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A Study of the Impact of Individual Thermal Control on User Comfort in the Workplace

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In modern offices, individual user control has been replaced by centrally operated thermal systems, and in Scandinavia, personal offices by open plan layouts. The impact of user control on thermal comfort and satisfaction was examined. This study compared a workplace, which was designed entirely based on individual control over the thermal environment, to an environment that thermal control was provided as a secondary option for fine-tuning: Norwegian cellular and British open plan offices, respectively. The Norwegian approach provided each user with control over a window, door, blinds, heating and cooling as the main thermal control system. In contrast, the British practice provided a uniform thermal environment with limited openable windows and blinds to refine the thermal environment for occupants seated around the perimeter of the building. Quantitative and qualitative methodologies were applied to measure users' perception of thermal environment, empirical building performance and thermal control. The results showed a 30% higher satisfaction and 18% higher comfort level in the Norwegian offices compared to the British practices. However, the energy consumption of the Norwegian case studies was much higher compared to the British ones. A balance is required between energy efficiency and thermal comfort of the user.

Keywords: Thermal comfort, individual control, cellular plan, open plan, workplace

Introduction

The history of workplace design shows the continuous demand of users to control their thermal environment [1]. However, climate change, technological advances, economic challenges, new ways of working, organisational changes and goals have driven the design away from the immediate demands of users. Organisational goals are currently replacing workers' rights, including those pertaining to thermal control [2]. Recently the Workers' Council has been losing its impact to protect the demands of users in Europe [2]. In this context, cellular plan offices no longer respond to organisational changes and challenges in the twenty-first century, due to their high cost and lack of flexibility [2,3]. As a consequence, open plan offices with limited environmental control are replacing personal offices with high levels of individual thermal control in Scandinavia [4,5]. In the open plan workplace, users' control over the thermal environment is being replaced by automated thermal systems in order to simplify regulating the thermal environment and to avoid individuals tampering with the system [6,7]. In the future thermal control is predicted to become central to the design of the workplace, as flexible ways of working replace assigned workstations [8]. However to attract a talented workforce and maintain performance, organisations will have to provide work environments that meet the demands of users [9], and occupants prefer individual thermal control in order to feel comfortable [10-12], thus user orientated design of these systems becomes paramount.

Previous related works

Previous studies recommended the application of thermal control [13]. It is established that adaptive opportunity or thermal control is based on the flexibility of the building to provide control for occupants to adjust the thermal environment according to their requirements [14-16]. Furthermore, an environment with high adaptive opportunity is likely to prove more comfortable than one with low opportunity, because people will take advantage of the actual and potential variations in room temperature [14,15]. Access to thermal control, such as a thermostat, improves user satisfaction [17,18]. Leman (1996) determined that perceptions of good control are often associated with better comfort and satisfaction and responsive, accessible, simple and user friendly environmental control systems increase user satisfaction [12,16]. Acceptance of the thermal environment is directly related to the expectation of the occupant, and there are individual differences in perceiving this environment and users' expectation of comfort as well as a controlled and refined thermal environment is increasing [19,20]. Bordass et al. (1993) established that although building managers prefer to eliminate user control over the thermal system, limited local control is associated with more discomfort, and more management time to respond to complaints [6]. Thermal and environmental control are recommended as part of the architectural design of the building and visual access to outdoor climatic conditions is suggested [14]. However, environmental control is considered mainly for 'fine-tuning' in case of a system failure [22] rather than the main system to control the thermal environment.

Previous studies on user satisfaction, thermal control and adaptive opportunity (particularly in the open plan office layout) have shown that thermal control increases user comfort [6] and satisfaction [2-4]. However, this study examined the effect of high levels of individual control over the thermal environment when provided compared to a workplace with limited thermal control. Two distinct workplace contexts based on different architectural designs and contexts of the two countries were used as case studies. The context of the two countries [25] and the impact of Works' Council and work regulations influenced their design of the workplace and environmental control [1]. The offices were operated according to user and organisational demands with respectively high and low levels of individual control over the thermal environment.

The Norwegian and British offices operated with high and low levels of thermal control over the thermal environment, respectively. This study compared user comfort and satisfaction in these two particular contexts, as user satisfaction is related to higher levels of productivity [26], which is beneficial for both individuals and organisations. The case study buildings were selected from recently constructed buildings (less than ten years old) and their performance was evaluated to limit the impact of the quality of the indoor thermal environment on users' view. The occupants' comfort and satisfaction were recorded and compared between the two case studies and users' view of thermal control was investigated through follow up interviews.

Methodology

The study compared users' comfort and satisfaction as well as the energy consumption of two workplace settings with high and low environmental control systems. Buildings A and B were the Norwegian practices with high levels of thermal control and Buildings C and D were the British practices with low levels of thermal control. The relationship between users' view and thermal performance of the building were further investigated. A combination of quantitative and qualitative methodologies was applied with a particular emphasis on grounded theory. User comfort and satisfaction were compared in two cellular plan offices in Norway and two open plan offices in Scotland in summer 2012 and the duration of the study in each building was one week. The fieldwork was undertaken during the summertime, as overheating in this season is becoming a major problem in the workplace in European countries [27,28]. During the study period, outdoor climatic conditions in the two contexts were close. During the fieldwork, the outdoor temperature measurements at the building locations reached up to 26°C in Norway and 23°C in Scotland respectively.

The Norwegian offices provided every occupant with a personal room and a high level of thermal control according to the Norwegian work regulations [29]. In contrast, the British practices provided thermal control for limited occupants seated around the perimeter of the open plan offices. The majority of the occupants seated away from the windows have no access to any means of thermal control. Award winning practice examples were selected for this comparison to ensure a good standard of indoor air quality and to limit the impact on user comfort and satisfaction. The building performance was evaluated through environmental measurements, and in accordance with the standards and benchmarks (section 3). The ASHRAE standards were applied in this study as the most widely used measure of thermal comfort. Users' comfort and satisfaction were recorded through online survey questionnaires using a tablet computer in order to simplify the data collection, easier data storage, analysis and comparison, as well as to reduce the possibility of errors [30]. Simultaneous environmental measurement was applied. Participants' views of thermal control were also investigated through semi-structured interviews. Overall, 313 responses were received and all participants responded (response rate) to both questionnaire and interviews. The thermal environment as measured during the study period is presented in Table 1.

Table 1. Information regarding the researched floor in each building.

Clothing convention and representative activities were observed. Generally summer clothing was worn (Clo 0.5) and sedentary activities took place in the buildings and this information was included in the PMV analysis, presented in section **Error! Reference source not found.**. The questionnaire included questions related to the ASHRAE Standard. Two key questions in the questionnaire were based on the ASHRAE seven-point scale [31], presented in Table 2.

Table 2. Extract from the questionnaire in regard to the thermal environment based on the ASHRAE seven-point scale [31].

A PCE-GA 70 air quality meter was used to record the environmental factors, including the dry bulb temperature (0.1oC resolution and ±0.5oC accuracy), relative humidity (0.1% resolution and ±3% RH accuracy) and carbon dioxide level (up to 6000ppm, 1ppm resolution and ±50 ppm accuracy). The mean radiant temperature was calculated using the ASHRAE Thermal Comfort Tool 2 [32] and surface measurements. In order to measure the latter, eight data loggers were used: the Tiny Tag Plus 2 TGP-4500: the dry bulb temperature (from -25oC to +85oC and 0.01oC accuracy) and relative humidity (from 0% to 100% and ±3% RH accuracy). A data logger was set to record the external temperature and humidity and seven data loggers were set internally at the floor, desk and ceiling levels. A sample of these measuring points is presented in Figure 1. Statistical regression analysis was applied in this study, which is the main analysis method in the field studies of thermal comfort [33].

Figure 1. Sample of measuring points in Building B.

Building performance

The study aimed to investigate the relationship between thermal control and user comfort and satisfaction. Therefore, an analysis of the building performance was undertaken to demonstrate that the thermal environment of the case study buildings were broadly compatible. The intention was therefore to help identify those issues related to environmental control and their impact on user satisfaction and comfort. The building performance of all four case study buildings were analysed in terms of the ventilation system, carbon dioxide level, energy and thermal performance. Generally, sedentary activities took place in the buildings. The Norwegian offices (Buildings A and B) provided much larger workstations for each occupant compared to the British workplaces (Buildings C and D), as a personal room was provided for each occupant, as presented in Table 1 and Figure 2.

Figure 2. Sample plans of buildings B and D.

Ventilation system

In the cellular plan offices, air conditioning was working and each occupant was provided with access to an openable window, blinds, door and the ability to adjust the cooling or heating. In the open plan offices, the centrally controlled mechanical system was operating, while only limited occupants seated around the perimeter of the building had access to openable windows and blinds, as presented in Figure 3. The mechanical systems operated from two hours in advance of the occupants' arrival until two hours after their departure and they were switched off over the weekends. The regular working hours in the Norwegian practices were eight to four and in the British offices nine to five. All four buildings receive direct solar gain during the day and occupants control it through blinds.

Figure 3. Sections of environmental control and summer day ventilation systems: (a), (b): Norwegian cellular plan offices and (c), (d): British open plan offices.

Figure 3 also illustrates the summer day ventilation in the four buildings. In Building A, an openable window, mechanical ventilation, radiant cooling, and a radiator were in operation. Mechanical ventilation was centrally controlled. In order to allow the occupant to change the room temperature, a thermostat was available. It switched on either the radiator or the radiant cooling system in accordance with the current room temperature and the user's demand. This is the main cause for the high energy consumption in this building, as explained in section 3.3. In Building B, an openable window, mechanical ventilation and radiant cooling were in operation and only air conditioning was centrally controlled. Building C was mainly a naturally ventilated building with automated top windows and vents to ensure a good indoor air quality. The bottom windows were manually controlled by occupants. In Building D, openable windows and displacement ventilation were in operation. The former was controlled by occupants. This information is presented in Table 3. Air velocity was detected less than 0.1 m/s in all buildings, which was within the acceptable range.

Table 3. Heating, cooling and ventilation systems in the four buildings.

Carbon dioxide level

The carbon dioxide level of the four buildings was compared against the ASHRAE Standard [34]. It showed an acceptable indoor air quality and the carbon dioxide level of the majority of the workstations was below 600 ppm, as presented in Figure 4. The carbon dioxide level is lower in buildings B and C compared to the other two buildings, particularly building D, which is a deeper open plan office and the concentration of the carbon dioxide exceeded 800 ppm. Overall, the carbon dioxide level in all four buildings was within the acceptable range.

Figure 4. Carbon dioxide level: comparing the four case study buildings.

The SPSS regression analysis showed no significant relationship between carbon dioxide level and comfort (P value = 0.433 > 0.05) as well as satisfaction (P value = 0.120 > 0.05).

Energy consumption

The energy bills, which were provided by the management of the buildings, were analysed. The energy consumption analysis showed that except for one of the Norwegian cellular plan offices, all the other buildings are within the acceptable range of the CIBSE benchmark [35], as presented in Figure 5. Building A in particular had a much higher energy consumption that exceeds the limit (1550 Kwh/m2 per year). This was mainly due to the application of contradictory thermal systems to provide occupants with thermal control and comfort, as explained in section **Error! Reference source not found.**. Building C was the most energy efficient case study, due to the application of natural ventilation. Overall, the British open plan offices are much more energy efficient (150 and 160 Kwh/m2 per year) compared to the Norwegian cellular plan offices (1550 and 550 Kwh/m2 per year). Although the major part of the energy was consumed during the cold season, there was still a clear gap in the energy consumption of the Norwegian and British practices in summer. This suggests that providing individual thermal control comes at a price.

Figure 5. Energy consumption KWh/m2 per year: comparing the buildings against the benchmark [35].

Thermal comfort predictions

The indoor climatic conditions in the case study buildings were steady. The Predicted Mean Vote (PMV) analysis was applied to examine the thermal performance of the four buildings using the ASHRAE Thermal Comfort Tool [32], which was based on the ASHRAE Standard 55-2010 [36]. Several thermal factors were considered in this analysis, including the dry bulb temperature, relative humidity, mean radiant temperature, air velocity, clothing, activity, location of the person in the room and from the walls and windows. The analysis indicated that the occupants of the four buildings are expected to feel neutral or slightly cool, as presented in Figure 6.

Figure 6. The PMV analysis.

Figure 7 shows the thermal performance of the buildings against the ASHRAE Standard 55-2013 [37], which is in line with results of Figure 6. The thermal performance of all workstations was similar and within the acceptable range although many of them fell into the winter comfort zone (1 clo), particularly in buildings A and D. The management of the four buildings set the thermal environment according to the acceptable range. However, mainly dry bulb temperature was considered in their measurements. In contrast, in the analysis of this section operative temperature was considered (a combination of the Mean Radiant Temperature and the dry bulb temperature). The MRT was lower than the dry bulb temperature, therefore the operative temperature was closer to the lower boundary of comfort zone.

Figure 7. Thermal performance according to the ASHRAE Standard 55-2013 [37].

All four buildings provided high standards of indoor thermal environment and they were expected to provide comfortable thermal environments. Therefore, the comfort and satisfaction levels of the participants were less likely to be affected by a poor indoor air quality; this was confirmed in the follow up interviews. The regression analysis also confirmed this as well, as there was no significant relationship between the PMV and users' comfort (P value = 0.569 > 0.05) and satisfaction (P value = 0.694 > 0.05), as presented in Table 4.

Overall, the regression analysis showed no significant relationship between user comfort and satisfaction and environmental variables, including carbon dioxide, light, noise and thermal variable based on the PMV model, as presented in Table 4.

Table 4. Regression analysis of users' view and environmental variables.

Individual thermal control

The comfort and satisfaction of the respondents between the Norwegian and British practices were compared using quantitative analysis of the survey questionnaires. This study was looking for high quality environments that provided users with unconditional satisfaction and comfort. Therefore from the ASHRAE seven-point scale, only two responses ('satisfied' and 'very satisfied') that represented a satisfaction status with confidence were considered as a 'satisfied' response. The same instruction was applied to evaluate comfort: only 'comfortable' and 'very comfortable' responses were considered as 'comfortable'.

Satisfaction

The relationship between satisfaction and the type of plan (cellular and open plan layouts) was investigated using the SPSS linear regression analysis on the survey questionnaires, as presented in Table 2. The ASHRAE scale [31] was used in the analysis, as presented in Table 2. Overall, the mean of satisfaction on this scale for all four buildings was 1.03: close to 'slightly satisfied'. The results indicated a significant relationship between satisfaction and the type of plan (P value = 0.000 < 0.05). In addition, the regression analysis showed a significant relationship between satisfaction and the availability of thermal control (P value = 0.000 < 0.05). Availability of thermal control was divided into five groups: no control; window or blind; both window and blind; window, blind, door and thermostat; window, internal and external blinds, door and thermostat. Building B provided the highest level of thermal control, due to an additional blind. The first three categories were in regard to the open plan offices and occupants seated in the middle of the open plan had no control over the thermal environment. Satisfaction was compared between the four buildings, as presented in Figure 8. The two darker bars representing the Norwegian buildings were similar and the number of 'satisfied' respondents was high. The satisfaction in the two British practices was also close and many respondents reported feeling 'slightly dissatisfied' and 'neutral'. The number of 'slightly dissatisfied' respondents is higher in building C compared to building D. Overall, the analysis indicated higher satisfaction levels in the two Norwegian cellular plan offices compared to the two British open plan offices.

Figure 8. Satisfaction level in the four case study buildings.

Based on the information presented in Figure 8, satisfied occupants ('satisfied' and 'very satisfied' responses) were calculated and presented in Table 5. The satisfaction level of the respondents of the cellular plan offices was at least 30% higher than that of the respondents of the open plan layouts.

Figure 1. Type your title here. Obtain permission and include the acknowledgement required by the copyright holder if a figure is being reproduced from another source.

Table 5. Satisfied respondents in the four buildings.

Comfort

The relationship between user comfort and the type of plan was investigated using the SPSS linear regression analysis on the survey questionnaires, as presented in Table 5, and the ASHRAE scale [31], as presented in Table 2, was used in the analysis. Overall, the mean of satisfaction on this scale for all four buildings was 1.48, which is between 'slightly comfortable' and 'comfortable'. The results showed a significant relationship between the two variables (P value = 0.000 < 0.05). In addition, the regression analysis showed a significant relationship between comfort and the availability of thermal control (P value = 0.000 < 0.05), the categories are explained in section **Error! Reference source not found.**. The comfort level was compared between the four buildings, as presented in Figure 9. It showed higher comfort levels in the two cellular plan offices compared to the two open plan offices.

Figure 9. Comfort level in the four case study buildings.

Based on the information presented in Figure 9, comfortable occupants ('comfortable' and 'very comfortable' responses) were calculated and presented in Table 6. The comfort level of the respondents for the Norwegian practices was at least 18% higher than that for the British buildings.

Table 6. Comfortable respondents in the four buildings.

Interviews

In order to validate the results of the questionnaire, semi structured interviews were carried out and the interest of the respondents in their current office layout as well as using thermal control was investigated. Over 90% of the respondents of the cellular plan offices were not interested in moving into an open plan layout, due to the lack of thermal control and privacy. Over 70% of them actively adjusted the window, blind, door, or thermostat. They emphasised individual differences in perceiving the thermal environment. They found the thermal settings of their colleagues' offices uncomfortable and, hence, preferred not to share an office with them. Over 70% of the participants of the open plan offices preferred to stay in the open plan layout, due to socialising and they considered personal offices as isolated. However, they expressed their dissatisfaction regarding the lack of thermal control at their workstation and also highlighted individual differences in the perception of the thermal environment. They tried to passively adjust themselves to the thermal environment. Although they had different clothing layers at their workstations, as presented in Figure 10, they did not consider this sufficient, convenient or satisfactory. There was a limit in taking off clothing layers, warming up cold hands and little that could be done about the lack of fresh air in the middle of the open plan office. In an extreme case, one respondent kept a sleeping bag in a drawer to wear when working in the cold winter days, as presented in Figure 10. Some respondents preferred to work from home when they found the thermal environment uncomfortable.

Figure 10. Sorting clothing layers and a sleeping bag in the British open plan office.

Over 90% of the respondents of the Norwegian cellular plan offices preferred to have individual control over the thermal environment. However, 80% of the respondents of the British open plan offices initially preferred a centrally operated thermal system. Their main reasons being the 'others', who they shared an office with, their individual differences and the difficulty in satisfying everyone through a uniform thermal environment. They preferred not to be in charge of the temperature control to avoid the responsibility for setting an optimum temperature to satisfy everyone. Some respondents explained their previous experiences when a thermostat was available in the open plan office and the unpleasant arguments amongst colleagues to set the temperature. They were concerned about 'colleagues, who preferred extreme conditions, getting hold of the thermostat'. They preferred a centrally operated thermal system to set the temperature so that none of their colleagues could tamper with it. A follow up question was posed: 'In case there were no other colleagues to be concerned about, would you still prefer a centrally operated thermal system?' Most of them immediately expressed their desire to control the temperature. The respondents, who generally preferred a centrally operated thermal system, did not want to spend time or energy on setting the temperature but wanted to focus on their work instead. However, even these respondents wanted a degree of control either to set the temperature in the beginning or in case they were uncomfortable.

Discussion

The results indicated that the Norwegian cellular plan offices with high levels of individual thermal control had higher levels of user satisfaction and comfort compared to the British open plan offices with limited thermal control. This was in line with the previous work stating that higher thermal control is associated with higher user comfort and satisfaction [6,10-16,23-25]. The significance of this study was in comparing the two distinct approaches (Norwegian and British) in providing thermal control in the workplace. The analysis based on the thermal measurements showed a good quality of building performance indicating that comfortable thermal environments were expected in all four buildings, and, thereby suggesting limited impact on user comfort and satisfaction. The regression analysis indicated no significant relationship between users' comfort and satisfaction and environmental variables, including carbon dioxide level, light, noise and PMV. The quantitative analysis of satisfaction and comfort (based on the survey questionnaire) indicated a significant relationship between these two variables and the type of plan. The occupants of the two Norwegian cellular plan offices reported at least a 30% higher satisfaction level and 18% higher comfort level compared to the occupants of the two British open plan offices. The follow up interviews revealed that the satisfaction of the occupants of the Norwegian cellular plan offices was related to the availability of thermal control for every individual. Access to individual thermal control was one of the occupants' main priorities, and the lack thereof resulted in their dissatisfaction, particularly in the open plan offices, as when uncomfortable they had no option but to tolerate the thermal condition. Some occupants put on inconvenient clothing layers or preferred to work from home. A limit of field studies of thermal comfort is the complexity of the context followed by various variables that influence user comfort [7], such as psychological issues and social habits that are recommended for further research. In this study, the follow up interviews were applied to validate the results of the surveys and to limit the influence of the other factors.

The main approach to provide thermal comfort in the British open plan office is the provision of a uniform, standard thermal environment [38] and a centrally operated thermal system. The last of which is to ensure the indoor air quality, particularly when occupants prefer not to open the windows. User control is provided as a secondary option only for 'fine-tuning' in case of a system failure [22] or in case occupants are uncomfortable [6]. Overall, thermal comfort is offered to occupants through a centrally operated system and an optional adaptive opportunity is provided in case of inconvenience. This option is only provided for occupants seated around the perimeter of the building, while the majority of the users seated further from the windows are not provided with any means of control. In this study, the interviews indicated that even the occupants who had access to openable windows and blinds did not use them as desired, out of respect for the preference of 'other' colleagues. Occupants preferred not to access a thermostat in the open plan office to avoid the responsibility to set a uniform temperature to satisfy everyone, due to individual differences. However, in the case where no 'other' colleagues were influenced by their decision, their initial preference was to be able to adjust the temperature.

In contrast, the Norwegian context is user-oriented and the work legislation supports the rights of users to access individual thermal control [1,29]. This is reflected in the design of the workplace: cellular plan offices with high levels of individual control over the thermal environment. This is the main thermal system and occupants are expected to adjust the thermal environment of their personal office according to their requirements. Centrally operated thermal systems are considered as a secondary or background system to ensure a good quality of indoor environment according to workplace legislation [29]. In the Norwegian context, rather than presenting comfort to the occupant, the means to provide a comfortable condition is provided for every occupant so that individuals find their own comfort by actively using thermal control according to their immediate thermal needs. Individual differences are respected in this context and the office layout and thermal control are designed accordingly. In this study, the occupants of the Norwegian cellular plan offices expressed their satisfaction with the availability of individual control over the thermal environment. They did not want to share an office with colleagues because of individual differences in perceiving the thermal environment and because they preferred to adjust the thermal environment in their personal rooms according to their needs.

The main difference between the Norwegian cellular plan and the British open plan offices is not just the separation of workstations by walls, but in the context of providing high levels of individual thermal control. For instance, the management of building D, which was the British open plan building, had personal offices. However, they had no control over the thermal environment in their office except a glass door. Their personal offices had no windows, blinds or means to control the temperature and light. In the interviews, the occupants of the British personal offices expressed their dissatisfaction with the lack of availability of thermal control in their offices. This confirmed other studies, as the quality of the workplace environment was significantly different in these two contexts [39]. In contrast to the British practices the Norwegian case studies provided high levels of thermal control and therefore high user satisfaction. However, this came at a price: the two Norwegian practices were much less energy efficient compared to the two British practices. Inefficiency in energy and the use of space as well as being expensive and inflexible to respond to modern organisational changes [2,3] are the main causes of the move from cellular plan offices to open plan layouts in Scandinavia [4,5]. The case studies in this work are either energy efficient or comfortable through providing thermal control for every individual. Although reducing the energy consumption is essential, user comfort is also important and providing a suitable environment for individuals is essential to maintain satisfaction and productivity accordingly [25]. Therefore, a balance between energy efficiency and providing comfort for individuals is required, as either extreme poses difficulties for the other. To achieve this, user orientated design must become integral to the building operation strategy.

Conclusion

This study investigated user comfort when different qualities of thermal control were provided in two distinct contexts. They followed two separate paths in designing the workplace: user-oriented and business-oriented with high and low levels of thermal control, respectively. Although previous research emphasised the impact of thermal control on user comfort and satisfaction [6,10-12,23,24], they were mainly applied in open plan settings, where thermal control was considered as a secondary option for fine-tuning. This work compared such settings with personal offices that based on the regulations provided high levels of thermal control for every individual as the main source of regulating the thermal environment to find their own comfort in a way that it does not influence the settings of other occupants. Currently in practice, such settings are being replaced by open plan layouts with limited thermal control and management prefer centrally operated thermal systems rather than user control.

This study found that a balance between energy consumption and thermal comfort is dependent on the provision of individual control over the thermal environment to achieve user comfort and satisfaction. Overall, rather than presenting comfort to the occupants, buildings should provide a degree of flexibility in a sustainable way to allow users to adjust their thermal environment according to their individual requirements to find their own comfort.

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References

[1] Van Meel, J. 2000. The European Office: Office Design and National Context, Rotterdam, 010 Publishers.
[2] Van Meel, J. & De Jonge, H. 2006. *Office Cultures: International Differences in Workplace Design*. In: Worthington, J. (ed.) *Reinventing the Workplace*. London: Architectural Press, Elsevier.
[3] Myerson, J. 2008. *Power of the Network*: *Transitions in Working Life from Taylorist Time and Motion to Networked Space*. In: Glynne, J. & Iackney, F., eds. *Networks of Design*: Proceedings of the 2008 Annual International Conference of the Design History Society (UK), 2008 University College Falmouth. Universal Publishers.
[4] Axéll, C. & Warnander, A. 2005. *How to Create Optimal Office Solutions*. MSc, KTH University.
[5] Gadsjö, A. 2006. Hur påverkas hyresgästanpassningar framtida hyresintäkter? (How Does Improvement in Tenant Influence The Future of Rental Income?). KTH.
[6] Bordass, B., Bromley, K. & Leaman, A. 1993. *User and Occupant Controls in Office Buildings.* Building Use Studies.
[7] Roaf, S., Horsley, A. & Gupa, R. 2004. *Closing the loop; Benchmarks for sustainable buildings*, London, RIBA Enterprises Ltd.
[8] Harris, R. 2006. *Real Estate and the Future*. In: Worthington, J. (ed.) *Reinventing the Workplace*. London: Architectural Press, Elsevier.
[9] Katsikakis, D. 2006. *New Real Estate Models to Support Distributed Working*. In: Worthington, J. (ed.) *Reinventing the Workplace*. London: Architectural Press, Elsevier.
[10] Melikov, A. 2004. *Personilised Ventilation*. Indoor Air, 14**,** 157-167.
[11] Arens, E., Humphreys, M. A., De Dear, R. & Zhang, H. 2010. *Are 'Class A' Temperatue Requirements Realistic or Desirable?* Building and Environment, 45**,** 4-10.
[12] Leaman, A. 1996. *User satisfaction.* Building evaluation techniques. London: McGraw.

[13] De Dear, R. & Brager, G. 2002. *Thermal Comfort in Naturally Ventilated Buildigns: Revisions to ASHRAE Standard 55*. Energy and Buildings, 34, 6: 549-561

[14] Baker, N. & Standeven, M. 1995. *A Behavioural Approach to Thermal Comfort Assessment*. International Journal of Solar Energy, 19**,** 21-35.

[15] Humphreys, M. A. 1996. Thermal Comfort Temperatures World-Wide: The Current Position. WREC 1996.

[16] Leaman, A., Bordass, B. & Cassels, S. *Flexibility and Adaptability in Buildings: the 'Killer' Variables.* Building Use Studies, 1998 London. UsableBuildings.

[17] Huizenga, C., Abbaszadeh, S., Zagreus, L. & Arens, A. 2006. *Air Quality and Thermal Comfort in Office Buildings: Results of a large Indoor Environmental Quality Survey*. Indoor Enviornmental Quality. Center for the Built Environment, UC Berkeley.

[18] Brager, G. & Baker, L. 2009. *Occupant Satisfaction in Mixed-Mode Buildigns*. Building Research and Information, 37, 4: 369-380.

[19] Leaman, A. 1993. *The Importance of Response Time*. Hong Kong Building Journal, June.

[20] Moezzi, M. 2009. *Are comfort expectations of building occupants too high?* building Research and Information, 37**,** 79-83.

[21] Indraganti, M., Ooka, R. & Rijal, H., B. 2013. Thermal Comfort in Offices in Summer: Findings from a Field Study under the 'Setsuden' Conditions in Tokyo, Japan. Building and Environment, 61**,** 114-132.

[22] Hawkes, D. 2002. The Selective Environment; An approach to environmentally responsive architecture, London, Spon Press.

[23] Wagner, A., Gossauer, E., Moosmann, C., Gropp, T. & Leonhart, R. 2007. Thermal comfort and workplace occupant satisfaction: Results of field studies in German low energy office buildings. Energy and Building, 39, 758-769.

[24] Newsham, G., Brand, J., Donnelly, C., Veitch, J., Aries, M. & Charles, K. 2009. *Linking Indoor Environment Conditions to Job Satisfaction: A Field Study.* Building Research and Information, 39**,** 129-147.

[25] Charkham, J., P. 1995. Keeping Good Company: A Study of Corporate Governance in Five Countries, Oxford, Oxford University Press.

[26] Van Der Voordt, T., J. M. 2003. *Productivity and Employee Satisfaction in Fexible Workplaces.* Journal of Corporate Real Estate, 6**,** 133-148.

[27] Nicol, F. & Humphreys, M. A. 2005. *Maximum Temperature in Buildings to Avoid Heat Discomfort.* International Conference 'Passive and Low Energy Cooling for the Built Environment'. Santorini, Greece.

[28] Tuohy, P., Rijal, H. B., Humphreys, M. A., Nicol, J. F., Samuel, A. & Clarke, J. *Comfort driven adaptive window opening behaviour and the influence of building design.* Building simulation, 2007.

[29] Arbeidstilsynet 2003. Control and Guidance on Working: Veiledning om klima og luftkvalitet på arbeidsplassen - fulltekst. In: Arbeidstilsynet (ed.). Norway.

[30] Brager, G. S. & Baker, L. 2009. *Occupant Satisfaction in Mixed-Mode Buildings*. Building Research and Information, 37, 369-380.

[31] ASHRAE 2009. *ASHRAE Handbook: Fundamentals.* SI Edition ed. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

[32] Huizenga, C. 2011. *ASHRAE Thermal Comfort Tool CD, Version 2:* Maintains Consistency with ANSI/ASHRAE Standard 55-2010. ASHRAE.
[33] McCartney, K. J. & Nicol, F. 2002. *Developing an Adaptvie Control Algorithm for Europe*. Energy and Buildings, 34, 623-635.
[34] ASHRAE 2001. *ASHRAE Fundamental Handbook*, Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
[35] CIBSE 2003. *Energy Consumption Guide 19: Energy Use in Offices. Best Practice Programme*. The Chartered Institution of Building Services Engineers.
[36] ASHRAE 2010. *ASHRAE Standard 55*. In: Cooper & W., K. (eds.) *Thermal Environmental Conditions for Human Occupancy*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.
[37] ASHRAE 2013. *ANSI/ASHRAE Standard 55-2013: Thermal Environmental Conditions for Human Occupancy.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
[38] Nicol, F., Humphreys, M. A. & Roaf, S. 2012. *Adaptive Thermal Comfort: Principles and Practice*, Routledge.
[39] Duffy, F. 1992. *The Changing Workplace*, London, Phaidon Press Limited.

List of tables

Table 1. Information regarding the researched floor in each building.

Information regarding the floor of the building, which is included in the research						
Buildings	**Floor area m^2**	**Number of workstations in each floor**	**Size of each workstation m^2**	**Workstations considered in this study**	**Male**	**Female**
Building A	2000	100	10	95	53	42
Building B	840	24	14	77	41	36
Building C	1000	125	5	72	34	38
Building D	1680	525	3.5	69	37	32

Table 2. Extract from the questionnaire in regard to the thermal environment based on the ASHRAE seven-point scale [31].

Currently at my desk, regarding the thermal environment I feel:							
Very comfortable	Comfortable	Slightly comfortable	Neutral	Slightly uncomfortable	Uncomfortable	Very uncomfortable	No strong opinion
+3	+2	+1	0	-1	-2	-3	
Currently at my desk, the overall environment makes me feel:							
Very satisfied	Satisfied	Slightly satisfied	Neutral	Slightly dissatisfied	Dissatisfied	Very dissatisfied	No strong opinion
+3	+2	+1	0	-1	-2	-3	

Table 3. Heating, cooling and ventilation systems in the four buildings.

Building	Location	Natural ventilation	Mechanical ventilation	Heating Installation	Heating working in summer?	Cooling installation
A	Norway	Openable windows	Mechanical ventilation-ceiling	Radiator	Yes	Radiant cooling
B	Norway	Openable windows	Mechanical ventilation-ceiling	Radiator	No	Radiant cooling
C	UK	Openable windows	Perimeter ventilation-automated top windows	Radiator	No	No
D	UK	Openable windows	Mechanical ventilation-underfloor	Radiator	No	No

Table 4. Regression analysis of users' view and environmental variables.

P values based on the SPSS linear regression analysis (P values > 0.05)				
	Carbon dioxide	**Light**	**Noise**	**PMV**
Comfort	0.433	0.250	0.946	0.569
Satisfaction	0.120	0.740	0.162	0.694

Table 5. Satisfied respondents in the four buildings.

Buildings	Percentage of satisfied respondents
Building A	63.10%
Building B	64.90%
Building C	32.00%
Building D	27.50%

Table 6. Comfortable respondents in the four buildings.

Buildings	Percentage of comfortable respondents
Building A	77.90%
Building B	76.60%
Building C	56.90%
Building D	58.00%

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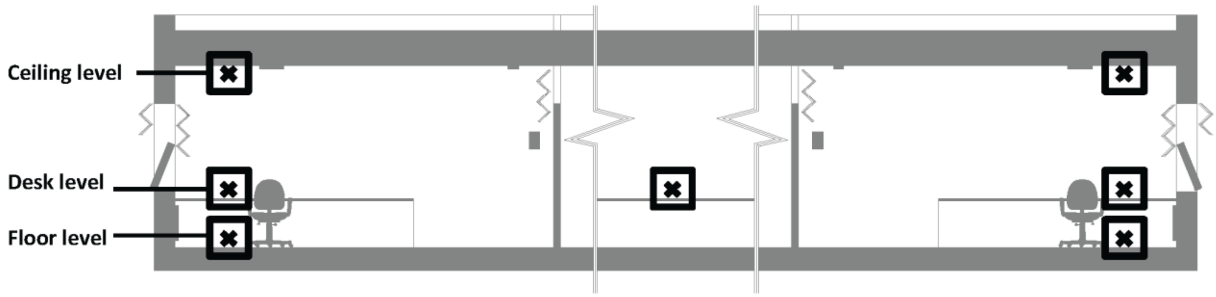

Figure 1. Sample of measuring points in Building B.

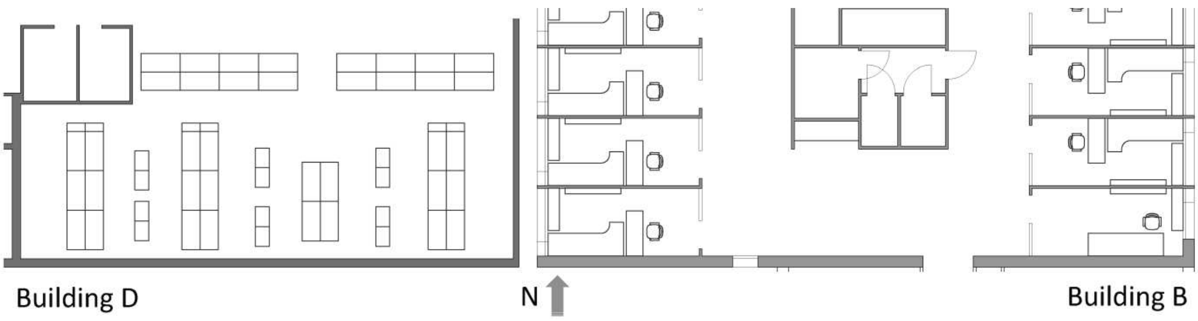

Figure 2. Sample plans of buildings B and D.

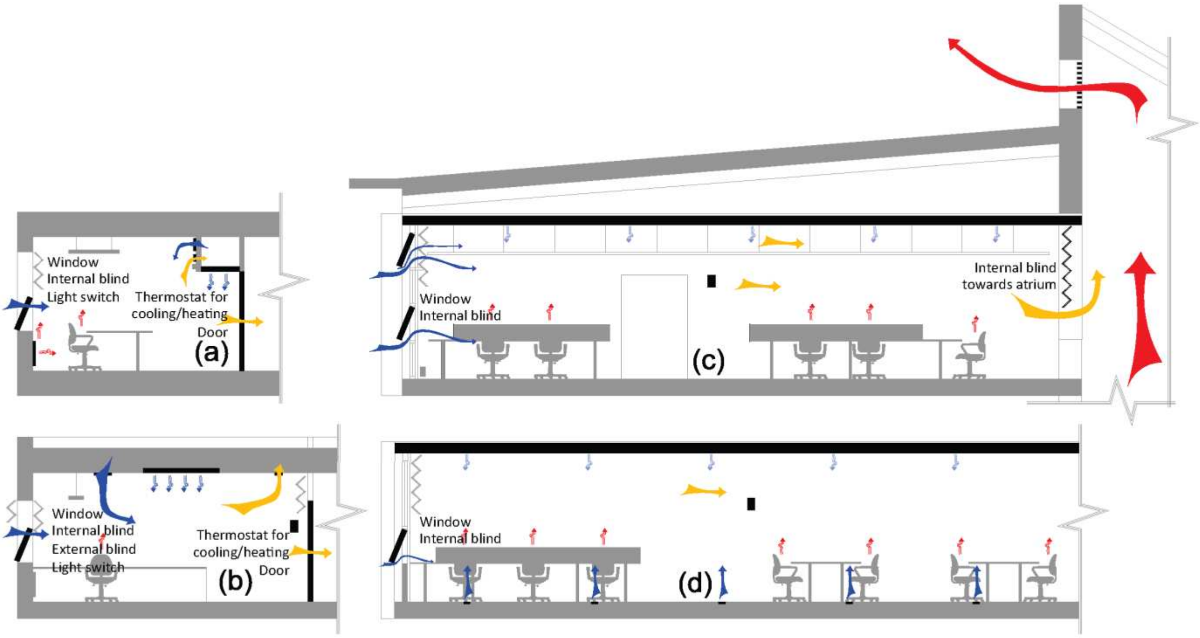

Figure 3. Sections of environmental control and summer day ventilation systems: (a), (b): Norwegian cellular plan offices and (c), (d): British open plan offices.

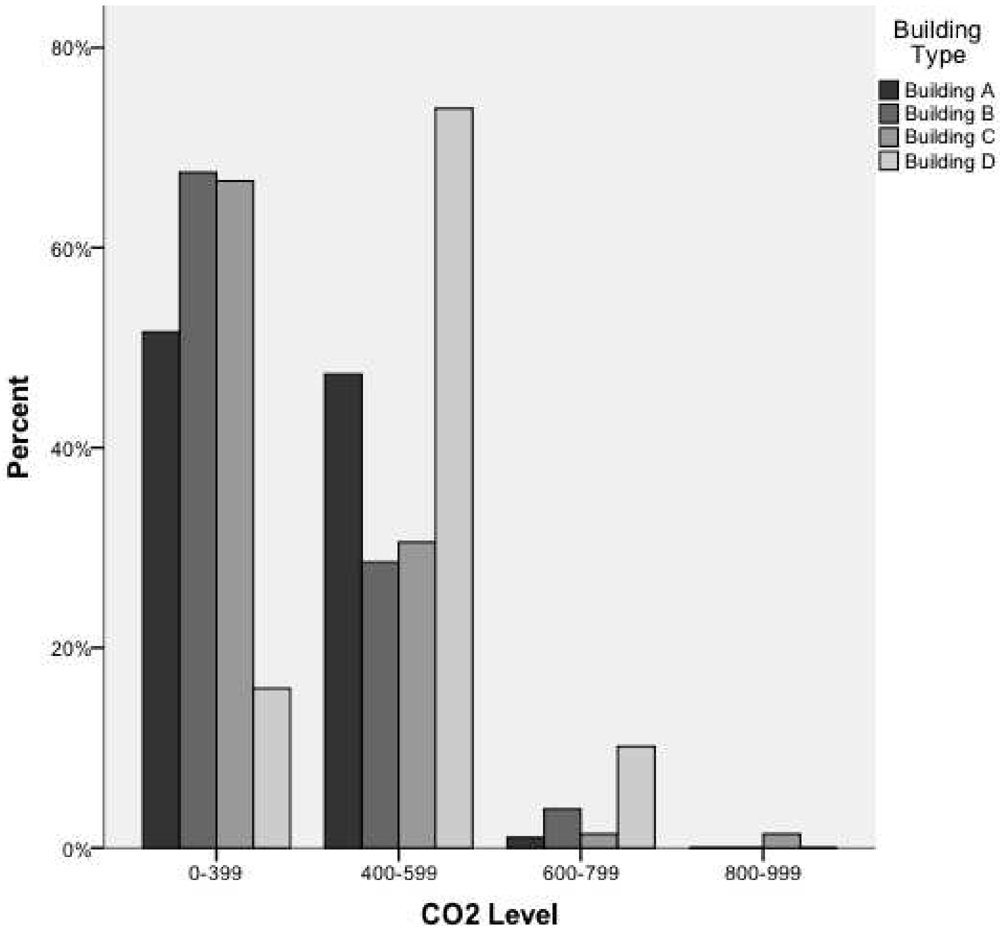

Figure 4. Carbon dioxide level: comparing the four case study buildings.

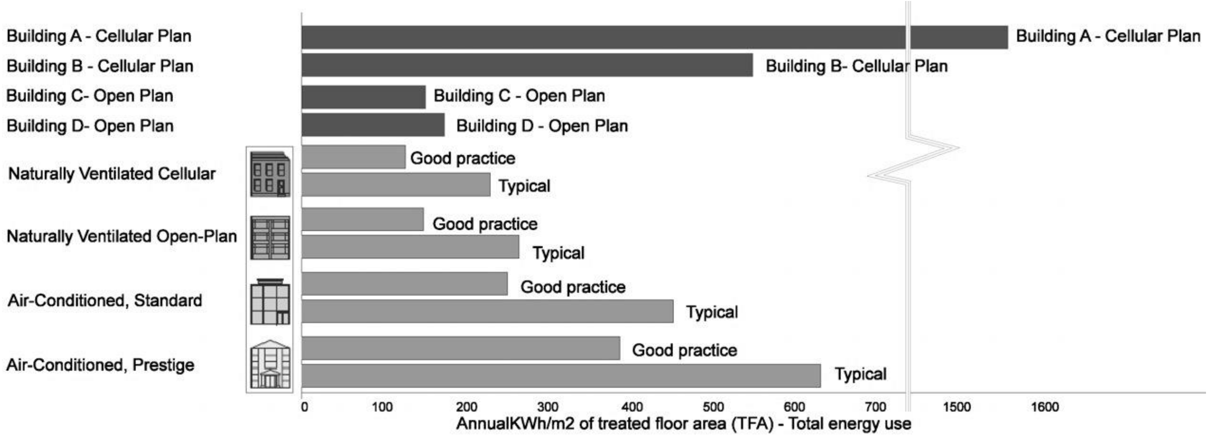

Figure 5. Energy consumption KWh/m2 per year: comparing the buildings against the benchmark [36].

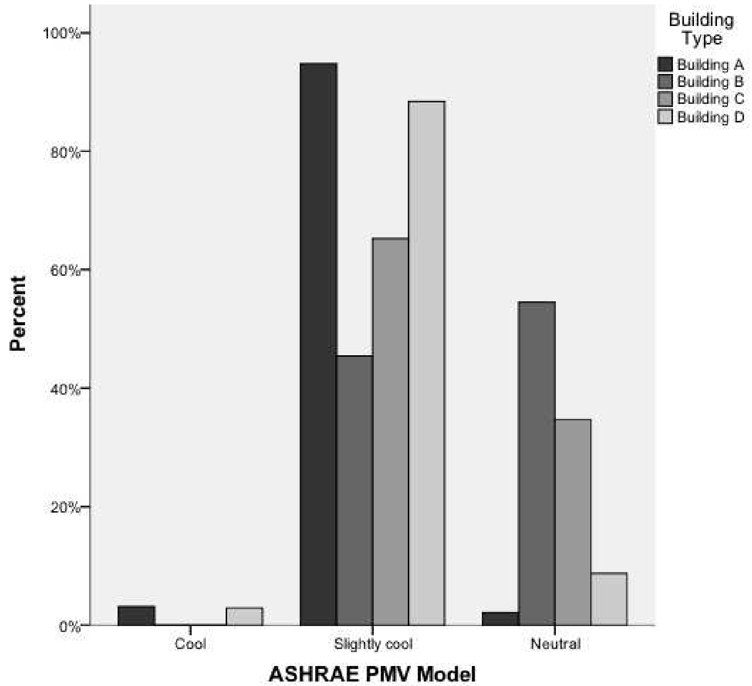

Figure 6. The PMV analysis.

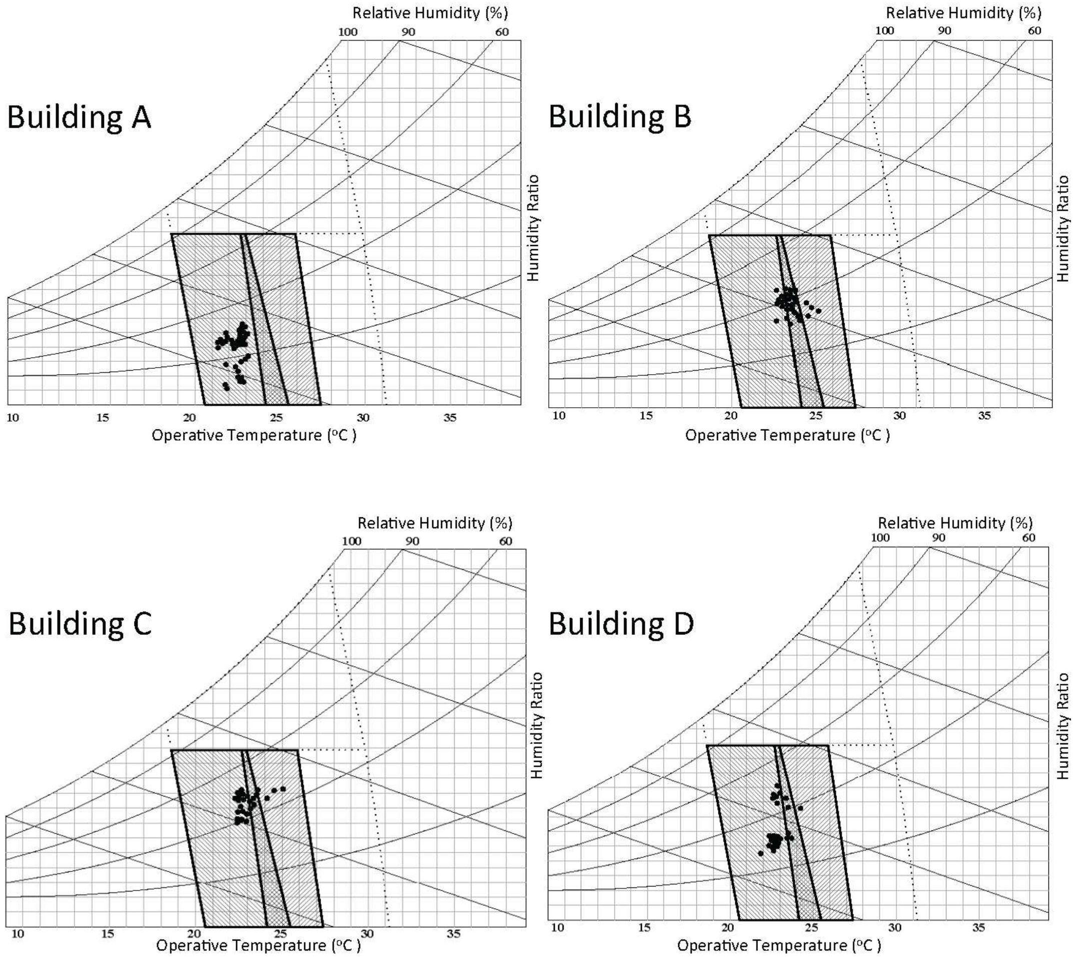

Figure 7. Thermal performance according to the ASHRAE Standard 55-2013 [38].

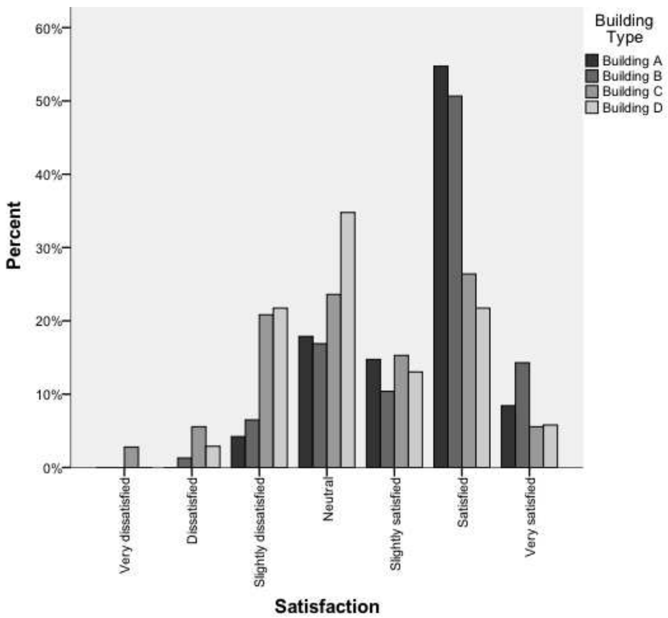

Figure 8. Satisfaction level in the four case study buildings.

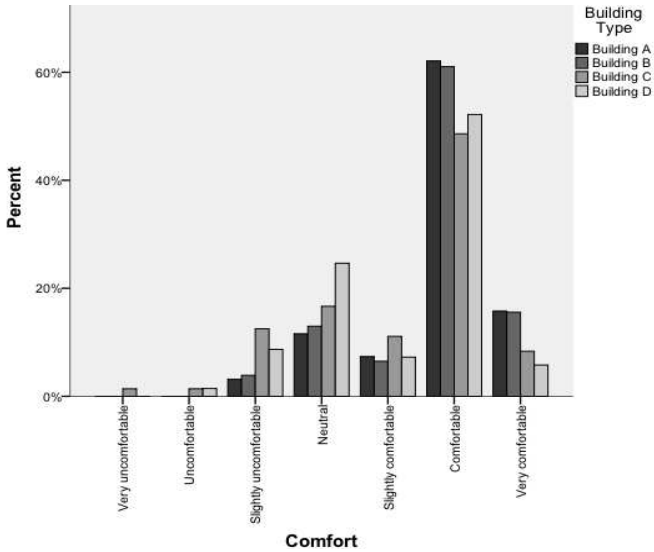

Figure 9. Comfort level in the four case study buildings.

Figure 10. Sorting clothing layers and a sleeping bag in the British open plan office.