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Predictive Heating Control and Perceived Thermal Comfort in a Norwegian Office Building

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Abstract: An office building in Trondheim, Norway, was used as a case study to test the influence of Predictive Control (PC) for the optimization of energy use on the employees' thermal comfort. A predictive control was implemented in the Building Energy Management System (BEMS) by operating on the supply temperature of the radiator circuit. A questionnaire was given to the employees to evaluate to what extent the operation of the predictive control influenced their perceived thermal comfort. Several factors known to influence employees' satisfaction (such as office type, perceived noise level, level of control, perceived luminous environment, perceived indoor air quality, adaptation strategies, well-being) were investigated in the questionnaire. The evaluation shows that the occupants rated the perceived thermal comfort as equally good compared to the business-as-usual operation. This is an important finding toward the user acceptance of such predictive control schemes.

Keywords: thermal comfort; predictive heating control; office building; perceived control; occupants' satisfaction

1. Introduction

The pursuit of reducing operational energy use in buildings to comply with the progressively stricter limits posed by the EU walks necessarily the path of implementing increasingly advanced Building Automation and Control Systems (BACS). BACS are defined [1–4] as software providing automation, monitoring, control, and optimization within the safe operation of building service equipment in order to maximize energy efficiency, reduce cost, minimize environmental impact, and provide indoor comfort. BACS are employed in the operation of various building services, such as domestic hot water production, lighting, heating and cooling, shading, mechanical and natural ventilation, and onsite power generation.

Within BACS, control systems and strategies play a fundamental role in ensuring the safe and optimized operation of the pieces of equipment to achieve operational energy savings, operational costs, and indoor comfort. Modern control and energy management systems offer the potential to optimize energy systems use and reduce energy consumption. As an example, model-predictive control (MPC) is a well-established method for anticipating the buildings' energy use in response to forecasted inputs in order to reduce their CO_2 emissions [5,6]. MPC is based on the concept of solving an optimization problem in single time steps for which both updated information on the building performance and forecasted inputs are given. MPC has been tested for building energy management as a multi-objective tool with the goal of achieving reductions in energy use, energy cost, peak-load shaving, etc. Applications of MPC have been tested and simulated on the operation of energy systems for space heating, ventilation, and air conditioning systems. Several studies show a consistent potential for energy and cost savings by using MPC. According to Kathirgamanathan et al. [7], data-driven predictive control shows an average saving of 23% for either cost or energy consumption compared to rule-based control systems when either simulated or tested in different non-residential buildings. According to Berouine

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et al. [8] the simulation of applying MPC to the operation of an air-conditioning system in a single-zone building shows a 68% energy saving in comparison to a conventional On–Off control. Nagpal et al. [6] simulate the application of MPC to reduce electricity use in a smart residential building. Their study shows that their proposed implementation of MPC in the Building Energy Management System (BEMS) achieves a 34% reduction in energy use when compared to a baseline scenario in which the BEMS operates without any optimization strategy. Yang et al. [9] tested the performance of an MPC implemented in the control of the air-conditioning and mechanical ventilation systems of two single-zone, an office and a lecture theatre, in Singapore. Their tested MPC shows a reduction of 58% and 37% for the energy use for cooling in the office and lecture theatre, respectively. However, Zhang and Chong [10] show in their review on the application of MPC for building operation that 70% of the research on MPC for building operation is based on simulation studies, whereas only 17% of the research demonstrates MPC in real full-scale buildings.

Despite the effectiveness of achieving energy savings in buildings where fully automatic control systems are operating, the limited availability to the buildings' occupants of environmental controls has been shown to reduce the occupants' perceived comfort [11–15], especially in open landscape layouts. As shown by Bordass et al. [11], users' perceived level of control diminishes for increasing numbers of occupants in the same room, due to the sharing of control (e.g., lighting, windows, shading) among more co-workers and lower accessibility to its operation. As found by Schweiker and Wagner [14], by increasing the number of occupants in an office environment, the perceived control and the thermal acceptability range decrease. As highlighted by Hellwig [15], the possibility for the occupants to exercise an effective behavior (control) to contrast a discomfort caused by the environment is perceived as pleasurable and hence it increases the occupants' perceived comfort. The limitation to exercising control and in general adaptive opportunities to reach personal comfort has been shown to induce stress in the occupants [16]. In this regard, Lolli et al. [13] found that the automatic operation of blinds in a single test cell environment led to a higher visual discomfort for the users and more frequent expressed desire to adjust the blinds, in comparison to a similar test cell where the users could operate the blinds manually. Similarly, Shahzad et al. [12] found that occupants in single-cell offices with higher levels of control expressed higher comfort than occupants of open landscapes with lower levels of control. However, the energy intensity per occupant measured in the open landscapes was 12% lower than that in the single-cell offices.

Several studies [17–22] on MPCs focus on the optimization of buildings' operation by mainly considering the energy use, the energy cost, and the occupant's thermal comfort as the parameters of analysis. Several other aspects that may influence the occupant's thermal preferences, such as perceived control, types of adaptation strategies, health, and sources of disturbance are often not investigated in such studies. Given the different objectives between the building occupants (higher comfort) and the BEMS (optimized energy use and cost), this work investigates the effect of implementing a Predictive Control (PC) in the energy management of an office building on the indoor environmental, psychological, and physiological factors that may influence the occupants' thermal comfort. Specifically, this paper has two objectives:

1. To evaluate to what extent the application of the PC influences the occupants' thermal comfort.
2. To investigate to what extent the occupants' perceived control, adaptation strategies, health, and the occurrence of stress factors influence the occupants' thermal comfort.

An office building located in Trondheim, Norway, is used as a case study, in which the existing operation of the BEMS is modified by implementing a PC in the building energy management. The output of the predictive control is the setpoint for the supply temperature of the water-based radiator circuits for the next 12 h aiming to keep a desired indoor air temperature setpoint while minimizing the radiator supply temperature. This paper is structured as follows: first, the method and limitations of the test (specifically on the number of participants, the length of the test, and investigated environmental parameters) are explained; second, the results of the survey are presented; third, the consequences of the findings of this paper and the limitations of the experiment are discussed; fourth and last, conclusions from this work are drawn.

2. Materials and Methods

The investigation of the perceived thermal comfort is part of a project on data-driven intelligent heating of office buildings, which aims to reduce energy use for heating while maintaining or possibly improving the occupants' thermal comfort. Data-driven intelligent heating is pursued by the implementation of a predictive control algorithm in the BEMS of office buildings. The thermal comfort survey aims to see whether occupants rate the thermal comfort worse or better with the implemented predictive control algorithm. This Section provides information on the case study building and practical limitations of the study, the approach toward the predictive control algorithm, and the questionnaire description.

2.1. Description of the Case Study

The case study building is a 6-story office building located in Trondheim. The building consists of a triangular block of offices built around an internal glass-covered courtyard for a total floor area of 4350 m^2. This work focuses on Block A, located toward the south-west side of the building (Figure 1). Different office settings are used in Block A: 1st floor is occupied by the canteen and restaurants; 2nd, 5th, and 6th floor have open landscape offices, whereas 3rd and 4th floor have single office layouts. Block A has a total capacity of 450 working stations distributed on a floor area of 1520 m^2.

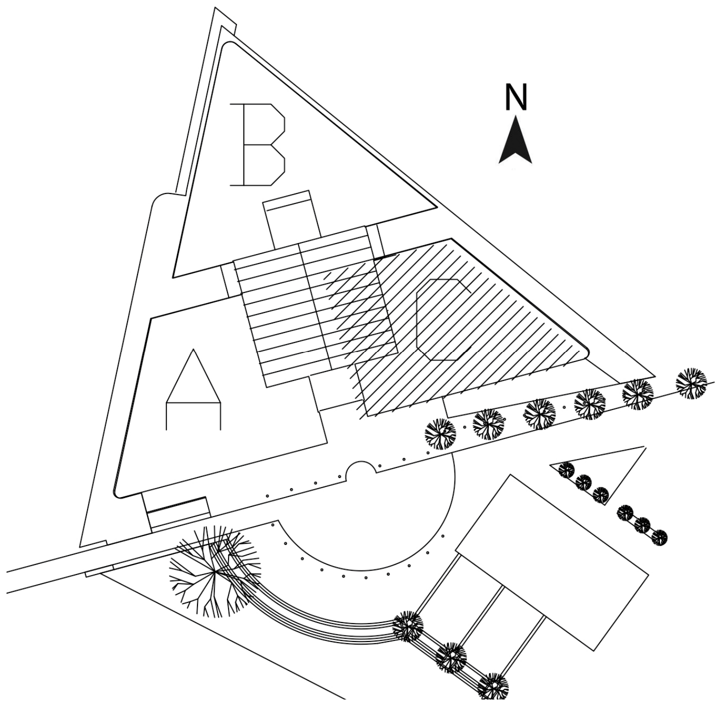

Figure 1. Schematic plan of the office building. The survey is performed for occupants in Block A (**bottom left**).

2.1.1. Landscape Office Layout

Figure 2 shows a floor of the building with a typical open landscape layout. Working stations are arranged in islands of four desks, of which two desks are adjacent to the windows on the external wall, and two desks are adjacent to the corridor. Depending on the size of the office, between 18 and more than 30 workstations are present in each landscape. Employees use a casual dress code. Employees sitting next to the external façade can manually operate the windows. Sun shading is automated and operated by solar radiation intensity. The automation system can be overridden by the employees via switches located either on the wall or hanging from luminaires, as shown in Figures 3 and 4. At least one control switch for the sun shading is present in each landscape. This means that some employees are very distant from the control switch. Internal curtains are also present. Water-based radiators with thermostats are located below the external windows. The occupants have access to controllers for the thermostat setpoints, which are located on the walls (Figure 4). By performing several tests on the thermostat controllers, these were found not to actually change the supply temperature in either the HVAC system or in the radiator circuits, despite the digital screens of the controllers showing to work properly. It was also found that the occupants were little aware of the placement or the existence of these controllers. Ceiling-mounted ventilation ducts with perforated diffusers run above the desks. Some working areas (mainly meeting rooms) face the internal atrium and, since they do not have an outside view, they are not affected by external weather conditions.

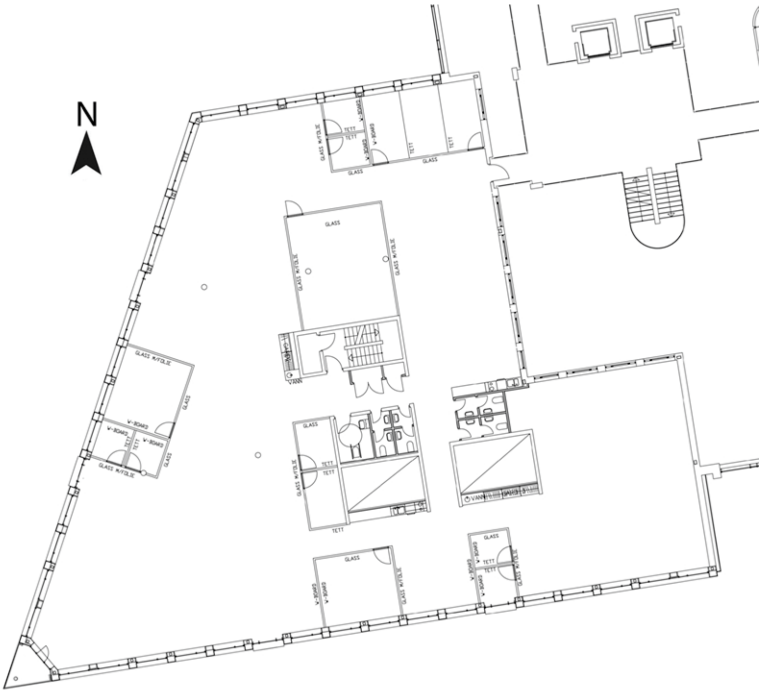

Figure 2. Landscape layout of a typical floor in Block A.

Figure 3. (**Left**): desk arrangement in a typical landscape layout: (**Centre**): daylight sensor for the operation of the external shading. (**Right**): ceiling-mounted diffuse ventilation channel.

Figure 4. (**Left**): thermostat regulator mounted on a radiator. (**Right**): wall-mounted thermostat controller.

2.1.2. Singe Office Layout

Figure 5 shows a floor of the building with a typical single office layout. Approximately 30 single offices and 10 meeting/break rooms are located on both 3rd and 4th floor, respectively, as shown in Figure 6. Some of the offices face the internal atrium. Each single office is typically shared by two employees (as shown in Figure 6 right). A dress code of a two-piece suit (corresponding to circa 1.00 clo) is used by the employees in the single-cell offices only. Water-based radiators with thermostats are located below the external windows. As in the landscape layout, the occupants have access to temperature setpoint controllers, which are placed next to the entrance door of each cell office. These controllers were similarly found not to factually operate on either the HVAC system or the radiator circuits, the reason for which is explained more in detail in the discussion Section. Indoor curtains are installed on the windows, and an automated shading system is installed on the external façade. This is controlled by solar radiation and can be overridden by the employees.

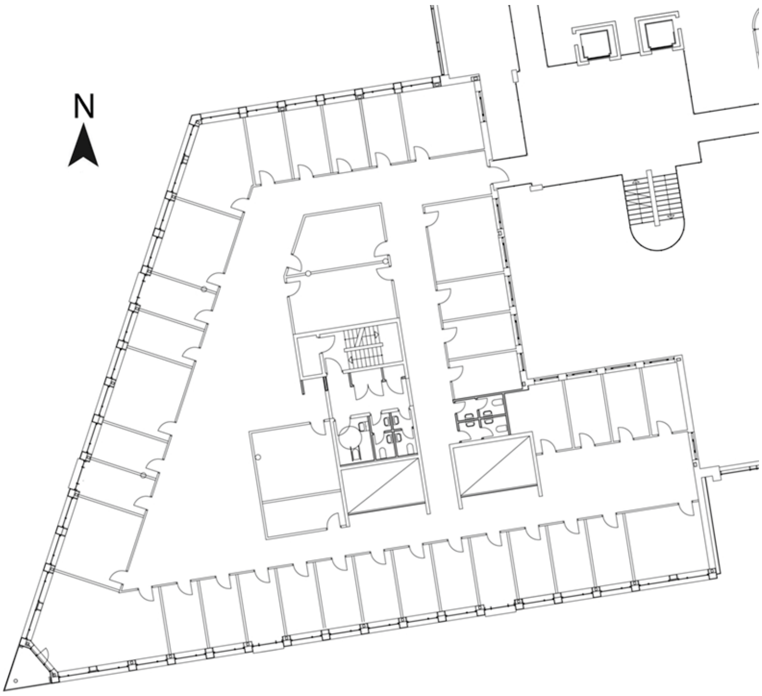

Figure 5. Cell-office layout of a typical floor in Block A.

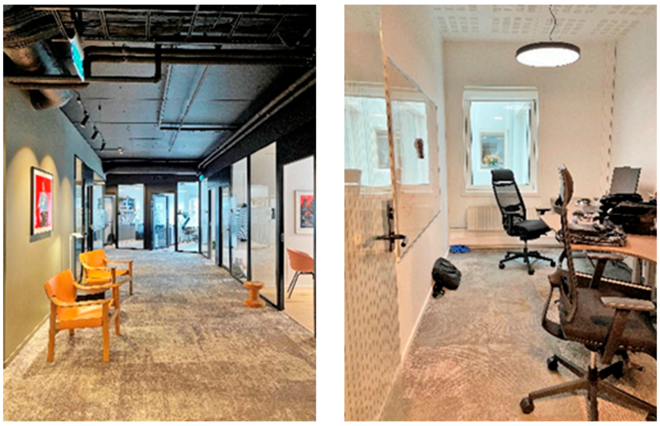

Figure 6. (**Left**): distribution corridor and access to single offices. (**Right**): internal desk arrangement in a typical single office.

2.1.3. Predictive Control of the Heating System

The building is connected to the district heating network of Trondheim and has a water-borne heat distribution system. In the project, the supply temperature of the radiators connected to the heat distribution system is adjusted independently of the outdoor air temperature. The predictive control algorithm checks every hour whether there is a heating demand in the rooms. If there is no heating demand, the radiator supply temperature is decreased. The algorithm then evaluates whether the measured room air temperature is higher or lower than the working setpoints in a case-specific number of rooms (e.g., 10 rooms). If the number of rooms that require heating is above the case-specific value, the supply temperature of the radiators is adjusted upwards toward the value of the heating curve. The case-specific value is chosen in cooperation with the building owner and the facility manager. A data-driven (black-box) model is used to predict the room air temperatures for the next twelve hours. This model uses the supply temperature as input to predict the room air temperature (which is measured by the sensors installed with the BEMS system), so that the control algorithm can decide which supply temperature is sufficient to satisfy the room temperature working setpoint. An analysis of the room temperatures was performed hourly to assess whether this was below the defined temperature setpoint. The use of the predictive control ensured that the time of the violation of the threshold below the minimum setpoint was minimal, thus providing a more stable thermal environment. The predictive control, therefore, does not operate by modifying the given temperature setpoint in each room. The model for the room temperature prediction is based on a global transformer architecture, particularly an encoder–decoder transformer. A detailed description of the prediction model is in [23]. The data-driven model is trained on 2 years of measurements that were performed before and during the project. Additional inputs to the data-driven model are weather forecast information, time of the day, as well as parameters related to the operation of the HVAC system, such as the status of the circulation pump, fan operation, and measured temperatures in the radiator circuits and ventilation system.

Regarding room temperature measurements, most room regulators are placed at around 1.5 m height from the ground. Each single-cell office has a room temperature sensor, whereas the open-space offices each have several sensors depending on the landscape area. Figure 7 shows the approximate position of the room regulators (measurement points of indoor air temperature).

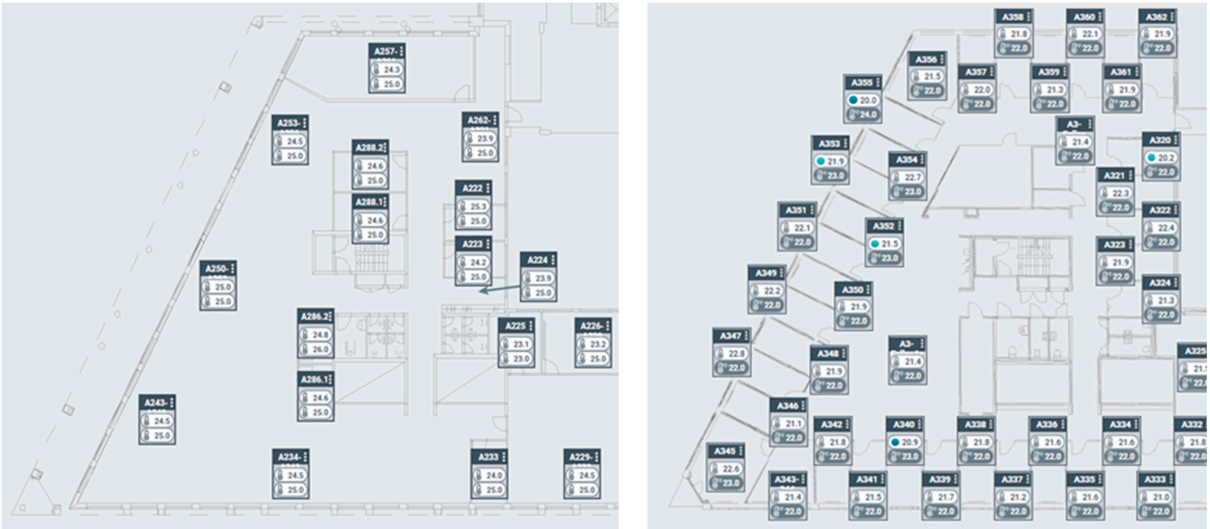

Figure 7. Location of indoor air temperature sensors for a floor with landscape layout (**left**) and cell offices layout (**right**).

2.2. Questionnaire Description

A questionnaire was developed to assess the variation in the perceived thermal comfort of the employees with and without the implementation of the predictive control in the BEMS. The goals of the questionnaire were two:

- Evaluate to what extent the new predictive control strategy modifies the employees' perceived thermal comfort.
- Evaluate the effect of other environmental and stress factors that may influence the employees' perceived thermal comfort.

An initial pilot study of the questionnaire was conducted in the researcher's own office, the ZEBLab in Trondheim. The goal of the pilot study was to estimate the response rate and response time to the questionnaire, in order to refine the number of questions before testing them in the case study. The pilot study was conducted during the last week of October 2022. Based on the results of the pilot study, the number of questions was reduced to 11, to make sure the response time was not going to exceed 2 min.

The questionnaire was delivered daily to the 324 office occupants who accepted to be part of the survey. These did not represent the total number of occupants since some did not agree to take part in the survey. A Netigate (www.Netigate.net, accessed on 31 January 2023) link was sent to the participants' emails once per day every day (at about 8:30 a.m.), and a reminder once per day every day (at about 12:00 p.m.). It was decided to send the questionnaire at the beginning of the working days to give the respondents as many hours as possible to answer. Since a typical working day in Norway begins at 8:00 a.m., it was assumed that a respondent answering at 8:30 a.m. had enough time to acclimatize to the indoor environment, as explained in more detail in Section 2.3. The participants could not answer the questionnaire twice on the same day (if they wished to do so) as this action was blocked. The identity of the respondents was not traceable, and the questionnaire was anonymous. The Netigate link was sent daily from 31 January 2023 to 16 February 2023, and from 21 March 2023 to 31 March 2023. The respondents were informed that the scope of the questionnaire was to assess their own perceived thermal comfort in the working environment. The respondents were informed of changes in the control system of the BEMS days after the start of the survey period and were not aware when the new control system was in operation. The questionnaire consisted of six sets of questions, which were divided as follows:

1. Type of workplace used by the respondent, single selection (private cell office, shared cell office, open landscape). The respondents were asked to notify whether they were sitting in an office or at home.
2. Floor number of workplace
3. Outside view (provided by pictures) from the closest window. Since on some of the floors, the office rooms are not given a unique identifier, this question helped locate the respondent's workspace in the building and the closest indoor temperature sensor (as shown in Figure 4). This also ensured the anonymity of the respondents.
4. Control, divided as follows:
    a. Question 4a: perceived control of indoor environment, discrete 5-points Likert scale (from minimum control to maximum control).
    b. Question 4b: Acceptability of perceived control, discrete 5-points Likert scale (from totally unacceptable to totally acceptable).
5. Perceived thermal comfort, divided as follows:
    a. Question 5a: perceived indoor temperature, discrete 7-points Likert scale (from cold to hot)
    b. Question 5b: acceptability of indoor temperature, discrete 5-points Likert scale (from totally unacceptable to totally acceptable).
    c. Question 5c: adaptation measures, multiple selections (operation of thermostat, windows, shading, change of clothing)
    d. Question 5d: sources of discomfort, multiple selections (light, noise, air quality, temperature)
6. Well-being and overall satisfaction:
    a. Question 6a: well-being, such as experienced symptoms, multiple selections (headache, dizziness, irritated/dry eyes, stuffy/irritated nose, dry mouth, cough)
    b. Question 6b: overall satisfaction with the indoor environment, discrete 5-points Likert scale (from totally unsatisfied to totally satisfied).

The respondents' sex, age, and geographical origin were not asked in the questionnaire to ensure the respondents could not be identified. As per information provided by the employer, the occupants were 49% females and 51% males at the time of the survey. However, given the anonymity of the questionnaire, it was not possible to associate each response with the respondent's sex. It is therefore assumed that the sex distribution of the responses follows the ratio 49/51 for females and males respectively. Several studies have shown that such factors may influence the Thermal Sensation Vote (TSV)–indoor temperature relation. According to Schellen et al. [24] and Karjalainen [25], female participants in thermal comfort surveys prefer higher indoor temperatures than male participants. Parson [26] found that female participants express lower TSVs than males in cool environments, but similar TSVs in warm environments. Kruger and Drach [27], Karyono [28], and Indraganti and Rao [29] did not find a statistically significant difference between male and female TSV preferences, despite female participants showing a preference for a warmer environment. Given the almost equal balance of male and female employees, the influence of sex on thermal comfort is not expected to play a significant role. Different age and geographical origin may also play a role in determining the thermal comfort satisfaction. Fanger found no correlation between age and thermal satisfaction [30]. However, Choi et al. [31] found that, given an equivalent thermal environment, participants 40 years old and above may show a higher level of satisfaction than the younger ones. As shown by Zaki et al. [32], cultural habits and geographical origin may also be factors influencing thermal comfort.

2.3. Indoor Air Temperature Data Acquisition

Indoor air temperature measurements were acquired from the Building Energy Management System (BEMS). The BEMS records indoor air temperatures via the sensors installed in the office rooms and landscapes. These sensors were placed concurrently with the installation of the BEMS system. Given their positioning in the landscape offices was far from the majority of the workstations, and the fact they do not measure the operative temperature, they could not provide an accurate representation of the thermal environment felt by the occupants. The sensors corresponding to the location of the respondents with respect to orientation and floor were identified by the answered outside view and floor number in the questionnaire (questions 2 and 3). To time-match the respondents perceived thermal comfort and Thermal Sensation Votes (TSVs) to the corresponding indoor air temperatures, it was decided to use an average of 30 min of the temperature recorded before the starting time of the questionnaire. This was done for each response. The ground for choosing a 30 min average was defined according to the results of studies on human acclimatation and thermoregulation responses. According to these studies [33–35], the physiological responses and thermal sensations of subjects are shown to stabilize after circa 20–30 min.

3. Results

This Section presents the results from the survey performed in the case study. The results are divided as follows: results of the energy use during the survey period, response distribution, occupants' perceived control, perceived thermal comfort with and without the control algorithm, adaptation strategies, reported stress factors, and occupants' reported health symptoms.

3.1. Energy Use during the Period of the Survey

The survey was performed from February 2023 to March 2023. The predictive control algorithms were implemented and tested from 20th February 2023 onwards.

As with any control-related projects, it is challenging to claim exactly how much energy has been saved compared to a baseline. Due to the applied nature of this project, it was decided to use the data provided by the consultant who is in charge of the building energy management. The consultant provides normalized energy–temperature curves for specific weekly energy use. The energy use for district heating is measured at the main meter, considering all heat demand in the building. It can be seen from Figure 8 that when the predictive control is active and for outdoor temperatures below 5 °C, the weekly specific energy use (blue line) is lower than both the normalized baseline for the previous year (grey line) and the measured energy use for the same year without the predictive control. The indoor building setpoint was 22 °C on average for both operational conditions. This value is the result of how single setpoints were set in the BEMS system. The PC algorithm did not modify the setpoints during the period of the survey, but operated by minimizing the time the indoor temperature was dropping below the given setpoints. Table 1 shows the linear regression output calculated for the measured energy use when the building was operating with either the predictive control or without the predictive control. By using the equations in the table, a hypothetical average energy use for the building was calculated for the outdoor temperature range between −15 °C and 20 °C. The ratio between the two averages calculated with and without the PC shows a theoretical 10% lower energy use in favor of the building operation with the PC. It must be noted that such calculations do not represent the actual efficiency of the system with the PC, given the few collected data points, and the fact that changes in energy use come from different variables such as the use of zones.

Figure 9 and Table 2 show the relationship between the average indoor and outdoor temperatures recorded during the operation with or without the PC. As seen in Figure 9, the deviation between the 30 min average indoor temperature (measured at the time of each response) and the corresponding daily indoor average temperature is lower when the PC was in use in comparison to when the BEMS was operating without the PC. The use of the PC provided a more stable indoor thermal environment and a lower occurrence of perceived temperature to be less than the daily average temperature. For the range of indoor–outdoor temperature difference between 17.5 °C and 22.5 °C, the corresponding deviation from the daily average of indoor temperature is less than 0.5 °C with the PC and exceeds 1.0 °C without the PC. This is shown in Table 2, as well, where the average difference between the daily indoor temperatures and the response temperatures is −0.7 °C when the PC was not in use, and 0.2 °C when the PC was in use. It is worth noting that the temperature values given in Figure 9 and Table 2 are not representative of the local temperature perceived by the occupants in the open landscapes, because of the distance between the working desks and the measuring points, as explained more in detail in the following Sections.

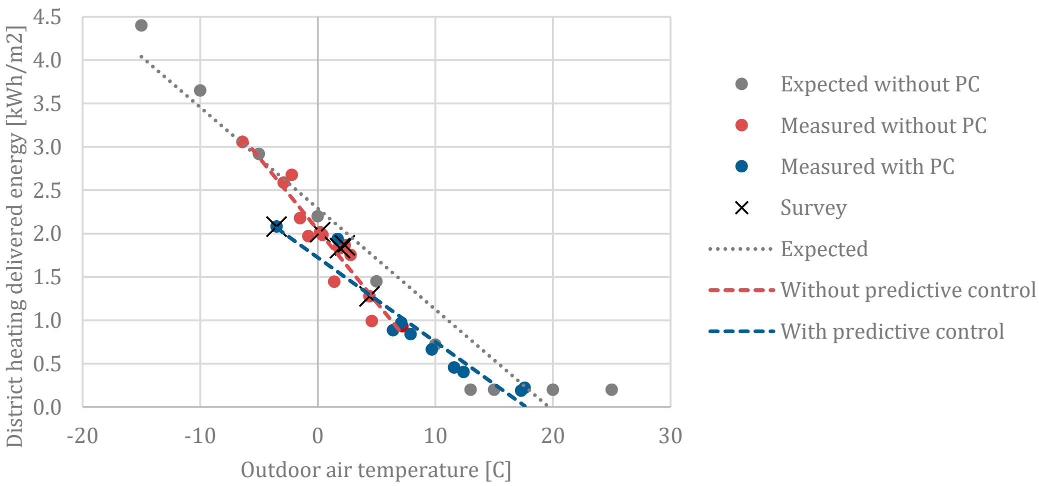

Figure 8. Energy-use curve for a selected period, measured energy use with the predictive control vs. expected baseline (without the use of the predictive control).

Table 1. Outputs from linear regression of the measured energy use for the two operational conditions (with and without PC).

	Indoor Temperature Setpoint	Linear Regression	r	r^2
Without PC	22 °C	y = −0.17 + 2.04	0.953	0.908
With PC	22 °C	y = −0.10 + 1.72	0.958	0.919

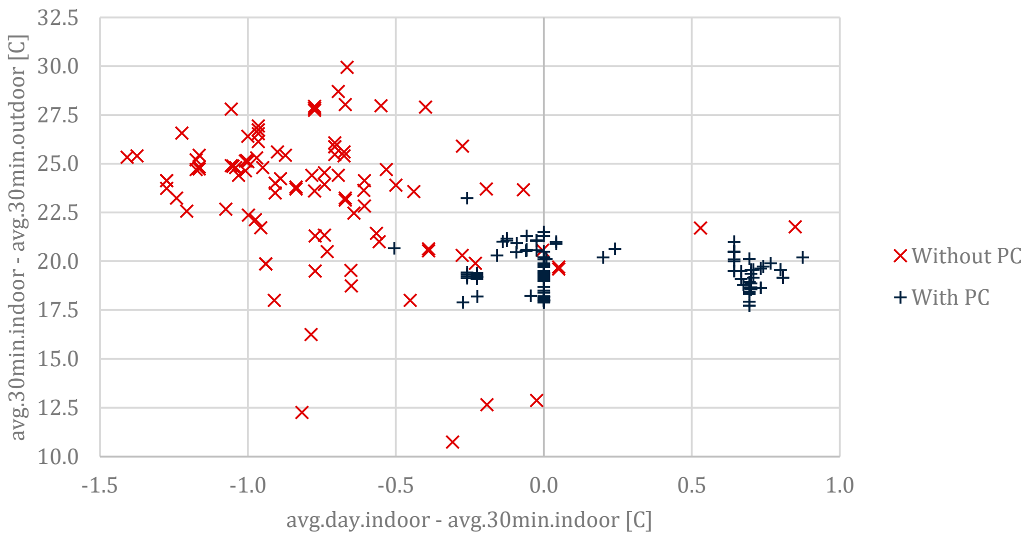

Figure 9. Differences between 30 min average indoor temperatures, 30 min average outdoor temperatures, and day average indoor temperatures for the operation with and without the predictive control.

Table 2. Mean and standard deviation of indoor and outdoor 30-min average temperatures, day indoor average temperatures, and their differences for operation with and without the predictive control.

	30-min. mean.outd.temp [C]		30-min. mean.ind.temp [C]		day mean.ind.temp [C]		day.mean—ind.temp. [C]		ind.temp.—outd.temp. [C]	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
no PC	0.2	2.92	23.6	0.82	22.9	0.68	−0.7	0.38	23.4	3.47
PC	3.1	0.83	22.5	0.60	22.7	0.80	0.2	0.45	19.5	1.05

3.2. Survey Response Distribution

An initial screening of the survey responses registered in the Netigate database was undertaken to exclude from the statistical analyses the responses, which were not valid due to incompleteness or not useful because the respondents were not in the office. A total of 270 unique responses were registered of which 14 were incomplete, 17 reported "not in office", and 3 reported "not in Block A". Therefore, 236 responses were considered valid and used for the statistical analyses presented in this chapter. Figure 10 shows the occupants' responses distributed per day, office type, and office orientation. The first period of the survey shows a very low response rate. This was due to poor communication with the contact persons regarding their helping role to ensure high participation in the survey. This was sorted out in the second period of the survey when the occupants' engagement increased largely. An average of 11 unique responses per day was recorded throughout the survey period. The low average response rate was due to little participation in the questionnaire during the first period, as shown in Figure 10. As a comparison, the second period of the survey (from 21.03 onwards) shows 22 unique daily responses on average. Of all the occupants who were given the survey link, just 3% answered the questionnaire daily. It is worth noting that many of the working stations were found during visits to the building, especially on the floor with single-cell offices, where the employees, due to the nature of their work, stayed out of the office most of the days. The responses are distributed among the two types of working spaces as follows: 94% (n = 223) to open landscapes, and 6% (n = 13) to cell offices. Regarding the orientation of the office where the respondents were sitting, 47% of them reported being toward the South, 38% toward the West, and 15% toward the internal foyer. The responses are distributed during the working day as follows: 28% before 10:00 a.m., 39% between 10:00 a.m. and 1:00 p.m., and 39% after 1:00 p.m.

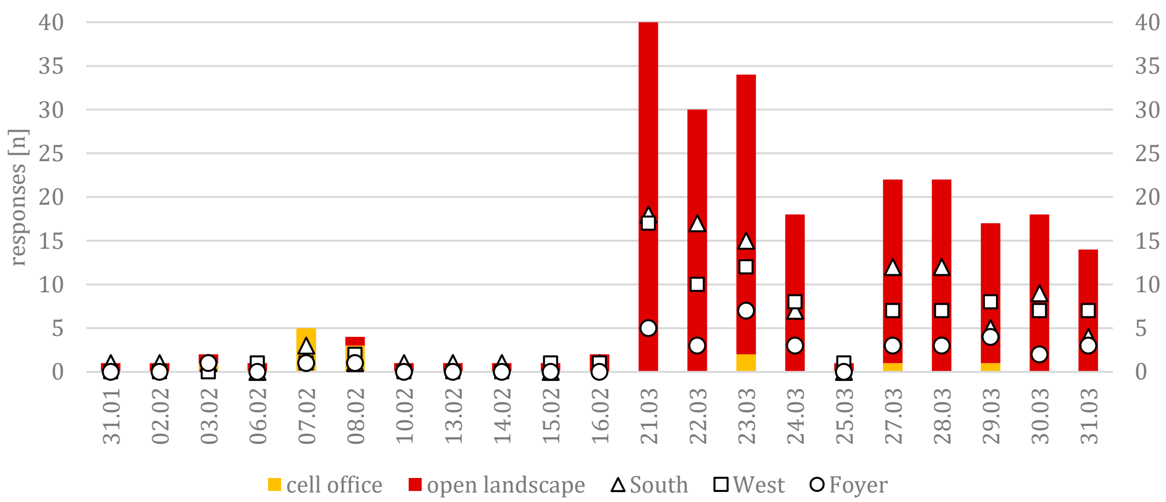

Figure 10. Number of unique responses distributed per office type and office orientation.

As shown in Figure 10, most of the responses came from occupants sitting in landscape offices, especially those sitting on the fifth floor. During the visit to the building, a very low occupancy rate was noted on the floors occupied by single-cell offices. This is due to the legal and administrative nature of these employees' jobs, which requires them often to work outside the building during the day. Since most of the respondents were sitting in a landscape layout, the analyses presented in the following Sections show the answers given by those sitting in this type of workspace only.

3.3. Thermal Comfort in Open Landscape

Results in this and the following Sections are given for the respondents sitting in open landscapes only, due to the low response in cell offices.

Figure 11 on the left shows on the left the distribution (counts) of all the TSVs given by the occupants in the landscape offices (n = 223). Nearly half of the responses (46%) were given to a Neutral TSV, 12% to Slightly warm (TSV = +1), and 22% to Slightly cool (TSV = −1), showing therefore a slightly higher number of TSVs in the left side of the diagram. Figure 11 right shows the relative distribution of the TSVs across the three different building orientations: South (n = 106), North-West (n = 87), and the internal foyer (n = 30). The percentages represent the relative occurrence of each TSV to the total TSVs counted for each orientation. The slightly higher occurrence of cool TSVs (TSVs −3 to −1) in the North-West side of the building in comparison to the TSVs reported in the office oriented toward the South and toward the internal foyer hints at the influence of lack of direct solar radiation on the employees' thermal sensations. Between January 31st (beginning of the survey) and March 31st (end of the survey), the daily variation in the solar azimuth is between 150° and 210° (January), and 90° and 270° (March). The North-West façade, which is oriented at circa 280°, therefore did not receive direct solar radiation during the survey period. The higher relative occurrence of Neutral sensation votes reported in the landscape offices facing the internal foyer hints that the working areas close to the external glazed facades may have had lower local air temperature than those measured by the sensors.

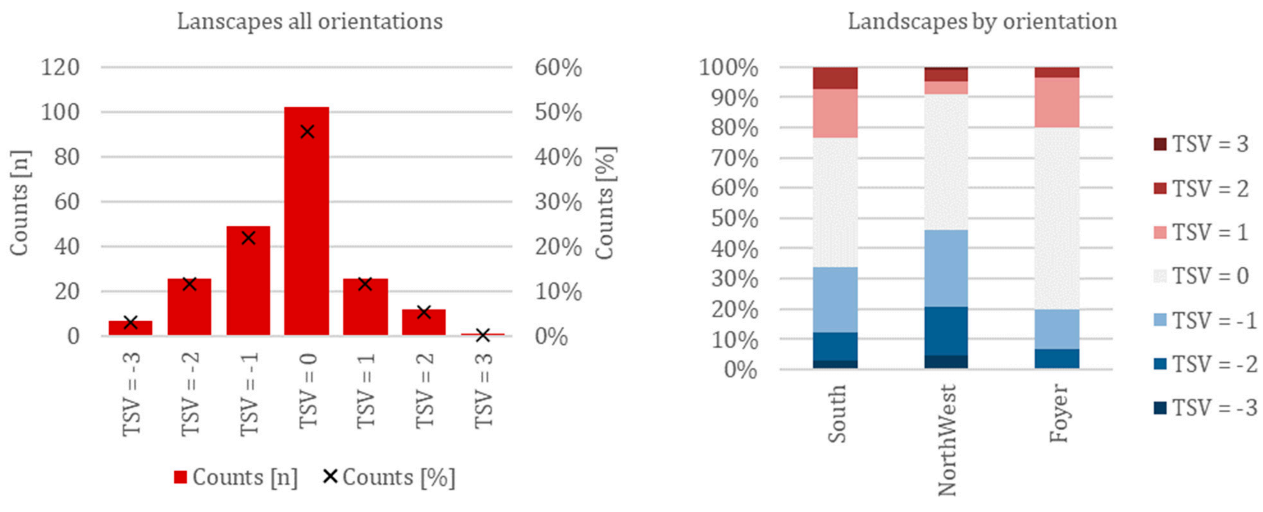

Figure 11. (**Left**): distribution of TSVs (Q. 5a) in all open landscapes, (−3 = Cold, 0 = Neutral, 3 = Hot). (**Right**): relative distribution of TSVs (Q. 5a) by landscape orientation.

Figure 12 shows the distribution of the Thermal Sensation Votes (TSVs) reported (Question 5a) by the employees sitting in open landscapes, plotted against the measured indoor air temperature. The indoor air temperature ranges reported for TSVs −3 to TSV +2 largely overlap each other, showing the mismatch between measured temperatures and local temperatures felt by the respondents. Most of the air temperatures reported for TSV 0 (Neutral) fall between 22.4 °C (1st quartile) and 23.5 °C (3rd quartile), whereas for TSV −2, they fall between 22.0 °C and 24.0 °C, and for TSV −1 between 21.9 °C and 23.5 °C. Table 3 presents Pearson's linear correlation *r* between the variable Q.5a (perceived thermal sensation) and the indoor temperature. Pearson's correlation was calculated in SPSS v.29.

A value of r between ±0.6 and ±1.0 entails a strong correlation, between ±0.3 and ±0.6, a moderate correlation, and between 0 and ±0.3, a weak correlation [36]. It is assumed that for values of $p < 0.05$, the relationship between the listed variables is statistically significant. The correlation between TSVs and indoor temperature is weak and statistically non-significant, given $r = 0.107$, $p = 0.112$, n = 223. The limitation given in executing the questionnaire survey in the building led to a mismatch between the recorded indoor temperatures and the temperatures felt by the respondents, due to the distance between the location of the measurement points and the working desks, and because additional sensors could not be installed to measure the operative temperature. Similar results are obtained when evaluating the correlation between the TSVs and the indoor temperature for the times the BEMS was operated with and without the PC, as shown in Table 3.

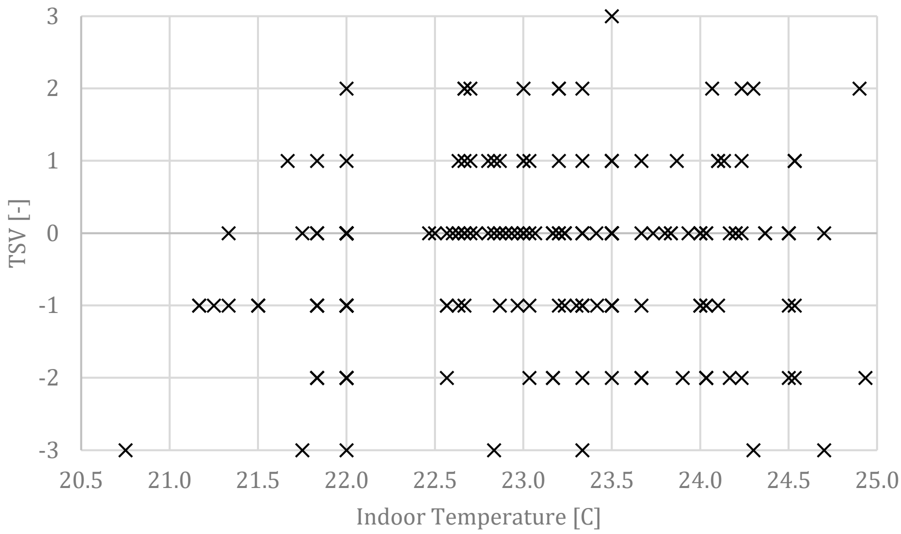

Figure 12. Distribution of TSVs (Q. 5a) in open landscapes, (−3 = Cold, 0 = Neutral, +3 = Hot), against indoor air temperature measured for the 30 min average.

Table 3. Correlation between TSVs and indoor temperature.

	All Landscape Responses	Landscape: BEMS without PC	Landscape: BEMS with PC
r	0.107	0.108	0.302
p	0.112	0.283	0.001
n	223	101	122

3.4. *Effect of Predictive Control on the Occupants' Thermal Comfort*

Figure 13 on the left shows the distribution of the occupants' thermal sensations for BEMS operated with either the PC (n = 122) or without the PC (n = 101). A larger percentage of Neutral votes was given when the PC was in use (51%) in comparison to when the PC was not in use (40%). The difference between Neutral votes and the slightly cool and cool votes (TSV = −1 and −2, respectively) is also larger when the PC was in use than when the PC was not in use. This difference is also shown in the distribution of the level of acceptability of the perceived thermal comfort (Figure 13 right), where a slightly lower share of "unacceptability votes" (values 1 and 2 in the scale) was recorded when the PC was in use.

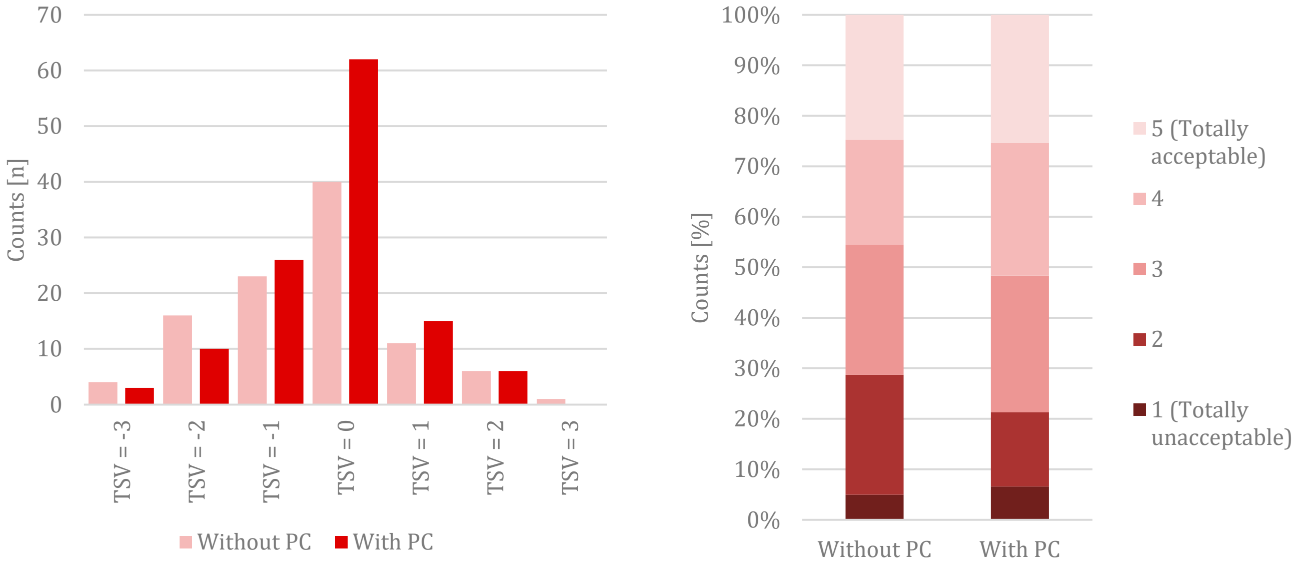

Figure 13. (**Left**): distribution of TSVs (Q. 5a) for landscapes with the BEMS operated either with or without PC. (**Right**): level of acceptability (Q. 5b) of the perceived thermal comfort in landscapes, for the BEMS operated either with or without the PC.

It can be argued that the occupants experienced a more positive thermal environment when the PC was in use due to the variation in the indoor temperature being less frequent, as shown in Figure 9. However, when the PC was not in use, the average outdoor temperature was almost 3 °C lower than the outdoor temperature measured when the PC was in use, as shown in Figure 9 and in Table 2. It is therefore possible that those respondents sitting close to the windows may have felt a colder local temperature when the PC was not in use than when the PC was in use; hence, the difference in thermal preferences between the two operating conditions.

Since the indoor air temperature could not be used as a reliable variable for evaluating the occupants' thermal comfort response in the two operational conditions (with and without the PC), the analysis proceeds by considering the influence of other factors (perceived control, occupants' health, adaptation strategies, sources of discomfort) on the occupant's perceived thermal comfort. In order to do so, the acceptability of the indoor temperature (Question 5b) is used as a proxy for evaluating the occupants' satisfaction with their perceived local environment. This is evaluated against a set of variables to assess whether other factors other than the local indoor temperature (which could not be measured) influence the occupants' satisfaction between the two operating conditions. Table 4 reports the Pearson linear correlation r between the TSV acceptability and the variables listed in the table. A value of r between ± 0.6 and ± 1.0 entails a strong correlation, between ± 0.3 and ± 0.6, a moderate correlation, and between 0 and ± 0.3, a weak correlation [36]. Variables Q. 5c, Q. 5d, and Q. 6a are calculated by summing the number of inputs provided by the respondents (these were multiple-selection choices) by the assumption that a larger number of inputs corresponds to a higher level of discomfort.

Perceived control and acceptability of perceived control show moderate-to-strong correlation values, hinting that satisfaction with the thermal environment is connected to the level of perceived control, and vice versa. Since, in both operational conditions, a similar relationship is found, it is assumed that variables Q. 4a and Q. 4b did not exert a significant influence on determining the different occupants' thermal perception between the two operational conditions, as shown in Figure 13. Variable Q. 5c shows a weak negative correlation for the whole dataset (open landscape), but a non-statistically significant relationship when analyzing the two sub-sets (with and without the PC). It may be assumed that the occupants who performed multiple actions to adapt to the thermal environment failed to meet their desired thermal comfort level; hence, the negative relationship. The first action taken by the respondents was to put more clothes on (n = 72), followed by removing one or more pieces of clothing (n = 31). Less immediate actions, such as opening/closing windows and shading, and operating the thermostats were performed less frequently during the survey. It is argued that the respondents preferred to take adaptation strategies that did not conflict with the preferences of other employees (e.g., operation of windows, shading, thermostat). The preference for clothing adjustments represents 34% of the total responses, in contrast to 4% for thermostat adjustments. Variables Q. 5d and Q. 6a show a weak-to-moderate negative relationship since a higher number of negative inputs (environmental or physiological) influences the occupants' perceived thermal comfort. It is interesting to note that external sources of discomfort had a larger negative influence on the perceived thermal satisfaction than the respondents' own experienced health symptoms.

Table 4. Correlation between TSV acceptability (Q. 5b) and different variables given from the questionnaire.

TSV Acceptability (Q. 5b)	Landscape: BEMS without PC (n = 101)	Landscape: BEMS with PC (n = 122)
	r	*r*
Perceived control (Q. 4a)	0.446 **	0.309 **
Acceptability of control (Q. 4b)	0.668 **	0.555 **
Sum of adaptation strategies (Q. 5c)	−0.196 **[a]	
Sum of stress factors (Q. 5d)	−0.389 **	−0.451 **
Sum of symptoms (Q. 6a)	−0.352 **	−0.282 *

* sig. < 0.05; ** sig. < 0.01; [a] sig. < 0.05 was found for the analysis of the whole dataset only (open landscape).

3.5. Overall Satisfaction in Open Landscape

In this Section, the variable Q. 6b (overall satisfaction of the working environment) is evaluated against the other input variables given in the questionnaire to assess the influence exerted by the environmental, psychological, or physiological factors experienced by the occupants. This analysis is performed to understand whether the occupants' perceived satisfaction was dominated by either their thermal satisfaction or other parameters. Pearson's correlation coefficients are derived for each relationship and presented for both the operational conditions (with and without the PC). As shown in Table 5, the two operational conditions did not influence the perception of the occupants' toward their working environment, as the respective correlation coefficients fall within similar ranges. Variables Q. 5b and Q. 4b show the strongest correlations with the occupants' overall satisfaction, meaning that both thermal satisfaction and control satisfaction were perceived as important factors in daily working routines. Variable Q. 5d shows the strongest negative correlation, as un-controllable external sources of discomfort were considered detrimental to working activities. Experienced health symptoms (Q. 6a) show a stronger correlation with overall satisfaction than with thermal satisfaction, as seen in Table 4. The correlation with variable Q. 5c did not produce statistically significant results.

Table 5. Correlation between Overall satisfaction with the working environment (Q. 6b) and different variables given from the questionnaire.

Overall Satisfaction (Q. 6b)	Landscape: BEMS without PC (n = 101)	Landscape: BEMS with PC (n = 122)
	r	*r*
Perceived control (Q. 4a)	0.479 **	0.463 **
Acceptability of control (Q. 4b)	0.666 **	0.719 **
TSV acceptance (Q. 5b)	0.780 **	0.631 **
Sum of adaptation strategies (Q. 5c)	−0.180 **[a]	
Sum of stress factors (Q. 5d)	−0.557 **	−0.542 **
Sum of symptoms (Q. 6a)	−0.506 **	−0.477 **

* sig. < 0.05; ** sig. < 0.01; [a] sig. < 0.05 was found for the analysis of the whole dataset only (open landscape).

A further analysis performed on the relationship between either variable Q. 4a or Q. 4b and variable Q. 5c shows a weak negative correlation for the whole dataset (open landscape), but a non-statistically significant relationship when analyzing the two sub-sets (with and without the PC). On the other hand, a moderate relationship ($r = -0.383$, sig. < 0.01) is observed between variable Q. 4b and Q. 5d, hinting that uncontrolled disturbances are perceived as detrimental to the acceptability of own level of control. It is therefore worth analyzing more in detail such a relationship.

Weak negative correlations are observed between variable Q. 4b and the following stress factors: *poor air quality* ($r = -0.281$, sig. < 0.01), *too hot* ($r = -0.207$, sig. < 0.05), *too cold* ($r = -0.275$, sig. < 0.01). Stronger negative correlations are found for the same stress factors with variable Q. 6b: *poor air quality* ($r = -0.415$, sig. < 0.01), *too hot* ($r = -0.314$, sig. < 0.01), *too cold* ($r = -0.343$, sig. < 0.01). To these, *too noisy* ($r = -0.234$, sig. < 0.01) and *too dark* ($r = -0.138$, sig. < 0.05) are observed to be negatively correlated, yet weakly. It is therefore observed that poor air quality was experienced as the strongest stress factor to negatively influence the occupants' overall satisfaction with the environment. However, a measurement of the CO_2 concentration could not be performed, due to the limitations of the case study, and thus a solid argument for addressing this response to the poor ventilation in the building.

Figure 14 shows a graphical summary of the main variables that have been analyzed so far and gives an overview of those variables with the observed strongest influence ($r > 0.5$) on the occupants' thermal satisfaction (Q. 5b) and overall satisfaction (Q. 6b). It is observed that acceptability of control (Q. 4b) plays the strongest positive influence on both Q. 5b and Q. 5b, whereas variable Q. 5d plays the strongest negative influence on the overall satisfaction (Q. 6a). A slightly stronger influence, yet weak, is observed to be exerted by the perceived control (Q. 4a) and its acceptance (Q. 4b) on the thermal acceptance (Q. 5b) recorded when the building was operated without the PC.

A final set of analyses is performed to understand whether the building orientation may have played a role in defining the occupants' preferences. A strong correlation is observed between Q. 6a and Q. 5b for the respondents sitting in the South ($r = 0.737$, sig. < 0.01, n = 106) and North-West ($r = 0.728$, sig. < 0.01, n = 87) sides of the building, whereas a moderate correlation is observed between these two variables for the office side facing the foyer ($r = 0.456$, sig. <0.05, n = 30). A further analysis shows a moderate correlation between Q. 6b and Q. 5d ($r = 0.584$, sig. < 0.01, n = 30). However, a significant relationship between Q. 6b and single stress factors is not observed for the office side toward the foyer. The highest reported stress source was poor air quality (39%), followed by noise (14%), and 23% of the respondents sitting in that part of the building reported no stress factors.

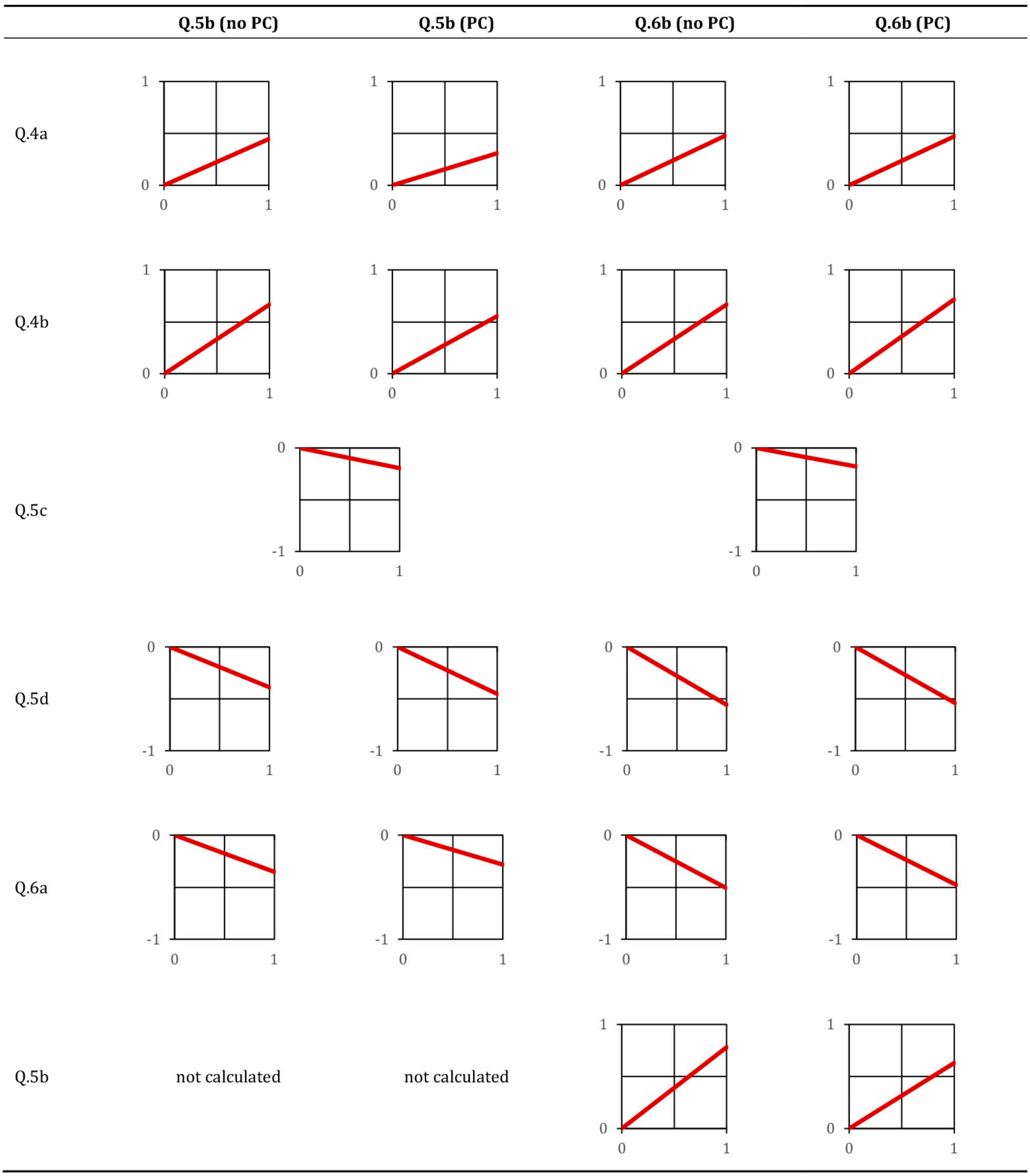

Figure 14. Graphical summary of all the correlations calculated for the above variables: Q. 4a = level of control, Q. 4b = acceptability of control, Q. 5b = acceptability of thermal sensation, Q. 5c = sum of adaptation strategies, Q. 5d = sum of stress factors, Q. 6a = sum of symptoms, Q. 6b = overall satisfaction.

4. Discussion

As described in this paper, the objectives of the questionnaire were to evaluate to what extent the use of the predictive control of a building heating system influences the employees' thermal comfort. Additional factors that may have influenced the occupants' overall comfort have been investigated in this paper. A series of limitations occurred during the on-site measurements and investigations, and these are discussed in this Section.

This case study is of a very applied nature, thus having some practical limitations, which are described in this Section. The building is in normal operation and one of the requirements of the project is to not install any additional hardware and sensors in the building. The scalability of the developed predictive control solution was of high priority throughout the whole project. Initially, the aim was to adjust room temperature setpoints for each zone based on the PC. However, after initial tests to set room temperature setpoints, it was found that the room regulators have two setpoints: a basis setpoint whose settings can be modified, and a "working setpoint", which is a deviation from the basis setpoint by ±1 K to ±2 K. The basis setpoints vary across the zones, but they are predominantly between 22 °C and 23 °C. The deviations of the working setpoints depend on settings that are programmed into the room regulators. The working setpoints are those applied for room temperature regulation and thus affect the valve opening of the radiators to provide zone heating. It was not possible to modify the settings given for the working setpoints and thus apply any room temperature setpoint proposed by the predictive control algorithm. It was therefore decided to neglect the idea of adjusting room temperature setpoints to make use of the building's thermal mass and rather focus on the deviation of the radiator supply temperature as an energy-saving measure. Occupants can adjust room temperature setpoints at the room regulator, but the requested setpoint change is not communicated to the automation system so that the real applied setpoint remains the working setpoint set from the BEMS. This means that any action of the occupants to meet their desired thermal comfort by operating the setpoints has no practical effect on modifying the indoor air temperature.

As shown in Figure 8, the predictive control was effective in reducing the weekly energy use in comparison to the normalized baseline for the same period (energy management without the predictive control), as demonstrated in similar studies [7–9] and it concurrently provided a more stable indoor thermal environment, as shown in Figure 9. It was observed that when the predictive control was in use, the occupants reported Neutral votes more frequently than those when the predictive control was not in use, as shown in Figure 13. However, despite this result showing a positive influence of the predictive control on the perceived thermal comfort, a conclusive argument cannot be drawn, being the measured indoor temperature is not correlated to the local temperatures felt by the occupants. This was because the positioning of the sensors in the open landscapes was not in proximity to the workstations and the sensors did not measure the operative temperature. An average lower outdoor temperature was measured during the time the building was operating without the PC in comparison to when it was operating with the PC. Local thermal discomfort may have occurred, yet not measured, for those respondents sitting close to windows due to cold air draft. To ensure the anonymity of the questionnaire, it was not possible to ask whether the respondents were sitting by the corridor or by the window. This highlights the limitation of this study with regard to the placement of indoor air sensors close to the working stations. The hypothesis that outdoor air temperature may have influenced the thermal perception of part of the respondents is supported by the higher frequency of Neutral votes cast by the occupants sitting toward the internal foyer (Figure 11), and thus not experiencing cold draft from the internal glazing. On the other hand, a stronger relationship was observed between overall satisfaction (Q. 6b) and reported stress factors (Q. 5d), than between overall satisfaction and thermal satisfaction (Q. 5b). It can be argued that the occupants sitting toward the foyer valued their thermal satisfaction less than other personal preferences. Since those sitting toward the foyer do not have access to an outside view and outdoor air, these factors may have influenced the overall satisfaction score. It must be noted that a question with "lack of view" was not included in the questionnaire. This hypothesis is supported by several studies [37–41] that highlight how access to external views and appropriate daylighting conditions improves office occupants' mood and their satisfaction with their working conditions. According to Veitch [39], occupants with access to daylight within 5 m from their working desk reported higher satisfaction than those sitting far from windows. A study by Heschong [38] shows that access to daylight and outside view has a positive impact on occupants' mental function and attention. However, windows are a source of glare and potentially of outdoor noise, which was found to be a distracting factor and detrimental to productivity [41,42]. Despite the potential occurrence of outdoor noise and glare, occupants are reported to prefer windows close to their desks for having access to the outside view [43–45].

Perceived thermal comfort is influenced by sex [24–26], as female respondents tend to prefer warmer temperatures than males. The distribution of the male/female respondents is assumed to follow the ratio of males (51%) and females (40%) employed in the building, as per the information provided. Given an almost equal distribution, it is assumed that the influence of sex on thermal perception is not significant.

As found by several authors [37,46–52], open landscape offices are a cause of limited performance and stress due to limitations to employees' personal spaces and increased noise levels. The aim of increasing social interaction and communication and of increasing employee density in office spaces has led to the design of more open landscape workspaces instead of separate cellular offices. However, there is significant evidence of decreased social interaction and face-to-face communication by using open workspaces [46,47]. Open-plan work environments tend to limit employees' ability to concentrate on their tasks and limit the employees' privacy and personal spaces, and they may cause a decline in social interaction and overall effectiveness [48]. Göçer et al. [37] analyzed a dataset of 9794 post-occupancy evaluation surveys from 77 Australian open-plan offices. From their analyses, "Building/office aesthetics and quality" and "noise distraction and privacy" were found to be the two strongest predictors of perceived productivity in low-performance offices. Lack of privacy can cause employees to have a harder time concentrating and focusing on their tasks due to limited visual and sound privacy, which may inhibit their cognitive performance, increase stress, and decrease their wish to engage in social interaction at work [49–51]. In addition, the increased level of noise can become a persistent distraction for workers [52]. The objective of the questionnaire presented in this work was to assess whether sitting in either an open landscape or a single-cell office would have shown different reactions to stress factors. Due to the low response obtained by the occupants sitting in single-cell offices, this comparison could not be carried out. However, some considerations can be drawn from the responses given by the employees in open landscapes.

As shown in Figure 14, sources of stress factors were negatively correlated with both thermal satisfaction (as two of the questions in Q. 5d asked about thermal-connected stress) and overall satisfaction. Single stress factors with observed highest negative correlation with Q. 6b were *poor air quality* ($r = -0.415$, sig. < 0.01) and *too cold* ($r = -0.343$, sig. < 0.01). Noise was found to be weakly correlated to overall satisfaction ($r = -0.234$, sig. < 0.01). The results found confirm a negative effect of noise on occupants' satisfaction, despite this being weaker than other stress factors. It was not possible to verify the occupants' perceived indoor air quality with measurements of CO_2 levels (because sensors could not be installed in the building) or measurements of the airflow at the room outlets (because the BEMS system did not provide detailed information in this regard).

Availability, perception, and exercise of control in office spaces are found to be a predictor of employees' satisfaction with indoor working conditions. According to several studies [11–15,53,54], occupants in office buildings prefer to have a high degree of control over their immediate surroundings, including thermostats, shading devices, and operable windows. Hauge et al. [55] pointed out that occupants of single offices perceive themselves to be more in control of the temperature, ventilation, lighting, and noise than occupants of open landscapes. As shown in Figure 14, adaptation strategies (Q. 5c) were observed to have a negative weak correlation with either the occupants' thermal satisfaction or their overall satisfaction. Such a negative correlation can be augmented by the fact the occupants did not succeed in meeting their expected level of satisfaction by their actions. The responses given for the adaptation strategies showed that increasing or decreasing their own clothing levels was preferred, whereas those actions in the working environment (operation on windows, shading, thermostats) were less preferred. This finding is in line with research conducted by Schweiker and Wagner [14] who showed that at increasing the number of occupants in an office space, the interaction with the working environment diminishes, whereas the changing of clothing level increases. It may be assumed that actions to modify settings in open workplace environments require face-to-face interaction with co-workers, which is somewhat hindered in open landscapes, as suggested by Bernstein and Turban [47]. As found by Rasheed et al. [51], 54% of respondents sitting in office rooms with more than eight occupants reported having changed behavior due to the increased number of coworkers.

With regard to stress factors, poor indoor air quality was reported more frequently than other sources of stress, and its high occurrence, in connection to the reported noise disturbances, may be the cause of the symptom of *heavy-headedness*. Poor indoor air quality due to high concentrations of CO_2 have been reported to be detrimental to learning and work performance in several studies [56–59]. Open-plan workplaces are reported to reduce the occupants' acoustic comfort [40,49,50,52,60,61]. According to Hongisto et al., speech intelligibility is detrimental to job performance when background chatting becomes intelligible by the occupant, e.g., when the speech information is understandable by the receiver [50]. Kaarlela-Tuomaala et al. compared office noise discomfort after the relocation of occupants from private offices to an open-plan workplace. The occupants reported that speech and laughter were the most disturbing sounds in both office types, but more distracting in the open-plan layout, whereas constant and predictable noise (e.g., from HVAC and computers' fans) were reported to be less distracting [61]. Noise disturbances were reported due to renovation work occurring in the neighboring block during the survey. This may explain those responses that highlighted high noise levels in the environment. However, due to the limitations given in the case study, it was not possible to measure sound and air pollutant levels during the survey. From the results of the survey, it may be concluded that perceived low temperatures, poor air quality, noise, and perceived low level of control were the likely causes of the reported overall low satisfaction with the working environment. Similar findings are shown in [46,51,61].

5. Conclusions

A predictive control (PC) was implemented in the Building Energy Management System (BEMS) of an office building in Trondheim. A questionnaire was given to the employees to evaluate to what extent the operation of the predictive control influenced their perceived thermal comfort. Several factors known to influence employees' satisfaction (such as office type, perceived noise level, level of control, perceived luminous environment, perceived indoor air quality, adaptation strategies, health) were investigated in the questionnaire.

The predictive control proved effective in reducing the weekly average energy use during the test period in comparison to the expected trend of energy use of the building without the predictive control. The variation in the 30 min average indoor air temperature from the daily average indoor air temperature was lower when the PC was in use than when the PC was not in use. This provided a more stable indoor thermal environment.

The number of responses given by the employees sitting in single-cell offices (n = 13) was too low to be used for a significant comparison to those given in the open landscape offices (n = 223).

The respondents sitting in the open landscape reported a higher thermal satisfaction and a higher rate of Neutral votes when the building was operated with the predictive control. However, it cannot be concluded that the implementation of the PC in the BEMS was the only cause of a higher reported thermal comfort by the respondents. A measured higher outdoor temperature may have played a role in determining the thermal satisfaction of at least those respondents sitting by the office windows. The limitations given by this specific case study did not allow a precise measurement of the indoor temperature at the desks.

Control perception and acceptability, environmental stress factors, and health of the respondents were analyzed in the questionnaire. It can be concluded that their influence on thermal satisfaction did not show a significant difference when the building was operated either with or without the predictive control. This excludes such variables from being a possible cause of the different thermal satisfaction reported between the two operational conditions.

Acceptability of control and environmental stress factors were observed to be the strongest positive and negative influence, respectively, on the respondents' thermal satisfaction.

Acceptability of control and thermal satisfaction were observed to have a similarly strong influence on the respondents' perceived overall satisfaction with the working environment. Stress factors were observed to have the strongest negative influence on the perceived overall satisfaction.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

BACS	Building Automation and Control Systems
BEMS	Building Energy Management System
MPC	Model Predictive Control
PC	Predictive Control
SD	Standard Deviation
TSV	Thermal Sensation Vote
Symbols	
n	sample size
p	p-value of hypothesis testing
r	Pearson's correlation coefficient
r^2	Coefficient of Determination of the regression line

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