Improving energy efficiency through the optimization of buildings' operational regime: simulation based case studies

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Abstract

The ongoing EU-funded project RESSEEPE explores, in addition to the hardware-centric solutions, the potential for the enhancement of energy efficiency in public edification through the optimization of buildings' operational regime. For the purpose of this contribution, we report on the simulation-based studies on three public buildings across Europe within the framework of the RESSEEPE project: A secondary School in Skellefteå, Sweden, a hospital in Terrassa, Spain, and a university building in Coventry, UK. The case studies provide a basis for the formulation of a general modelling and analysis process for the implementation of advanced control scenarios, as well as an evaluation of the extent to which these measures can contribute to enhancing the building performance in different European climates.

1. Introduction

Energy efficiency measures in the domain of existing buildings may be broadly classified as either hardware-centric or software-centric. While the former measures target building hardware (e.g., thermal quality of the building envelope, efficiency of environmental control equipment), the latter focus on building operation processes (Schuss et al. 2013). Given this background, the ongoing EU-funded project RESSEEPE (RESSEEPE, 2014) explores, in addition to the hardware-centric solutions, the potential for the enhancement of energy efficiency in public edification through the optimization of buildings' operational regime. Specifically, one of the project's objectives is to compare the energy and indoor-environmental performance of a number of existing facilities before and after real or virtual implementation of control improvement measures. The suggested control scenarios focus on predictive building systems control and passive environmental strategies. For the purpose of this contribution, we report on the simulation-based studies on three public buildings across Europe within the framework of the RESSEEPE project: A secondary School in Skellefteå, Sweden (Balderskolan), a hospital in Terrassa, Spain, and a university building in Coventry, UK (George Eliot building). The case studies provide a basis for the formulation of a general modelling and analysis process for the implementation of advanced control scenarios, as well as an evaluation of the extent to which these measures can contribute in enhancing the building performance in different European climates.

2. Approach

2.1 Small-scale energy models

In order to evaluate the effectiveness of advanced control scenarios with the aid of dynamic performance simulation, a number of demo buildings' small-scale thermal performance models have been built in the well-known building performance simulation tool EnergyPlus (EnergyPlus 8.1.0, 2014). In the case of the George Eliot building, the model includes a large classroom, four small classrooms/offices and the corridor between these rooms. The Balderskolan model consists of a number of classrooms located on the ground floor. In the Terrassa hospital model four typical north-facing and south-facing patient rooms were modelled. Figures 1 to 3 illustrate the geometry of the small-scale EnergyPlus models (visualized by OpenStudio plugin for SketchUp) for demo buildings in three RESSEEPE demo sites.

The building models were generated based on the best information available and a number of assumptions. The small-scale energy models enabled us to perform faster parametric simulations to evaluate the effectiveness of the retrofit measures with different configurations. It is also worthwhile to mention that the small-scale energy models have a relatively generic nature. That is, even though they have been derived from specific buildings, they can serve to evaluate the effectiveness of measures in the same type of rooms (with similar functions) in similar weather conditions.

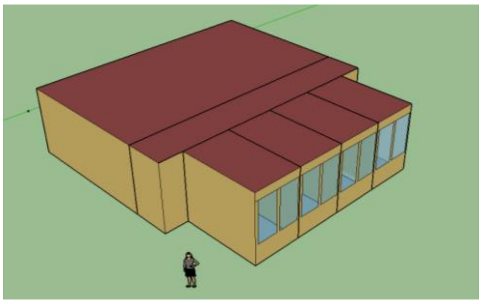

Fig. 1 – EnergyPlus model geometry for George Eliot building

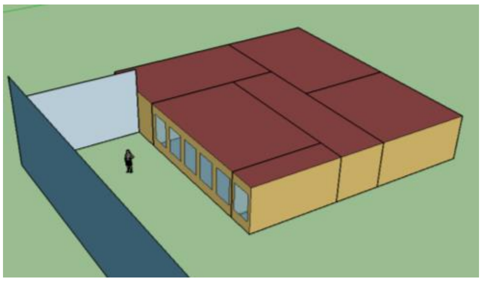

Fig. 2 – EnergyPlus model geometry for Balderskolan

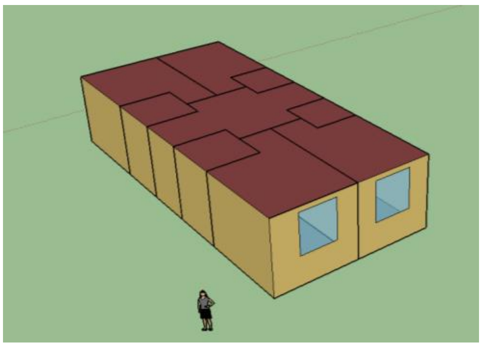

Fig. 3 – EnergyPlus model geometries for Terrassa hospital

2.2 Typical year historic weather data

To perform dynamic simulation studies on potential retrofit measures, we obtained hourly weather data from the closest possible weather stations to the demo sites, namely Coventry airport, Skellefteå airport, and Sabadell (as an interpolated city). The Meteonorm 7.1 software tool (Meteonorm, 2014) was used to provide the data and generate typical year weather data files for the simulation tool. To generate the typical year weather data, temperature data from the period 2000 – 2009 and radiation data from 1991 – 2010 were used.

2.3 Dynamic simulation-based studies

2.3.1 Baseline model

Table 1 summarizes the baseline HVAC system operational assumptions. Note that, in case of Skellefteå demo building, it has been assumed that the HVAC system does not operate during the summer holidays (i.e. June to mid-August).

Table 2 summarizes the baseline assumptions in small-scale demo building energy models with regard to infiltration, mechanical ventilation and ventilation heat recovery.

2.3.2 Conventional HVAC system time scheduling and set points optimization

To evaluate the impact of adjusting heating and cooling set-points (and where applicable the system scheduling) on building heating and cooling

Table 1 – Assumptions with regard to HVAC set-points and availability schedule

Demo building	Coventry	Barcelona	Skellefteå
Heating set-point	21	21	21
Cooling set-point	24	24	24
Heating availability schedule	Weekdays: 5:00 to 22:00 Weekends:	Always on	Weekdays: 5:00 to 17:00 Weekends: off
Cooling availability schedule	Nominal working hours	Always on	Nominal working hours

Table 2 – Modelling assumptions pertaining to infiltration, mechanical ventilation & heat recovery

Demo building	Coventry	Barcelona	Skellefteå
Infiltration rate [h^{-1}]	0.55	0.2	0.2
Mechanical ventilation availability	No	Yes	Yes
Mechanical outdoor air flow rate per zone [m^3/s]	-	0.02	0.30
Mechanical ventilation availability schedule	-	Occupied hours	Occupied hours
Ventilation heat recovery availability	-	No	Yes
Sensible heat recovery effectiveness	-	-	0.80

demands, we conducted parametric simulations using each demo building energy model. The parametric study involved simulating all demo building models with heating set-points of 18 to 24°C and cooling set-points of 21 to 27°C (with steps of 0.5).

In the case of the Coventry and Skellefteå demo buildings, which do not operate constantly, we also considered the impact of setting back the thermostat during the early morning preheating phase.

2.3.3 Predictive HVAC systems time scheduling and set points optimization

Integrating short-term weather forecast data and occupancy predictions in the building or zone controller provides opportunities to maintain thermal comfort conditions more efficiently, i.e. with less heating and cooling loads on the secondary and primary systems. More specifically, weather forecast and predicted occupancy data allow the controller to detect those days of the year that despite having relatively cool temperatures in the morning, the building/zone is expected to be overheated at midday due to high solar gain, high outdoor temperatures, high internal gains or a combination of these factors. In such a situation, the early morning preheating (or the whole heating when applicable) can be deactivated without compromising thermal comfort. Such a predictive control does not only reduce/remove the morning heating demand, but also reduces the afternoon cooling load, as a smaller amount of heating energy should be removed from the building.

To evaluate the effectiveness of this strategy, we exposed the demo building energy models to specific outdoor environment conditions obtained from local historic data, which offer the above-mentioned possibility.

2.3.4 Passive cooling with day-time ventilation

One of the strategies considered to be implemented in demo buildings is the use of ventilation to reduce the building cooling load. Introducing outdoor air to the building can be accomplished via manually or automatically operable windows or via the HVAC system, which is known as free cooling or outdoor air economizer.

In a simulation-based evaluation of this strategy, in order to avoid overcooling, a minimum indoor temperature was set to activate natural ventilation (or free cooling). Cleary, this can only be applied in automated implementations. Table 3 summarizes the assumptions with regard to daytime ventilation strategy for different demo building models.

2.3.5 Passive night-time ventilation using weather forecast

Predictive nighttime ventilation involves ventilating the building during the night if predicted performance of the building shows cooling demand on the following day. Due to the lack of real-time indoor environment and weather forecast

Table 3 – Modelling assumptions in daytime natural ventilation

Demo buildings	Coventry	Barcelona	Skellefteå
Air change rate [h^{-1}]	4	4	4
Minimum indoor temperature	23.0	23.0	23.0
Availability schedule	Occupied hours	8:00 to 16:00	Occupied hours

data at this stage in RESSEEPE, to evaluate the potential of this strategy, we replicated this predictive strategy as follows: The night-time ventilation is applied to the building energy models if the following day's temperature exceeds 18°C for at least four hours. In the case of the Terrassa demo building, which is operating constantly, we also set a minimum outdoor temperature for ventilation to prevent an increase in heating loads caused by the cold outdoor air entering the zones.

2.3.6 Automated shading

To numerically analyze the effectiveness of automatically controlled shading devices, we applied a low-reflectance medium-transmittance shade (see Table 4) inside and outside of the models' windows, controlled based on the amount of radiation on the windows (150 W/m² as baseline shading operation threshold and variable set-points in parametric simulations). To see the impact of utilizing a shading device on both thermal and lighting electricity demands, we used EnergyPlus daylighting simulation module. Toward this end, one or two daylight control points (depending on the zone area) were placed in each zone. We set 500 [lux] as the desired lighting level on these control points. The overhead lights dim continuously and linearly from (maximum electric power, maximum light output) to (minimum electric power, minimum light output) as the daylight illuminance increases. The lights switch off completely when the minimum dimming point is reached.

Table 4 – Assumed properties for the modelled shade

Shade properties	Value
Solar Transmittance [-]	0.4
Solar Reflectance [-]	0.2
Visible Transmittance [-]	0.4
Visible Reflectance [-]	0.2
Infrared Emissivity [-]	0.9
Infrared Transmittance [-]	0.0
Thickness [m]	0.005
Conductivity [W/m.K]	0.1

3. Results and discussions

This section presents the results of the conducted simulation studies to evaluate the effectiveness of the proposed technologies in reducing the building heating and cooling demands.

The parametric study to evaluate the impact of adjusting heating and cooling set-points involved simulating all demo building models with heating set-points of 18 to 24°C and cooling set-points of 21 to 27°C. Figure 4 shows the results of parametric simulation for the Coventry demo building. Even though the impact of this technology can be considered as "common sense", the quantitative results could encourage more sensitivity to the operating indoor temperature in demo buildings.

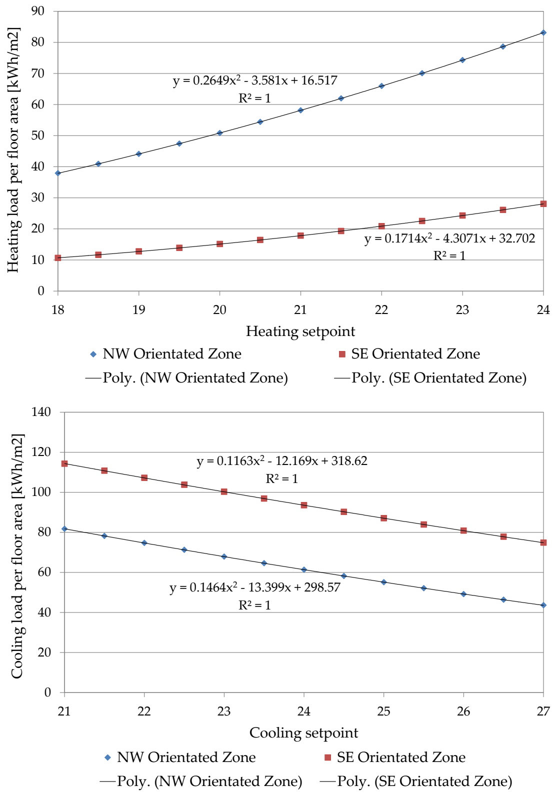

Fig. 4 – Heating (up) and cooling (down) load per floor area with different set-points, Coventry demo building

Table 5 and Table 6 show the results of setback temperature parametric simulations for Coventry and Skellefteå demo buildings. From the tables, even with a setback temperature of 16°C during early morning hours, heating demand can be reduced noticeably, especially in the classrooms with high heat gains during the day.

Table 5 – Coventry demo building heating load with different setback configurations

Models	Setback temperature	Heating load [kWh/m²]	
		SE	NW
Baseline	-	17.8	58.1
Thermostat setback 3 hours before occupancy	14	8.7	47.0
	15	9.3	47.7
	16	10.1	48.7

Table 6 – Skellefteå demo building heating load with different setback configurations

Models	Setback temperature	Heating load [kWh/m²]	
		North	South
Baseline	-	42.2	34.1
Thermostat setback 3 hours before occupancy	14	33.0	25.7
	15	33.7	26.3
	16	34.5	27.2

The results of time scheduling and set points optimization simulations show that in both the Coventry and Skellefteå demo buildings, predictive HVAC scheduling and set-point optimization can contribute to reduce heating and cooling demands. Figure 5 compares the simulated indoor temperate of the Coventry demo building, with baseline conventional control and the predictive scheduling strategy on a spring day. From the figure, it can be seen that, without compromising thermal comfort during working hours (indoor temperature above 18°C), implementation of predictive control reduces both heating and cooling loads, as it sets back the thermostat or deactivates the heating system in the early morning hours, which lowers the midday indoor temperatures and the associated cooling demand. It should be noted that, due to the continuous operation of HVAC system in hospital buildings, this technology is not applicable in the Barcelona demo building.

Table 7 to Table 9 show the results of heating and cooling loads obtained from baseline and daytime ventilated models for the Coventry, Barcelona and Skellefteå demo buildings. The results clearly show

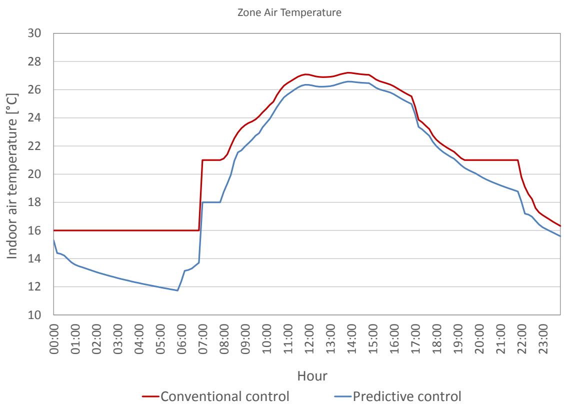

Fig. 5 – Simulated hourly indoor air temperature on a spring day with conventional and predictive control, Coventry demo building

the effectiveness of this technology in RESSEEPE demo buildings. From the tables it can be seen that, with controlled daytime ventilation (here based on minimum indoor temperature), it is possible to largely reduce the cooling demands in all demo sites without any noticeable increase in heating loads.

Table 7 – Coventry demo building heating & cooling demands with & without daytime ventilation

Models	SE zones		NW zones	
	Heating demand [kWh/m²]	Cooling demand [kWh/m²]	Heating demand [kWh/m²]	Cooling demand [kWh/m²]
Baseline	17.8	93.5	58.1	61.3
Daytime ventilation	19.4	39.4	58.7	34.4

Table 8– Barcelona demo building heating & cooling demands with & without daytime ventilation

Models	North zones		South zones	
	Heating demand [kWh/m²]	Cooling demand [kWh/m²]	Heating demand [kWh/m²]	Cooling demand [kWh/m²]
Baseline	60.3	75.4	21.9	95.3
Daytime ventilation	60.4	69.1	22.0	83.9

Table 9 – Skellefteå demo building heating & cooling demands with & without daytime ventilation

Models	North zones		South zones	
	Heating demand [kWh/m²]	Cooling demand [kWh/m²]	Heating demand [kWh/m²]	Cooling demand [kWh/m²]
Baseline	42.2	5.7	34.1	12.3
Daytime ventilation	42.5	2.6	34.7	6.4

Table 12, the parametric simulation results show that the night-time cooling strategy can contribute to a reduction in cooling load up to 10% in the Coventry and Sweden demo buildings and more than 15% in the Barcelona demo building. However, it may also lead to a smaller increase in heating demand, which can be avoided by setting a minimum outdoor temperature for ventilating the building (as modelled here for Barcelona demo building).

Table 10 – Coventry demo building heating & cooling demands with & without night time ventilation

Scenarios	ACH	SE zones		NW zones	
		Heating demand [kWh/m²]	Cooling demand [kWh/m²]	Heating demand [kWh/m²]	Cooling demand [kWh/m²]
Base	-	17.8	93.5	58.1	61.3
1	4	18.6	90.6	58.9	57.8
2	6	18.8	90.1	59.2	56.9
3	8	19.0	89.7	59.4	56.3
4	10	19.1	89.4	59.6	55.8

Table 11 – Barcelona demo building heating & cooling demands with & without night time ventilation

Scenarios	Min outdoor temperature	SE zones		NW zones	
		Heating demand [kWh/m²]	Cooling demand [kWh/m²]	Heating demand [kWh/m²]	Cooling demand [kWh/m²]
Base	-	60.3	75.4	21.9	95.3
1	-	64.6	62.7	25.8	81.7
2	16	60.4	64.1	21.9	83.4
3	17	60.3	65.2	21.9	84.7
4	18	60.3	66.7	21.9	86.4

Table 12 – Skellefteå demo building heating & cooling demands with & without night time ventilation

Scenarios	ACH	SE zones		NW zones	
		Heating demand [kWh/m²]	Cooling demand [kWh/m²]	Heating demand [kWh/m²]	Cooling demand [kWh/m²]
Base	-	42.2	5.7	34.1	12.3
1	4	43.0	4.9	34.6	10.9
2	6	43.5	4.8	35.1	10.7
3	8	44.0	4.7	35.5	10.5
4	10	44.4	4.7	36.0	10.4

With regard to the automated control of the shades, first, we controlled the shading devices with a set-point of 150 W/m² for the amount of radiation on the windows. The simulation results (Table 13 to Table 15) suggest that in the Coventry and Barcelona demo buildings an exterior shade can largely decrease the cooling demand without any noticeable increase in heating and electricity demands. In the case of the Skellefteå demo building, only an exterior shade in the south zone can be beneficial to some extent. However, considering climatic conditions and the adjacent buildings (see Figure 2), adding automated shading devices does not seem to be a promising measure for this building.

We also simulated the variations in building energy demands with different thresholds of incident solar radiation on windows. The results suggested that a set-point of 150 W/m² incident solar radiation can be seen as an optimum threshold to activate the shading device for all demo buildings. Figure 6 shows the variations in the Coventry demo building's energy demands with different activation set-points for shading devices.

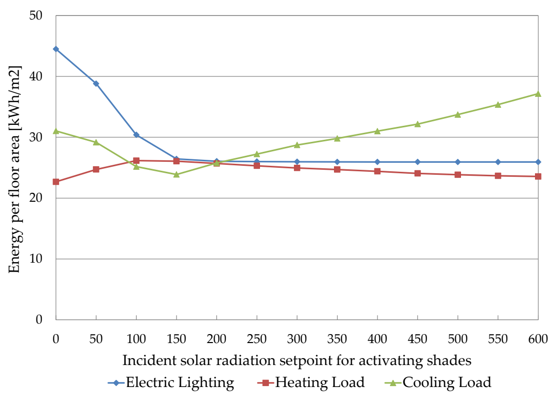

Fig. 6 – Variations in heating, cooling & electric lighting demand with different set-points to activate the shades, Coventry demo building, SE zone (up), NW zone (down).

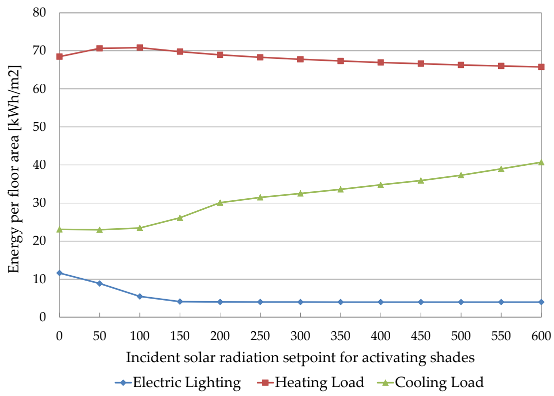

Table 13 – Coventry demo building heating, cooling & lighting electricity demands with shades (Activation set-point of 150 W/m2)

Scenarios	SE zones			NW zones		
	Heating demand [kWh/m²]	Cooling demand [kWh/m²]	Lighting demand [kWh/m²]	Heating demand [kWh/m²]	Cooling demand [kWh/m²]	Lighting demand kWh/m²]
Baseline	23.2	48.1	25.9	65.4	45.3	4.0
Interior shade	24.2	42.3	26.5	67.6	43.1	4.1
Exterior shade	26.1	23.9	26.4	69.8	26.1	4.1

Table 14 – Barcelona demo building heating, cooling & lighting electricity demands with shades (Activation set-point of 150 W/m2)

Scenarios	North zones			South zones		
	Heating demand [kWh/m²]	Cooling demand [kWh/m²]	Lighting demand [kWh/m²]	Heating demand [kWh/m²]	Cooling demand [kWh/m²]	Lighting demand [kWh/m²]
Baseline	51.3	61.5	9.0	14.8	103.8	6.4
Interior shade	53.7	60.6	11.1	22.1	93.0	7.8
Exterior shade	54.3	56.4	11.0	32.8	71.0	7.5

Table 15 – Skellefteå demo building heating, cooling & lighting electricity demands with shades (Activation set-point of 150 W/m2)

Scenarios	North zones			South zones		
	Heating demand [kWh/m²]	Cooling demand [kWh/m²]	Lighting demand [kWh/m²]	Heating demand [kWh/m²]	Cooling demand [kWh/m²]	Lighting demand [kWh/m²]
Baseline	42.7	3.7	9.2	34.5	9.0	8.6
Interior shade	42.8	3.6	9.3	35.0	8.4	8.9
Exterior shade	43.0	3.4	9.3	36.5	5.4	8.8

4. Conclusion

This paper reports on the simulation-based studies on the effectiveness of advanced control strategies in three public buildings across Europe within the framework of the RESSEEPE project: A secondary School in Skellefteå, Sweden, a hospital in Terrassa, Spain, and a university building in Coventry, UK.

5. Acknowledgement

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References

EnergyPlus 8.1.0, U.S. Department of Energy, http://apps1.eere.energy.gov/buildings/energyplus/.

Meteonorm 7.1, Meteotest, http://meteonorm.com/en/.

RESSEEPE. Retrofitting Solutions and Services for the enhancement of Energy Efficiency in Public Edification. http://www.resseepe-project.eu.

Schuss, M., Tahmasebi, F., Vazifeh, E.M., Mahdavi, A. 2013. Toward Improving Energy Efficiency of Existing Buildings via Monitoring-Supported Predictive Systems Control, CLIMA 2013 - 11th REHVA World Congress and the 8th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings, Prague, Czech Republic.