. The development achieved DGNB-gold certification, reflecting high standards for sustainability. The construction method employed offsite-manufactured 3D volume modules that were transported to the site and assembled, enabling faster construction schedules and improved quality control compared to traditional methods.

Figure 2.2: Modular apartment unit during construction showing the prefabricated volume module approach. The mechanical cabinet containing heating and ventilation connections is visible.

The research activities focused on Building H, which contains studio apartments served by a dedicated technical room housing the DHW and space heating substations.

2.2 Domestic Hot Water System

The DHW system in Building H uses a Danfoss Akva Therm LV substation connected to the district heating network via an external plate heat exchanger (model XB06H1-26). On the secondary side, two 350-litre storage tanks are connected in series, providing a total capacity of 700 litres of accumulated hot water. The bottom of the second tank and the top of the first tank are connected through a pipe, allowing stratified storage.

When there is demand and the tanks require recharging, cold water enters the bottom of the first tank. The water is heated by circulating through the plate heat exchanger, with the charging pump (P4) and motorised valve (M1) controlled by a Danfoss ECL Comfort 310 controller operating according to application A377.1. The system also includes a circulation loop (pump P3) to ensure acceptable waiting times for hot water at the taps.

Figure 2.3: DHW system and district heating substation in the technical room, showing the storage tanks (blue) and the Danfoss heating substation.

Key control parameters include:

- **Comfort mode**: Reference temperature at the top of the second tank (R6) set to 53°C
- **Saving mode** (00:00–04:30): R6 reduced to 50°C
- **Charging temperature setpoint** (R9): 56°C at sensor S9
- **Stop difference parameter**: Controls when charging stops based on the temperature difference between the setpoint and the bottom tank sensor (S8)
- **Post-run time**: Duration the charging pump continues after the valve closes

Figure 2.4: Danfoss ECL Comfort 310 controller used to regulate the DHW system charging and temperature control.

The district heating supply temperature to the building typically ranges between 70°C and 75°C. Initial analysis revealed that the mean return temperature from the DHW system was approximately 45°C—significantly higher than the targets for fourth-generation district heating networks.

2.3 Space Heating System

The space heating system uses a Danfoss H228 substation equipped with a brazed plate heat exchanger (model XB37M50). Heat is distributed to the apartments via:

- **Radiators**: Located in the main living spaces, controlled by thermostatic radiator valves (TRVs)
- **Floor heating**: Installed in bathrooms, providing supplementary heating
- **Ventilation**: Rooftop air handling units (AHUs) provide mechanical ventilation with heat recovery and include an air heating coil to ensure sufficiently high temperatures to avoid cold draughts

Figure 2.5: Interior of a studio apartment showing the kitchenette area with radiator and thermostatic radiator valve (TRV) for space heating control.

Figure 2.6: Komfovent air handling unit on the roof during construction. The AHU provides mechanical ventilation with heat recovery for the entire building.

During the project, it was discovered that 15 of 16 main heating valves in the building had been undersized during original construction. These valves were replaced under warranty by ScandiByg in late 2024, which temporarily constrained the project's ability to implement and test optimisation measures.

2.4 Data Infrastructure

The building was instrumented with multiple data sources intended to support research activities:

Danfoss ECL Platform: The ECL Comfort 310 controller provides readings from built-in sensors at 1-hour resolution, including supply and return temperatures for both DHW and space heating systems, tank temperatures (S6, S8), charging temperature (S9), and pump/valve status signals.

Neogrid Platform: Gateways installed in the technical room provide 1-minute resolution data from additional sensors connected to the ECL, including motor positions and pump signals. Data from the rooftop ventilation units were also accessible via this platform in many buildings.

Figure 2.7: Neogrid Technologies gateway providing high-resolution data access from the building control systems.

Heat Cost Allocation Provider Meters and Sensors: The original project plan specified installation of 523 sensors across Building H, including:

- 106 heat cost allocators on radiators
- 154 temperature and relative humidity sensors in apartments
- 32 detailed heat meters
- Window/door contact sensors

Most of these sensors were installed at various stages during the project. The infrastructure was intended to provide daily consumption readings for cold water, hot water, electricity, and thermal energy from existing meters in each apartment, with higher-resolution (15-minute) data available for indoor climate sensors. However, the heat cost allocation provider's main challenge has been collecting and sharing the data reliably. Persistent system failures, data quality issues, and incomplete data exports have obstructed nearly any opportunity to perform research using this data source, as detailed in Chapter 3.

Supplementary Instrumentation: To address gaps in the available data, temporary sensors were installed during specific measurement campaigns, including Hobo data loggers with contact temperature sensors and a KATflow 200 ultrasonic flow meter for measuring cold water flow to the DHW system Sol Vilaplana (2023). Additionally, Danfoss provided an ECA 32 expansion module with six additional Pt1000 temperature sensors, which were connected to the ECL 310 controller to enable more detailed monitoring of the DHW system during dedicated measurement campaigns Wildfeuer (2024). These supplementary sensors provided critical data for model development and validation when the primary data infrastructure was unavailable.

2.5 Stakeholder Landscape

The project involved coordination among multiple stakeholders:

- **Boligfonden DTU**: Building owner and operator, responsible for maintenance and resident relations
- **Heat cost allocation provider**: Data provider responsible for meter installation, data collection, and transmission, who ultimately failed at their tasks
- **ScandiByg**: Original constructor, responsible for warranty-related repairs, and provider of architectural drawings
- **Neogrid Technologies**: Gateway provider for controller data access
- **Danfoss**: Manufacturer of substations and controllers, provided technical consultation
- **Holte Fjernvarme**: District heating operator for the part of the Lyngby area of the building is situated

This multi-stakeholder environment created coordination challenges that significantly impacted the project timeline, as detailed in Chapter 3.

Chapter 3

Challenges and Strategic Pivots

This project faced significant external challenges that necessitated strategic redirections in research focus. This chapter documents these challenges transparently, both to explain the project's trajectory and to provide lessons learned for future data-dependent research initiatives.

3.1 Data Provider Challenges

The primary cause of the project's multi-year delays was persistent failure by the heat cost allocation provider to deliver a usable dataset. The issues were multifaceted and spanned the entire project duration.

3.1.1 Initial Disruption (2022)

In July 2022, the data provider experienced a cyberattack that disrupted email and data access across their European operations. This delayed initial sensor installations and data sharing at a critical early stage of the project. While the immediate disruption was eventually resolved, it set a precedent for communication difficulties that persisted throughout the collaboration.

3.1.2 Sensor Installation Discrepancies

The original project plan specified installation of 523 sensors in Building H, including 106 heat cost allocators, 154 temperature and humidity sensors, and window/door contact sensors. However, a site audit and data analysis revealed major discrepancies between planned and actual installations. As of March 2025, only 105 sensors were visible in the data exports for Building H. A final installation list was never provided despite repeated requests, making it impossible to verify which sensors were actually operational.

3.1.3 Data Quality Issues (2022–2025)

Throughout the project, students and researchers reported systematic data quality problems:

- **Missing timestamps and non-unique entries**: Sensors recording at resolutions higher than one hour produced identical timestamps with multiple different readings. For example, a sensor set to 15-minute intervals would show four readings all timestamped at the same hour.

- **Random data gaps**: Energy meter readings and heat cost allocator data contained unexplained gaps, sometimes spanning entire weeks for complete properties.
- **Malfunctioning sensors**: The window/door contact sensors consistently transmitted incorrect values (encrypted error messages rather than open/closed status), rendering this critical data source unusable for the intended analysis of occupant behaviour.
- **Resolution limitations**: Despite repeated requests for 15-minute resolution data to support dynamic thermal modelling, data was often only available in daily aggregates.

3.1.4 Critical System Failure (November 2025)

The most consequential failure occurred just weeks before the project deadline. Despite assurances in August 2025 that data flow issues had been resolved and high-resolution data would be available, the system failed catastrophically in November 2025.

The technical cause was confirmed by the provider on 17 November 2025: a fatal conflict between the PiiGAB gateway configuration and server capacity. The gateways were configured to store 15-minute readings and upload files every 15 minutes. When the dedicated server reached capacity and stopped accepting files, poor communication between gateway and server caused files to backlog, leading to permanent data loss.

As a workaround, the provider reconfigured the system to upload once daily, but this inadvertently caused data to be aggregated into daily values rather than preserving 15-minute resolution. When the configuration was reverted, the gateways began failing to upload entirely. As of the project conclusion, the system remained non-functional.

3.1.5 Pattern of Reactive Response

A consistent pattern emerged throughout the project: technical and data quality issues were typically only addressed after repeated, urgent, and detailed escalations. On several occasions, the project team was informed that issues had been resolved, only to discover upon investigation that problems persisted. This created a cycle of delayed student projects and stalled research progress.

3.2 Building System Faults

In late 2024, systematic heating complaints from residents prompted an investigation that revealed the buildings had fundamental heating system issues: 15 of 16 main heating valves had been undersized during original construction by ScandiByg.

This discovery had two consequences for the project:

- **Recommissioning required**: The valves were replaced under warranty by ScandiByg, a process that extended through late 2024.

- **Project work halted**: Boligfonden DTU explicitly requested that researchers not interfere with the heating system during the investigation and repair period to avoid jeopardising the warranty claim. This pause prevented implementation and testing of optimisation measures.

3.3 Strategic Pivots

The data availability challenges forced a series of strategic pivots in student thesis projects, each building on the previous work while redirecting focus to achievable objectives.

3.3.1 Pivot 1: IDA-ICE Simulation (Jakob Jelstad, 2023)

The first student project intended to investigate indoor climate data for thermal analysis. When this data proved unavailable, the project pivoted to parametric simulations using IDA-ICE software. This produced a validated simulation framework for modular studio apartments (Jelstad 2023), establishing the theoretical foundation for understanding thermal behaviour in these highly insulated buildings.

3.3.2 Pivot 2: DHW Digital Shadow (Eloi Sol Vilaplana, 2023)

The second student project also encountered data unavailability. Rather than abandoning the research, the focus redirected to the DHW installation, where data from the Danfoss ECL controller and Neogrid platform provided sufficient information for analysis. This pivot proved highly productive: a complete digital shadow of the DHW system was developed in Dymola, validated against measured data, and used to identify control optimisations capable of reducing return temperatures by approximately 20°C (Sol Vilaplana 2023).

3.3.3 Pivot 3: DHW Continuation (Johannes Wildfeuer, 2024)

A subsequent project was scheduled to utilise the indoor climate data but continued facing availability issues. The work therefore extended the DHW system analysis, validating the digital shadow model with additional measurement campaigns and addressing issues discovered during earlier work, including the repositioning of a misplaced temperature probe (Wildfeuer 2024). This work refined and expanded the DHW optimisation methodology with greater accuracy and complexity than the initial baseline work.

3.3.4 Pivot 4: Grey-box Methodology Development (Filip Gligić, 2024–2025)

The final student track began with a special course project in late 2024, during which data remained unavailable. The project focused on analysing existing building energy meter data to characterise heat consumption patterns in common areas versus private apartments (Gligić 2024).

For the subsequent Bachelor's thesis in 2025, limited data finally became accessible. This enabled development and testing of a thermal grey-box methodology using CO_2 concentration data to estimate ventilation rates and indoor climate sensors to construct apartment-level heat balance models (Gligić 2025). However, the data quality issues documented above prevented full application of this methodology to the complete dataset.

3.4 DHW Publication Barrier

Beyond the space heating analysis, the DHW optimisation track faced an additional obstacle. The project demonstrated that optimal control configurations—specifically, slowing the charging rate by reducing pump flow and adjusting the stop difference parameter—could dramatically lower return temperatures. However, implementing these controls in the actual system revealed heat exchanger fouling caused by high district heating supply temperatures.

The fouling prevented safe implementation of the improved controls: slowing the charging rate with a fouled heat exchanger would risk inadequate hot water temperatures for residents. At flow temperatures below 50°C, there is a significant risk of *Legionella* growth in the storage tanks (Yang et al. 2016). Critically, this health risk would be imperceptible to residents, who typically require only about 40°C for showering and 45°C at the tap—temperatures that could still be achieved even with a compromised system.

Boligfonden DTU has recognised the need for system upgrades, including installation of a mixing shunt to reduce supply temperatures and a chemical de-calcification system to prevent persistent fouling. Until these upgrades are completed, field demonstration of the optimised controls—and the associated publication—must be deferred.

3.5 Lessons Learned

Several lessons emerge from these challenges:

- **Data dependency risk**: Research projects dependent on third-party data infrastructure carry significant risk. Contingency plans and alternative data sources should be established early.
- **Verification requirements**: Assurances of data quality and availability should be verified independently before committing student projects and research timelines.
- **Documentation value**: Detailed documentation of issues, as maintained throughout this project, provides both accountability and a resource for future negotiations with service providers.
- **Pivot opportunities**: Strategic pivots, while disruptive, can yield valuable methodological contributions. The DHW digital shadow and grey-box modelling approaches developed through these pivots represent transferable tools applicable to similar buildings.

Despite these substantial obstacles, the project achieved its core objective of developing validated methodological frameworks. The following chapters document these achievements in detail.

Chapter 4

User Experience Analysis (WP2)

Work Package 2 aimed to qualitatively analyse the experiences and behaviours of occupants concerning the heating systems and thermal comfort. Semi-structured interviews were conducted with residents who have technical backgrounds in building energy and indoor climate—a deliberate choice to test whether expertise improves system operation outcomes.

4.1 Methodology

Three residents were interviewed using a semi-structured format covering thermal comfort, heating system use, ventilation perceptions, window-opening behaviour, and billing experiences. Conversations were transcribed and analysed thematically.

As a group, the interviewees represent an unusually expert population: all three are undergoing doctoral-level training in building energy, HVAC systems, indoor climate, or related fields such as building envelope performance and district-level energy systems. Their combined residency spans approximately eight years across multiple buildings in the development (Buildings A, C, D, F, and H), providing experience with different apartment types including studios and two-bedroom corner units, various floor levels from ground to top floor, and multiple facade orientations. This diversity of technical expertise and lived experience makes them ideally positioned to provide informed commentary on the heating and ventilation systems—and makes their struggles with these systems all the more significant.

4.2 Window Opening Behaviour and Ventilation Perceptions

4.2.1 Window Opening Despite Mechanical Ventilation

A striking finding was that all three residents regularly open windows for "fresh air" despite the apartments being equipped with mechanical ventilation with heat recovery (MVHR). The building employs a hybrid (mixed-mode) ventilation strategy: the MVHR system provides controlled air exchange and heat recovery during heating season, while window opening is the intended mechanism for cooling during warm weather. However, residents perceived insufficient fresh air from the mechanical system year-round:

> *"In order to make the air quality nice, I always open the window."* (Resident 3)

> *"I just want some fresh air."* (Resident 2)

One resident explained that a friend advised regular window opening for health reasons: *"I've heard about some health problems because if you didn't open the window, something happened... my friend recommended me to open the windows during the day, at least for five or 10 minutes."* This advice contradicts the design intent of the MVHR system during heating season but has been accepted as necessary behaviour.

Residents in corner apartments with windows on multiple facades can achieve effective cross-ventilation: *"We open two windows, one in the main one and one of the bedroom, so that air flow is coming and going out completely."* However, residents in single-sided studios face significant limitations. One resident noted: *"If I open the window I feel less air getting in... if I open my door and then there's going to be the air flow through my room. But normally people keep the door closed."* Security and privacy concerns prevent corridor-based cross-ventilation—one resident recounted experiences with strangers entering rooms and accidentally opening wrong doors, leading to habitual door-locking behaviour.

This creates an asymmetry where corner apartments can naturally ventilate effectively through cross-ventilation to cool their dwelling, while single-sided studios cannot achieve equivalent airflow without opening doors to the corridor, which residents consistently avoid. During the heating season, this window-opening behaviour defeats the heat recovery function of the ventilation system and increases heating demand significantly. In highly insulated buildings where ventilation is the dominant heat loss mechanism, unnecessary window opening represents a potentially substantial source of energy waste.

4.2.2 Imperceptible Ventilation System

Multiple residents reported that the mechanical ventilation system is essentially imperceptible in the living spaces, contributing to their uncertainty about whether it is functioning adequately:

> *"I never feel the ventilation system in the dorm. In the bathroom, somehow I can feel it. But in the living part, I didn't feel it."* (Resident 3)
>
> *"I even don't know where I can adjust the ventilation system."* (Resident 3)

The invisibility of the ventilation system reinforces residents' reliance on window opening as a more tangible form of air exchange.

4.2.3 Kitchen Hood Inadequacy

The kitchen hoods were reported as insufficient for cooking activities, particularly for residents whose cooking style involves high-oil preparation or extended cooking times. This provides another reason for window opening beyond fresh air desires:

> *"When we are cooking, we use a lot of oil... I think the hood is not that powerful. So after cooking I normally also open the window for quite a long time."* (Resident 2)
>
> *"The ventilation above this cooking area is not so good, so I need some fresh air... not for cool but just to have a nice smell."* (Resident 3)

"From this thing on top of the oven I can say sometimes has an annoying noise." (Resident 1)

One resident noted that certain cooking styles can generate *"a lot of internal heat gains"* with cooking sessions lasting *"two or three hours."* When the kitchen hood proves insufficient, residents open both windows and doors to create cross-ventilation for odour removal—introducing significant uncontrolled air exchange.

4.3 The "Too Energy Efficient" Paradox and Thermal Behaviour

4.3.1 Overheating from High Insulation

One resident described the building in terms that encapsulate a central challenge of high-performance construction:

> *"For winter, I think that building is too energy efficient. So sometimes I think I'm wasting kind of energy... Because I turn on the convective heating, but I feel very warm and then I need to open the window to ventilate."* (Resident 2)

This statement reveals a fundamental disconnect: the building's excellent insulation, designed to minimise heating demand, may create conditions where minimal heating input causes overheating. Residents then compensate by opening windows—negating the efficiency benefits. The perception of "wasting energy" is accurate, but the waste occurs through window opening rather than through the heating system itself.

4.3.2 Free-Riding on Neighbours' Heat

One resident explicitly recognised that his middle-floor, interior position allows him to benefit from neighbours' heating, further contributing to the perception of excessive efficiency:

> *"My room is kind of in the middle of other rooms... it's kind of sandwiched in the middle, so I think I can take some advantage from my neighbors. So even though I turn off my heating system, I feel not that cold."* (Resident 2)

This awareness is technically accurate—interior apartments with minimal exterior surface area have much lower heating requirements than corner or top-floor units. However, it also reveals a free-rider dynamic where some residents effectively receive heat subsidised by their neighbours, while the billing system may not fully account for these transfers.

4.3.3 Summer Overheating by Position

All residents reported summer overheating issues, with strong dependence on apartment position:

> *"The room I lived in facing South, that's very bad condition during summer. Very, very bad. I think not only me, many people, we don't want to stay in the room during summer, during daytime."* (Resident 2)

> *"Especially on the third floor, highest floor. It's very hot. Both the east and west facing very hot."* (Resident 3)
>
> *"On the ground floor it's OK. Not so warm."* (Resident 3)

North-facing ground floor apartments remain comfortable year-round (*"The North face, it's comfortable the whole year"* - Resident 3), while south- and west-facing top-floor apartments become unbearable during summer. The high insulation levels that reduce winter heating demand also trap solar gains in summer. Without active cooling and with limited solar shading, these apartments experience serious overheating during hot periods.

This finding is important for the grey-box modelling work: assumptions about closed windows and interior doors may not hold during sunny warm weather when residents keep doors and windows open to manage overheating.

4.4 Heating Control Difficulties

4.4.1 Binary Control and Rapid Response

Multiple residents described difficulty achieving comfortable temperatures through the thermostatic radiator valves (TRVs), perceiving them as operating in a binary rather than proportional manner:

> *"It's a little bit hard for me to precisely adjust the heating system... either too much or totally turn it off... there's kind of no middle setting."* (Resident 2)
>
> *"If I open it at 5, it's too much. Four is quite OK and even three I think is quite cozy, but 5 is too much."* (Resident 3)

This difficulty is compounded by the system's rapid response time. While one resident found the response acceptable (*"The reaction time is a little bit... it takes a little bit time to reach the comfort range, but I think it's good enough"*), another reported very fast heating: *"When I open the thermostatic valve I can feel like instant, like in 5 minutes the radiator gets hot very quick... the indoor temperature gets raised up in 30 minutes."*

The combination of perceived binary operation and fast response likely reflects the interaction between the highly insulated envelope and the heating system. In buildings with very low heat loss, even modest heating input can rapidly overshoot the desired temperature. Residents may respond by opening windows (losing heat) rather than finding an appropriate valve setting. These differing perceptions may also reflect variations in TRV commissioning quality across apartment blocks or individual comfort expectations.

4.4.2 TRV Removal and Modification

Perhaps most concerningly, one resident described removing the thermostatic valve head from his radiator and not replacing it:

> *"Most of people will kind of took out the thermostat and then you can see the valve inside and then many people start to kind of release some air... and then you can feel it's changed dramatically."* (Resident 2)

> *"For me and some of my friends who are living in Lundtoftevej, we do not put the valve back. Just keep it open. Otherwise we just turn it off."* (Resident 2)

This practice—which the resident believes is common among other technically educated residents—fundamentally degrades system performance. Without the thermostatic head, the radiator valve is either fully open or manually closed, eliminating the proportional control that enables temperature regulation. The resident's justification (*"it's changed dramatically"*) suggests the TRV may have been incorrectly commissioned or the valve may have been stuck, leading to a workaround that creates larger problems.

4.4.3 Night Setback Behaviour

All three residents practise night setback by reducing or turning off heating when leaving the apartment. One resident explicitly framed this as learned behaviour:

> *"In China I always leave it open, not closed. And this behaviour is... I've come to Denmark and there's some knowledge—I know you should have this type of behaviour to save energy."* (Resident 3)

Resident 3 described a detailed routine: *"When I'm back home, I open it four to five, and when I go to sleep, I close it to like two, and next day morning I leave the dorm, I fully close it. So it somehow aligns with a night setback strategy."*

While night setback is often promoted as energy-saving practice, its effectiveness is limited in highly insulated buildings. The thermal mass and low heat loss coefficient mean that temperature drop during absence is minimal, while the subsequent reheating creates demand peaks and temperature overshoot. This suggests that energy-saving behaviours transmitted through social norms in Denmark may not be optimal for these particular buildings.

4.5 Billing Feedback and Perceived Performance

4.5.1 Refunds as False Validation

All three residents reported receiving refunds on their utility bills, creating a perception of good energy behaviour:

> *"They paid back some amount to us... they calculate if you use less, just pay back to you."* (Resident 1)
>
> *"Every year I get like more than 2000 refund... I think it's OK because I use a lot of heat. I'm not good with the cold environment, so I always open like 4 to 5."* (Resident 3)
>
> *"Every year I got the money back. So I think it's fine."* (Resident 2)

The refund mechanism does not necessarily validate efficient operation. The initial monthly charges include a safety margin, and the threshold for refund may be set conservatively. Resident 3's statement is particularly revealing: they receive substantial refunds despite self-reporting high setpoints and considerable heat use. Meanwhile, Resident 2 receives refunds while having removed their TRV and frequently opening windows during heating.

This creates a perverse incentive structure: the billing system tells residents their behaviour is acceptable when quantitative analysis suggests otherwise.

4.6 Synthesis: The Expert Struggle Paradox

The most significant finding from WP2 is that residents with doctoral-level expertise in building energy, HVAC systems, and indoor climate still struggle to operate their heating and ventilation systems optimally. If experts cannot achieve optimal operation, the expectation that general occupants will do so is unrealistic.

This is not a user education problem that can be solved with better manuals or training. Rather, it reflects fundamental challenges in the system-user interface:

- **Invisible systems**: The mechanical ventilation provides no perceptible feedback to residents, leading them to doubt its effectiveness and supplement with window opening.
- **Counterintuitive dynamics**: In highly insulated buildings, behaviours that seem energy-saving (night setback) may provide minimal benefit, while seemingly wasteful behaviours (maintaining constant temperature) may be more efficient.
- **Misleading feedback**: The billing system provides annual aggregate feedback with significant time delay, preventing residents from understanding the consequences of specific behaviours.
- **Absent guidance**: Residents receive no real-time information about whether their current heating consumption is appropriate for conditions.

4.7 Implications for System Design

These findings provide strong justification for the automated feedback systems proposed in this project. The grey-box model developed under WP3 (Chapter 6) enables prediction of expected heating consumption for normal operation (i.e., closed windows) under given weather conditions. When actual consumption exceeds this baseline, the system can identify the likely cause (e.g., window opening during heating) and provide targeted feedback to residents.

Such a system would address the fundamental information asymmetry between the building's actual thermal dynamics and residents' mental models of how their systems work. Rather than relying on resident expertise—which even experts lack—the system would provide just-in-time guidance based on measured performance.

Chapter 5

Domestic Hot Water System Optimisation

The DHW system emerged as the most successful track of the project, yielding a validated digital shadow model and clear pathways to substantially reduce district heating return temperatures. This chapter documents the methodology, findings, and implementation challenges.

5.1 Background and Problem Statement

District heating networks are transitioning to lower operating temperatures to improve efficiency and enable integration of renewable heat sources. A key barrier to this transition is high return temperatures from building installations—particularly DHW systems with accumulative storage tanks, which often return water at temperatures far above what is achievable with optimal control.

High charging flow rates in DHW storage tanks can disrupt thermal stratification, subsequently raising return temperatures to the district heating network. Strong inlet momentum and high charging power promote internal mixing in stratified tanks, diminishing temperature layering and increasing the temperature of water returned to the network.

Initial monitoring of Building H revealed that the mean return temperature from the DHW system was approximately 45°C. Given that fourth-generation district heating targets lower return temperatures, and that Holte Fjernvarme has recently implemented penalty tariffs for high return temperatures, there was substantial potential for improvement.

5.2 Digital Shadow Development

The primary source for this section is Wildfeuer (2024), which refined and expanded the baseline work by Sol Vilaplana (2023).

5.2.1 Modelling Approach

The original control configuration in Building H used the following parameters in the Danfoss ECL 310:

Table 5.1: Original DHW system control parameters

Parameter	Original Value
Charging pump flow (P4)	0.50 kg/s (30 L/min)
Stop difference	-18 K
Post-run time	1 minute
Comfort temperature (R6)	53°C
Charging temperature (R9)	56°C

A cyber-physical model (digital shadow) of the DHW installation was developed using Dymola, a simulation environment based on the Modelica language. The term "digital shadow" is used rather than "digital twin" because the model operates unidirectionally—receiving data from the physical system but not yet controlling it. The model represents all major physical components:

- Two 350-litre storage tanks connected in series
- Plate heat exchanger (XB06H1-26) connecting to the district heating network
- Charging pump (P4) and circulation pump (P3)
- Motorised valve (M1) with PI controller
- All associated piping, sensors, and control logic

The control logic replicates the Danfoss ECL Comfort 310 controller's Application A377.1, including the tank temperature control, return temperature limitation, and charging start/stop logic based on temperature differences.

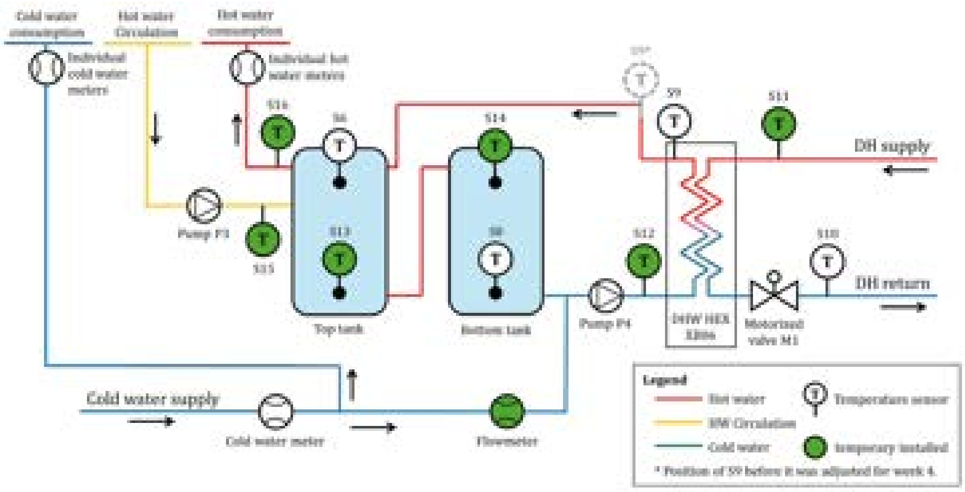


Figure 5.1: Schematic diagram of the DHW system showing the dual storage tanks, plate heat exchanger, and sensor locations. Source: Wildfeuer (2024).

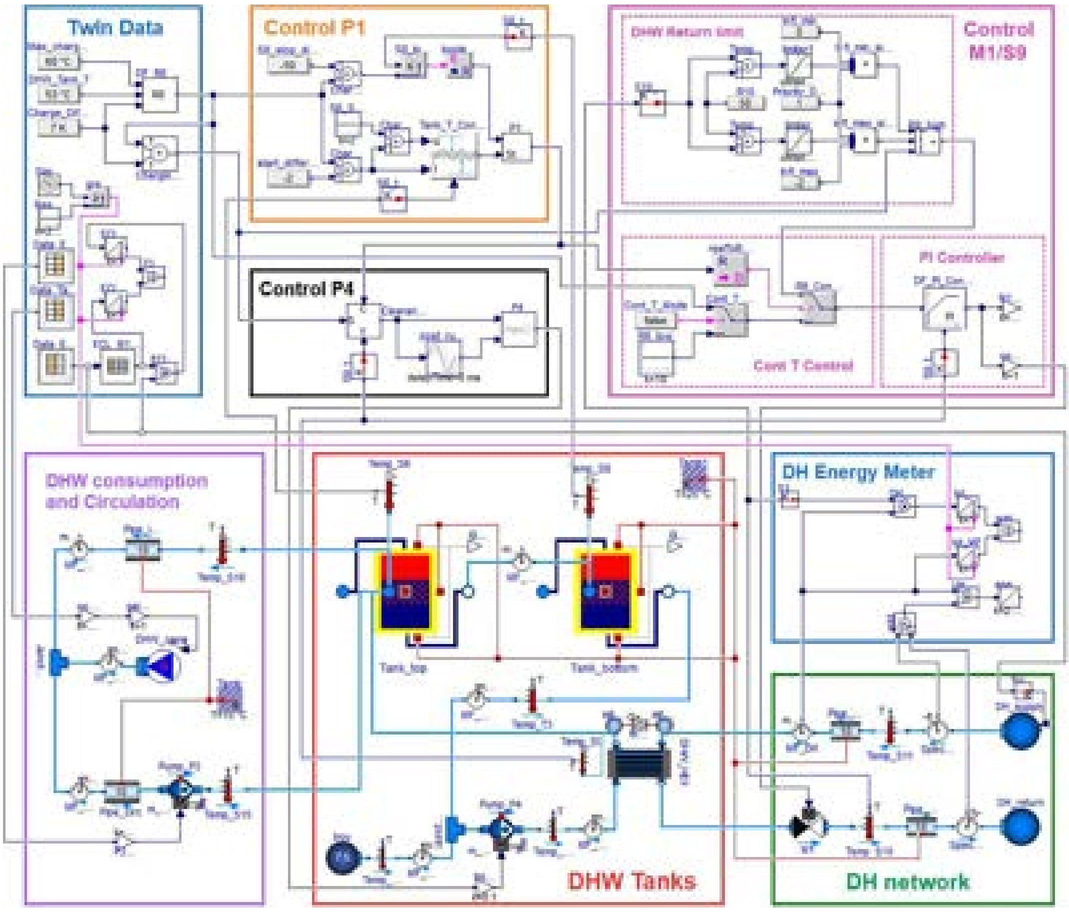


Figure 5.2: Dymola model structure showing the component representation of the DHW system. Source: Wildfeuer (2024).

5.2.2 Data Sources

The model was developed and validated using data from multiple sources:

- **Danfoss ECL platform**: Built-in sensors S6 (top tank temperature), S8 (bottom tank temperature), S9 (charging temperature), S10 (DH return temperature), and pump/valve status signals at 1-hour resolution
- **Neogrid platform**: Higher-resolution (1-minute) data for the same sensors
- **ECA 32 expansion module**: Six additional Pt1000 temperature sensors (S11–S16) connected to the ECL 310 controller, provided by Danfoss for dedicated measurement campaigns. As shown in Figure 5.1, these sensors were positioned at key locations including the district heating supply inlet (S11), heat exchanger secondary outlet (S12), tank interconnection points (S13, S14), circulation return (S15), and cold water inlet (S16), enabling detailed monitoring of system dynamics not captured by the standard sensor configuration.
- **Supplementary instrumentation**: Hobo temperature loggers and KATflow 200 ultrasonic flow meter installed during dedicated measurement campaigns

The initial model development used data from May 2023, capturing approximately 12 days of normal operation during the late heating season.

5.2.3 Iterative Development Strategy

The model evolved through an iterative, data-driven approach:

- **Basemodel DHW 0**: Focused on control logic verification against May 2023 data
- **Basemodel DHW 1**: Extended to full system representation, verified against February 2024 data (Week 4)
- **Optimisation models (DHW 2–6)**: Systematic investigation of improvement opportunities

Each iteration incorporated lessons from validation discrepancies and new measurement data.

5.3 Model Validation

The model was validated by comparing simulated outputs against measured sensor data across multiple variables.

5.3.1 Tank Temperatures

Simulated temperatures at sensors S6 (top of second tank) and S8 (bottom of first tank) closely matched measured values:

- **S6 mean temperature**: Simulated 51.4°C vs measured 51.7°C (difference: 0.3°C)
- **S8**: Good agreement in both charging and idle periods

The model correctly reproduced the two operational regimes: comfort mode (R6 = 53°C) and saving mode (R6 = 50°C, active 00:00–04:30).

5.3.2 Return Temperature

The district heating return temperature (S10) is the key performance indicator for district heating integration. Validation showed good agreement in patterns, with both simulation and measurement showing characteristic peaks during charging cycles and lower temperatures during idle periods.

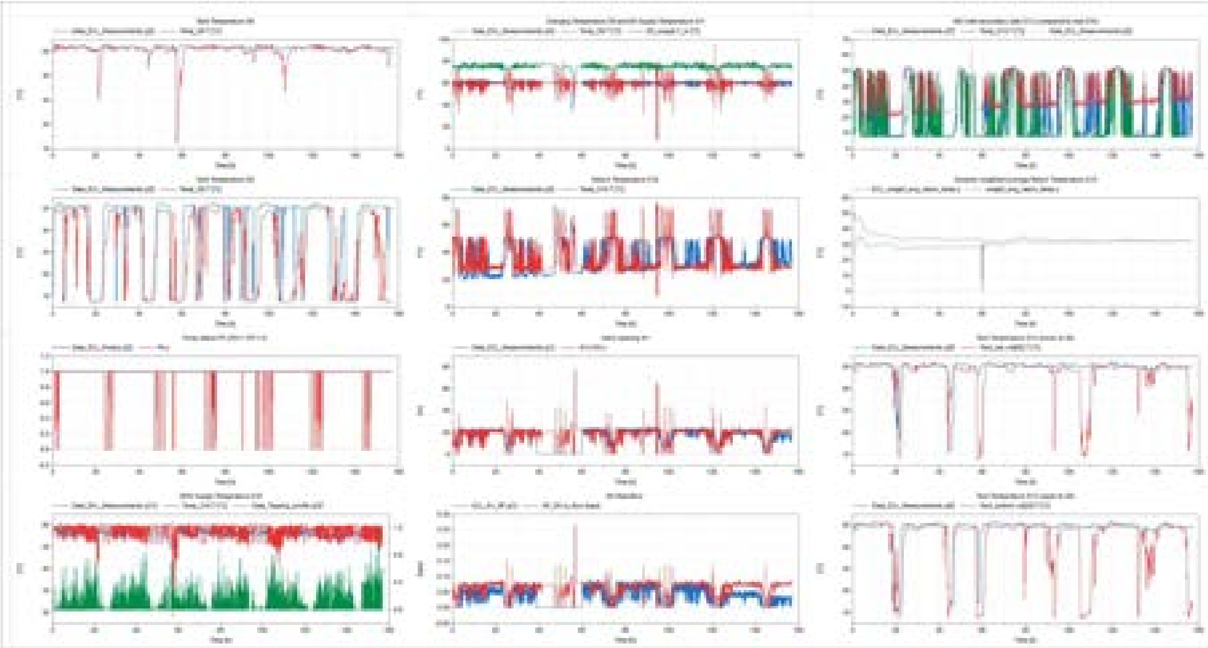


Figure 5.3: Validation of simulated return temperature against measured data, showing characteristic charging cycle patterns. Source: Wildfeuer (2024).

5.4 Optimisation Results

The validated model was used to systematically investigate control parameter changes that could reduce return temperatures while maintaining adequate hot water supply.

5.4.1 Charging Flow Reduction

The most impactful improvement was reducing the charging pump flow. Reducing charging power helps maintain stratification in storage tanks and keeps DH return temperatures low. Simulations across ten flow rates (0.05–0.50 kg/s) revealed:

Table 5.2: Effect of charging flow rate on return temperature

Charging Flow	Mean Return Temp (S10)	Reduction
0.50 kg/s (baseline)	44.14°C	—
0.30 kg/s	38.2°C	5.9°C
0.10 kg/s	26.8°C	17.3°C
0.05 kg/s	29.56°C	14.6°C

Lower charging flows allow the heat exchanger to operate more efficiently, achieving better temperature exchange between the primary and secondary sides. However, flows below 0.10 kg/s may be insufficient during peak demand periods, making 0.10 kg/s (6 L/min) the recommended value.

5.4.2 Stop Difference Parameter

The stop difference parameter determines when charging stops based on the temperature at the bottom of the first tank (S8). Increasing the magnitude of this parameter (from -18 K to -39 K) allows charging to continue while colder water reaches S8, achieving better stratification.

With the baseline flow of 0.50 kg/s, this change alone reduced return temperature from 44.14°C to 43.8°C—a negligible improvement because the high flow rate prevents good stratification regardless of stop condition.

The value of -39 K was selected to ensure charging stops when S8 reaches approximately 11°C (the cold water inlet temperature) during saving mode.

5.4.3 Post-Run Time Elimination

The post-run time parameter keeps the charging pump running briefly after the valve closes, intended to extract residual heat from the heat exchanger. However, analysis revealed this causes problematic behaviour: with the valve closed, the pump circulates water that rapidly cools, causing temperature drops at S6 that trigger unnecessary new charging cycles.

Eliminating the post-run time (setting to 0 minutes) removed temperature peaks in the return temperature and reduced the weighted mean from 44.14°C to 35.25°C.

5.4.4 Combined Optimisation

Applying all three improvements simultaneously achieved dramatic results:

Table 5.3: Summary of optimised DHW control parameters

Configuration	Mean Weighted Return Temp (S10)
Baseline	44.14°C
Optimised	24.90°C
Reduction	**19.24°C**

The optimised parameters are:

- **Charging flow**: 0.10 kg/s (6 L/min)
- **Stop difference**: -39 K
- **Post-run time**: 0 minutes

These changes are straightforward to implement through the ECL controller interface and require no hardware modifications.

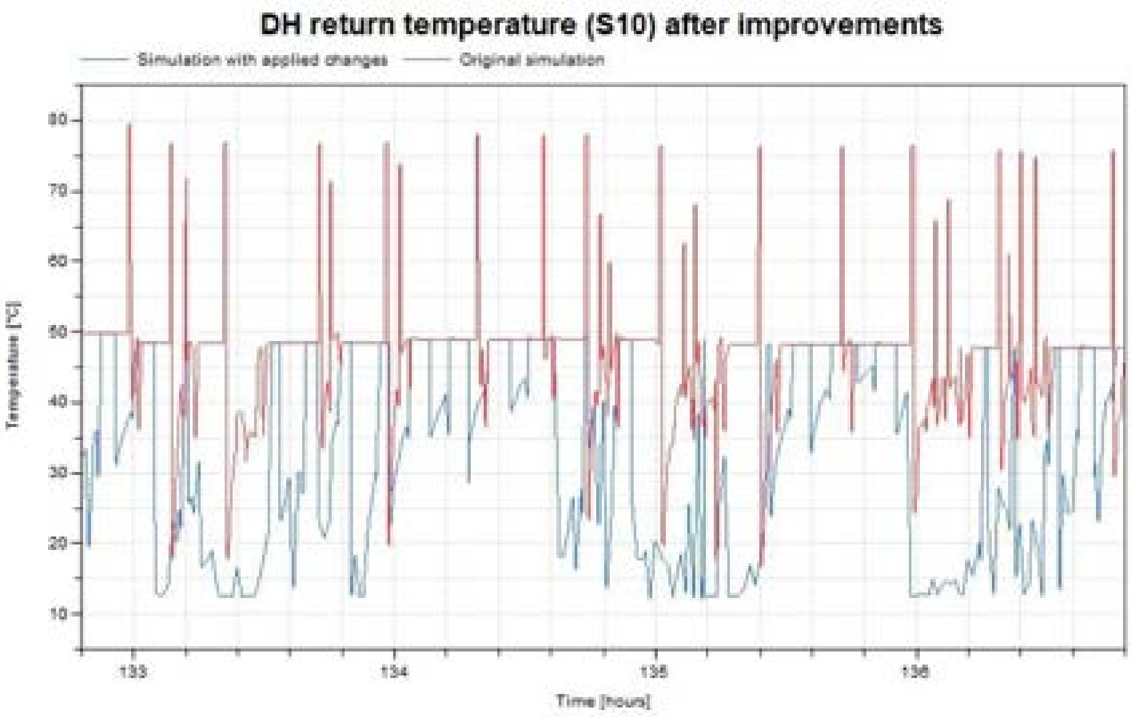


Figure 5.4: Comparison of return temperature profiles between baseline and optimised configurations, demonstrating the approximately 20°C reduction achievable. Source: Sol Vilaplana (2023).

5.5 Implementation Challenges: Heat Exchanger Fouling

5.5.1 Discovery of Fouling

When control parameter changes were implemented in the real system in late 2023, an unexpected problem emerged. The reduced charging flow, while beneficial for return temperatures, reduced the flow velocity through the heat exchanger. Combined with the high district heating supply temperatures (>70°C) in the Lyngby network, this created conditions favourable for mineral fouling (calcite formation) (Bansal and Müller-Steinhagen 1993).

The fouling progressively degraded heat exchanger performance. Symptoms included:

- Rising return temperatures (above 60°C) despite optimised control settings
- Charging temperatures (S9) failing to reach setpoint
- Dangerously low tank temperatures (below 50°C at S6), creating *Legionella* risk

5.5.2 Health Risk Context

The low flow temperatures present a significant health concern that would be imperceptible to residents. *Legionella* bacteria can proliferate in water systems at temperatures below 50°C (Yang et al. 2016). Critically, residents typically require only about 40°C for showering and 45°C at the tap—temperatures that could still be achieved even with a compromised system. Thus, a fouled heat exchanger could create dangerous conditions in the storage tanks while residents remain unaware of any problem.

5.5.3 Root Cause Analysis

Research on crystallisation fouling identified three coinciding conditions that promote scale formation in heat exchangers (Bansal and Müller-Steinhagen 1993):

1. High heat flux between primary and secondary sides
2. Surface temperatures above the saturation temperature for dissolved minerals
3. Hard water with high mineral content

The Lyngby area has relatively hard water, and the high DH supply temperatures create surface temperatures well above the calcite saturation point. Descaling treatment was attempted but had only a minor temporary effect—the fouling was too severe and had progressed beyond what chemical treatment could repair.

5.5.4 Implementation Barrier

The fouling issue creates a fundamental barrier to implementing the optimised controls without infrastructure upgrades. Sustainable implementation requires either:

- **Mixing shunt installation**: Limiting supply temperature to DHW heat exchangers (<63°C) to prevent mineral fouling. This is the lower-cost option.
- **Water softening system**: Ion exchange treatment to remove calcium and magnesium from incoming water. Higher cost but provides comprehensive protection for the entire DHW system including pipes and fixtures.

Until these upgrades are completed, field demonstration of the optimised controls—and the associated journal publication—must be deferred.

5.6 Summary

The DHW optimisation work demonstrated that optimal control parameters can reduce district heating return temperatures from approximately 45°C to below 25°C—a reduction of approximately 20°C. The key changes require no capital investment, only modification of ECL controller settings:

- Reducing charging pump flow from 0.50 kg/s to 0.10 kg/s
- Increasing stop difference parameter from -18 K to -39 K
- Eliminating post-run time (0 minutes instead of 1 minute)

However, implementation revealed an important caveat: reduced flow rates can accelerate heat exchanger fouling in hard water areas with high district heating supply temperatures. Sustainable implementation requires infrastructure upgrades (mixing shunt or water treatment) before the optimised control configuration can be safely deployed.

Chapter 6

Space Heating Analysis and Grey-box Modelling (WP3/WP4)

This chapter documents the development and validation of a thermal grey-box model for analysing space heating performance in the studio apartments. The work progressed through two phases: an initial analysis of building-level heating consumption patterns, followed by the development of an apartment-level predictive model. The primary source for this section is Gligić (2025), building on the exploratory analysis in Gligić (2024).

6.1 Building-Level Consumption Analysis

Prior to developing the detailed grey-box model, an exploratory analysis was conducted to characterise heat consumption patterns across all eight buildings at Lundtoftevej 162 (Gligić 2024). This analysis used data from the 2022–23 heating season (October 2022 – April 2023), with consumption categorised into three types: heat supplied via air handling units (which serves both common areas and individual apartments through the supply air), radiator-based heating in communal spaces, and heating supplied directly to individual dwelling units.

The analysis revealed widespread inefficiencies:

- Building A exhibited disproportionately high AHU-delivered heating consumption. The data showed persistent overconsumption across all months of the heating season, suggesting systematic issues with AHU control settings, such as an abnormally high supply air temperature setpoint or insufficient exhaust airflow, rather than isolated incidents.
- Buildings F and D showed excessive heating in individual apartments. This persistent overconsumption may indicate insufficient supply airflow or excessive exhaust airflow, as it seems unlikely that such a systematic overconsumption could derive from occupant habits unique to this building.

These findings identified AHU configuration settings and unbalanced airflows as potentially significant sources of energy waste—relatively straightforward issues to address through AHU supply temperature adjustments and improved commissioning.

6.2 Grey-box Model Development

6.2.1 Thermal Characteristics of Modular Studios

The studio apartments at Lundtoftevej 162 have characteristics that make ventilation the dominant heat loss mechanism:

- Near-zero energy design with very low transmission losses through the building envelope
- Limited facade area (each apartment is long and narrow with minimal external wall exposure)
- High insulation levels (approximately 10 cm of mineral insulation between apartments minimising inter-unit heat transfer)
- Proportionally high ventilation (despite small floor areas, mechanical ventilation must provide adequate airflow for occupants)

6.2.2 Model Structure

The grey-box model treats each apartment as a single thermal zone and calculates the theoretical heating demand by solving the steady-state heat balance equation:

$$Q_{\text{heat}} = Q_{\text{trans}} + Q_{\text{vent}} - Q_{\text{solar}} - Q_{\text{met}} - Q_{\text{elec}} \tag{6.1}$$

where:

- Q_{heat} = heating demand [W]
- Q_{trans} = transmission losses through facade [W]
- Q_{vent} = ventilation losses [W]
- Q_{solar} = solar heat gains through windows [W]
- Q_{met} = metabolic heat gains from occupants [W]
- Q_{elec} = internal gains from electrical appliances [W]

Each component is quantified on a daily basis using measured data and empirically calibrated parameters.

6.3 Ventilation Rate Determination

A key innovation of this work is the empirical determination of apartment-specific air change rates (ACH) using CO_2 decay analysis. This method uses internally generated CO_2 as a natural tracer gas, eliminating the need for artificial tracer injection (Few and Elwell 2021).

6.3.1 CO_2 Decay Method

The procedure identifies periods when:

- CO_2 concentrations are decreasing exponentially
- Windows are confirmed closed (via window contact sensors)
- Occupancy has recently ceased (indicated by falling CO_2)

An exponential decay model is then fitted to these periods to extract the ACH:

$$C(t) = C_{\text{outdoor}} + (C_0 - C_{\text{outdoor}}) \cdot e^{-\text{ACH} \cdot t} \tag{6.2}$$

where $C(t)$ is the CO_2 concentration at time t, C_0 is the initial concentration, and C_{outdoor} is the ambient outdoor concentration (typically 400–420 ppm).

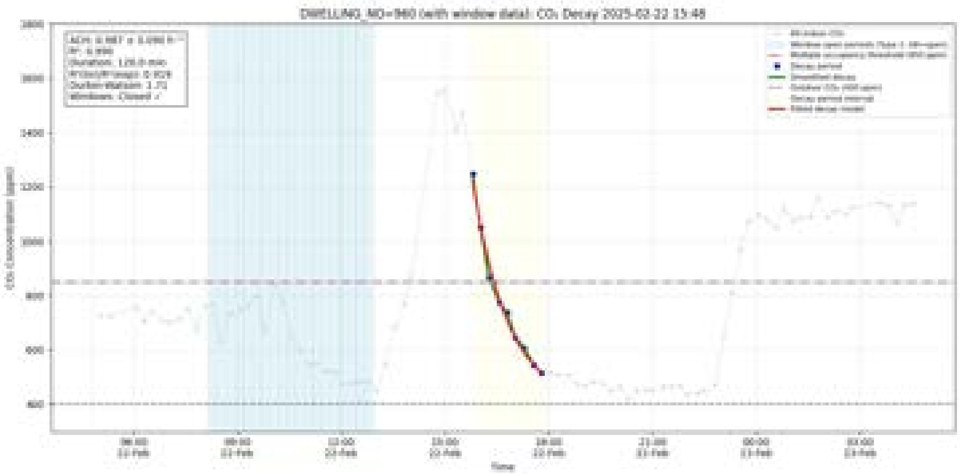


Figure 6.1: Example of CO_2 decay analysis showing the exponential decay after occupancy cessation, used to determine the apartment air change rate. Source: Gligić (2025).

The determined ACH values for the analysed apartments ranged from 0.9 to 1.2 h^{-1} (median values), consistent with design expectations for modern mechanically ventilated buildings. It should be noted that mechanical ventilation rates were not measured directly, so the CO_2 decay analysis captures total ventilation comprising both mechanical and natural ventilation airflows.

6.4 Internal Heat Gains

6.4.1 Metabolic Heat Gains

Rather than using fixed occupancy schedules, the model estimates dynamic metabolic heat gains using a CO_2 mass balance approach. The CO_2 generation rate is calculated from measured concentration changes, and this is converted to metabolic heat assuming standard relationships between CO_2 emission and metabolic rate.

This approach captures the actual variability in heat gains associated with occupancy patterns between apartments—variability that would be missed by assumed schedules.

6.4.2 Electrical Appliance Gains

Internal heat gain from appliances is assumed equal to metered electricity consumption, as all electrical energy eventually becomes heat. This is a reasonable approximation, though it neglects portable battery storage in devices such as laptops and mobile phones.

6.5 Heat Balance Calibration

Initial implementation of the heat balance model revealed a systematic imbalance: calculated heat gains consistently exceeded calculated losses. This indicated either an underestimation of losses or overestimation of gains.

The discrepancy was addressed by introducing an infiltration factor representing additional uncontrolled air exchange beyond the mechanical ventilation component captured by CO_2 decay. Since the building is fairly airtight, this additional air exchange is attributed to mechanically induced infiltration driven by supply/exhaust imbalance in the AHU system.

The calibrated infiltration factor of 40% brought the model into balance, implying that roughly 40% more air is exhausted mechanically than is supplied mechanically in Building H. As a result:

- Approximately 60% of total ventilation enters through the mechanical supply air valves
- The remaining 40% enters through the building envelope as mechanically induced infiltration, driven by the negative pressure created by the exhaust-dominated system

This finding is consistent with the AHU control panel observations presented in Section 6.7, which confirmed significant flow mismatches across multiple buildings.

6.6 Model Validation and Fault Detection

The calibrated model was applied to predict daily heating consumption for each apartment. Comparing predictions against actual metered consumption reveals operational anomalies.

6.6.1 Window-Opening Correlation

Strong correlation was observed between window-opening events (detected via window contact sensors) and excess heating consumption above model predictions. On days when windows were open while heating was active, actual consumption exceeded predictions by significant margins.

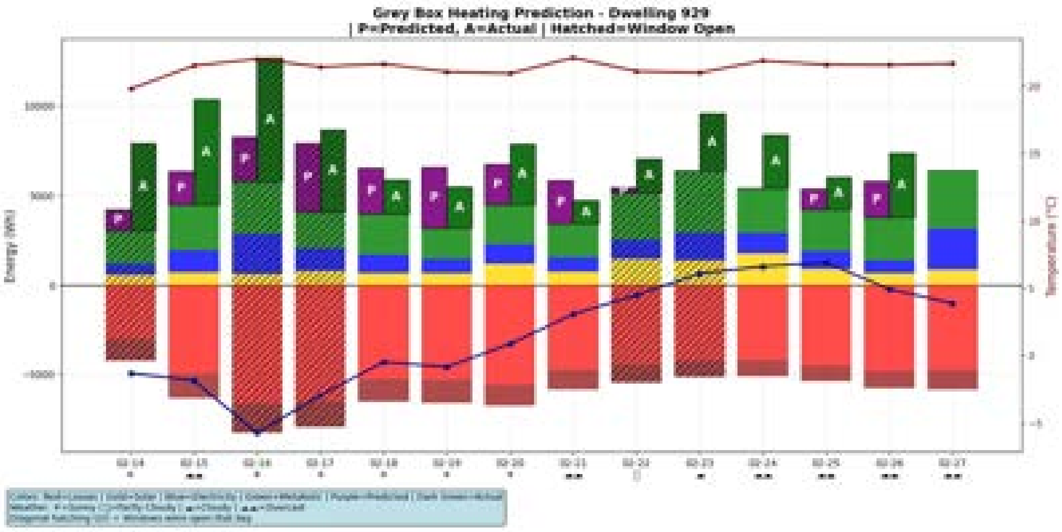
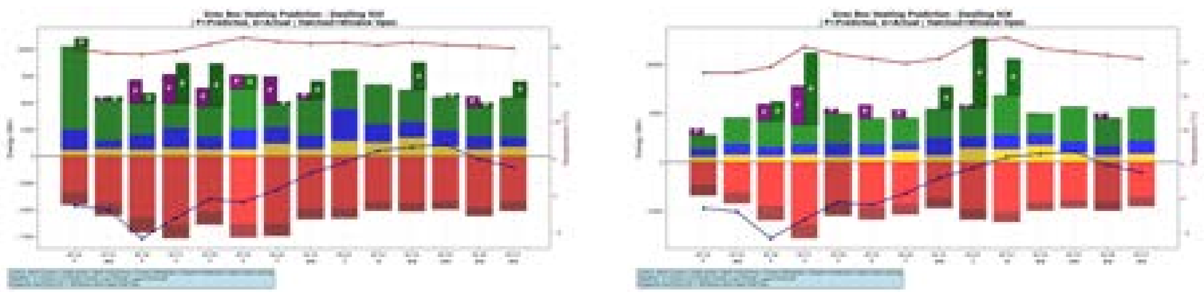


Figure 6.2: Grey-box model validation showing predicted vs. actual heating consumption. The stacked bars represent the heat balance components: red indicates transmission and ventilation losses, while gold (solar gains), blue (electrical appliance gains), and green (metabolic gains) show the offsetting internal and solar heat gains. The purple bar shows the model's predicted heating demand, and the dark green bar shows actual metered consumption. Weather conditions are indicated by symbols: (sunny), (partly cloudy), (cloudy), and (overcast). Diagonal hatching (///) indicates days when windows were open. Source: Gligić (2025).

6.6.2 Unnecessary Heating Detection

In some dwellings, the model predicted zero heating demand on certain days (passive gains being sufficient), yet residents still operated heating—representing fundamentally unnecessary consumption.



(a) Dwelling with good agreement between predicted and actual consumption

(b) Dwelling showing excess consumption correlated with window opening

Figure 6.3: Comparison of grey-box model predictions across different apartments, illustrating how the model identifies both well-operated and problematic dwellings. Source: Gligić (2025).

The grey-box model successfully captures the general trend of heating consumption and, more importantly, effectively highlights deviations that signify specific suboptimal operational conditions. Sensitivity analysis confirmed that the model is robust to ±10% variation in the key ACH parameter.

6.7 Common Area Analysis

Analysis of the rooftop air handling units revealed likely poor commissioning, with indications of supply/exhaust airflow imbalance. Control panel data from Buildings B, C, F, G, and H confirmed significant flow mismatches.

Most notably, Building G was found to be operating with a 76% flow imbalance—exhausting nearly double the air volume it supplies—creating substantial negative pressure that forces cold air infiltration through the building envelope.

Figure 6.4: AHU control panels showing supply and exhaust flow rates in Buildings G (left) and H (right). The imbalance between these values drives infiltration through the building envelope.

Based on the analysis, the following interventions are recommended:

- **Airflow rebalancing**: Addressing the supply/exhaust imbalance improves energy efficiency by maximising heat recovery while minimising infiltration/exfiltration.
- **Ventilation supply temperature adjustment**: Fine-tuning supply air temperatures for common area AHUs offers immediate energy savings with minimal capital investment by reducing the oversupply of airborne heating.

6.8 Supply Temperature Limitation Consideration

An alternative approach to addressing heating inefficiency—constraining the space heating supply temperature to limit heat output to normal operation needs—was considered during this project. Limiting the heating system supply temperature could:

- Mitigate window opening impact (residents would receive immediate feedback in the form of cooled indoor temperatures when windows are open)
- Mitigate the impacts of TRV removal (by operating close to the maximum valve opening position during normal operation)
- Discourage night setback (by slowing or limiting the reheating process)

- Encourage continuous heating (preventing demand peaks from reheating)

However, the radiator/floor heating combination present in these apartments makes supply temperature limitation difficult to implement effectively. Radiators require higher supply temperatures than floor heating due to their smaller heat transfer surface area. If supply temperatures were reduced to levels acceptable for floor heating (approximately 35°C), the radiators in the main living space would be unable to meet design heat loads during cold periods. Conversely, maintaining temperatures adequate for radiators would provide excess capacity to the bathroom floor heating.

Limiting supply temperatures for the radiator system may simply shift the heating load to the bathroom floor heating, as residents may leave bathroom doors open to compensate for reduced radiator output. For these reasons, this approach was not recommended, and the project instead encourages an automated feedback systems over supply temperature limitation.

6.9 Summary

The grey-box modelling work developed a methodology for predicting expected heating consumption in highly insulated studio apartments. There were several findings from the small sample size in Building H:

- Ventilation is the dominant heat loss mechanism, with empirically determined air change rates of 0.9–1.2 h^{-1}
- A 40% flow imbalance (exhaust > supply) is likely driving significant mechanically induced infiltration
- The model can effectively identify excess consumption correlated with window opening

The methodology could provide the foundation for an automated feedback system that can alert residents when their consumption deviates from expected normal operation.

Chapter 7

Key Findings and Recommendations

This chapter synthesises the technical findings from the preceding chapters and provides actionable recommendations for Boligfonden DTU.

7.1 Summary of Technical Findings

7.1.1 DHW System: 20°C Return Temperature Reduction Achievable

The digital shadow model demonstrated that optimal control parameters—specifically, reduced charging flow (0.10 kg/s), increased stop difference (-39 K), and eliminated post-run time—can reduce district heating return temperatures from approximately 45°C to below 25°C. This represents a substantial improvement in district heating efficiency and positions the building favourably for return temperature penalty tariffs.

However, implementation revealed an important caveat: reduced flow rates can accelerate heat exchanger fouling in hard water areas with high district heating supply temperatures. The fouling created a health risk by allowing tank temperatures to fall below 50°C, enabling potential *Legionella* growth—a risk that would be imperceptible to residents who only require 40–45°C at the tap. Descaling treatment had only a minor temporary effect, as the fouling was too severe and irreparable. Sustainable implementation requires infrastructure upgrades (mixing shunt or water treatment).

7.1.2 Space Heating: Ventilation Dominates Heat Loss

The grey-box modelling indicated that ventilation is the dominant heat loss mechanism in these highly insulated apartments. The empirically determined air change rates (0.9–1.2 h^{-1}) are consistent with design values, but the calibration of the heat balance required incorporating an infiltration factor of approximately 40%—indicating that uncontrolled air exchange contributes significantly to total heat loss even in modern, well-sealed buildings.

7.1.3 Occupant Behaviour: A Critical Variable

The qualitative interviews and quantitative grey-box analysis converge on a central finding: occupant behaviour is a key driver of energy inefficiency. Specific findings include:

- **Window opening during heating**: Strong correlation between excess heating consumption and window-opening events. Residents open windows for "fresh air" despite mechanical ventilation with heat recovery.
- **Night setback practice**: All interviewed residents practice night setback, a behaviour learned after arriving in Denmark. In highly insulated buildings, the energy benefit is marginal while demand peaks and temperature overshoot are introduced.
- **Control difficulty**: Residents describe heating as "binary"—either insufficient or excessive—leading to compensating behaviours (opening windows to cool overheated spaces). This is consistent with research showing that occupants frequently use TRVs in a binary manner rather than proportional control (Bruce-Konuah et al. 2018).
- **False validation from billing**: Residents who receive utility refunds interpret this as confirmation of good behaviour, even when their described practices (high setpoints, removed valves, open windows) suggest otherwise.

7.1.4 The Expert Struggle Paradox

Perhaps the most significant qualitative finding is that residents with doctoral-level expertise in building energy systems still cannot operate their heating optimally. This strongly suggests that intuitive operation is not achievable with current system designs, and automated feedback mechanisms are necessary.

7.2 Recommendations for Boligfonden DTU

7.2.1 Immediate Actions (Low Cost, High Impact)

Common Ventilation:

- Review and adjust supply air temperatures for rooftop AHUs serving all buildings
- Address supply/exhaust airflow imbalance identified in the analysis (particularly Building G at 76% imbalance)
- Prioritise buildings based on consumption data

DHW System Monitoring:

- Continue monitoring return temperatures via ECL platform
- Establish baseline metrics for heat exchanger performance to indicate fouling

7.2.2 Infrastructure Upgrades (Capital Investment Required)

The optimal DHW control configuration cannot be safely deployed until the following upgrades are completed:

- **Mixing shunt installation**: Limit supply temperature to DHW heat exchangers ($<$63°C) to prevent mineral fouling. This is the lower-cost option.

- **Alternative—Water softening system**: Ion exchange treatment to remove calcium and magnesium from incoming water. Higher cost but provides comprehensive protection for the entire DHW system including pipes and fixtures.

7.2.3 Resident Communication

Information Campaign:

Develop resident communication addressing common misconceptions:

- Mechanical ventilation provides adequate fresh air; window opening is not necessary and wastes heat
- Night setback provides minimal benefit in highly insulated buildings
- Thermostatic valves regulate temperature, not heating intensity—extreme settings cause overshoot
- Temperature regulation requires functional thermostatic valves; removing or disabling them degrades performance

Billing Transparency:

Consider providing more detailed billing information that shows actual consumption relative to expected consumption for the apartment type and weather conditions, rather than only showing aggregate cost. This would help residents understand whether their behaviour is truly efficient.

7.2.4 Future Monitoring and Feedback

The grey-box model developed in this project provides the foundation for an automated feedback system. Recommended implementation:

1. Deploy the predictive model to establish an upper limit for expected heating for each apartment
2. Provide residents with actionable feedback such as: "Your heating consumption yesterday was 40% above expected. If your window was open while heating, please be aware that this wasted substantial energy."

This addresses the information asymmetry that prevents residents from understanding the consequences of their behaviour.

7.3 Broader Implications

The findings from this project have implications beyond Lundtoftevej 162:

- **Modular construction**: The methodologies developed are transferable to the growing stock of modular residential buildings in Denmark, which share similar thermal characteristics.

- **DHW optimisation**: The digital shadow approach and identified control parameters can be applied to similar Danfoss ECL-controlled installations throughout the district heating network.
- **User interface design**: The Expert Struggle Paradox suggests that building systems should be designed for automated optimisation rather than relying on occupant expertise.
- **Data infrastructure**: The challenges documented with the heat cost allocation provider highlight the need for robust data quality assurance in research-dependent monitoring projects.

Chapter 8

Conclusions and Path Forward

8.1 Assessment Against Original Objectives

This project was funded to achieve five objectives. The following assesses progress against each:

8.1.1 Objective 1: Qualitatively analyse occupant experiences and behaviours

Status: Achieved.

Semi-structured interviews with three residents with technical backgrounds revealed important behavioural patterns: window opening despite MVHR provision, night setback of uncertain benefit, TRV modification, and misinterpretation of billing signals. The key finding—that even experts cannot operate these systems optimally (the "Expert Struggle Paradox")—has significant policy implications for building design and resident communication strategies.

8.1.2 Objective 2: Characterise all heat flows using thermal models

Status: Achieved.

The grey-box model successfully characterises heat flows at the apartment level, quantifying facade transmission losses, ventilation losses (with empirical ACH determination using CO_2 decay analysis), solar gains, metabolic heat, and electrical gains. The DHW digital shadow model provides detailed characterisation of the domestic hot water heat flows. Both models demonstrate predictive capability.

8.1.3 Objective 3: Detect and diagnose faults and poor operation

Status: Achieved.

Multiple faults were detected:

- AHU supply/exhaust imbalance in multiple buildings (particularly severe in Building G with 76% imbalance)
- DHW heat exchanger fouling due to high supply temperatures and reduced flow rates
- Window-opening during active heating identified via grey-box model deviations

Note: The identification of undersized heating valves was Boligfonden DTU's own work, conducted during their warranty investigation, and is not claimed as a project outcome.

8.1.4 Objective 4: Optimise regulation of space heating systems

Status: Partially achieved.

The DHW system optimisation achieved dramatic results (20°C return temperature reduction) but implementation was blocked by heat exchanger fouling. Space heating optimisation recommendations have been formulated (AHU temperature adjustment, airflow rebalancing, resident feedback system) but implementation awaits infrastructure corrections and resolution of the data provider issues.

8.1.5 Objective 5: Document technical requirements for low-temperature operation

Status: Achieved for DHW; partially achieved for space heating.

DHW requirements are fully documented: optimal control parameters, infrastructure prerequisites (mixing shunt), and expected performance improvements. For space heating, the project did not directly calculate supply temperature requirements for normal demand. Two obstacles prevented this:

1. Insufficient apartments with valid data to characterise normal consumption patterns
2. Floor heating having lower temperature requirements but being limited by mutual supply to radiators

The grey-box methodology is documented and transferable, but direct supply temperature guidance awaits additional validated data.

8.2 Dissemination

The project has produced the following outputs:

Student Theses:

- Jelstad (2023): IDA-ICE parametric simulation framework
- Sol Vilaplana (2023): Initial DHW digital shadow development
- Wildfeuer (2024): DHW model refinement and validation (primary DHW source)
- Gligić (2024): Building-level consumption analysis (Special course)
- Gligić (2025): Grey-box thermal model with CO_2 decay ventilation estimation

Technical Reports: This final report and supporting technical documentation provided to Boligfonden DTU.

Planned Publications: Two journal papers are planned once infrastructure improvements enable field validation:

1. DHW optimisation methodology and validated field results
2. Grey-box space heating model with fault detection and CO_2-based ventilation estimation

8.3 Path Forward

Completing the remaining work requires:

- **DHW infrastructure**: Installation of mixing shunt or water treatment system by Boligfonden DTU, followed by implementation of optimised control parameters and validation of return temperature improvements.
- **Data infrastructure resolution**: Either repair of the existing heat cost allocation provider system or transition to an alternative data provider, to enable full-scale application of the grey-box methodology.

The work positions Lundtoftevej 162 as a test bed for ongoing heating optimisation research at DTU. The methodologies developed are transferable to the growing stock of modular residential buildings in Denmark and provide practical tools for achieving the low-temperature operation necessary for sustainable district heating.

8.4 Acknowledgements

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Finally, the three resident interviewees generously shared their experiences and insights, providing qualitative depth that complements the quantitative analysis.

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