Digital Buildings
Facility Management and Fault Detection
Module 2 - Report

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June 09, 2025

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Facility Management Reflection

1.1 Introduction

Facilities management (FM) is no longer limited to fixing broken systems or responding to maintenance requests. Over the past decades, it has transformed into a broader discipline that supports the entire life of a building. This includes not just operations, but also early involvement in design, construction, and planning. Rather than focusing only on short-term tasks, FM now takes a long view, concerned with how a building performs, ages, and adapts to user needs over time. In this sense, FM connects multiple domains, such as engineering and digital technologies, to ensure that buildings remain functional, efficient, and responsive. This shift reflects a deeper understanding of the built environment as a dynamic system rather than a static product.

The growing complexity of building systems has brought facility management closer to building science, particularly in how buildings perform in real conditions. For example, thermal comfort—often misunderstood as simply maintaining room temperature involves managing humidity, airflow, and occupant behavior, all of which fall under the scope of FM. Similarly, monitoring indoor air quality has become essential not only for health and safety, but also for improving energy efficiency. These concerns show how FM today is more than just operational oversight; it is a science-informed, user-centered practice that relies on data and environmental understanding.

1.2 Understanding Facility Management

While the previous section outlines how facility management has evolved into a strategic, interdisciplinary field, a deeper understanding requires looking at how FM operates as both a technical system and a decision-making framework.

Facility management brings together diverse domains—maintenance, energy performance, asset management, space use, and occupant comfort—but its true complexity lies in how these domains interact over time. A building is not just a collection of systems to be maintained, but a dynamic environment shaped by human use, environmental forces, and technical constraints. For example, when a facility manager adjusts HVAC schedules based on occupancy data, they are not simply managing air flow—they are negotiating between comfort, energy cost, and system lifespan. These trade-offs reflect FM's central role in balancing competing demands through continuous observation and adaptation.

Understanding FM also involves recognising its potential as a feedback mechanism within the building lifecycle. Data collected during operations, such as energy consumption trends, maintenance history, or user complaints, can provide valuable input for future design decisions. However, this feedback loop is rarely automatic. In practice, gaps between designers, operators, and occupants often prevent knowledge from circulating effectively. Recognising this limitation is part of understanding FM not just as a set of tools, but as an organisational and communicative process.

From a building science perspective, FM offers a platform where theoretical models—thermal comfort standards, energy simulations, airflow predictions—are tested against real-world behaviour. It is in this space that science meets uncertainty. Buildings do not always behave as predicted, and systems degrade or are used in unexpected ways. The facility manager is often the one who must translate models into action, judgment, and sometimes compromise.

In short, to understand FM is to see it not only as what it manages, but as how it manages: a balancing act between data and judgment, between user needs and system logic, between ideal conditions and lived realities.

1.3 Applicability of Engineering Profile to Facility Management

In this section, the authors explore five key aspects of facility management that correspond with their engineering background. Supported by relevant research articles, each aspect will be briefly highlighted and discussed in terms of its fundamentals throughout the building life cycle, practical and technological usage, and career prospects that the authors believe would satisfy prior engineering experience and completed university courses. The identified core competencies in facility management are based on the standards set by the International Facility Management Association [1].

1.3.1 Project Management

To begin with, Project Management (PM) is one of the core competencies that is essential throughout the entire building life cycle, including concept, design, construction, commissioning, and renovation. In complex structures such as laboratories, airports, and hotels, PM ensures cost control, adherence to schedules, and quality management. For museums or schools, it also ensures that learning and preservation space is designed with long-term flexibility and sustainability is implemented. Additionally, PM in FM contributes to various technological aspects, such as real-time tracking of personnel, materials, and equipment, which enhances security, safety, quality control, logistics, and productivity monitoring [2]. These are areas where engineering students like ourselves can utilize the knowledge obtained from the university courses in the Construction Management study line. Furthermore, this core competence opens up to various roles such as facility project manager, construction project manager, and project coordinator.

1.3.2 Information and Technology Management

Secondly, Information and Technology Management (ITM), which involves assessing technology needs, implementing systems, and maintaining and upgrading technology systems, protection, and cybersecurity, is another competence that the authors would like to highlight. Effective communication and robust information-sharing are vital for attaining the strategic goals of facilities management (FM). BIM-IoT integration is seen as a significant factor for innovation and improving FM processes, supporting dynamic asset management applications, but there are also other technologies that can be included in BIM, namely, Augmented Reality (AR), Radio-frequency Identification (RFID), and Geographic Information System (GIS) [2]. These areas offer engineering students like ourselves a valuable opportunity to apply university knowledge in construction digitalisation. Additionally, suitable roles for this specific specialisaiton include Smart Building Engineer, BIM Manager, Digital Facility Coordinator, and Building Systems Integration Specialist.

1.3.3 Risk Management

Thirdly, the other one of the five selected core competencies, Risk Management (RM), is to ensure building operations' health, safety, and continuity throughout their life cycle. Whether in airports dealing with security, laboratories handling hazardous materials, or schools needing emergency preparedness, comprehensive risk strategies reduce vulnerabilities and support long-term resilience. The practical tasks for engineers are to assess structural, environmental, and operational risks using various cutting-edge methods such as simulations, sensitivity analysis, quantitative analysis, and more. Risk Analysis and Risk and Reliability Assessment university courses would prepare engineering students for these particular duties. The roles for this particular competence are Facility Risk Manager, Safety and Compliance Engineer, Disaster Preparedness Consultant, and Infrastructure Resilience Specialist, who implement solutions such as fire suppression systems, seismic reinforcements, and fail-safe automation.

1.3.4 Operation and Maintenance

Fourthly, Operation and Maintenance (O&M) is to get buildings to function safely and efficiently after construction, often for decades. This is especially critical in 24/7 operations like hotels, airports, and hospitals, where downtime is unacceptable. Proper O&M enables occupant comfort, extends equipment life, and reduces operating costs. This is where the engineers like ourselves could apply the knowledge and contribute by optimizing preventive and predictive maintenance schedules, troubleshooting HVAC and electrical systems, and introducing automation for energy control. This would translate to lower life cycle costs and higher asset value, which is a win-win situation for the building owners. Moreover, a well-maintained system would also contribute to energy conservation and reduced emissions. Various roles, such as Facility Operations Engineer, Building Systems Technician, Asset Manager, and Energy Performance Consultant, are offered in this particular FM specialization.

1.3.5 Sustainability

Last but not least, sustainability is a driving force in modern FM, relevant from material selection during design to energy consumption during operation. In all the types of structures, namely, university campuses and offices, sustainability in FM is to ensure healthy indoor environments and to reduce ecological footprints. In factories and airports, it is to align with ESG (Environmental, Social, and Governance) goals and regulatory compliance [3]. This is where engineers design energy-efficient HVAC systems, integrate renewable energy sources (like solar panels, or even on-shore and off-shore wind turbines), and conduct life cycle assessments. These efforts would help building owners lower operational costs and gain ESG recognition. Governments also benefit from progress toward climate goals, while the planet gains from reduced emissions and resource conservation. With increasing global focus on decarbonization and sustainable cities, this area offers exciting roles such as Sustainability Engineer, Environmental Consultant, Green Building Advisor, and Energy Auditor.

1.4 Links Between Facility Management, BIM, and Digital Twin

The increased use of digital tools has made this science-informed approach to facility management more practical and scalable. Building Information Modelling (BIM), for instance, is not only used in early design but also serves as a platform for storing equipment data and coordinating maintenance activities throughout the building's life. Digital Twins go a step further by simulating how a building responds to different operating conditions, offering predictive insights into energy use or system failure. When paired with IoT-based monitoring, these tools allow facility managers to detect problems early, adjust strategies in real time, and plan upgrades based on actual performance rather than assumptions.

However, this shift also introduces new challenges. Having access to real-time data does not automatically lead to better outcomes. Many organisations still struggle to interpret complex performance data or to integrate it meaningfully into decision-making. The value of these digital tools depends not only on the technology itself, but on the capacity of FM professionals to translate data into action. In this context, understanding FM as a continuous learning process, rather than a fixed set of procedures, becomes essential for achieving long-term performance and sustainability goals.

1.5 Conclusion

This reflection has offered a logical breakdown of facility management, beginning at a fundamental level and building towards the everyday application of engineering competence. Through examination of areas of activity like project management, information and technology management, risk management, operation and maintenance, and sustainability, the writing highlights how engineering profiles align with and enhance facility management practices. Besides, the integration BIM and DT technologies emphasizes the evolving digital landscape and its transformative impact on facility operations. Collectively, these insights emphasize the interdisciplinary nature and future-oriented significance of facility management.

Fault Detection in Building Energy Systems

2.1 Introduction

In the last several years, the concept of digital buildings has been at the forefront, driven by technology breakthroughs and the increasing need for energy efficiency. Digital buildings leverage operational data to streamline building performance, make building occupants more comfortable, and reduce energy consumption. As there is integration with a multitude of sensors and intelligent systems, there is monitoring and management in real time, and thus it becomes imperative to maximize the use of this data to identify and remove operational inefficiencies.

Fault detection is among the key aspects in building energy systems' efficiency and comfort. Faults in those systems can result in increased energy consumption, discomfort for the occupants, and expensive operation. By detecting and removing the faults in a timely manner, building managers have a good chance to significantly enhance the overall performance and sustainability of their energy systems.

This report seeks to identify operating faults in a real case study of a single-family home located in Aarhus, Denmark. By analyzing operational data, including thermostat settings, indoor air temperatures, and heat meter readings, the report aims to uncover thermal comfort issues and develop effective rules for detecting faults.

2.2 Data Overview

The dataset provided for the assignment represents time series data collected during a field experiment on residential space heating in a single-family house in Aarhus, Denmark [4].

Data were gathered from multiple sources such as thermostats, sensors, and heat meters. However, the data of interest of this study are primarily the zonal temperature (`temp_zt_*`), temperature setpoint (`sp_*`), and the position of the valve (`valvepos_*`) of the three active spaces (kitchen, living room, and dining room). The description of each column is presented in Table 2.1.

Table 2.1: Description of columns in the synchronized heating dataset.

Column Name	Description
`Timestamps`	Timestamps for each data record (time series index).
`temp_zt_*`	Temperatures from Z-wave thermostats in various rooms.
`sp_*`	Set-point temperature for Z-wave thermostats in respective rooms.
`valvepos_*`	Valve position (%) of thermostats in the respective rooms.

2.3 Analysis of Thermal Comfort Issues

As ASHRAE [5] defines, thermal comfort is the condition of mind that expresses satisfaction with the thermal environment. To achieve this goal, multiple environmental and personal parameters, such as air temperature, radiator forward and return temperature, humidity, clothing insulation, and metabolic activity of occupancy, are detected. However, in residential buildings, for example, the experimental building, air temperature is often the most practical and dominant indicator of comfort. Typical thermal comfort ranges for indoor temperature fall between 20°C and 24°C.In this study, the comfort thresholds are adapted to reflect the actual control setpoints applied during the experiment. The setpoints in three active rooms (kitchen, living room, and dining room) range between 20°C and 22°C. Therefore, the comfort analysis is centered around deviations from these specific values rather than generic standard bounds. A thermal discomfort is flagged when the actual room temperature deviates from the setpoint by more than ± 1.5°C for more than 15 minutes. This criterion is chosen to exclude transient fluctuations and emphasize sustained deviations that are likely to affect occupant comfort.

In this analysis, thermal comfort is evaluated based on the following parameters:

- **Room temperature**: measured air temperature in each zone;
- **Setpoint temperature**: the control target defined by the thermostat;
- **Discomfort event detection**: defined as a temperature deviation of more than ± 1.5°C from the setpoint lasting longer than 15 minutes.

The figures below illustrate the temperature dynamics, setpoints, and overheating events for the kitchen, living room, and dining room. Overheating events are marked as green dots. These visualizations help assess system behavior and thermal comfort compliance.

2.3.1 Kitchen

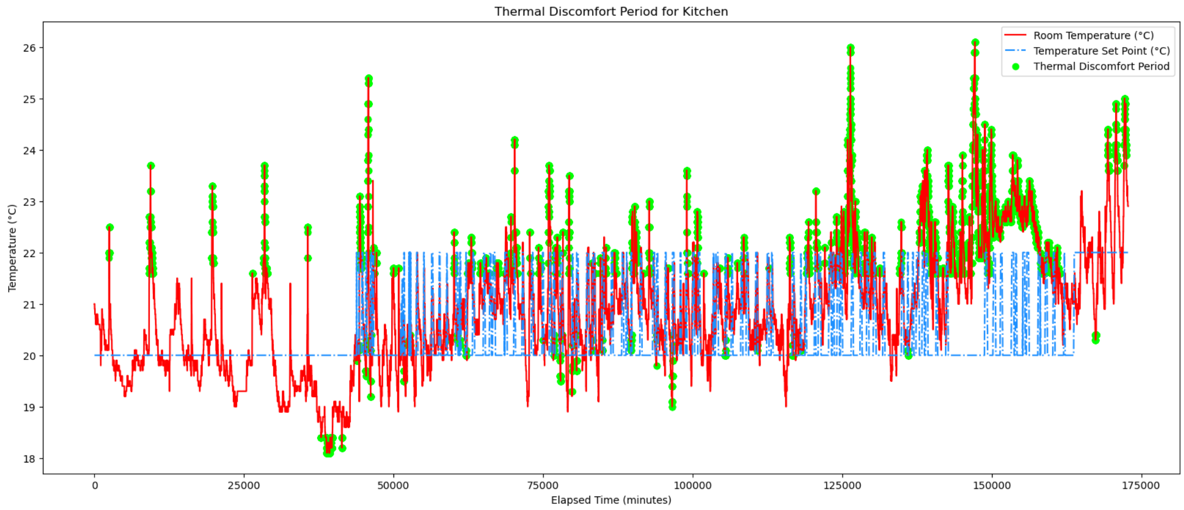

Figure 2.1: Kitchen thermal discomfort

The kitchen figure 2.1 demonstrates a recurrent overheating issue, with temperatures frequently exceeding the setpoint by 2–4°C. Extreme cases peak at 26°C while the setpoint remains near 20–21°C. The frequent spikes and green markers indicate poorly tuned control algorithms, high thermal gains, or possibly thermal inertia effects. The kitchen's layout, insulation, and proximity to other heat sources may exacerbate the problem. This behavior signifies a critical need for control refinement.

2.3.2 Living Room

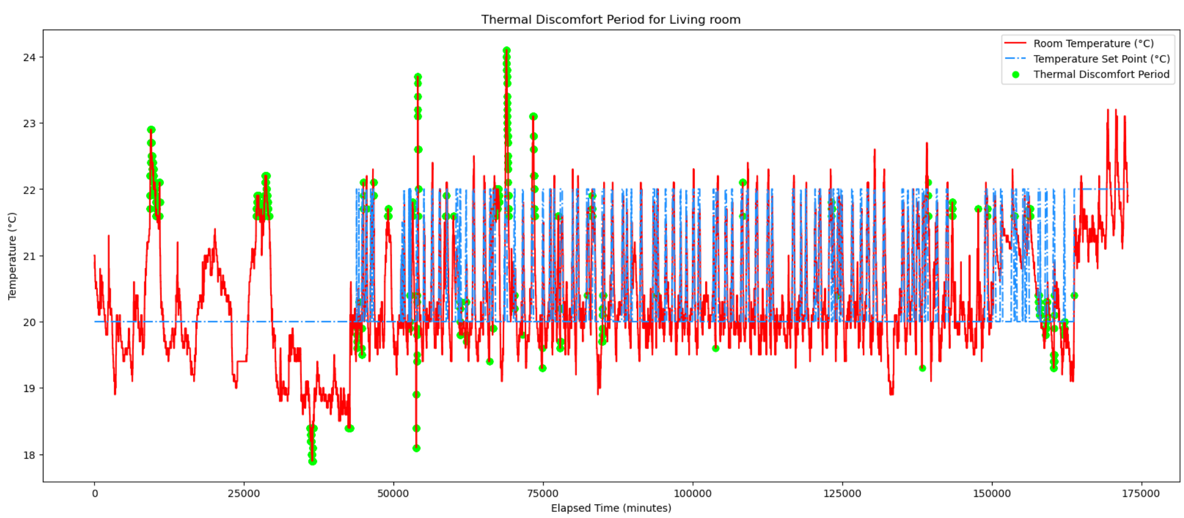

Figure 2.2: Living room thermal discomfort

The living room figure 2.2 shows relatively stable temperature control with minimal overheating. Most of the room temperature values hover below or slightly around the setpoint. However, during early phases (e.g., before minute 50,000), there are notable periods of underheating, with the room temperature falling below 19°C. This suggests insufficient heat delivery or slow response time in the heating system. Few green markers indicate minor overheating, likely caused by delayed heat dissipation.

2.3.3 Dining Room

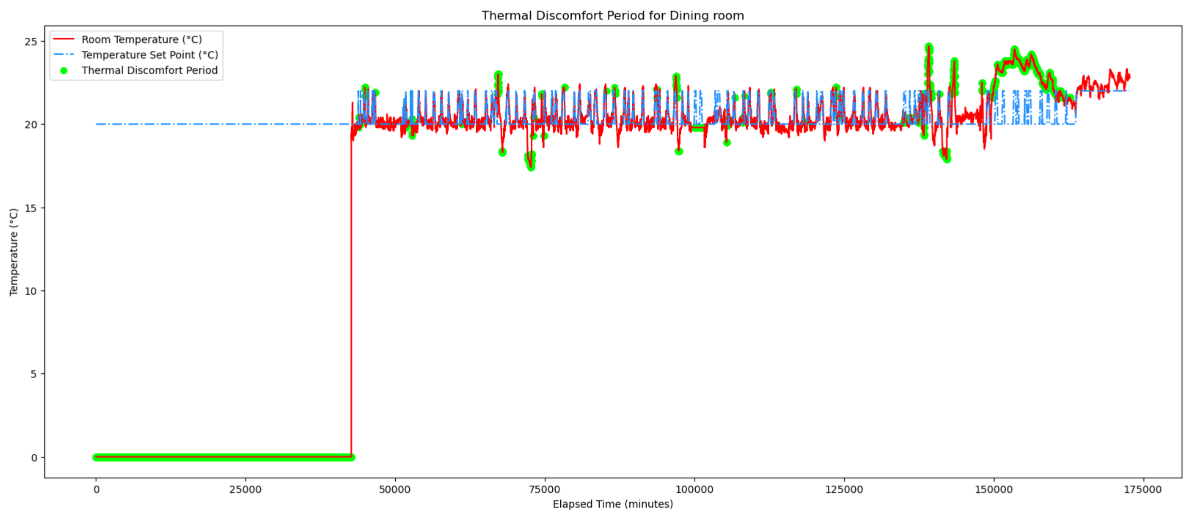

Figure 2.3: Dining room thermal discomfort

Figure 2.3 initially exhibited faulty sensor data (constant 0°C), indicating either a malfunction or initialization lag. Once the sensor recovered, temperature control became significantly more stable. Overheating events were sparse and mild, suggesting effective regulation. However, the early data drop-out highlights the importance of reliable sensing for maintaining comfort.

2.3.4 Summary of Findings

This section reveals different behavior patterns across the three active rooms. The kitchen exhibited the most persistent overheating, indicative of control limitations. The living room demonstrated relatively stable performance, with only minor instances of both underheating and overheating. The dining room experienced initial data loss due to sensor malfunctions, which rendered early observations inconclusive. However, during periods of valid data collection, the temperature closely tracked the setpoint with minimal deviations. Instances of thermal discomfort were rare, which suggests relatively effective control behavior in the absence of sensor faults.

These figures provide a clear foundation for the development of zone-specific fault detection strategies. In the next section, it is to formalize a set of data-driven rules to detect potential anomalies in system operation, such as ineffective valve behavior, overheating with low valve opening, or unstable control commands. These rules are designed to interpret the patterns observed in this chapter into actionable diagnostics for system evaluation and optimization.

2.4 Rule Development for Fault Detection

Fault detection rules have been put in place to monitor system performance in each of the active spaces (kitchen, living room, and dining room). These include detecting overheating when the temperature exceeds the set point by more than 1.5 °C while the valve is less than 10% open, identifying valve ineffectiveness when the valve is open more than 90% yet the temperature remains more than 1.5 °C below the set point, and recognizing controller instability if the set point changes more than three times within a span of 60 minutes. Each rule operates independently, and plots in the following subsections are utilized to show where these conditions are triggered. The probable root causes, accompanied by the patterns and trends of occurrence, are also discussed.

2.4.1 Overheat

Figure 2.4 illustrates that the kitchen overheating fault can be understood in terms of a mismatch between the thermal dynamics of the space and the control logic of the heating system. The fault condition — where the room temperature is over 1.5°C above the set point when the valve is nearly closed, smaller than 10% — refers to the fact that there is a tendency for residual heat to accumulate in the room even though active heating is low. This could be caused by factors such as low response of the system, poor heat dissipation, or ambient gains of heat (e.g., from cooking appliances or direct sunlight).

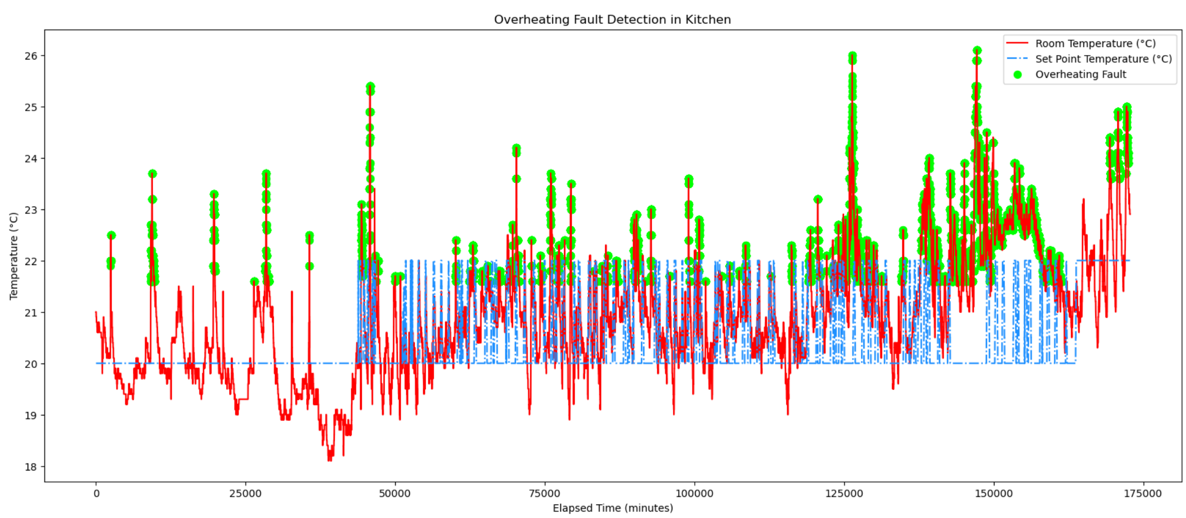

Figure 2.4: Kitchen overheat

Based on the time series plot 2.4, the overheating faults in the kitchen exhibit a clear temporal pattern. The green markers indicating faults are clustered during periods when the room temperature spikes significantly above the set point, particularly beyond 21°C. These events are not uniformly distributed but tend to occur in distinct bursts, especially between 50,000 and 175,000 minutes of elapsed time. This suggests that the root cause—such as heat accumulation or delayed system response—is more likely to manifest during specific operational or environmental conditions. For instance, these periods may coincide with times of day when the kitchen is actively used (e.g., cooking) or when external heat gains are higher (e.g., sunlight through windows). The pattern implies that the overheating is not random but tied to predictable usage or environmental cycles, which could be leveraged to improve fault prediction and system tuning.

Moreover, the overheating faults in the living room, depicted in Figure 2.5, are triggered when the fault detection rule applies. The plot shows that the set point temperature remains relatively stable around 20°C to 22°C, while the room temperature (red line) fluctuates more widely. The presence of green markers (faults) during these peaks suggests that the heating system is not adequately regulating the temperature, possibly due to thermal lag, external heat gains (e.g., sunlight through large windows), or internal heat sources like electronics or occupancy in the dining room. The fact that the valve is nearly closed during these events indicates that the system is attempting to reduce heating, but the room continues to warm, pointing to ineffective heat dissipation or delayed control response.

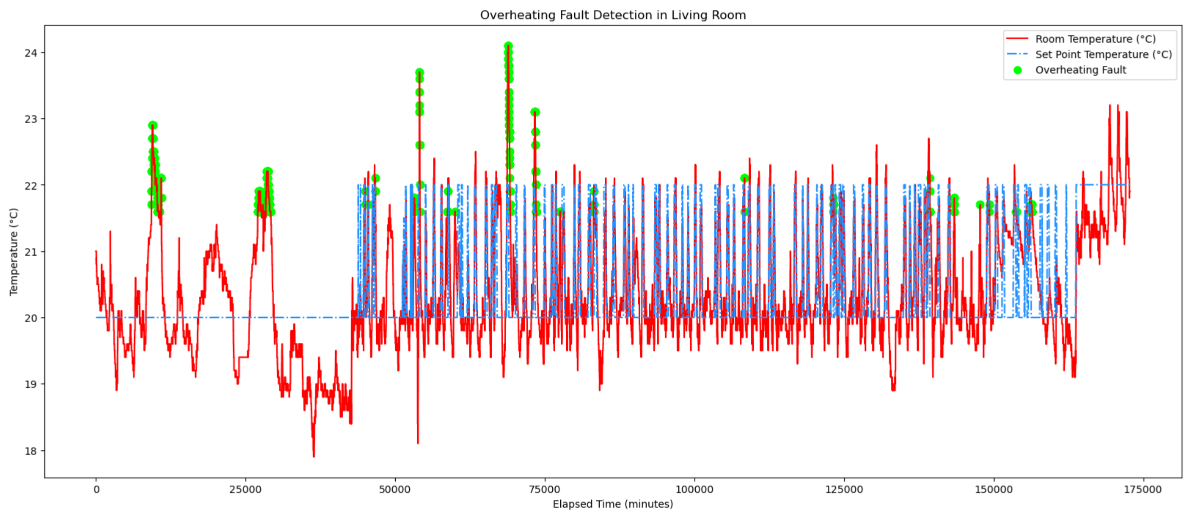

Figure 2.5: Living room overheat

The overheating faults in the living room occur sporadically but consistently throughout the timeline, with clusters of green markers appearing during periods of sharp temperature increases. These clusters are especially noticeable in the middle and later segments of the time series (e.g., after 50,000 minutes), similar to the kitchen. This suggests that the root cause is not random, but likely tied to recurring environmental or usage patterns, such as afternoon sun exposure, evening occupancy, or inadequate ventilation. The consistent set point implies that the issue lies not in the control target but in the system's ability to maintain it under varying conditions.

Additionally, the plot of the dining room in Figure 2.6 shows that the room temperature initially rises sharply from around 0°C to 20°C, then fluctuates around the set point for the rest of the time. Despite the set point remaining stable at approximately 20°C to 22°C, green markers (indicating faults) appear during periods when the room temperature spikes above this threshold. This suggests that the heating system may be overcompensating after initial cold conditions, or that external heat sources (like solar gain or occupancy) are contributing to temperature overshoots.

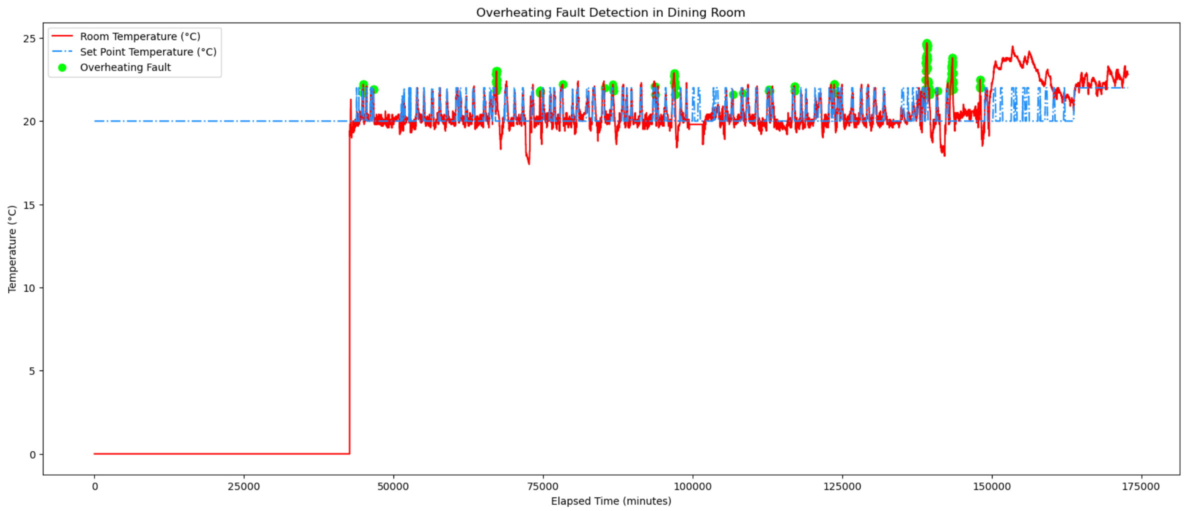

Figure 2.6: Dining room overheat

The overheating faults in the dining room are scattered throughout the timeline, but they tend to occur after the initial warm-up phase, once the room has stabilized around the set point. This indicates that the faults are not due to startup behavior but rather ongoing control issues or environmental influences. The green markers are more frequent during temperature peaks, suggesting that the system struggles to maintain comfort during transient heating events. These could be linked to meal times, sunlight exposure, or irregular use of the space, all of which can introduce heat gains that the system fails to anticipate or mitigate effectively.

2.4.2 Controller Instability

The controller instability fault is identified when there are more than three set-point changes within a 60-minute period. In the kitchen plot illustrated in Figure 2.7, the set point temperature, represented by a blue dashed line, remains relatively stable between 20°C and 22°C; however, the presence of green markers indicates instances when this stability is interrupted. Such events suggest that the control system may be facing issues like conflicting control inputs (e.g., manual overrides versus automated schedules), sensor noise or miscalibration, and poorly tuned control algorithms that react excessively to minor deviations.

The green markers indicating controller instability faults are scattered throughout the timeline. This suggests that the issue is periodic and may not be tied to predictable external factors like time of day or occupancy. Instead, it may reflect inconsistencies in control logic or user behavior. The room temperature (red line) shows significant fluctuations, which may be both a cause and a consequence of the unstable set-point behavior.

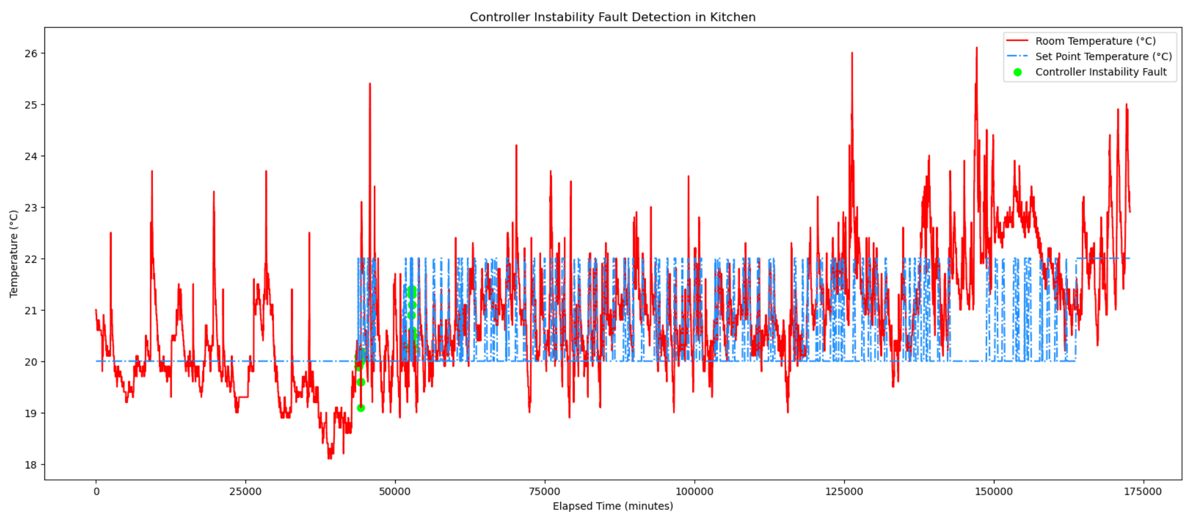

Figure 2.7: Kitchen controller instability

Moreover, in the living room plot, illustrated in Figure 2.8, the fluctuation of the set point—the blue dashed line—is highlighted by green markers indicating rule violations. Such incidents signal that the control system is undergoing frequent change, possibly due to user overrides, conflicting schedules, overly sensitive automated control logic response to minor temperature excursions, or problems such as sensor noise and misinterpretation of occupancy patterns.

The green markers are periodically distributed across the timeline, with no strong clustering, indicating that the instability is irregular rather than tied to specific times of day or operational phases. The room temperature (red line) fluctuates moderately, suggesting that while the space is generally stable, the control system may be overcorrecting or responding too frequently to perceived changes. This could be improved by smoothing control inputs or introducing output lag in the control logic.

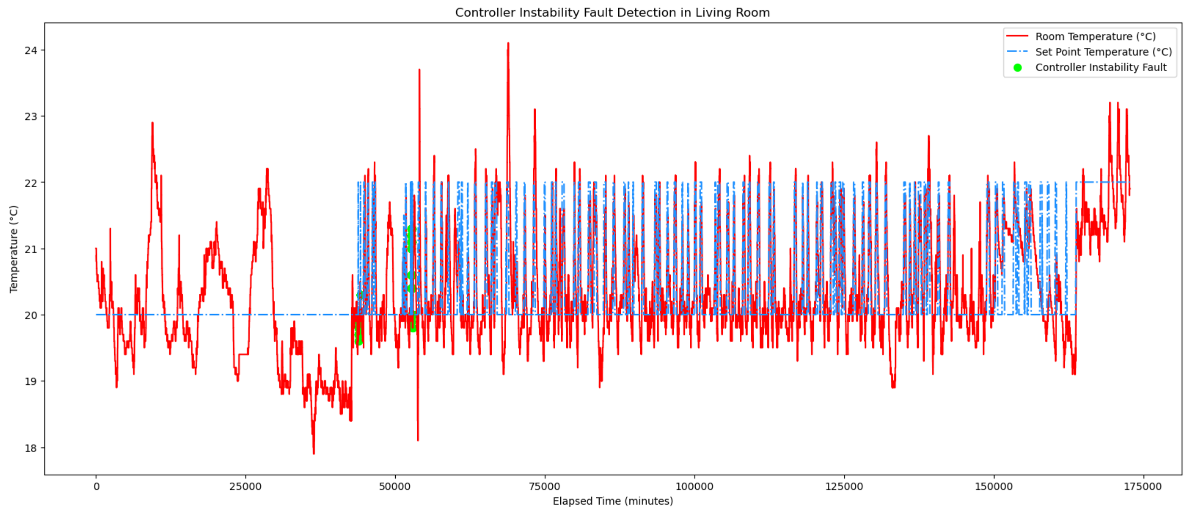

Figure 2.8: Living room controller instability

Additionally, in the dining room plot shown in Figure 2.9, the set point temperature, indicated by the blue dashed line, stays relatively stable around 20°C to 22°C, while the room temperature, shown by the red line, rises from 0°C and fluctuates around this set point. Although the set point appears stable, green markers reveal moments when the rule is violated, suggesting small but frequent adjustments that may not be easily detected at this scale. These adjustments could be caused by automated control systems reacting too aggressively, conflicting schedules or user overrides, or sensor noise and misinterpretation of environmental changes. Such rapid fluctuations can lead to discomfort and inefficiencies, particularly in a dining room where thermal stability is usually preferred.

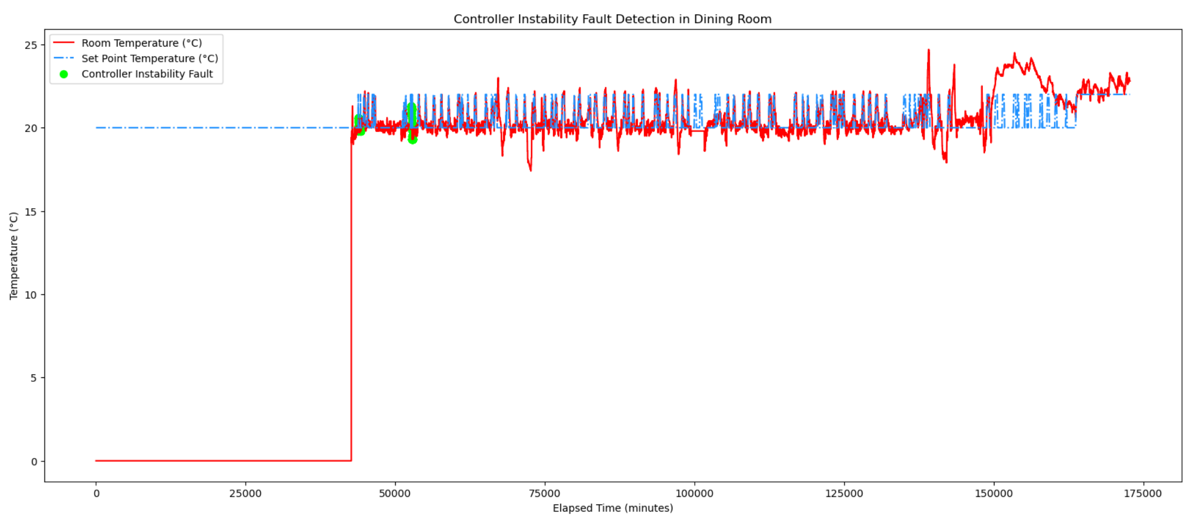

Figure 2.9: Dining room controller instability

The green markers scattered randomly on the timeline show that the instability occurs at random times and is not connected to any stages of operation. There are no faults detected during the early warm-up phase, which suggests that the problem is most likely to occur after the system has reached its target area, maybe due to undesired fine-tuning efforts or overcorrection carried out by the controller.

2.4.3 Valve Ineffectiveness

In Figure 2.10, the kitchen heating system is functioning properly, as reflected by the valve's behavior. The valve was found not to remain open for more than 90% of the time when the room temperature still stood higher than 1.5°C below the set point, implying that the system could provide heating needs when needed.

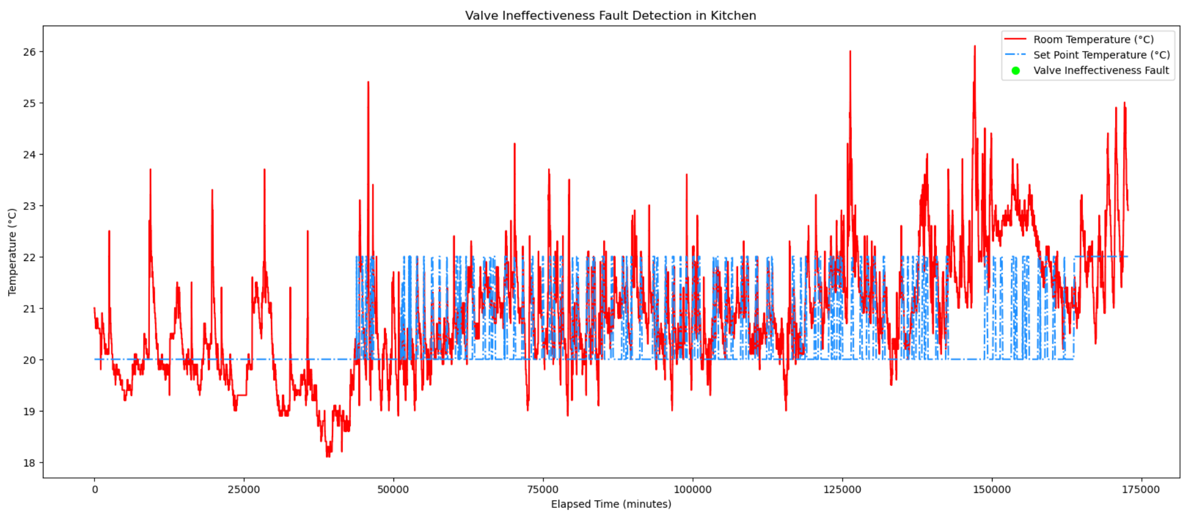

Figure 2.10: Kitchen valve ineffectiveness

However, as indicated by the presence of green dots in the living room plot in Figure 2.11, this suggests that the heating system operated at near full capacity but failed to adequately raise the room temperature. Potential root causes for this issue may include insufficient heating capacity for the room size or heat loss rate, poor insulation, or drafts causing rapid heat loss, or obstructed or malfunctioning radiators.

The green scatter points indicate that valve ineffectiveness is not constant but occurs under specific conditions, such as cold weather periods or high heat demand, periods of high ventilation with open windows, and transient occupancy patterns that increase heat loss. During these events, the room temperature (represented by the red line) tends to lag behind the set point (the blue dashed line), further emphasizing that the system struggles to meet heating demand even when the valve is nearly fully open.

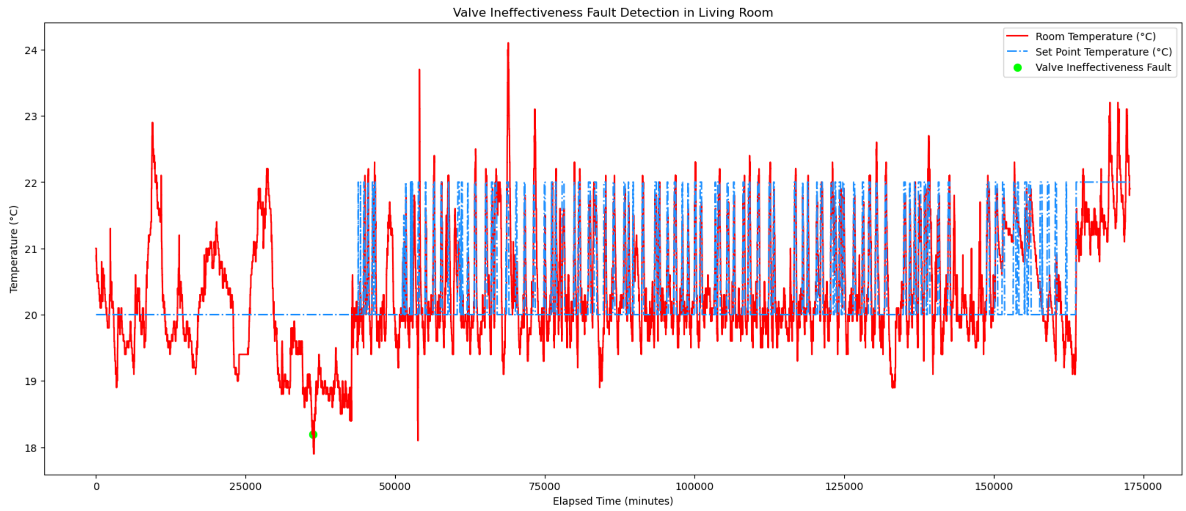

Figure 2.11: Dining room valve ineffectiveness

Furthermore, in the dining room, the plot indicates the presence of green dots, signifying that a fault condition occurred in the dining room, where the heating system operated near full capacity but failed to adequately raise the room temperature. Possible root causes for this issue, particularly in the living room, may include undersized heating equipment relative to the room's thermal load, significant heat loss due to poor insulation or air leakage, or obstructed or malfunctioning radiators.

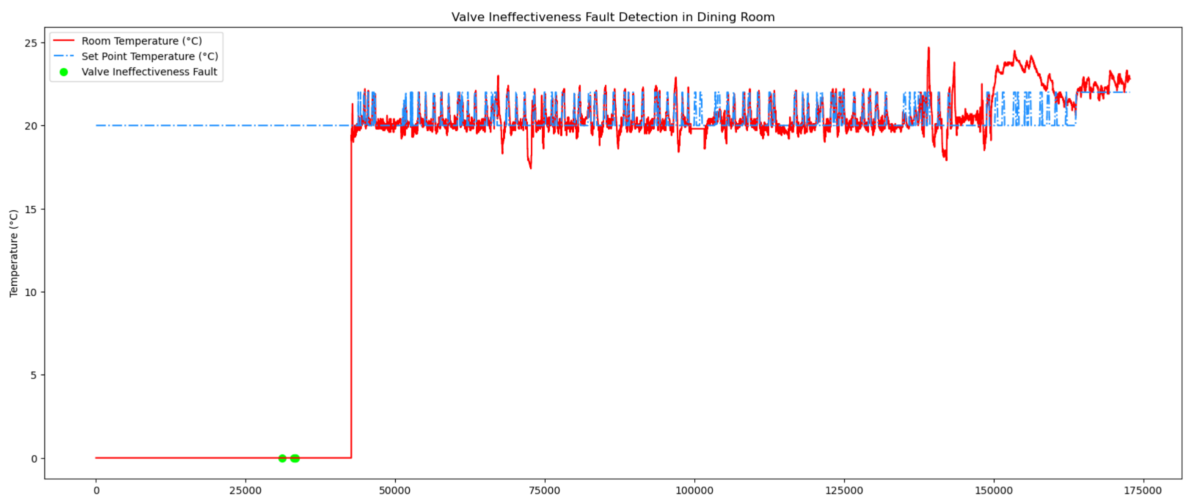

Figure 2.12: Dining room valve ineffectiveness

The green markers are in a patternless way, primarily after a warm-up session when the room temperature stabilized at around 20°C, indicating that the system is struggling to keep individuals comfortable at certain moments. This may be due to low outside air temperatures, high ventilation or infiltration rates, and occupancy or usage patterns that are short-term in nature. Furthermore, room temperature lags behind the set point in such a situation, justifying the truth that the system is unable to meet the heating demand despite maximum valve opening.

2.5 Conclusion

This report investigated thermal comfort performance and operational fault detection in a residential space heating system using real-world data from a single-family house in Aarhus, Denmark. By analyzing room temperatures, thermostat setpoints, and valve positions, the study provided a comprehensive assessment of occupant comfort.

The thermal comfort evaluation revealed distinct performance patterns across the three actively controlled rooms. The kitchen exhibited continual overheating, primarily due to internal heat gains from cooking activities and insufficient control responsiveness. This highlights the importance of zone-specific control strategies that take into account functional room characteristics, particularly in kitchens, where intermittent but intense heat sources are common. In contrast, the living room showed mostly stable temperature regulation, with occasional underheating and signs of valve ineffectiveness. The dining room initially suffered from sensor failure, but after data recovery, temperature tracking aligned closely with setpoints, although mild overheating and signs of insufficient heating capacity were still observed during high-demand periods.

Three rule-based fault detection strategies are defined for available room temperature, valve position, and setpoint data. These rules addressed: (i) overheating when room temperature exceeded the setpoint by more than 1.5 °C while the valve remained nearly closed, (ii) valve ineffectiveness when the valve was fully open but the room temperature stayed below the setpoint, and (iii) unstable control behavior identified through frequent changes in setpoint. Each rule effectively highlighted recurring operational issues in the respective zones and corresponded well with the patterns observed during the comfort analysis.

This study thus presents an experimental investigation into thermal behavior and system fault detection in a digitally managed residential building. Its aim is to use empirical data to inform facility management practices and evaluate how current control strategies perform under real-life conditions. The focus on several interpretable rules grounded in real sensor data allows for practical diagnostic approaches applicable in similar building contexts.

For future work, several directions could extend the findings of this study. First, the current rules are based on fixed thresholds (e.g., ± 1.5 °C or valve positions at 10% and 90%), which may not fully capture the thermal behavior of each zone. Future implementations could adopt adaptive thresholds informed by historical data or room-specific profiles.

Second, the current fault detection rules check the system conditions at individual time points or over short windows. This can lead to false positives when there are brief fluctuations that do not represent real problems. To address this, the rules could be improved by requiring that a fault condition must last for a longer period, such as several consecutive samples, before being triggered. This would reduce noise in the detection and better reflect actual operational faults.

Third, since the kitchen often shows overheating, it would be useful to design control strategies that are specific to its use. For example, the system could lower the heating setpoint during cooking hours. This change can help reduce the impact of internal heat gains from cooking. Finally, the detection rules developed in this study could be connected to the heating control system in real time. This means that when a fault is detected, the system could automatically respond by adjusting the valve, changing the setpoint, or sending an alert. Adding this type of feedback could make the system more adaptive and help solve problems faster.

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Appendices

Appendix A: Python script for fault detection and rule development

```
## FAULT DETECTION

import pandas as pd
import matplotlib.pyplot as plt

# Load the dataset
data = pd.read_csv('data_synchronized.csv')

# Define columns for each room
rooms = {
    'kitchen': {
        'temperature': 'temp_zt_kitchen',
        'setpoint': 'sp_kitchen',
        'valvepos': 'valvepos_kitchen'
        },

    'dining room': {
    'temperature': 'temp_zt_diningroom',
    'setpoint': 'sp_diningroom',
    'valvepos': 'valvepos_diningroom'
    },

    'living room': {
        'temperature': 'temp_zt_livingroom',
        'setpoint': 'sp_livingroom',
        'valvepos': 'valvepos_livingroom'
    }
}

# Define the thermal discomfort rule

def detect_discomfort(data, room):
    discomfort_periods = []
    temp_col = rooms[room]['temperature']
    sp_col = rooms[room]['setpoint']
```

```

    for i in range(len(data)):
     if abs(data[temp_col][i] - data[sp_col][i]) > 1.5:
        discomfort_periods.append(i)

    return discomfort_periods

# Plot time series for each room
for room in rooms:
    temp_col = rooms[room]['temperature']
    sp_col = rooms[room]['setpoint']
    # valvepos_col = rooms[room]['valvepos']

    discomfort_periods = detect_discomfort(data, room)
    plt.figure(figsize=(20, 8))
    plt.plot(data[temp_col], label='Room Temperature ( C )', color='red')
    plt.plot(data[sp_col], label='Temperature Set Point ( C )', color='dodgerblue', linestyle='dashdot')
    # plt.plot(data[valvepos_col], label='Valve Position', color='silver')

    plt.scatter(discomfort_periods, data[temp_col][discomfort_periods], color='lime', label='Thermal Discomfort Period')

    plt.title(f'Thermal Discomfort Period for {room.capitalize()}')
    plt.xlabel('Elapsed Time (minutes)')
    plt.ylabel("Temperature ( C )")
    # plt.ylim(0, 27)
    plt.legend()
    # plt.grid(True)
    # plt.savefig(f'{room.replace(" ", "_")}_thermal_discomfort.png')
    plt.show()

print("Time series plots generated and saved for each room.")


## FAULT DETECTION RULES
import pandas as pd
import matplotlib.pyplot as plt

# Load the dataset
data = pd.read_csv('data_synchronized.csv')

# Define the columns for each room
rooms = {
```

```
    'kitchen': {
        'temp': 'temp_zt_kitchen',
        'set_point': 'sp_kitchen',
        'valve_pos': 'valvepos_kitchen'
    },
    'dining_room': {
        'temp': 'temp_zt_diningroom',
        'set_point': 'sp_diningroom',
        'valve_pos': 'valvepos_diningroom'
    },
    'living_room': {
        'temp': 'temp_zt_livingroom',
        'set_point': 'sp_livingroom',
        'valve_pos': 'valvepos_livingroom'
    }
}

# Convert timestamps to elapsed time in minutes
data['elapsed_time'] = (pd.to_datetime(data['Timestamps']) - pd.to_datetime(data['Timestamps'][0])).dt.total_seconds() / 60

# Function to plot data with fault detection markers
def plot_fault_detection(room_name, room_data, fault_indices, fault_type):
    plt.figure(figsize=(20, 8))
    plt.plot(room_data['elapsed_time'], room_data[room_cols['temp']], label='Room Temperature ( C )', color='red')
    plt.plot(room_data['elapsed_time'], room_data[room_cols['set_point']], label='Set Point Temperature ( C )', color='dodgerblue', linestyle='dashdot')
    # plt.plot(room_data['elapsed_time'], room_data[room_cols['valve_pos']], label='Valve Position (%)', color='green')
    plt.scatter(room_data['elapsed_time'].iloc[fault_indices], room_data[room_cols['temp']].iloc[fault_indices], color='lime', label=f'{fault_type} Fault', s=50)
    plt.xlabel('Elapsed Time (minutes)')
    plt.ylabel('Temperature ( C )')

    # plt.ylim(0, 27)

    plt.title(f'{fault_type} Fault Detection in {room_name.replace("_", " ").title()}')
    plt.legend()
    # plt.grid(True)
    plt.show()
```

```python

# Rule 1: Overheating
for room_name, room_cols in rooms.items():
    room_data = data[['elapsed_time', room_cols['temp'], room_cols['
        set_point'], room_cols['valve_pos']]]
    fault_indices = room_data[(room_data[room_cols['temp']] > room_data[
        room_cols['set_point']] + 1.5) & (room_data[room_cols['valve_pos']]
         < 10)].index
    plot_fault_detection(room_name, room_data, fault_indices, 'Overheating
        ')

# Rule 2: Controller Instability
for room_name, room_cols in rooms.items():
    room_data = data[['elapsed_time', room_cols['temp'], room_cols['
        set_point'], room_cols['valve_pos']]]
    set_point_changes = room_data[room_cols['set_point']].diff().abs() > 0
    fault_indices = set_point_changes.rolling(window=60).sum() > 3
    plot_fault_detection(room_name, room_data, fault_indices[fault_indices
        ].index, 'Controller Instability')

# Rule 3: Valve Ineffectiveness
for room_name, room_cols in rooms.items():
    room_data = data[['elapsed_time', room_cols['temp'], room_cols['
        set_point'], room_cols['valve_pos']]]
    fault_indices = room_data[(room_data[room_cols['valve_pos']] > 90) &
        ((room_data[room_cols['set_point']] - room_data[room_cols['temp']])
         > 1.5)].index
    plot_fault_detection(room_name, room_data, fault_indices, 'Valve
        Ineffectiveness')
```