# A field study of space heating control using acceptable set-point temperature estimation: winter experiment in Japan office

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**Abstract.** Energy conservation for space heating is important because a large portion of total energy consumption is used for space heating in cold regions. For example, space heating accounts for 40% and 18% of energy consumption in non-residential buildings in the EU and Japan, respectively. We have recently proposed a new space-heating control method that estimates acceptable set-point temperature based on survival analysis of historical data on set-point temperature adjustments by occupants in a space. By using survival analysis to estimate acceptable set-point temperatures, the proposed method adjusts the set-point temperature of the space to the estimated minimum acceptable value. We present the results of a field study of the proposed method which was performed in winter 2017-2018 in Japan. In this study, we applied the proposed method. Performance evaluation experiments were carried out twice in the winter. The energy-saving rate was from 3% to 45%, and the occupant acceptance ratio exceeded 80% in both experiments. The results obtained in this study confirm that the proposed method is acceptable to occupants, while having a possibility of energy-saving.

## **1** Introduction

Appliances for space heating are among the most important targets for energy conservation, because space heating accounts for a large proportion of total energy consumption in some regions. For example, space heating is responsible for about 40% of the energy consumption in non-residential building in the EU [1] and about 18% in Japan [2]. Space heating is expected to use 35 000 PJ worldwide and consume energy the most among energy-consuming objects by 2050, despite the fact that energy consumption for space heating is declining year-by-year [3]. Zero energy buildings (ZEBs) are increasing popular [4-6], and energy conservation for space heating is an important factor in realizing ZEBs in cold regions. Limits on power generation in ZEBs make it necessary to save as much possible. Therefore, energy as energy-saving technologies for space heating are indispensable not only for ordinary buildings, but also for ZEBs.

Advances in smartphone technologies have made it easy to directly collect thermal sensation data from building occupants (occupant feedback). Some studies have used such occupant feedback via smartphones or PC applications for HVAC control [7–12]. These studies aimed at utilizing occupant feedback data to realize energy conservation while maintaining occupant comfort. Occupant feedback was generally collected within a fixed timeframe, and controls performed when aggregated occupant feedback within the timeframe exceeded a threshold. However, the durations of room temperature and set-point temperature were not considered in the control methods of previous studies.

To develop a control method that combines occupant feedback with duration of set-point temperature, we have proposed a control method based on estimated acceptable set-point temperature [13-15], where effectiveness of the proposed method was evaluated for residential area. This method regards set-point temperature adjustments by occupants as occupant feedback and considers set-point temperature records in its estimations. Key estimations in this method are based on survival analysis, a statistical method widely used in medical statistics for analysing time until an event occurs [16]. Besides medical events, survival analysis can be applied to other events of interest, and here we use it to construct a statistical model for set-point durations from historical data on set-point temperature adjustments. The details of the proposed method are described below.

We have confirmed the effectiveness of energy conservation through the proposed method in a residential area of a building in France [14,15]. This building was used as a demonstration experiment for realizing a positive-energy building (PEB), a concept similar to that of ZEB, but for buildings that consume less energy than they generate (through use of renewable energy, combined heat and power units, etc.) The results showed that the proposed method can reduce energy consumption for space heating by about 20% by following occupant adjustments of set-point temperature and updating acceptable set-point temperature as learned from this occupant feedback. In this evaluation, we did

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not explicitly confirm that acceptable set-point temperature as estimated by the proposed method were actually acceptable to the building occupants. Also, because the proposed method was evaluated in a residential area using a home energy management system (HEMS), we did not verify whether the proposed method is useful in non-residential spaces, particularly offices. Some office buildings have building energy management systems (BEMS) [17], and the proposed method may be more suitable to office areas because it can be executed by BEMS.

The purpose of this paper is to verify whether the proposed method is acceptable to occupants while still achieving energy conservation. To that end, we performed an office field test in winter 2017-2018 in Japan. In this experiment, we considered the occupant acceptance ratio, defined below, in addition to the energy saving rate.

The remainder of this paper is organized as follows. Section 2 outlines survival analysis and the proposed control method. Section 3 explains the office experiment conducted in Japan. Section 4 gives the results of the field test. We discuss the results in Section 5. Finally, Section 6 concludes this paper.

## 2 Overview of the proposed method

The following is an overview of survival analysis and the proposed control method. We gave a similar explanation of the proposed method in [13–15].

Before explaining survival analysis, we review the characteristics of set-point temperature adjustments by occupants. The duration of an acceptable set-point for space heating is liable to be long, because occupants will likely not change the set-point to a higher one soon. In contrast, the duration of an unacceptable set-point is often short, because the occupants will soon raise the setpoint. From these characteristics of set-point temperature, it may be necessary to consider set-point durations to develop a control method that maintains occupant comfort. We therefore use survival analysis, which as mentioned above combines time and events. In addition, survival analysis considers censoring. In this paper, a set-point change to a higher temperature is considered as an event in the proposed method, while adjustment to a lower set-point, or halting of space heating is censored. Figure 1(a) shows an example dataset for survival analysis. The lines marked "E" or "C" are times over



(a)

The marks "E" and "C" indicate an event and a censoring, respectively.

which sample points are monitored, with E indicating an event and C indicating a censoring. This line is called the survival time. "Event" indicates a status of interest, and "censoring" indicates any non-event status. The study period in Figure 1(a) indicates the observation time over which sample points are monitored. In medical statistics, we often want to know how long patients with a disease will survive. In this case, we regard death as an "event" and other reasons for loss of a patient are "censored."

In survival analysis, we use this data to construct the survival probability, which is the probability that a sample point will survive for a given time (see Figure 1(b)). According to this definition, the survival probability is mathematically given as

$$F(t) = \Pr(T > t), \ 0 < t < \infty$$
(1)

where T is a random variable representing the time until the occurrence of an event. Pr (T > t) is the probability that no event occurs before time t. The calculation of F(t) considers the status of sample points. We often model this F(t) by the Weibull distribution, such that F(t)is given by

$$F(t) = \exp\left(-\left(\lambda t\right)^p\right), \ \lambda, p > 0 \tag{2}$$

where  $\lambda$  and p are scale and shape parameters, respectively. The parameters are generally calculated by maximum likelihood estimation.

Survival analysis is a useful tool for analysing setpoint temperature adjustments because its duration continues for some time, and we can regard changes by occupants via a thermostat or a controller as events or censorings. From this viewpoint, we construct a statistical model for set-point temperature duration to estimate acceptable set-point temperature.

The proposed method estimates acceptable set-point temperature and adjusts the set-point temperature to the minimum acceptable value.

Figure 2 shows the flow for estimating acceptable temperatures for space heating. In this example, we assume that 19 °C is unacceptable and that 20 or 21 °C are acceptable. In Figure 2(i), the duration of the unacceptable set-point temperature tends to be short, while that for the acceptable set-point temperature tends to be long. As mentioned above, we consider that a setpoint change to a higher temperature is an event and adjustment to a lower set-point, or halting of space heating is censored. We calculate the survival probability F(t) for each set-point from data comprising durations and labels. We consider the survival probability F(t) for each set-point to be an acceptable rate as follows. The acceptable rate F(t) at each set-point temperature is calculated by the Weibull distribution. Figure 2(ii) shows behaviors of acceptable and unacceptable set-point temperatures. As Figure 2(ii) shows, F(t) for 19 °C decreases steeply, while those for 20 °C and 21 °C do not. Parameters  $\lambda$  and p determine the form of F(t). By using a decision boundary, we can determine whether a set-point temperature is acceptable, based on the positional relationship between point  $(\lambda, p)$  and the



Fig. 2. Schematic of estimation of acceptable set-point [13–15].

boundary (Figure 2(iii)). The decision boundary is calculated beforehand from durations and labels for temperatures whose acceptability has been given by some occupants. In this study, we used the decision boundary obtained from the data by residents in Japan.

We next describe changing set-point temperature to its minimum acceptable value from estimations by the above method. We can suppose that the minimum setpoint temperature should be the most energy-saving setpoint among the estimated acceptable values. However, we cannot tell which set-point is the minimum acceptable one when first applying the proposed method; it is necessary to first use a set-point temperature lower than that set by occupants over a certain period, during which a system giving a control instruction to a HVAC appliance applies no changes. We thus adhere to the following procedure.

- 1. Allow occupants to use space heating without constraint for a fixed time, such as one week.
- 2. From data obtained during the previous step, estimate the minimum acceptable set-point temperature. Then, change the set-point temperature to one lower than the minimum acceptable set-point several times each day. Conduct this trial over a fixed period, such as one week.
- 3. Check whether the applied lower set-point temperatures are acceptable. If so, use it over another fixed time. Otherwise, use the minimum acceptable set-point temperature.
- 4. Repeat steps 2 and 3. (Step 1 might be repeated if control time is enough.)

The proposed method assumes that lowering set-point temperature can lead to more energy-saving. This

assumption may hold only in cold periods; it might not be valid in warmer periods.

Parameter  $\lambda$ 

## **3 Office experiment**

### 3.1. Office areas for experiment

We used two office rooms: a small, closed room and a large, open room. Figure 3 shows the layouts of the two rooms. In Figure 3, boxes labeled "A/C" indicate the locations of ceiling air conditioner (A/C) indoor units. There were two A/C indoor units in the small room. The large room had six A/C indoor units in the office space



**Fig. 3.** Schematic of two office rooms. One is a small, closed room; the other is a large, open one.

and four in a conference space, which are not depicted in Figure 3. Each A/C indoor unit is controlled by a remote controller. A/C indoor units in the small room were controlled simultaneously.

To realize the proposed method, we set up a system that collected set-point temperature adjustments by occupants and input set-point temperatures to the A/C indoor units.

## 3.2. Field test

Figure 4 shows the flow (experimental steps) of the field tests, which were conducted in the office rooms in winter 2017–2018. The flow comprises three steps. The first step was data collection only. The second step was a phase where the temperature was set 1 °C below the minimum acceptable set-point as learned from data from the first step. This corresponds to step 2 of the procedure described in Section 2. The minimum acceptable setpoint was calculated for each of the A/C indoor units other than those in the small room. A/C indoor units in the small room had the same minimum acceptable setpoint temperature. The third step was an evaluation phase, where we randomly allocated days when the proposed method was applied (the minimum acceptable set-point learned from data during the second step was input by the system) and not used in a 1:1 ratio. After the third step, we returned to the first step. In the second and third steps, we did not change set-point temperature when it was already below the target value. Note that we repeated the first step where no control was done by the system for fear that long-term control by the system might bring about occupant discomfort.

The field test was performed as follows: As Figure 4 shows, the data collection was first performed from the middle of December 2017. About two weeks after the data collection, we conducted the second step in Figure 4, where a set-point 1 °C lower than the minimum acceptable value was used for 6 days. We then conducted the performance evaluation for 10 days in the third step. We thus had 5 days each in which the proposed method was used and in which it was not (the minimum acceptable set-point was not input by the



Fig. 4. Experimental steps of the field test.

system). Using data from the performance evaluation step, we checked occupant acceptance ratios and energysaving rates under the proposed method, as defined in the following subsection. After the third step, we sequentially repeated all the three steps, where 6 and 5 and 10 days were used for the first and second and third steps, respectively. Therefore, we performed the performance evaluation step twice in the field test.

In this field test, there were three daily periods (10:00-12:00, 13:00-15:00, and 15:00-17:00). For each period, we estimated the minimum acceptable set-point and applied 1 °C lower than it at step 2 of Figure 4. At step 3 of Figure 4, we applied the estimated minimum acceptable value for each period on the days when the proposed method was used.

#### 3.3. Evaluation index of performance evaluation

This subsection defines the occupant acceptance ratio and the energy-saving rate used in the performance evaluation step (step 3 in Figure 4). The occupant acceptance ratio is the percentage of the number of trials in which occupants did not raise the set-point temperature above the minimum acceptable value, out of the total number of trials in which the minimum acceptable set-point temperature was used. The occupant acceptance ratio  $R_{OA}$  is given by

$$R_{\rm OA} = N_{\rm acceptance} / N_{\rm total} \times 100, \qquad (3)$$

where  $N_{\text{acceptance}}$  is the number of trials in which occupants did not change the minimum acceptable setpoint temperature and  $N_{\text{total}}$  is the total number of trials. Cases where the set-point used was below the minimum acceptable value but occupants did not raise it are regarded as acceptable. The occupant acceptance ratio was calculated over the three periods.

The energy-saving rate  $R_{ES}$ , an indicator of energy saved by applying the proposed method, is calculated as

$$R_{\rm ES} = (E_{\rm No\ control} - E_{\rm Control}) / E_{\rm No\ control} \times 100.$$
(4)

The numerator here is the difference between energy consumption on days when the system did not set the minimum acceptable temperature ( $E_{\text{No control}}$ ) and that on days when the system did set the minimum acceptable temperature ( $E_{\text{Control}}$ ). The denominator is  $E_{\text{No control}}$  alone.

We carried out performance evaluations twice in the field test, and the following section gives results for the performance indices in each evaluation.

## 4 Results

Figure 5 shows acceptable rates of set-point temperatures calculated from the data of an A/C indoor unit at step 2 in Figure 4 during the first evaluation. In Figure 5, we had three set-point temperatures:  $22^{\circ}$ C,  $23^{\circ}$ C and  $25^{\circ}$ C. Since  $23^{\circ}$ C was the minimum acceptable value before step 2, the proposed method adjusted set-point temperature of the A/C indoor unit to



**Fig. 5.** Acceptable rate of set-point temperatures for an A/C indoor unit (calculated from the data of step 2).

22°C at step 2. From the parameters obtained from the Weibull distribution in Figure 5, we classified 22°C as acceptable and used it at step 3.

Table 1 shows the minimum acceptable set-point temperature used in the two performance evaluation steps (step 3 in Figure 4). Here, we give the results for each A/C indoor unit. In Table 1, the "Small room" A/C indoor units are those in the small room, and indoor units "L1" through "L6" are those in the large room. These labels correspond to those in Figure 3. There are three set-points for each evaluation, which indicate set-points in the three periods.

 Table 1. Minimum acceptable set-point temperature at the performance evaluation step.

A/C indoor unit	1 <sup>st</sup> evaluation (°C)	2 <sup>nd</sup> evaluation (°C)
Small room	22/22/22	23/23/23
L1	22/22/22	21/21/21
L2	23/22/22	22/22/22
L3	21/21/21	22/22/22
L4	22/22/22	22/22/22
L5	22/22/22	23/23/23
L6	22/22/22	21/21/21

As shown in Table 1, the minimum acceptable setpoint temperatures are almost the same in each period except for indoor unit "L2." The minimum acceptable set-point temperatures for some A/C indoor units increased as the evaluation step changed; those for other indoor units decreased.

Figure 6 shows the occupant acceptance ratios in each evaluation step. The occupant acceptance ratios are given for each room (small and large). In the small room, the occupant acceptance ratio was 80% in the first



Fig. 6. Occupant acceptance ratio.

evaluation and rose to 100% in the second evaluation. The occupant acceptance ratio in the large room, which was the average of the ratios for all A/C indoor units in that room, was 93% in the first evaluation and 99% in the second evaluation.

Figures 7 and 8 show daily average energy consumption in the small and large room evaluations, respectively. In these figures, the first and second bars respectively indicate energy consumption in the first evaluation where the proposed control method was used ("Control") and where it was not used ("No control"). The third and fourth bars respectively correspond to the case where the proposed control was and was not used in the second evaluation. Energy consumption in the large room included the conference space. On a day of the first evaluation, the office rooms received a demand response (DR) signal from an electric power company. We omitted this day for calculation of the average energy consumption, because the occupants in the office rooms lowered set-point temperature according to the DR



**Fig. 7.** Daily average energy consumption in the small room evaluation.



Fig. 8. Daily average energy consumption in the large room evaluation.

#### signal.

From Figures 7 and 8, the energy-saving rates in the first and second evaluations were respectively about 42% and 3% in the small room. In the large room, the energy-saving rates were 28% and 35%. Note that average outside temperatures in the first evaluation were 7.0 °C and 2.8 °C for "Control" and "No control", respectively. In the second evaluation, the average outside temperatures were respectively 8.8 °C and 9.4 °C for "Control" and "No control."

# **5** Discussion

As explained above, 22°C in Figure 5 was estimated to be the minimum acceptable value after step 2 in Figure 4, while 23°C was the minimum acceptable value before step 2. We can achieve an energy-saving space-hating control in this way. Going through this step in the proposed method enables us to judge whether it is possible to use a set-point temperature lower than that adjusted by occupants. Lowering set-point temperature and checking its acceptance is a very important step in the proposed method.

The minimum acceptable set-point temperature may change over time, because of changes of acceptable indoor temperature. The acceptable indoor temperature is likely to depend on ambient temperature, occupant clothing, and other factors. Therefore, it is necessary to use an adaptive search method for the minimum acceptable set-point temperature. For this purpose, the proposed method checks whether the used set-point temperature is acceptable and updates regularly the minimum acceptable set-point temperature, as shown in Section 2. Table 1 shows that the minimum acceptable set-point temperature may change over time under the proposed method. This finding has also been confirmed in [15].

In the field test, we divided a day into three periods. From Table 1, the minimum acceptable set-point temperatures were almost the same over the three periods. Therefore, it may not be necessary to estimate minimum acceptable set-point temperature for space heating by period under the proposed method.

The occupant acceptance ratio exceeded 80% for both the small and large rooms. Figure 6 suggests that the minimum acceptable set-point temperature as calculated by the proposed method is satisfactory for occupants, to the extent that they did not change setpoint temperature set by the proposed method. After the first evaluation, we again performed the second step, where the temperature was set 1 °C below the minimum acceptable set-point. By repeating the second step in Figure 4, the proposed method may be able to gradually seek a minimum acceptable set-point temperature suitable to the occupants.

Figures 7 and 8 show that energy-saving rates varied from 3% to 42%. This result may be attributable to differences in average outside temperature between the days when the proposed control was and was not used. As mentioned above, the energy-saving rate in the first evaluation was affected by low outside temperatures on days when the proposed control was not used. In addition, the energy-saving rate of the large room in the second evaluation might have been affected by use of the conference space, although we did not monitor use of conference space A/C indoor units and randomly allotted usage days to normalize such effects. In spite of the possibility that the use of conference space A/C indoor units affects energy consumption, the small-room results in the second evaluation suggest that the proposed method is useful for energy conservation in a non-residential area, as we showed for residential areas in [13,15].

# **6** Conclusion

We presented the results of a field study of a new spaceheating control method that uses acceptable set-point temperature estimation based on survival analysis of historical data on set-point temperature adjustments by occupants in a space. The proposed method adjusts setpoint temperature in the space to an estimated minimum acceptable value. In order to grasp effectiveness of the proposed method in an office, we performed a field test in winter 2017-2018 in Japan. We applied the proposed method in two office rooms and assessed energy saving rate and occupant acceptance ratio. The performance evaluation experiment was carried out twice in the winter. The energy-saving rate was from 3% to 45%, whereas these values were affected by ambient temperatures. It is necessary to note that ambient temperatures were largely different between the days with and without control in the first evaluation. The occupant acceptance ratio exceeded 80% in both the experiments. The results obtained in this study suggest that the proposed method has a possibility of energy conservation, while maintaining set-point temperature that is acceptable to occupants in office rooms.

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