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Space Heating Control by Estimating Acceptable Set-Point Temperature Based on Survival Analysis

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ABSTRACT This study proposes space heating control that considers both the operating time and change status of set-point temperature. To estimate acceptable set-points from such data, survival analysis is used to model acceptable rates of set-points. The proposed method determines whether a given set-point is acceptable based on the shape parameters of the acceptable rate. According to the determination, the proposed method inputs a new set-point. The proposed method is evaluated using data obtained from an experiment where the proposed method was applied to apartments in a newly constructed building in France. Set-points for the apartments were input according to the proposed method in an experiment performed for 3 weeks from the end of November 2016. This study shows transition of input set-points that were estimated to be acceptable during the experiment. The present paper evaluates the use rates of input set-points by groups according to the estimated acceptability of input set-points. This study also shows rough computations of energy-saving effects by the proposed method. A benefit from considering the operating times of set-points is also presented. The results demonstrate that the proposed method likely uses a set-point suitable to each apartment for energy-saving, with avoiding incorrect estimation of acceptable set-points.

INDEX TERMS Acceptable set-point temperature estimation, space heating control, survival analysis, thermal comfort, zero energy building (ZEB).

I. INTRODUCTION

Development of zero-energy buildings (ZEBs) is under way globally [1], [2] and has been accompanied by the introduction of energy-saving technologies and active promotion of renewable energy. Since the renewable energy produced in a building is limited, realizing ZEBs requires saving as much energy as possible [3].

In the EU, for example, space heating consumes more than 40% of total energy consumption in non-residential sector and about 70% in the residential sector [4]. Therefore, to promote ZEBs, it is important to develop energy-saving technologies for space heating, which is one of the main functions of building automation [5]–[7].

With the advancement of smartphone applications, a growing number of studies use direct input by occupants when measuring the thermal comfort [8]–[12]. In these studies, direct inputs from occupants are collected through smartphone or PC applications and used for space heating and/or cooling control. Reference [13] estimated occupant comfort ranges from air-conditioner operations, and [14] used comfort range inputs by occupants to jointly minimize discomfort and energy use. After being input, the set-point temperature continues for some time. Therefore it is possible to consider not only the change status of occupant-operated set-points for space heating control, but also their operating time, since both depend on the thermal comfort of occupants. The aim of this study is to develop a space heating control method that considers both the change status and operating time of set-points.

To that end, this study proposes a control method based on acceptable set-points estimated from historical set-point data comprising change statuses of set-points and their operating times. In space heating operations, after a set-point

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temperature has continued for some time, the occupant may change it to a higher or lower set-point. This study applies survival analysis to such historical data. Survival analysis is a data-driven statistical approach used mainly in medical statistics to assess the times until the occurrence of an event, such as death or disease progression [15]. Here, survival analysis is applied to data consisting of operating time and the change status when the operating time ends.

This paper extends previous studies by the author. One of these studies [16] used household data collected in Japan to obtain a decision boundary that determines whether a set-point is acceptable. Details of this decision boundary are described below. Reference [17] obtained energy-saving possibilities by assuming a decision boundary applied to room temperatures measured in 200 volunteer households in France. The proposed method was not actually applied in that study, but rather evaluated through data analysis. Further, the present study uses data different from those used in [17]. Reference [18] partially reported the first experimental evaluation, where the proposed method was actually applied in 36 apartments in France. That study showed how the acceptability of set-points is estimated using the proposed method, and presented brief energy-saving estimation results. A short report of partial results was also given in [19]. This paper presents further evaluation of the experiment described in [18]. The main extensions are as follows:

1) Analysis of input set-points by groups according to the estimated acceptability of input set-points during the experiment, including confirmation of the data in the week following the experiment.
2) Estimation of energy saving results for the acceptable and unacceptable input set-point groups.
3) An illustration of the benefits of considering the operating times of set-points.

Through these verifications, this paper clarifies the effectiveness of the proposed method and identifies remaining issues.

The remainder of this paper is organized as follows. The next section briefly introduces survival analysis. Section III gives an overview of the proposed method. Section IV describes the experiment and the system configuration for space heating in a building. Section V evaluates the proposed method, section VI describes the results of its use, and section VII discusses those results. Section VIII concludes the paper.

II. INTRODUCTION TO SURVIVAL ANALYSIS

This section introduces survival analysis, which is the core technique in the proposed method. Survival analysis treats sample points (objects), which have a "time" and "status." As described below, in the proposed method time and status are regarded as the operating time under a set-point and its change status. Fig. 1(a) shows a survival analysis dataset. The study period is the time during which sample points are observed. Sample points are indicated by horizontal lines marked E ("event") or C ("censored" or "censoring"). The horizontal line is the time from start to end of observation of a sample point. At the end of an observation, each sample point is labeled with "event" or "censoring." An "event" is a status of interest, while any other status is "censored." For example, an event may correspond to the death of a patient in medicine or the failure of a machine part in maintenance engineering. In contrast, "censoring" samples may correspond to the withdrawal of a sample point for some reason, such as the end of the study period. Application of survival analysis requires determinations of what should be regarded as an event and thereby what should be censored.

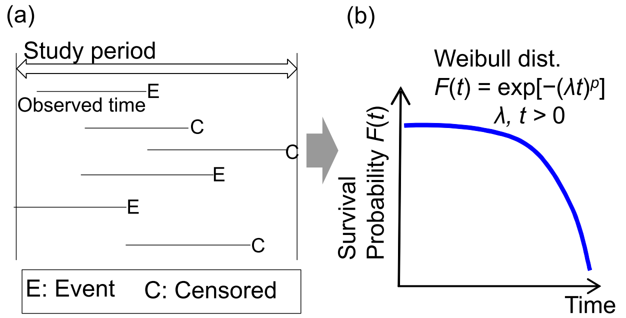

FIGURE 1. Overview of data for survival analysis and survival probability. The marks E and C indicate change statuses.

From the data, survival analysis calculates the survival probability, namely, the probability that a sample point will survive for some time (Fig.1 (b)). The survival probability (survival rate) is defined as

$$F(t) = \Pr(T > t), \quad 0 < t < \infty, \tag{1}$$

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 within time t. The calculation of $F(t)$ considers the status of sample points. The likelihood function for estimation of $F(t)$ is

$$L(\boldsymbol{\theta}) = \prod_{i=1}^{N} f(t_i; \boldsymbol{\theta})^{\delta_i} F(t_i; \boldsymbol{\theta})^{1-\delta_i}, \tag{2}$$

where i is the index of a sample point, δ_i denotes the status of the sample point (event: 1; censoring: 0), t_i is the time until that status occurs, and $\boldsymbol{\theta}$ are parameters for $F(t)$. The function $f(t)$ is the derivative of $F(t)$. $f(t)$ is used for sample points with events and $F(t)$ is used for those that are censored.

III. PROPOSED CONTROL METHOD

This section provides an overview of the proposed space heating control method, which comprises two parts: estimation of whether a given set-point is acceptable to occupants, and input of set-point based on that estimation.

Fig. 2 shows the flow for estimating acceptable set-points. Fig. 2(i) shows a schematic for historical data describing set-points and occupancy of a heated space, from which data for the proposed method are produced. As shown, 19°C, 20°C, and 21°C are used in this example, which changes the

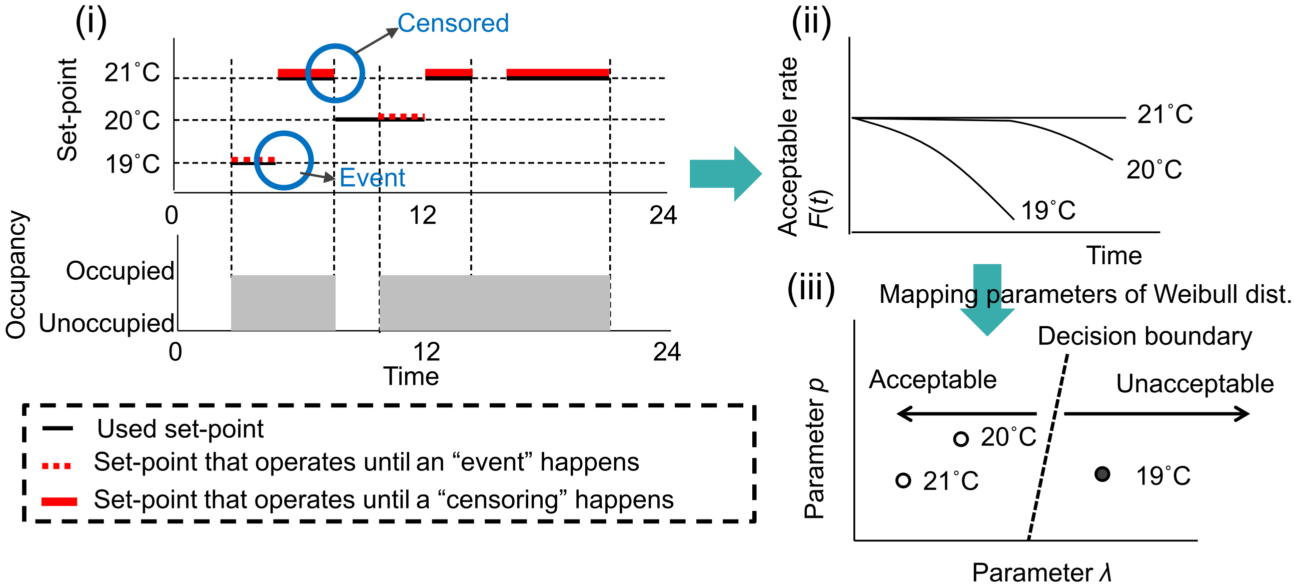

FIGURE 2. Schematic of acceptable set-point estimation. In this example, the set-points 20°C and 21°C are acceptable though 19°C is unacceptable.

19°C and 20°C set-points to 21°C. "Event" is added as the change status to the operating times for these set-points. The space is unoccupied when 21°C is used, and space heating is halted in another case where 21°C is used. The operating times for these cases are censored. Here, the operating times where the set-point was changed to a higher one are regarded as an event, and all other cases are censoring such as if the heated space becomes unoccupied or the set-point is changed to a lower one.

Inset (ii) of Fig. 2 illustrates survival rate $F(t)$ from the data described in Fig. 2(i). Here, $F(t)$ is modeled by the Weibull distribution, one of the most common parametric models used in survival analysis. $F(t)$ is then given by

$$F(t) = \exp[-(\lambda t)^p], \quad \lambda, p > 0, \tag{3}$$

where λ and p are scale and shape parameters, respectively. The survival rate of a set-point is called "acceptable rate" hereafter. In space heating, the operating time of an acceptable set-point tends to be long, while that of an unacceptable set-point tends to be short. Therefore, a set-point whose $F(t)$ steeply decreases with respect to time t can be regarded as unacceptable. Shapes of acceptable rates of set-points depend on the parameters of the Weibull distribution.

Fig. 2(iii) shows the parameter space formed by λ and p, where each set-point in Fig. 2(ii) is mapped. Set-points are estimated as acceptable based on the positional relationship between point (λ, p) and a decision boundary. The left side of the decision boundary is acceptable, so in Fig. 2(iii), 20°C and 21°C are acceptable and 19°C is unacceptable. This decision boundary is calculated from past data indicating whether certain temperatures are acceptable. A previous study [16] collected temperature operating times and their change statuses from volunteer Japanese families, who were asked to indicate whether certain temperatures were acceptable. That study applied a machine learning method (support vector machine) to those data to obtain the decision boundary used in the present study.

Using the estimation method described above, this study implements energy-saving control that considers the thermal comfort of occupants. The procedure is as follows:

1) Estimate acceptable set-points from the operating times of set-points and change statuses. Determine the minimum value from the acceptable set-points.
2) Input a set-point lower than the minimum acceptable value at regular intervals, such as two or three times a day. Continue this input for a fixed period, such as one week.
3) After the fixed period in step 2, determine whether the input set-point is acceptable from the data accumulated in step 2. If so, continue using it for another fixed period. Otherwise, use the minimum acceptable set-point as estimated from the data accumulated in step 2.
4) Repeat steps 1 through 3.

The proposed method updates the input set-point for the next period based on data obtained in the previous period. By repeating this procedure, the proposed method adaptively changes input set-points according to operating times and change statuses reflecting occupant thermal comfort.

IV. EXPERIMENT

A. ENVIRONMENT

The experiment was conducted in a residential area of a newly constructed building in Lyon, France. The residential area has 36 apartments. A home energy management system (HEMS) was installed into each apartment. This experiment was performed as part of a French-Japanese joint research project.

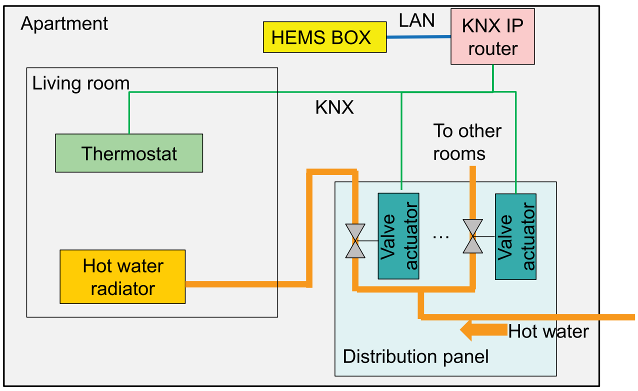

FIGURE 3. System configuration for space heating in an apartment used in the experiment.

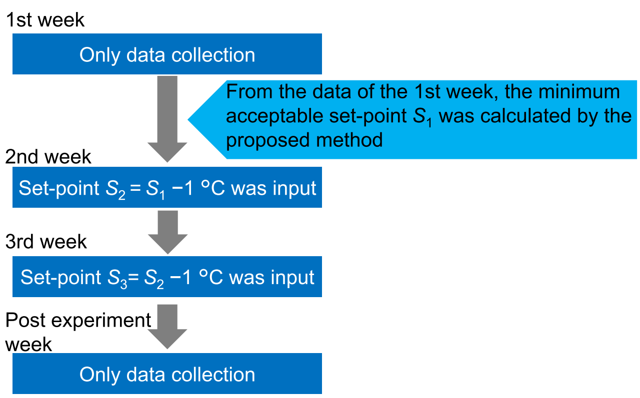

FIGURE 4. Flow of the experiment from the end of November 2016. The experiment was conducted over three weeks.

Space heating in the apartments was implemented using hot water produced by a 600-kW gas boiler and a 98-kW combined heat and power (CHP), both installed in the basement of the building.

The living rooms of the apartments were targeted in this experiment. Fig. 3 shows the system configuration for living room space heating in an apartment. Each living room had a thermostat (Theben VARIA 826 WH) and a hot water radiator. A valve actuator (Theben CHEOPS Drive) attached to a valve on a water distribution panel (Oventrop Multidis SF [20]) regulated water flow. Space heating control for each living room was realized by sending a valve opening value from the thermostat to the valve actuator. The valve opening value was calculated according to the set-point and room temperature as measured by the thermostat.

A HEMS BOX was installed in each apartment as a gateway and local controller. The HEMS BOX collected data about the set-point temperatures used in the thermostat via a network employing KNX, a home and building automation protocol widely used in Europe. Thermostat set-points could be changed manually or by using the HEMS BOX.

B. EXPERIMENT DESCRIPTION

Fig. 4 shows the flow of the experiment. The first week was used for only data collection. On Monday of the second week, the author checked the first week's data. In this check the author confirmed that the experiment was progressing smoothly, by knowing whether the data were collected properly, which set-point was used, and how long the residents occupied. The author then calculated the minimum acceptable set-point temperature S_1 for each living room, from the data collected in the first week. From Tuesday to Friday of the second week, set-point $S_2 = S_1 - 1$°C was input twice daily at predetermined times in each living room. On Monday of the third week, the author checked the data from the second week. From Tuesday to Friday of the third week, the set-point for each living room was changed to $S_3 = S_2 - 1$°C, regardless of the acceptability of set-point S_2. The aim here was to grasp occupant acceptability to lowered set-points during the experiment. Input of S_3 was again applied twice daily in the third week. The author set the lower limit for set-point temperature to 18°C, and kept the set-point from becoming lower than this limit in the experiment. The forth week was set as the post-experiment week, during which no set-points were input and only data collection was performed for further analysis of potential for the proposed method.

Before the experiment was performed, a briefing about the experiment was held to residents. A brochure about the experiment was also distributed to all apartments. Residents therefore knew in advance that set-points would be changed and could be reset by them as desired. Residents could also opt out of the experiment if they preferred.

The HEMS BOX collected the operating times and change statuses for each set-point. The HEMS BOX also estimated living room occupancies based on data from motion sensors installed in each room of the apartments [21]. The proposed method estimated whether each set-point was acceptable from those data.

While there are simulation studies about space heating control based on valve regulation [22], [23], the experiment in this study actually changed living room set-point temperatures.

V. EVALUATION

From the data obtained in the experiment, this study analyzed the following evaluation items.

A. TRANSITION OF ACCEPTABLE INPUT SET-POINTS

As described in section IV-B, set-points were input during the second and third weeks. The author checked transition of input set-points that were estimated to be acceptable by the proposed method. Note that some apartments had acceptable and unacceptable input set-points in the second and third weeks, respectively. The next section will describe the number of the apartments whose input set-point was acceptable or unacceptable. In addition, the next section will illustrate how set-points are estimated to be acceptable by the proposed method.

B. USE RATES OF INPUT SET-POINTS

The author calculated use rates of input set-points in each apartment from the operating times during the experiment.

The use rate of input set-point S is given by

$$R_S = \frac{OT_S}{OT_{SH}}, \tag{4}$$

where OT_S is the operating time of set-point S and OT_{SH} is the total operating time of space heating. Since input set-points to the apartments in a week were classified into acceptable or unacceptable, distributions of use rates of input set-points in the week are separately given for each group of the apartments whose input set-points were acceptable or unacceptable. In the following, these two groups are called "the acceptable" and "the unacceptable" groups for each week. The author also confirmed whether input set-points of the acceptable group in the third week were used in the post-experiment (fourth) week, and whether these set-points were estimated to be acceptable.

C. ENERGY SAVING BY THE PROPOSED METHOD

Energy saving rates were calculated for the acceptable and the unacceptable groups in the second and third weeks. The energy saving rate is estimated according to valve-opening values and their operating times, because energy consumption by hot water radiators was not measured. The author therefore assumed that energy consumption is proportional to valve openings. This assumption is described as the valve flow characteristic of an equal percentage valve [24]. Specifications for the hot water distributor show that a valve of this distributor has characteristics similar to an equal percentage valve [20]. The energy-saving rate of input set-point S in the second or third weeks as compared with set-point S_1 in the first week is estimated by

$$E_S = \frac{\left(V_{S_1} - V_S\right) \cdot OT_S}{V_{S_1} \cdot \left(OT_{S_1} + OT_S\right)}, \tag{5}$$

where V_S and V_{S_1} are the average valve opening values when set-point S and S_1 were used, respectively. (5) means a potential energy saving effect obtained by use of set-point S in comparison with only use of set-point S_1. Distributions of energy-saving rates of input set-points are separately given for the acceptable and unacceptable groups. Note that this estimation is a rough computation and should be regarded as a reference value for understanding that the valve-opening values were reduced by lowered set-points. The energy-saving rate was obtained for the living room of each apartment, so energy-savings in this study are given at the room level.

D. BENEFIT FROM CONSIDERING OPERATING TIMES OF SET-POINTS

As described above, the proposed method estimates acceptable set-points not only from set-point change status (event or censoring), but also from the operating time of set-points. By providing an estimation result of an unacceptable input set-point, this paper shows a benefit from considering the operating time of set-points.

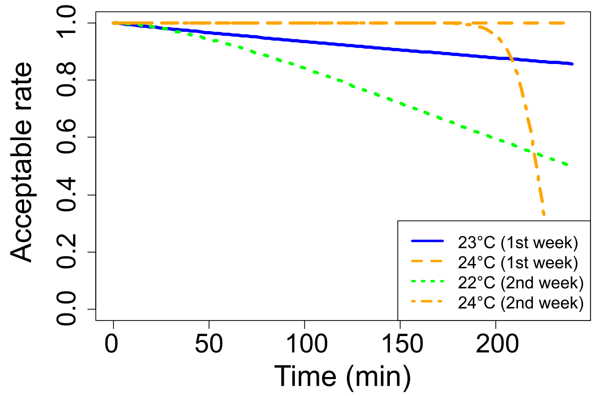

FIGURE 5. Acceptable rates of set-point temperatures for an apartment in the first and second weeks. In the first week, 23°C and 24°C were estimated to be acceptable. (See Fig. 6.) In the second week, the input set-point (S_2), 22°C, was estimated to be acceptable, while 24°C was also estimated to be acceptable.

VI. RESULTS

A. ACCEPTABLE INPUT SET-POINTS AND THEIR TRANSITION DURING THE EXPERIMENT

This subsection describes two results: how set-points were estimated to be acceptable by the proposed method, and how input set-points estimated to be acceptable were lowered during the experiment.

Fig. 5 shows acceptable rates of set-points of an apartment in the first and second weeks. The lines in this figure were obtained by applying the Weibull distribution to the operating times and the change statuses of each set-point, as described in Fig. 2(ii). The set-points 23°C and 24°C of the first week in Fig. 5 are estimated to be acceptable, because points (λ, p) of the acceptable rates of the set-points are found to be to the left of the decision boundary, as shown in Fig. 6. (Fig. 6 corresponds to Fig. 2(iii).) Therefore, the minimum acceptable value in the first week (S_1) was 23°C. The input set-point in the second week (S_2) was 22°C. Fig. 5 also shows acceptable rates for the set-points used in the same apartment in the second week. Although the positional relationship between the set-points of the second week in Fig. 5 (22°C and 24°C) and the decision boundary is not given here, the input set-point 22°C is estimated to be acceptable. Therefore, this apartment is classified into the acceptable group in the second week.

In the first week, minimum acceptable set-points were estimated for 23 apartments. Table 1 gives the number of the apartments that are classified into the acceptable and unacceptable groups in the second and third weeks. In Table 1, the acceptable and unacceptable groups in a week come from the acceptable group of the previous week. Table 1 shows that the input set-points for 3 out of the above-described 23 apartments were estimated to be unacceptable in the second week. In addition, one apartment was excluded in the second week, because it did not have normal data of valve-opening values. Table 1 also indicates that the input set-points for 5 out of 19 apartments of the acceptable group in the second week were estimated to be unacceptable in the third week. This is

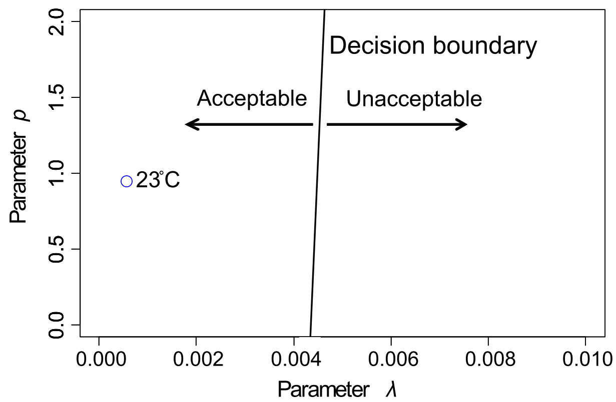

FIGURE 6. Positional relationship between the set-points of the first week in Fig. 5 and the decision boundary. 23°C and 24°C were to the left of the decision boundary and thereby they are estimated to be acceptable. (24°C was not depicted in this figure.)

TABLE 1. Number of the apartments classified into the acceptable and unacceptable groups in the second and third weeks. The acceptable and unacceptable groups in a week come from the acceptable group of the previous week.

Week	Acceptable group	Unacceptable group
Second week	19	3
Third week	14	5

because the unacceptable group in the third week is composed of the apartments whose input set-points of the third week were unacceptable and those of the second week were acceptable. Fig. 7 shows histograms of input set-points for the acceptable groups in the second and third weeks. Blue and green shadings show the input set-points for the second and third weeks, respectively. For comparison, a histogram of the minimum acceptable set-points obtained in the first week is also shown by red shading. To test for statistical differences between the distributions of set-points in each week, the author performed a multiple comparison test on the data. Applying the Wilcoxon rank sum test with Holm's adjustment [25], the p-value between the first and second weeks is 0.0041, the p-value between the first and third weeks is 4.0×10^{-5}, and the p-value between the second and third weeks is 0.0041. These results show that input set-points for the acceptable group were statistically significantly lowered during the experiment at the significance level of 0.01.

B. USE RATES OF SET-POINTS

Fig. 8 shows boxplots of the distributions of use rates of the set-points input to the apartments in the second and third weeks. These distributions are given for the acceptable and unacceptable groups for each week. The acceptable and unacceptable groups in the third week come from the acceptable group of the second week, as described in Table 1. Fig. 8 also shows the extent to which the set-points input in the third week were used in the fourth week. Use rates in the fourth week are also classified into the acceptable and unacceptable groups. These two groups in the fourth week come from

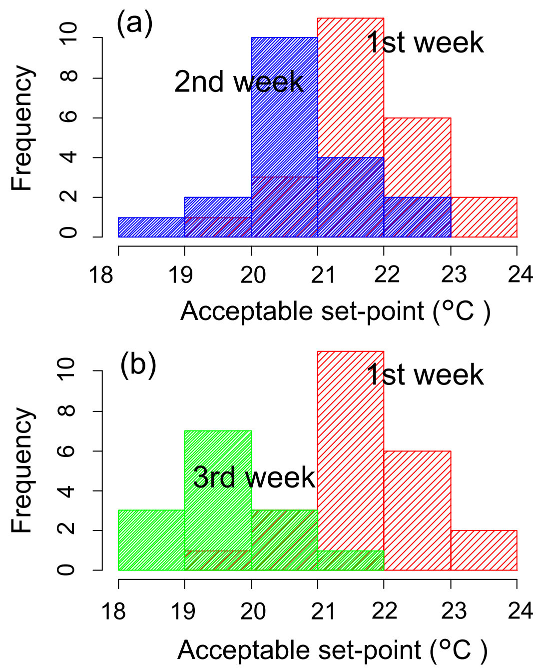

FIGURE 7. Histograms of the input set-points of the acceptable group in the second and third weeks. Blue and green shadings indicate the histograms of the second and third weeks, respectively. A histogram of the minimum acceptable set-point of the first week is also shown (red shading).

TABLE 2. Summary of use rates and energy-saving rates for the acceptable and unacceptable groups. Medians of the use rates are given from the second to fourth week. Those of the energy-saving rates are given in the second and third weeks. See Figs. 8 and 9.

Week	Group	Use rate	Energy-saving rate
Second week	Acceptable group	87%	34%
	Unacceptable group	45%	32%
Third week	Acceptable group	81%	38%
	Unacceptable group	36%	21%
Fourth week	Acceptable group	57%	N/A
	Unacceptable group	33%	N/A

the acceptable group in the third week. The number labels on each boxplot indicate the number of the apartments in each group. Table 2 summarizes medians of the use rates for the acceptable and unacceptable groups. (The energy-saving rates described below are also summarized.)

Fig. 8 shows that input set-points in the acceptable group are used longer than those in the unacceptable group. The use rates of the acceptable groups are not so different between the second and third weeks. The acceptable group in the fourth week, which used set-points input in the third week, has a wider range of use rate than those in the second and third weeks. Moreover, out of the acceptable group in the third week, 3 apartments had no data in the fourth week. In that week, 5 apartments did not use the set-points input in the third week and used higher ones. Note that no set-point was specified in the fourth week; residents themselves determined whether to continue using the third-week set-point in the fourth week.

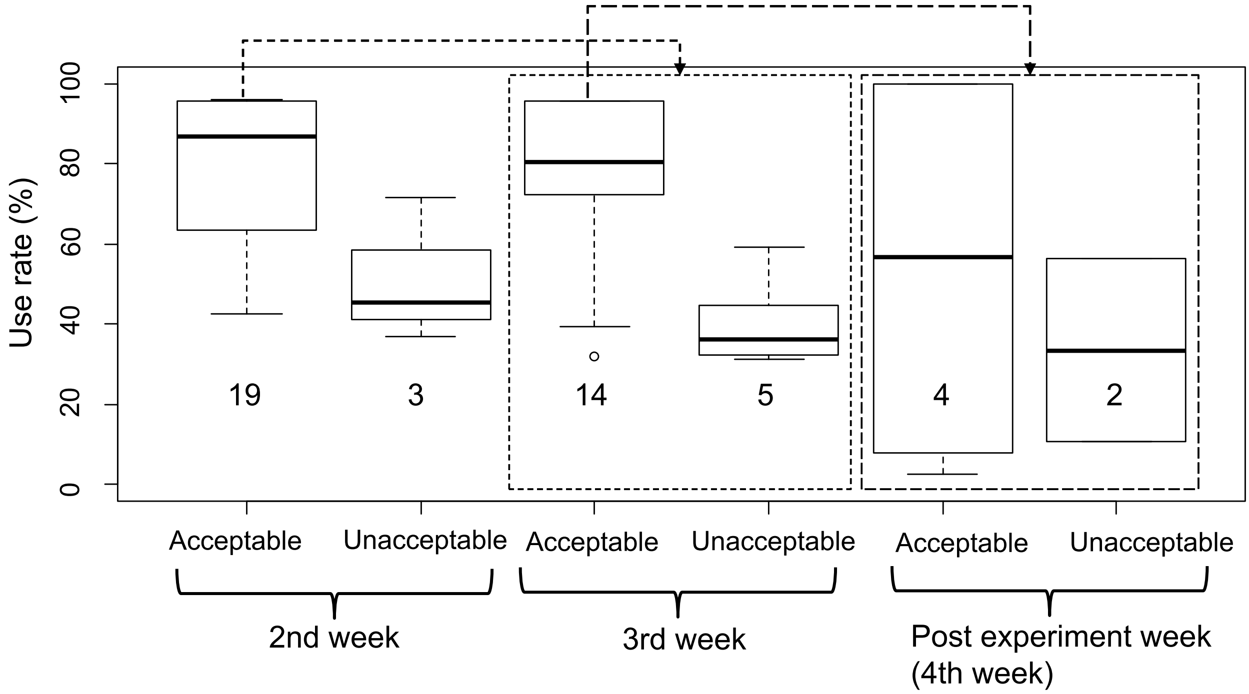

FIGURE 8. Boxplots of use rates of set-points input to the apartments. In each week, the boxplots are shown by acceptable and unacceptable groups. The thick solid line in each box is the median use rate, and the tops and bottoms of the boxes are, respectively, the 75th and 25th quantile use rates. The number labels on each boxplot indicate the number of the apartments in each group.

C. ENERGY-SAVING

Fig. 9 shows distributions of energy-saving rates for the acceptable and unacceptable groups in the second and third weeks. (See also Table 2.) Fig. 9 shows that the energy-saving rates of the acceptable groups are higher on median than those of the unacceptable groups. This observation can be explained by the result that the use rates of the input set-points in the acceptable group were higher. Fig. 9 also shows that the energy-saving rate in the third week is higher on median than that in the second week for the acceptable group. This is because lowered set-points in the third week reduced the valve-opening values more than in the second week. The energy-saving effect in Fig. 9 suggests that the proposed method is useful for energy-saving in the apartments overall if the proposed method is applied to each room of the apartments, because accumulation of energy-savings at the room level may contribute to energy-savings at the apartment and building levels.

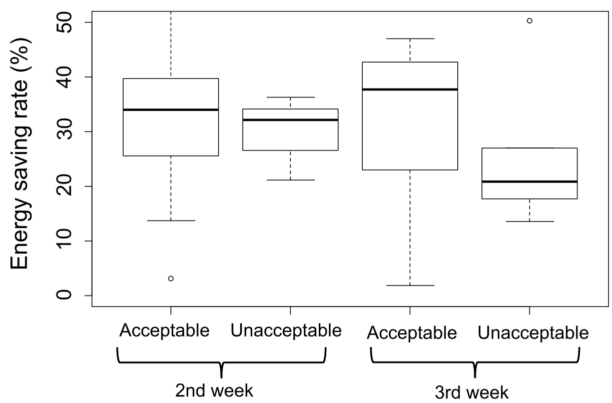

FIGURE 9. Boxplots of energy-saving rates in the second and third weeks. The boxplots are given by acceptable and unacceptable groups. The thick solid line in each box is the median energy-saving rate, and the tops and bottoms of the boxes are, respectively, the 75th and 25th quantile energy-saving rates.

D. BENEFIT FROM CONSIDERING OPERATING TIMES OF SET-POINTS

In the apartment treated in section VI-A, the input set-point in the third week ($S_3 = 21°C$) was estimated to be unacceptable. This apartment is thus classified into the unacceptable group in the third week. Fig. 10 shows an acceptable rate of 21°C for the apartment in the third week. In Fig. 10, the acceptable rate is given by not only the Weibull distribution but also the Kaplan-Meier estimate. Here, the Kaplan-Meier estimate is a non-parametric estimation method used in survival analysis. Downward steps in the Kaplan-Meier estimate in Fig. 10 indicate that set-point was changed to a higher set-point by the residents in the apartment. Among 40 records, there were only 2 changes from 21°C to a higher set-point in the third week, while 21 °C was input 8 times in the same week. Thus, a set-point of 21°C would likely be estimated to be acceptable by other methods, such as majority vote or average of occupant feedbacks [8]–[12], because there were only 2 changes from this set-point, and the change ratio is 0.25. Fig. 10 shows that the residents reset this set-point to a higher one within 20 minutes. The proposed method can consider

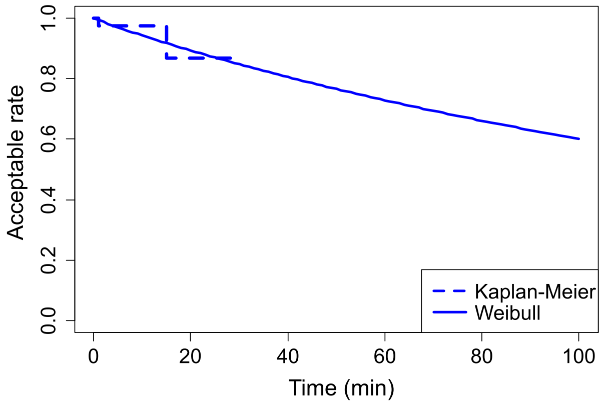

FIGURE 10. Acceptable rate of 21°C for the same apartment in the third week. The dashed line is given by the Kaplan-Meier estimate and the solid line is given by the Weibull distribution.

such quick resident reactions, because not only the change statuses but also the operating times are considered.

VII. DISCUSSION

Fig. 8 shows that the use rates in the acceptable group are higher than those in the unacceptable group for each week. In the fourth week, when no inputs were applied, 5 apartments belonging to the acceptable group in the third week used higher set-points than those input in the third week. As shown in Fig. 8, the use rate distribution for the acceptable group has a wider range in the fourth week. 2 apartments in the acceptable group used the third-week input set-points at less than 15% of use rate and adopted higher set-points most of time. The fourth week results probably suggest that some apartments used higher set-points without the proposed method, thereby losing energy-saving opportunities in terms of lowered set-points.

All except for one apartment participated in the experiment, and no complaints were received from participating households during the experiment, suggesting that twice daily input of set-points was not bothersome.

The proposed method is an extension of temperature setback control, which usually changes set-points to a fixed value such as a factory default. However, Fig. 7 shows that preferred set-points vary by apartment, so it is inappropriate to use the same value for all apartments in temperature setback control. The proposed method can determine what value should be used for each apartment. As an additional benefit of the proposed method, Fig. 10 shows that considering the operating times of set-points may be useful for avoiding incorrect estimation of acceptable set-points. In contrast, [11] proposed a drift control with a majority vote by occupants where set-point is changed every 30 minutes. The residents in this study may have found such frequent changes to be bothersome. Figs. 8 and 9 suggest that twice-daily set-point inputs are likely sufficient to keep set-points low.

In the experiment, set-points were lowered over three weeks. In the apartment whose results are shown in Figs. 5 and 10, $S_1 = 23$°C, $S_2 = 22$°C, and $S_3 = 21$°C. $S_3 = 21$°C was unacceptable; this apartment used a 23°C set-point in the third week, and mainly in the fourth week. Since the input set-point in the third week was 2°C lower than the minimum acceptable value in the first week, the input set-points in the third week were so much lower that some apartments, such as the one mentioned above, probably adopted the first week's set-point. Average temperatures outside of the building during the four weeks were 3.3°C, 2.8°C, 3.5°C, and 3.9°C. Therefore, the outside temperatures were not different between the weeks. In the above-described apartment, estimated daily occupation times of the second and third week were 682 min and 1105 min, respectively. This longer occupancy is probably one reason why the residents used a higher set-point in the third week. However, there is a possibility that the input set-point in the second week, S_2, was also acceptable in the third week. To further confirm that the proposed method adaptively updates input set-points, it is necessary to perform a trial in which a set-point is input again in one week after the same value has been input and acceptable in the previous week. This trial corresponds to step 3 in Section III.

As described above, the proposed method adaptively determines the input set-point for a new period according to the previous data. Since outside temperatures were similar during the experiment, there is need for evaluation of the proposed method across weeks when outside temperatures are quite different. A longer experiment, such as over an entire winter season, is needed to further evaluate this topic.

Energy savings in this study were obtained not from energy consumption of space heating, but estimated from reductions of the valve-opening values. These energy-saving results are thus given in terms of lowered set-points and subsequent reductions of the valve-opening values. Another evaluation that measures actual energy consumption should be demonstrated in a future study.

This study treated the living rooms where five people at most occupied. It remains unclear whether the proposed method applies to a large space accommodating more people, such as an office. Moreover, this study addressed only space heating. Future studies should extend the proposed method to space cooling, whose energy consumption is expected to increase [26]. The proposed method can likely be extended to space cooling by regarding a change status when set-point is shifted to a lower one as "event".

Some topics described here are currently under study in another research project [27] and should be explored further. Another topic for future work is incorporation of humidity as studied in [28] into the proposed method.

VIII. CONCLUSION

This paper presented space heating control that uses the operating times of set-point temperatures and their change statuses. By applying survival analysis to the data, the proposed method inputs a new set-point according to those estimated to be acceptable. This study experimentally evaluated the proposed method in actual use for over three weeks from the end of November 2016 in 36 apartments in a newly constructed building in France. The results show that the proposed method likely determines what set-point should be input to each apartment as an extension of setback control. Energy-saving effects have been confirmed in terms of lowered set-point temperatures and subsequent reductions of valve-opening values. There are several issues to be studied in future work. In particular, it is necessary to further confirm that the proposed method adaptively updates input set-points according to occupant feedback. To clarify this point, future work should include experiments where a set-point is re-input in the following period after the same value has been input and acceptable in one period.

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