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Potential on Comfort Enhancement and Energy Saving through Behavioral Change of Energy Users in Real European Buildings †

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Abstract: The study monitored 10 real European buildings to identify comfort enhancement potential and energy saving potential based on changing the behavior of building users. The results show that the office building could have saved up to EUR 2500 in energy during the study period while the healthcare centers could have saved more than EUR 1000. The highest energy saving potential is related to the use of the Heating, Ventilation and Air-Conditioning (HVAC) system. It has also been found out that there is a potential to improve comfort conditions in all the pilot buildings. The highest potential on comfort is identified in the improvement of the luminance conditions.

Keywords: building; energy saving; comfort enhancement; users behavior

1. Introduction

Buildings account for 40% of overall energy consumption in the European Union [1]. Energy related to occupant behavior is identified as one of the major factors influencing building energy consumption [2]. The authors of this paper have analyzed several European buildings such as schools, office buildings, healthcare centers and residential buildings to quantify the potential on comfort enhancement and energy saving through behavioral change of building users towards energy efficiency. In this line, the most promising users' behaviors changes have been identified.

Measurements on energy consumption, indoor conditions, outdoor conditions and other parameters such as occupancy or windows opening have been collected in the 10 buildings to estimate the energy saving potential by changing energy target behaviors related to the use of HVAC systems, appliances and lightings. In addition, the number of hours with no comfort conditions in occupied rooms due to CO_2 levels, temperature, relative humidity and luminance were estimated in order to evaluate comfort enhancement potential.

The paper explains the objective, need and methodology of the study, the monitoring data collected, the analysis to quantify energy saving and comfort enhancement potential, the results and the conclusions.

This work is part of an on-going EU-funded project called eTEACHER which aims at empowering energy end-users to achieve energy savings and improve comfort conditions within buildings through enabling behavioral change.

2. Materials and Methods

The experiment design consisted of intensively monitoring 10 European buildings at building and room/apartment level during 8 months from February until September 2019.

The 10 pilot buildings are real buildings and include a kindergarten (1976, 905 m^2, 1 floor, 20 users), a high school (1965, 5307 m^2, 3 floors, 120 users), an office building (2011, 3211 m^2, 3 floors, 130 users), a residential building (1984, 4540 m^2, 5 floors, 95 users) and 2 healthcare centers (2000/2002, 1270/2180 m^2, 2/2 floors, 577/915 users) in Spain as well as 4 residential buildings (2009, 67,900 m^2, 4 buildings, 1500 users) in Romania. The users of these buildings are facility managers, householders, office/medical staff, cleaning crew, security team, teachers and students. The technical systems are mainly HVAC systems, appliances and lighting systems which consume electricity, gas, fuel oil or waste depending on the building and system. The appliances depend on the type of building and are computers, printers, beamers and electric radiators, medical equipment, lab equipment and home appliances such as TVs, fridges, ovens, etc. The lighting systems are mainly fluorescent lamps and have sometimes central control and sometimes manual control. The HVAC systems include several types such as heating and cooling based on VRF heat pumps (variable refrigerant flow) and compact air-handling units, splits, district heating and radiators, boilers and radiators, boilers and underfloor heating, electric chillers and cold ceilings, air-water heat pumps and fan coils, air-air heat pumps (multi-splits), etc.

The measurements that were collected are:

At building level:

- Outdoor conditions: Temperature (°C), relative humidity (%), light level (lux), solar radiation (W/m^2)
- Energy consumption (kWh): lighting, HVAC, appliances

At room/apartment level:

- Energy consumption (kWh): lighting, HVAC, appliances
- Indoor conditions: temperature (°C), CO_2 (ppm), relative humidity (%), light level (lux)
- Other binary measurements: presence and windows opening

2.1. Comfort Analysis to Quantify Enhancement Potential

The comfort analysis is focused on 4 factors or variables: temperature, relative humidity, luminance and CO_2 level. The thresholds of these variables where comfort is guaranteed were defined according to the standards [3–6]:

- Indoor Temperature: 21–26 °C
- Indoor Relative Humidity: 40–60%
- Indoor Luminance: ≥500 lux (≥150 lux in residential buildings)
- Indoor CO_2 level: ≤800 ppm.

To characterize the comfort in every building, the monitoring temperature, relative humidity, luminance and CO_2 level were analyzed every hour to quantify the number of hours where the rooms/zones are occupied and these variables are out of the thresholds where comfort is guaranteed.

2.2. Target Behavior Analysis to Quantify Energy Saving Potential

In total, nine energy-related target behaviors were defined:

- Lighting use behavior: (TB1) Turning off lights when leaving a room or at the end of the day; (TB2) reduce use of unneeded lights checking lighting levels and needs during the day.
- Appliance use behavior: (TB3) Turn off appliances (computers, TVs, medical equipment, etc.) at the end of the day; (TB4) turn off appliances when away.
- HVAC use behavior: (TB5) Reduce thermostat temperature for heating when overheating; (TB6) increase thermostat temperature for cooling when undercooling; (TB7) ensure that windows and

doors are kept closed if heating/cooling is on; (TB8) turn off HVAC system if room/building is not in use for more than one hour; (TB9) ensure that air-conditioning and heating are not working at the same time.

The target behaviors were characterized for every building based on the monitoring data. Such characterization consisted of quantifying the number of hours that these target behaviors are not carried out by the users of the buildings, the energy (kWh) wasted during those hours and the cost of the energy wasted during those hours (EUR).

Table 1 summarizes how the target behaviors TB1, TB4 and TB6 were characterized as examples:

Table 1. Description of target behaviors' characterization.

Target Behavior	Description
TB1: Turning off lights when leaving a room or at the end of the day	Count number of hours in every monitoring room where there is no one present and the lights are on (presence = 0 and C_lighting > 0 kWh) Lighting energy consumed during those hours: (∑C_Lighting (kWh)) Cost of that energy: (e.g ∑C_Lighting kWh × 0.129893 EUR/kWh)
TB4: Appliances off when away from room for 1 h or more.	Count number of hours in every monitoring room that appliances are on, there is no one (C_appliances > 0 kWh and presence = 0) Appliances energy consumed during those hours: ($\sum C\_Appliances$ (kWh)) Cost of that energy (e.g. $\sum C\_Appliances$ kWh × 0.129893 EUR/kWh)
TB6: Increasing thermostat temperature for cooling when undercooling	Count number of hours in every monitoring room that temperature inside is high and heating is on (temp_i > 21 °C & C_cooling > 0 kWh) Cooling energy consumed during those hours ($\sum C\_cooling$ (kWh)) and cost of that energy (e.g., $\sum C\_cooling$ kWh × 0.129893 EUR/kWh)

3. Results

3.1. Comfort Enhancement Potential

A summary of the comfort analysis in the 10 buildings is shown in Table 2. It shows the percentage (%) of hours that monitoring rooms/apartments in every building are occupied and temperature, relative humidity or CO_2 level are out of the comfort range defined previously.

Table 2. Summary of comfort analysis. Percentage of occupied hours with no comfort.

Building	Temp	Rel. Humid	CO_2	Luminance
Office	20%	60%	5%	70%
HCC1	30%	60%	40%	45%
HCC2	18%	60%	20%	-
School 1	80%	80%	5%	90%
School 2	20%	50%	30%	95%
Residential 1	50%	60%	5%	100%
Residential 2	40%	20%	10%	-

Office building, Spain. It must be highlighted that the main problems are related to the lighting level and the relative humidity while temperature and CO_2 levels do not seem to be a problem. More than 60% of the occupied hours have relative humidity and luminance levels out of the thresholds where comfort is guaranteed.

Health care center 1, Spain. The results show that the main comfort problems are related to the relative humidity (>60% occupied hours). However, temperature, CO_2 and luminance are also sources of no comfort during more than 30% of occupied hours. Therefore, there is a key potential in order to improve the comfort in this building.

Health care center 2, Spain. According to the analysis, the main reason for no comfort is the relative humidity. The temperature and CO_2 levels do not present big problems in terms of comfort.

In this case, comfort in terms of luminance has not been analyzed since these measurements do not have enough quality.

School 1, Spain. The main reasons related to the lack of comfort in this building is due to the luminance level, temperature and relative humidity. CO_2 levels are within the comfort ranges most of the time: almost 100% of the occupied hours have luminance levels out of the comfort range in all monitoring rooms; almost 80% of the occupied hours have temperature out of the comfort range; almost 80% of the occupied hours have no comfort due to relative humidity. In conclusion, comfort has a high potential to be improved in this building.

School 2, Spain. According to the comfort analysis, the main problems of the comfort are related to the luminance. However, relative humidity and CO_2 level must be also improved to guarantee comfort: almost 100% of the occupied hours have luminance levels out of the comfort range in all monitoring rooms; more than 50% of the occupied hours have relative humidity out of the comfort range; about 30% of the occupied hours have no comfort due to relative humidity.

Residential building 1, Spain. The comfort in this building is not very good. The main problems are due to luminance where the requirements have been reduced to 150 lux since it is a residential building. However, temperature and relative humidity are also out of the range of the comfort during more than 40% of the occupied hours.

Residential buildings 2, Romanian. The comfort analysis shows that the main comfort problem is related to the temperature since more than 40% of occupied hours have temperatures above or below the comfort range.

3.2. Energy Saving Potential Based on Target Behavior Analysis

Following, the results in every study building are explained.

Office building, Spain. According to the target behavior analysis, the users of this building have had from March until September 2019: (TB1) Lights on when leaving a room or at the end of the day during 4504 h consuming 3585 kWh and EUR 465 during these hours; (TB2) Use unneeded lights during 4114 h consuming 12447 kWh and EUR 1616 during these hours; (TB3) Appliances on at the end of the day during 506 h consuming 16.22 kWh and EUR 2.10 during these hours; (TB4) Appliances on when away from room for 1 h or more during 2078 consuming 87.55 kWh and EUR 11.37 during these hours; (TB5) Thermostat temperature too high for heating when overheating during 233 h consuming 24.64 kWh and EUR 3.2 during these hours; (TB6) Thermostat temperature too high for cooling when undercooling during 2497 h consuming 1500 kWh and EUR 194 during these hours; (TB7) Heating/cooling on when windows or doors are opened during 5501 h consuming 1949 kWh and EUR 194 during these hours; (TB8) HVAC on when no one is present for 3285 h consuming 563 kWh and EUR 73.16 during these hours.

Therefore, the target behaviors with higher energy saving potential according to the data analyzed are those related to the use of lighting. They could have saved up to 16,000 kWh and EUR 2000 during this period of time.

Health care center 1, Spain. According to the target behavior analysis, the users of this building have had hours from April until September 2019: (TB1) Lights on when leaving a room or at the end of the day during 1189 h consuming 218 kWh and EUR 28.35 during these hours; (TB2) Use unneeded lights during 8 h consuming 0.9 kWh and EUR 0.11 during these hours; (TB3) Appliances on at the end of the day during 3170 h consuming 38.31 kWh and EUR 4.97 during these hours; (TB4) Appliances on and away from for 1 h or more during 10785 h consuming 160.57 kWh and EUR 20.85 during these hours; (TB5) Thermostat temperature too high for heating when overheating during 35 h consuming 0.12 kWh and EUR 0.016 during these hours; (TB6) Thermostat temperature too low for cooling when undercooling during 3938 h consuming 4039 kWh and EUR 524 during these hours; (TB7) Windows open when HVAC on during 1649 h consuming 1346 kWh and EUR 174 during these hours; (TB8) HVAC on when no one is present during 6195 h consuming 5410 kWh and EUR 702 during these hours.

Therefore, the most promising target behaviors in terms of energy saving potential are those related to the use of the cooling system (TB8 and TB6). They could have saved up to 9000 kWh and EUR 1200 during this period of time.

Health care center 2, Spain. According to the target behavior analysis based on monitoring data, users of this building have had from April until September 2019: (TB1) Lights on when leaving a room or at the end of the day during 207 h consuming 222 kWh and EUR 26.4 during these hours; (TB3) Appliances on at the end of the day during 1313 h consuming 29.35 kWh and EUR 3.49 during these hours; (TB4) Appliances on and away from for 1 h or more during 4382 h consuming 81.76 kWh and EUR 9.72 during these hours; (TB6) Thermostat temperature too low for cooling when undercooling during 7794 h consuming 4182 kWh and EUR 497 during these hours; (TB7) Windows open when HVAC on during 2777 h consuming 1577 kWh and EUR 187 during these hours; (TB8) HVAC on when no one is present during 8681 h consuming 4227 kWh and EUR 503 during these hours.

Therefore, the target behaviors with higher energy saving potential according to the data analyzed are those related to the use of the cooling system (TB6 and TB8). They could have saved up to 8500 kWh and EUR 1000 during this period of time.

School 1, Spain. According to the target behavior analysis based on monitoring data, users of this building have had from April until September 2019: (TB3) Appliances on at the end of the day during 241 h consuming 5.36 kWh and EUR 0.63 during these hours; (TB4) Appliances on and away from for 1 h or more during 894 h consuming 33.53 kWh and EUR 3.98 during these hours

In conclusion, target behavior related to appliances do not present a high energy saving potential. However, it should be considered that not all the appliances have been measured. It must be also highlighted that the use of lighting, windows and heating cannot be characterized with the existing monitoring data.

School 2, Spain. According to the target behavior analysis, users of this building have had from April until September 2019: (TB1) Lights on when leaving a room or at the end of the day during 4236 h consuming 113 kWh and EUR 13.47 during these hours; (TB3) Appliances on at the end of the day during 85 h consuming 1.79 kWh and EUR 0.21 during these hours; (TB4) Appliances on and away from for 1 h or more during 297 h consuming 10.24 kWh and EUR 1.21 during these hours; (TB6) Thermostat temperature too low for cooling when undercooling during 1179 h consuming 179.71 kWh and EUR 21.38 during these hours; (TB7) Windows open when HVAC on during 70 h consuming 110 kWh and EUR 13.09 during these hours; (TB8) HVAC on when no one is present during 72 h consuming 62.87 kWh and EUR 7.48 during these hours.

In conclusion, the target behaviors with higher energy saving potential are those related to the use of the cooling system (TB1, TB6, TB7).

Residential building 1, Spain. According to the target behavior analysis, users of this building have had: (TB4) Appliances on and away from for 1 h or more during 3644 h from April until July consuming 134 kWh and EUR 18.4 during these hours; (TB6) Thermostat temperature too low for cooling when undercooling during 4527 h from April until July consuming 271 kWh and EUR 37 during these hours; (TB7) Windows open when HVAC on during 58 h from April until July consuming 66 kWh and EUR 9 during these hours; (TB8) HVAC on when no one is present during 83 h from April until July consuming 409 kWh and EUR 56 during these hours.

In conclusion, the target behaviors with higher energy saving potential are those related to the use of the cooling system (TB6 and TB8). They could have saved up to 800 kWh and EUR 100 in these 4 months.

Residential buildings 2, Romanian. According to the target behavior analysis, users of this building have had from April until September 2019: (TB1) Lights on when leaving a room or at the end of day during 1 h consuming 1 kWh and EUR 0.1218 during these hours; (TB4) Appliances on and away from for 1 h or more during 96 h consuming 98 kWh and EUR 11.93 during these hours; (TB6) Thermostat temperature too low for cooling when undercooling during 164 h from consuming 164 kWh and EUR 19.72 during these hours; (TB7) Windows open when HVAC on during 979 h

consuming 996 kWh and EUR 121.31 during these hours; (TB8) HVAC on when no one is present during 190 h consuming 190 kWh and EUR 23 during these hours.

Therefore, the most promising target behaviors in terms of energy saving potential are (TB7) close windows if HVAC is on.

4. Discussion and Conclusions

The results have shown that all buildings have something to improve on in terms of comfort (temperature, relative humidity, luminance or CO_2 level). The highest potential to improve comfort is related to luminance and relative humidity. A positive finding is that CO_2 levels are quite good.

On the other hand, the most promising target behaviors in terms of energy saving potential are those related to the use of the cooling system: (TB6) Increasing thermostat if undercooling, (TB7) Close windows if HVAC is on, (TB8) Turn off HVAC if no one is present. It should be noted that the target behaviors focused on heating were not analyzed due to the weather conditions during the monitoring months. Another conclusion is that office buildings and health care centers seem to have higher energy saving potential by behavioral change.

After this study, it would be valuable:

- Checking other weather conditions. In this line, eTEACHER project will analyze an office building and a school in UK.
- Deploying ICT solutions to change energy behavior of these buildings' users. The building users of these pilots will be provided with an app to encourage energy behavior change during the demonstration phase of the eTEACHER project.
- Checking if the energy saving potential and comfort enhancement potential identified in this study are finally achieved. Energy savings and comfort enhancement will be analyzed after providing building users with the app to encourage their behavior change as part of the validation analysis of the eTEACHER project.

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References

1. Šajn, N. *Energy Efficiency of Buildings*; European Parliamentary Research Service, Brussels: May 2016
2. Hong, T.; Taylor-Lange, S.C.; D'Oca, S.; Yan, D.; Corgnati, S.P. Advances in research and applications of energy-related occupant behavior in buildings. *Energy Build.* **2016**, *116*, 694.
3. ASHRAE. *ASHRAE Fundamentals Handbook*; ASHRAE: Atlanta, GA, USA, 1997.
4. ASHRAE. *ANSI/ASHRAE Standard 65-2001, Ventilation for Acceptable Indoor Air Quality*; ASHRAE: Atlanta, GA, USA, 2001.
5. ASHRAE. *Standard 55-2017—Thermal Environmental Conditions for Human Occupancy*; ASHRAE: Atlanta, GA, USA, 2017.
6. ISO. *ISO7730 Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Thermal Comfort using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria*; International Organization for Standardization: Geneva, 2005.