Demonstration of heating demand peak shaving in smart homes

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Abstract. Flexible heating demand in buildings plays an important role in achieving a carbon neutral society. For the district heating system of Copenhagen, heating demand flexibility can help to eliminate the use of fossil-fueled boilers that are used during peak-load periods. In this project, field tests in 16 apartments were conducted, aiming to gain insights into the use of information and communication technologies (ICT) to manage heating systems operation for flexible demand. The apartments are equipped with sensors and devices interfaced to an ICT system composed of blocks responsible for data storage, monitoring and control. In the experiments, we controlled temperature setpoints of individual rooms during defined periods of the day, and continuously developed control strategies throughout the tests in the heating season 2018/19. The final algorithm was implemented with features to reduce the rebound effect and include residents feedback. All the algorithms are generic and can be applied in other smart homes where heating supply to rooms is controlled using thermostats. The ICT system architecture used in the experiments showed to be a feasible way to implement demand side management (DSM) in the heating system, and the learning process of the experiments resulted in improvements on the control strategies, leading to a better system performance.

1. Introduction

According to the Copenhagen 2025 Climate Plan [1], the City of Copenhagen aims to be the worlds first carbon neutral capital by 2025. One of the targets is to make its district heating carbon neutral, as 98% of the buildings in Copenhagen are supplied by district heating network [2]. For heat production in district heating, fossil-fueled boilers are currently brought into use during peak-load periods, i.e., 6:00-9:00 and 17:00-20:00, on particularly cold days. Therefore, a more flexible heating demand in buildings plays an important role in reducing CO2 emissions of district heating. The use of ICT to enhance the operation of buildings energy systems is a topic that has attracted attention in recent years. In the EnergyLab Nordhavn New Urban Energy Infrastructures project, Copenhagens Nordhavn district is used as a full-scale smart city energy lab to demonstrate how electricity and heating, energy-efficient buildings and electric transport can be integrated into an intelligent, flexible and optimized energy system [3]. As part of the EnergyLab Nordhavn project, we focus on heating demand management in buildings to enable heating flexibility for the reduction of fossil fuel use in district heating.

On average, residential energy demand accounts for 26% of total final energy demand in EU-28 countries and the share of space heating energy demand is 65% of the energy demand in the
residential sector [4]. A recently review of field studies on power grid integration of residential thermal energy storage concluded that existing field tests did not meet the flexibility challenges of smart grids with high share of renewable generation [5]. In comparison with the control of power grids, the control of district heating grids has a lower frequency due to thermal inertia in buildings and large lags in heat transmission and distribution networks, e.g. depending on the size of the network, the effect of the change of supply water temperature made at a heat production plant can only be seen a few hours later on the demand side, i.e. in buildings. Therefore, it is feasible to implement heating demand management for district heating grids. Although field tests of activating heating demand flexibility for district heating load management are still limited, promising results are shown in these tests. Liu et.al reported a 30% energy saving by adjusting and metering household heating systems in a large scale pilot study [6]. DSM demonstrations in two Finnish buildings with concrete structures showed a heat load reduction of 20-25% for a duration of 2-3 hours [7]. A field trial of demand shifting technology on a district heating network was conducted in the UK with reduced peak demand and a slight increase (3%) in heating consumption [8]. To gain more insights into the controllability of space heating demand, the management of heating demand for reducing fossil fuel usage and CO2 emission in district heating systems, we conducted field tests in 16 homes equipped with ICT technologies in Copenhagen, Denmark in the heating season of 2018/19. In this paper, we present the field tests with the focus on the learning process of the methodology.

2. Methodology
The focus of this section is on the explanation of the control strategies and algorithms used throughout the project based on the systems installed in the apartments.

2.1. Apartments characteristics
The apartments are located in a newly built multi-story residential building with a total of 72 apartments. The building was constructed in accordance with building class 2020 of the Danish Building Regulation BR15. This allows a maximum energy usage of 20 kWh/m2 per year [9] for heating, ventilation, cooling and domestic hot water. The apartments are thus expected to be very energy efficient with a high degree of insulation in both windows and external walls and a high level of air tightness. Each apartment consists of a main kitchen/living room area, one to four bedrooms, one large bathroom and for some apartments also one small toilet room.

2.2. Heating system
The space heating and domestic hot water of the apartments are provided by a district heating grid with a heat substation installed in the basement of the building. Heating in each room is provided by a floor heating system with the supply water temperature maintained at 35°C and water flow rate of each thermal zone is controlled by individual valves and respectively thermostatic controllers. The valves open when the difference between indoor temperature and room temperature setpoint is larger than 0.5°C.

2.3. ICT system description
The smart apartments are equipped with KNX systems, which connect sensors and devices for monitoring of indoor environment, occupancy detection and operation of heating, ventilation and lighting systems. Each KNX system is interfaced to a data management system located at PowerLabDK, DTU. The database is connected to a visualization tool, built on top of Grafana and InfluxDB, which allows real-time data verification. There is also an integration between the KNX systems and a MQTT broker, which can be used to publish messages to the KNX buses. The MQTT interface is used for controlling and reading data of KNX devices.
thermostatic controllers are KNX devices, so the temperature setpoint can be remotely adjusted by publishing messages to the MQTT broker. For the experiments, a Python script was used to communicate with the MQTT broker and remotely adjust temperature setpoints of living rooms using individual reference set points. Figure 1 shows the diagram of the ICT system. The algorithms used for the temperature control are described in subsection 2.4.

![Diagram of the ICT system](image)

**Figure 1.** Components of the ICT system.

### 2.4. Control strategy

The control strategy used in the experiments evolved according to the results obtained throughout the project including feedback from residents, aiming to optimize the operation of the system. Figure 2.4 shows the timeline of the project phases with respective algorithm used. The description of the control loop applied in different phases of the project can be seen on Algorithm 1, Algorithm 2 and Algorithm 3. The algorithms were implemented using Python, and a virtual machine (VM) was used to run these scripts according to schedules defined.

| Testing  | Algorithm 1 | Algorithm 2 | Algorithm 3 |
|----------|-------------|-------------|-------------|
| Dec 2018 | Jan 2019    | Feb 2019    | Mar 2019    |

**Figure 2.** Project timeline and algorithms used in each phase.

The first phase of the project started in December 2018, when experiments were conducted to test and fix small issues in the ICT system. The experiments were firstly applied in a single living room, and later extended to multiple living rooms. The tests used simple control signals (e.g. step response) that were sent to the apartments in defined timestamps, in order to verify if the system was responding accordingly. By the end of this stage, the control system was performing as expected. However, for some apartments it was only possible to solve the communication issues later in the project timeline.

After that, the second phase of the project started and demand peak shaving experiments were conducted using the loop described in Algorithm 1. The first step of the experiment was to define a reference temperature setpoint for each room (see Algorithm 1 – line 1). Note that for this first control strategy, the reference setpoint was heuristically defined according to the historical data of indoor temperature. Then, the VM was configured to run the script every five minutes, between 2:00 and 9:00 (see Algorithm 1 – lines 2 and 15). For living rooms, preheating was applied between 2:00 and 6:00, adding an offset of 1°C to the reference setpoint (see Algorithm 1 – line 7). For other rooms, preheating was not applied (see Algorithm 1 – line 12). In addition, during peak hours – between 6:00 and 9:00, the reference setpoint was reduced by 1°C in all rooms (see Algorithm 1 – lines 9 and 14).
Algorithm 1: Control loop version 1.

1. Heuristic definition of referenceSetpoint\_k for each room;
2. while 2:00 ≤ TIME ≤ 9:00 do
3.   for apartment\_j in apartments do
4.     for room\_k in rooms do
5.       if room\_k = living room then
6.         if 2:00 ≤ TIME ≤ 6:00 then
7.           currentSetpoint\_k ← referenceSetpoint\_k + 1°C
8.         else if 6:00 ≤ TIME ≤ 9:00 then
9.           currentSetpoint\_k ← referenceSetpoint\_k − 1°C
10.        else
11.          if 2:00 ≤ TIME ≤ 6:00 then
12.            currentSetpoint\_k ← referenceSetpoint\_k
13.          else if 6:00 ≤ TIME ≤ 9:00 then
14.            currentSetpoint\_k ← referenceSetpoint\_k − 1°C
15.          else
16.            wait 5 minutes
17.       end if
18.     end for
19.   end for
20. end while

Subsequently, some features were added to the control strategy to improve the results obtained during experiments of the second phase, and the algorithm evolved is described in Algorithm 2. The first change introduced is the way the reference setpoint was determined for the rooms. Instead of using an heuristic approach, the reference setpoint of each room was defined as the setpoint at 2:30 of the day (see Algorithm 2 – lines 1-4). The VM was scheduled to read the setpoints at 2:30 and then run the control loop every five minutes between 4:00 and 9:05 (see Algorithm 2 – lines 1 and 5). It was also observed from previous tests that the preheating time was too long, so it was reduced from 4 hours to 1 hour and 45 minutes (see Algorithm 2 – line 9). Moreover, the ending time of the preheating was changed from 6:00 to 5:45, because delays of around 15 minutes were observed in the system response during previous experiments (see Algorithm 2 – lines 11 and 18). Because of the delay, the peak reduction setting was scheduled to start 15 minutes ahead of the foreseen peak hours. Yet, the setpoint was constantly set to 20° during peak hours (see Algorithm 2 – lines 12 and 19). Lastly, it was added an action that change the setpoint back to the reference setpoint after 9:00 (see Algorithm 2 – line 21).

Algorithm 2: Control loop version 2.

1. if TIME = 2:30 then
2.   for apartment\_j in apartments do
3.     for room\_k in rooms do
4.       referenceSetpoints\_k ← currentSetpoints\_k
5.     end for
6.   end for
7. end if
8. while 4:00 ≤ TIME ≤ 9:05 do
9.   for apartment\_j in apartments do
10.  for room\_k in rooms do
11.    if room\_k = living room then
12.      if 4:00 ≤ TIME ≤ 5:45 then
13.        currentSetpoint\_k ← referenceSetpoint\_k + 1°C
14.      else if 5:45 < TIME ≤ 9:00 then
15.        currentSetpoint\_k ← 20°
16.      else if TIME > 9:00 then
17.        currentSetpoint\_k ← referenceSetpoint\_k
18.    else
19.      if 4:00 ≤ TIME ≤ 5:45 then
20.        currentSetpoint\_k ← referenceSetpoint\_k
21.      else if 5:45 < TIME ≤ 9:00 then
22.        currentSetpoint\_k ← 20°
23.      else if TIME > 9:00 then
24.        currentSetpoint\_k ← referenceSetpoint\_k
25.      end if
26.    end if
27.  end if
28.  wait 5 minutes
29. end for
30. end for
31. end while
Algorithm 3: Control loop version 3.

1. if \( \text{TIME} = 3:30 \) then
2. for apartment\(_i\) in apartments do
3. for room\(_k\) in rooms do
4. \( \text{referenceSetpoint}_k \leftarrow \text{currentSetpoint}_k \)
5. while \( 3:40 \leq \text{TIME} \leq 12:00 \) do
6. for apartment\(_i\) in apartments do
7. for room\(_k\) in rooms do
8. if room\(_k\) \( \neq \) (toilet OR bathroom) then
9. if \( 4:00 \leq \text{TIME} \leq 5:45 \) then
10. \( \text{currentSetpoint}_k \leftarrow \text{referenceSetpoint}_k \)
11. else if \( 5:45 < \text{TIME} \leq 12:00 \) then
12. \( \text{currentSetpoint}_k \leftarrow \text{referenceSetpoint}_k - 1.5^\circ\text{C} \)
13. wait 5 minutes
14. if \( \text{TIME} > 12:00 \) then
15. for apartment\(_i\) in apartments do
16. for room\(_k\) in rooms do
17. \( \text{currentSetpoint}_k \leftarrow \text{referenceSetpoint}_k \)
18. wait 1 minute

In the last test, more improvements i.e. including user feedback in the control and reducing rebound effect, were added to the control loop and it evolved to the process described in Algorithm 3. The VM was scheduled to read the reference setpoint at 3:30 (see Algorithm 3 – line 1), to run the script with the control loop between 3:40 and 12:00 (see Algorithm 3 – line 5), and to run an extra step after 12:00 (see Algorithm 3 – line 5). This last step was added to the control strategy in order to reduce the rebound effect, i.e. demand peak created if the setpoints of all rooms are increased at the same time. To mitigate it, a time delay of 1 minute was added after the setpoint of each room is changed (see Algorithm 3 – line 18). In this phase, the preheating was completely removed from the experiments, since it was verified that the thermal inertia of the building was capable to maintain the indoor temperature in a adequate level during heat cut-off, even without the preheating. Moreover, the setpoint was reduced for a longer period – between 5:45 and 12:00, and by a larger factor – reduction of 1.5\(^\circ\text{C}\). Lastly, based on user feedback from previous tests, bathrooms and toilets were excluded from the experiment as residents prefer to have warm floors in these rooms although the decrease in room temperature was not noticeable (see Algorithm 2 – line 8).

3. Results

The experiments using the control loops described in subsection 2.4 provided results that were used as a feedback for continuously developing the algorithm and eventually this led to the Algorithm 3. The system response of a single room to the application of the Algorithm 3, can be seen in Figure 3. The annotations made in Figure 3 are related to the script lines of Algorithm 3 according to the following:

- Annotation 1 \( \rightarrow \) Algorithm 3, line 4
- Annotation 2 \( \rightarrow \) Algorithm 3, line 10
- Annotation 3 \( \rightarrow \) Algorithm 3, line 12
- Annotation 4 \( \rightarrow \) Algorithm 3, line 17

The effect on peak demand shaving is shown in the bottom graph of Figure 3. Heating power of the home is much lower during 6:00-12:00 as heating was only permitted in bathrooms. Although the amount of peak demand reduction varies among homes, on average a reduction of 68% was reached in comparison with peak demand of the homes on non-experimental days with similar weather conditions.
4. Conclusion
Demand side management in the heating system plays a key role in the elimination of carbon emissions from our society, and the use of ICT to improve the operation of heating systems brings new resources for implementation. In this project, field tests in 16 apartments were conducted, using the existing ICT systems to manage heating systems operation for flexible demand. Based on residents feedback, algorithms were tested to control temperature setpoints of individual rooms during defined period of the day. The algorithms are generic using two inputs, i.e. room temperature and temperature setpoint, and providing on/off signal to valves of individual heating loops. These methods can be applied to other smart homes where heating supply is controlled using room thermostats.

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