Thermal Comfort Risks in District Heating System Controlled by Demand Response


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In future, demand response (DR) will play a significant role in smart district heating system. By utilizing dynamic energy price and thermal mass of building, it is estimated that the heat energy cost saving of DR for building owner is around 5%, when room air temperature is accepted to vary between 20 – 24.5°C. However, it is important to note that thermal comfort should not be sacrificed when DR is introduced in district heating.

Keywords: Demand response, district heating, thermal comfort, field test

Demand response with district heating system

Demand response (DR) consist of a group of methods where the end-user's energy load is modified to decrease the aggregated overall CO_2 emissions of the energy production and to enhance the efficiency of the whole energy system. The end-user´s load may be shifted from expensive peak load periods to cheaper off-peak periods, the peak load may be cut, or extra load may be induced to off-peak periods. As a result, the aggregated load in the energy system will be stabilized and the demand for the fossil-fuel intensive peak-power plants will decrease.

While DR has been explored commonly for electricity grid, it has not been used commonly in district heating system. Earlier demand response studies have predominantly dealt with the electricity loads. However, there is a potential to save energy costs and reduce CO_2 emission with district heating.

During the heating season, production cost of the district heating power varies quite a lot. In **Figure 1** shows an example of district heating hourly price in Finland containing both energy and transfer costs (Salo et al. 2018). The prices remain stable during summer time (i.e. April to middle of November (hours 2,100 – 7,900 in **Figure 1**) with an average value of 40.5 €/MWh and a standard deviation of 7.7 €/MWh. During winter time, the corresponding values are 68.0 €/MWh and 29.7 €/MWh.

Within DR controlled space heating, loading is typically executed when the energy is cheap. The room air temperature is then increased to load heat into the structures, which can be used during more expensive hours by lowering the indoor air temperature setpoint. **Figure 2** presents the principle of DR control, where heating power is controlled by the known price trend (e.g. for 24 hours in advance).

The control strategy itself could be rule-based or model-based. In the rule-based control algorithms studied at Aalto University, the decision-making was based on the outdoor and indoor air temperatures and the control signal generated from the dynamic price information (Martin 2018). The studied model predictive algorithms utilized sophisticated optimization algorithm (e.g. NSGA-II) where user can optimize contradictory functions e.g. energy costs and thermal comfort (Mäki 2019). However, based on the aforementioned studies, the saving potential of both rule-based and model-based control strategies is the same.

In an educational building, the simulated heat energy cost saving potential of DR with the dynamic district heating price (see **Figure 1**) is about 5% for a building owner, when room air temperature is accepted to vary between 20 – 24.5°C. At the same time, annual heating energy consumption decreased 3 to 5% in the studied building depending on the DR algorithm.

In the water radiator system, the heating power could be controlled at centralized or decentralized levels. Decentralized control refers to adjustments of mass flow of water radiators on room level (e.g. electronic radiator valve control), while centralized control refers to adjustments on system level (e.g. inlet water temperature control). By introducing room or zonal based decentralized control, it is possible to reach highest savings and decentralized control guarantee the set targets of thermal comfort in all rooms even when heat loads varied.

Overall thermal sensation with centralized DR control

In the centralized DR control strategy, inlet water temperature of district heating system is adjusted based on the price signal. Based on the energy price trend, the controls have effect on the inlet water and further on room air temperatures. Centralized strategies were studied in one of the wings (13,800 m²) of a campus building at the Aalto University (Mistra et al. 2019). The goal was to examine how much deviations could be incurred in the inlet water temperature and how, if at all, that affected occupant perceptions.

The building was refurbished in 2014 when ventilation, heating, and building management systems were upgraded. The original 2-pane windows were renovated and the renovated windows have a U-value of 1.0 W/m²K. The wing is equipped with mechanical supply and exhaust ventilation system with regenerative heat recovery. It is a variable air volume (VAV) system, controlling air flow rates based on the dual inputs of room air temperature and carbon dioxide concentration.

In testing the DR scenarios, an inherent assumption was that dynamical pricing would be available for district heating and a moving 24 hours, hourly price, would be known in advance, at any point in time. The district heating price used in the study is shown is **Figure 1**. The principle of the control strategy used is as described in **Figure 2**.

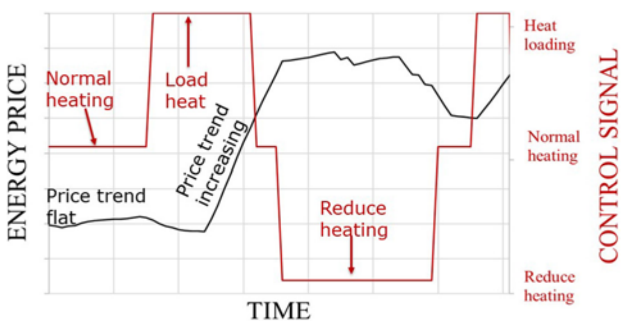

Figure 2. The principle of demand response control during changing price trend.

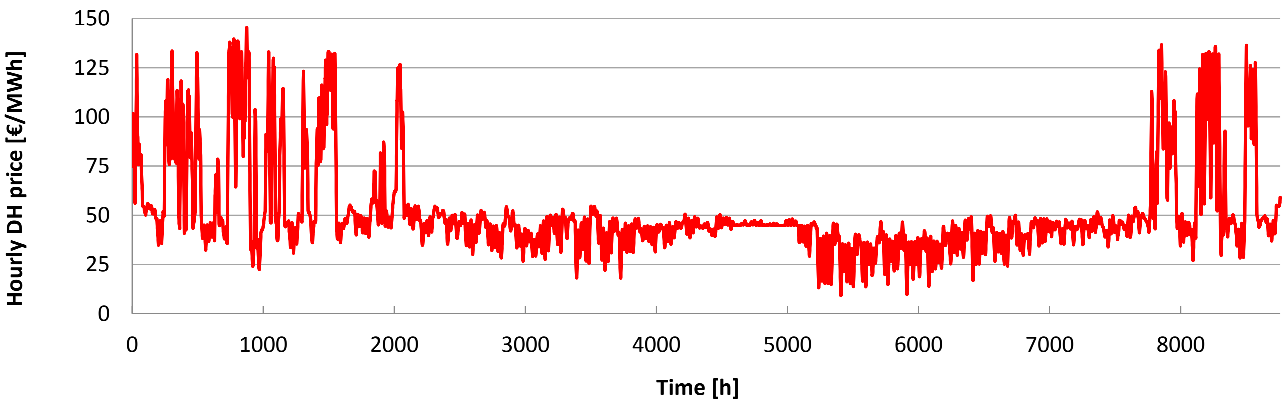

Figure 1. The dynamic district heating price of a typical producer in Finland.

During the test, the heating water supplied to every radiator in the wing was altered, where the maximum deviations of +11/−21°C were allowed for inlet water temperature between actual and standard values (see **Table 1**). The minimum and maximum outdoor temperatures for each weekly period are summarized in **Table 1**. The algorithm aimed at keeping room air temperature within 20 – 24.5°C

To ensure that all the occupied rooms kept within the required comfort zone, the algorithms depended on the mean air temperature of the coldest and warmest rooms. The coldest rooms were defined as rooms whose temperature was lower than 90% of the permanently occupied rooms of the wing and the warmest rooms were defined as rooms whose temperature was higher than 90% of the permanently occupied rooms in the wing. When mean air temperature of the coldest rooms fell below 20°C, or mean air temperature in the warmest rooms rose over 24.5°C, the standard control curve for inlet water temperature was used.

The recorded room air temperature data covered all the rooms in one wing, where some of these spaces were hallways, in the basement, housed equipment/machineries etc. Excluding such rooms, which were not meant for occupancy, left 115 rooms. The temperature data for these rooms was analyzed together to provide a summary view of indoor thermal conditions during the observation periods. **Figure 3** provides the mean, minimum, and maximum temperatures at each instant of record across all 13 weekly periods, for the 115 rooms.

Figure 3 depicts that the maximum and minimum temperatures show a broad range of variation. The current work was not intended towards narrowing

Table 1. *Ranges for outdoor temperature and heating water inlet temperature and deviations during the weekly DR control periods.*

Period	P2	P3	P4	P5	P7	P8	P9	P10	P11	P12	P13
Minimum outdoor temperature (°C)	1.0	1.1	−1.2	−1.5	1.1	0.4	−0.1	−3.2	−0.3	−10.1	−6.7
Maximum outdoor temperature (°C)	12.5	15.3	7.3	6.2	7.0	7.5	7.5	6.0	5.8	6.2	5.3
Range of deviation (°C)	−2.7	−3.8	−5.2	−5.5	−3	−5.8	−4.9	−6.1	−3.6	−21.1	−20.7
	2.1	5.7	5.8	5.7	0.8	5.2	5.8	5.5	7.3	10.7	10.9
Range of inlet water temperature (°C)	30.8	25.0	37.2	36.9	36.5	33.7	32.9	37.3	38.4	21.4	25.8
	45.1	48.4	54.1	52.4	46.8	50.2	52.3	51.5	55.1	66.6	62.8

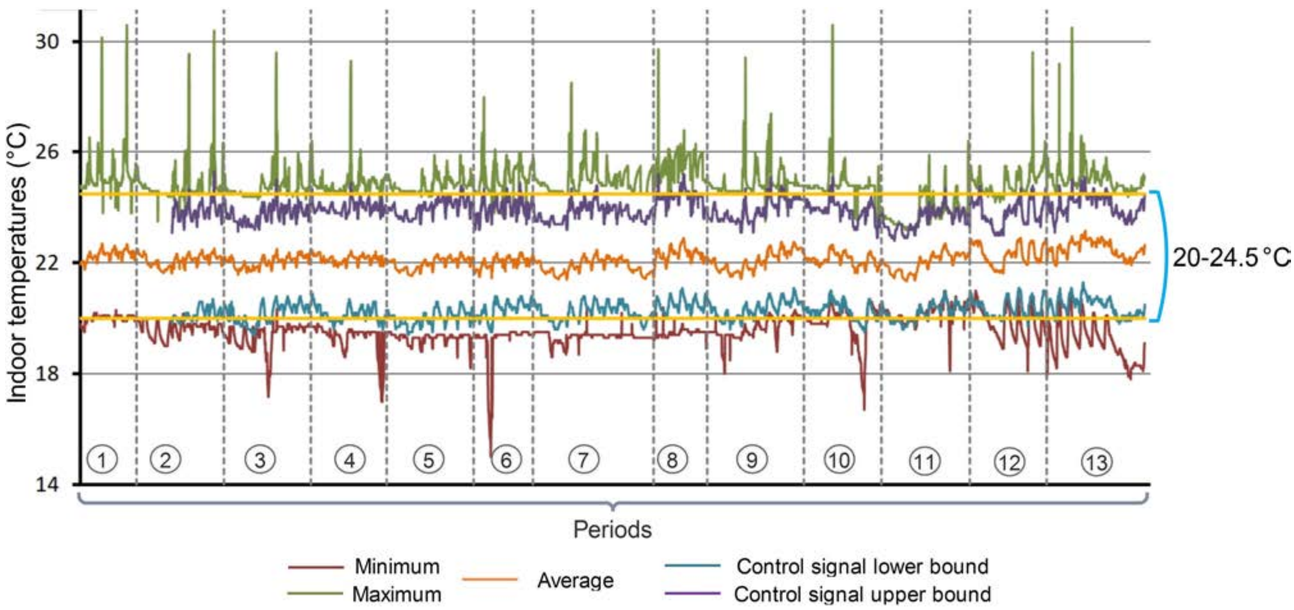

Figure 3. Summarized room air temperature conditions of the observed rooms.

Table 2. Occupant acceptance on thermal comfort during different periods.

Period	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13
Number:													
Negative	8	11	1	1	3	2	55	35	54	61	46	13	5
Positive	9	3	1	0	1	0	66	39	107	127	51	36	12
Percentage (%)													
Negative	47	79	50	100	75	100	45	47	34	32	47	27	29
Positive	53	21	50	0	25	0	55	53	66	68	53	73	71

down to the causes of such variations but, some possible reasons could be: higher/lower heat load than designed, balancing problem of water network or too high/low airflow rate for demand in certain spaces.

The results for room indoor temperatures show that the mean temperature pattern during the periods without DR control (P1 and P6) did not drastically deviate from the other periods when the DR strategies were implemented.

During the test periods, occupant acceptance on thermal comfort were collected (**Table 2**). Periods 12, and 13 fared particularly well with the occupants, each securing over 70% positive feedback in spite of the fact that much larger deviations in inlet water temperatures were allowed during these two periods.

It should be noted that during certain periods of implementations, very few feedbacks were received. However, based on the previous comfort studies, if the perception on thermal comfort is very low level, people start to compline anyhow. It seems so that it could be possible that the changes in the inlet water temperature can be as high as +10/–20°C without sacrificing thermal sensation of users. Because relatively low level of responses, more measurements are required to confirm this conclusion.

Conclusions

Based on simulations, demand response of district heating in public buildings gives around 5% heating energy cost savings, if room air temperature is accepted to vary between 20 – 24.5°C. Using centralized control strategy, the room air temperature of individual rooms is not possible to control accurately. In the studied building, the temperature variation is between 18 – 26°C in different rooms even demand response is not introduced. That makes challenging to get full benefit of demand response if there is no room or even zonal level decentralized control system. It seems so that it could be possible to change inlet water temperature quite a lot (about +10/–20°C) without users notice it. However, because relatively low level of responded persons, more measurement is required to confirm this conclusion. ■

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References

Martin, K. (2017). Demand response of heating and ventilation within educational office buildings; Master's Thesis. Aalto University. Espoo. http://urn.fi/URN:NBN:fi:aalto-201712187947.

Mishra, A. K., Jokisalo, J., Kosonen, R., Kinnunen, T., Ekkerhaugen, M., Ihasalo, H., & Martin, K. (2019). Demand response events in district heating: Results from field tests in a university building. Sustainable Cities and Society, 47, 101481. https://doi.org/10.1016/j.scs.2019.101481.

Mäki, A. (2018). Demand response of space heating using model predictive control in an office building; Master's Thesis. Aalto University. Espoo. http://urn.fi/URN:NBN:fi:aalto-201812146470.

Salo, S., Hast, A., Jokisalo, J., Kosonen, R., Syri, S., Hirvonen, J., & Martin, K. (2019). The Impact of Optimal Demand Response Control and Thermal Energy Storage on a District Heating System. Energies, 12(9), 1678. https://doi.org/10.3390/en12091678.