Design and control optimisation of adaptive insulation systems for office buildings. Part 2: A parametric study for a temperate climate

Energy 127 (2017) 634–649

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Design and control optimisation of adaptive insulation systems for office buildings. Part 2: A parametric study for a temperate climate

Qian Jin [a], Fabio Favoino [b, *], Mauro Overend [c]

[a] College of Architecture and Urban Planning, Tongji University, 1239 Siping Road, Shanghai, 200092, China
[b] Eckersley O'Callaghan Ltd., 236 Gray's Inn Road, London, WC1X 8HB, United Kingdom
[c] Glass and Façade Technology Research Group, University of Cambridge, Trumpington Street, CB2 1PZ, United Kingdom

ARTICLE INFO

Article history:
Received 6 February 2017
Received in revised form
20 March 2017
Accepted 20 March 2017
Available online 22 March 2017

Keywords:
Adaptive insulation
Building performance simulation
Parametric study
Multi-objective design
Temperate climate

ABSTRACT

This paper is the second of a two part study, which aims to evaluate the performance of adaptive insulation. Part 1 proposes a simulation framework for optimising adaptive insulation design and control parameters, it describes its implementation, and validates the simulation strategy qualitatively. This second paper applies the simulation framework, by means of a parametric study on a specific building typology in a particular climatic region, to explore the potential of adaptive insulation in this context. Alternative adaptive insulation configurations and control strategies for opaque wall applications are evaluated, for an office room in a temperate climate of Shanghai, in order to optimise two design objectives: total primary energy saving and thermal comfort. It is found that adaptive insulation, when properly designed and controlled, has significant potential to improve both design objectives simultaneously. For the case study considered in this paper, yearly energy savings and thermal comfort improvements of up to 50% could be achieved by adaptive insulation compared to an equivalent astatic insulation alternative. The performance improvements of the adaptive insulation depend on the design choices (thermal mass, position of the adaptive insulation, switching range of insulation) and control strategy adopted.

1. Introduction

Adaptive insulation provides an opportunity to reduce building energy use while improving the environmental quality, but there is a lack of information about its performance. When integrated into a building, its potential to reduce building energy use and improve indoor thermal comfort depends on many parameters, such as the range of achievable heat transfer coefficients, the way it interacts with thermal inertia, the control strategies adopted for its operations.

Although several technologies have been developed, as reviewed in Part I of this study titled “Design and control optimisation of adaptive insulation systems for office buildings. Part 1: adaptive technologies and simulation framework”, only few of them are assessed in terms of their building-integrated performance. Pflug et al. [1] evaluated the heating and cooling energy saving potential of a translucent dynamic insulation panel, for an office room in a temperate continental climate with a cold winter and a hot summer (Ludwigshafen, Germany). Two different insulation switching ranges, controlled by the temperature difference between indoor and outdoor environment, are compared to a conventional insulated building. The results show that only an 8% energy reduction can be achieved compared to the static solution, while 10% could be achieved by means of the static solution with additional free cooling. Moreover, if the insulation switching range is increased slightly, up to 20% energy reduction could be achieved, beyond what it is achievable with free cooling. Analogously thermal comfort could be significantly improved by dynamic insulation compared to both static insulation and static insulation with free cooling. Berge et al. [2] used a simplified thermal network to assess the reduction in energy use for an office building located in the cold climate of Helsinki. In this case dynamic insulation with an increasing adaptive thermal resistance range, controlled according to the occurrence of heating or cooling loads in the indoor environment, was simulated. Given the climate characteristics and that no thermal capacity of the

* Corresponding author.
E-mail address: fabio@eocengineers.com (F. Favoino).

http://dx.doi.org/10.1016/j.energy.2017.03.096

Nomenclature

λ	Thermal conductivity (W/mK)
U	Thermal conductance (W/m^{2}K)
R	Thermal resistance (m^{2}K/W)
WWR	Window-to-wall ratio
η_h	HVAC efficiency for heating
$SEER$	Seasonal energy efficiency ratio
f_{NG}	Fuel factor for natural gas
F_{El}	Fuel factor for electricity
ACH	Air change per hour
Q_{cool}	Cooling power (W/m^2)
Q_{heat}	Heating power (W/m^2)
T_{room}	Indoor air temperature (°C)
T_{out}	Outdoor air temperature (°C)
T_{op}	Operative temperature
T_{S_out}	Outdoor surface wall temperature (°C)
T_{S_in}	Indoor surface wall temperature (°C)
$T_{heating}$	Heating set point temperature
$T_{cooling}$	Cooling set point temperature
wf_{OH}	Overheating weighting factor
wf_{OC}	Overcooling weighting factor
T	thickness (m)
κ_e	External thermal capacity (kJ/m^{2}K)
κ_i	Internal thermal capacity (kJ/m^{2}K)
FM	Frontal mass (kg/m2)
D	Decrement Factor (−)
φ	Time lag (hours)
R_{INS}	Thermal resistance of the adaptive insulation
MPC	Model predictive control
RHC	Receding horizon control
E_{HEAT}	Heating primary energy use (W/m^{2}K)
E_{COOL}	Cooling primary energy use (W/m^{2}K)
E_{LIGHT}	Lighting primary energy use (W/m^{2}K)
E_{TOT}	Total primary energy use (W/m^{2}K)
LPD	Long-term percentage of dissatisfied
PPD	Average percentage of people dissatisfied
Occ	Occupation rate
H	Single time step for evaluating LPD
T	Total time step for evaluating LPD
$R_{INS,t}$	Variable adaptive insulation layer resistance for each time interval of the planning horizon
Pop	Optimal population size
Gen	Number of generation
PF	Pareto Front
DMC1	Decision making criteria 1: Minimizing total energy use
DMC2	Decision making criteria 2: Minimizing global thermal discomfort
DMC3	Decision making criteria 3: Identify the optimal solution that strikes the balance between minimizing total energy use and minimizing global thermal discomfort through TOPSIS approach
C1,C2,C3, C4, C5, C MPC	Control strategies, refer to Section 2.1
Hv_South_Out	Perpendicular solar radiation on south façade (W/m^2)

building was considered in the building simulation model, only cooling energy use could be reduced depending on the lowest value of thermal resistance that could be achieved by dynamic insulation.

These studies provide forms of building performance analysis limited to one specific technological solution, adopting a single specific control strategy. In addition, the possible mutual influence of the physical characteristics and the control of the dynamic insulation on the performance of the adaptive building envelope has been overlooked. This dependency is demonstrated for other cases of adaptive façades technologies, such as smart glazing, as in Refs. [3–6]. Although these latter papers analysed a different adaptive façade technology, they all highlight that the performance of a building adopting such a dynamic building envelope system strongly depends on the control strategy. Nevertheless the influence of the control strategy during adaptive façade operations on the optimal design characteristics of the adaptive systems (i.e. geometry, thermal and optical properties, physical characteristics of the building envelope element, position of the adaptive technology in the building envelope etc.) is generally overlooked as well.

The present paper is the second part of a two-part paper which endeavors to evaluate the potential building performance improvements of adaptive insulation in the opaque portion of the building envelope. In the first part the need to evaluate not only design options but also control parameters was discussed. For this purpose an innovative simulation framework and its implementation parameters were described. Finally the specific model adopted to simulate the adaptive insulation component was validated qualitatively.

In this second part the methodology and simulation framework are adopted to investigate the performance of an opaque adaptive insulation integrated in the South oriented façade of an office reference room in the temperate climate of Shanghai. The influence of different design and control parameters on the performance of adaptive insulation are explored by means of a parametric study. The results could guide possible future product development and building integration of such technologies.

In the second section of this paper the methodology for this case study is outlined, followed by the description of the parameters relative to the implementation of the simulation framework for this specific case study in the third section. Finally the results from the design and control optimisation are presented.

2. Methodology

The aim of this paper is to analyse the influence of design and control parameters of a dynamic insulation system on building performance (building energy use and thermal comfort). This is applied to a case study of adaptive insulation design, for an office room in the temperate climate scenario of Shanghai, China. Details of the office model can be found in Section 5.1 in Part 1. The fuel factors for natural gas f_{NG} and electricity f_{El} are 1.0012 and 1.0005, respectively, which were calculated from GB/T 2589 [7]. No information is found in literature about the energy cost of operating a dynamic insulation system, which could largely depend on the sensors and actuators needed to operate the adaptive façade. This is therefore not considered in this analysis.

The methodology consists in comparing the performance of different adaptive insulation design alternatives, which are all

Table 1
Opaque wall design alternatives.

	Units	1. UN_INS	2. INS_HW	3. INS_HW_2	4. INS_HW_EXT	5. INS_HW_INT	6. INS_HW_MID	7. INS_HW_MID_AC	8. INS_LW_EXT
t	M	0.20	0.23	0.25	0.23	0.23	0.23	0.28	0.10
U	W/m^2K	2.92	0.19	0.10	0.19	0.19	0.19	0.18	0.19
R	m^2K/W	0.34	5.34	10.34	5.34	5.34	5.34	5.70	5.19
κ_e	kJ/m^2K	8.97	5.40	2.70	3.00	130.00	130.00	62.80	17.50
κ_i	kJ/m^2K	5.02	5.20	2.70	73.00	3.00	77.70	77.70	16.90
FM	kg/m^2	400.00	401.00	401.00	401.00	401.00	401.00	301.00	41.00
d	–	0.57	0.03	0.01	0.20	0.34	0.33	0.34	0.99
φ	H	5.47	8.63	8.93	7.72	6.80	8.37	8.48	0.98

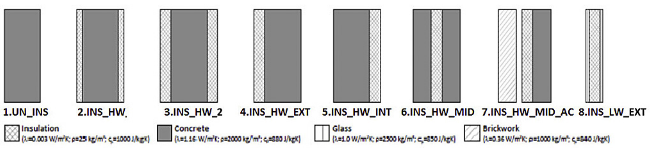


Fig. 1. Opaque wall design alternatives (left: external environment; right: internal environment).

operated according to alternative control strategies, by building performance simulation, adopting the bi-level approach presented in the part-one paper. This consists in evaluating/optimising alternative design options and different control strategies at the same time. In contrast with the "Bi-level" optimisation process described by Evins [8], a parametric analysis is performed here on both levels, i.e. each design alternative is evaluated with all different control alternatives and vice-versa. No design and operational parameters are considered for the HVAC level at this stage, even though it is acknowledged that the way the energy is transformed at the building site, or at the source, could affect optimal adaptive building envelope design and operations.

In this section the design variables and control strategies considered are described (Section 2.1). Secondly the performance objectives used to optimise design characteristics and operations of the adaptive insulation are detailed (Section 2.2). Subsequently, the parameters adopted for the implementation of optimised control strategies are described (Section 2.3).

2.1. Design and control variables

The parametric study aims to analyse the influence of design parameters of the adaptive insulation system as well as its control on building performance. The design variables are: 1) the layering of the opaque construction, more specifically the position of the adaptive insulation layer with respect to the thermal mass, the amount of thermal mass in general and its surface exposure to the internal or external environment; 2) the magnitude of the adaptive insulation switching range; 3) different control strategies of the adaptive insulation are considered, based on previous studies or optimised control strategies.

As far as the layering of the construction and amount of thermal mass is concerned, 8 different design alternatives are compared (Table 1 and Fig. 1) for an opaque wall with high (1–7) and low (8) thermal mass, heavy and light weight (HW, LW) respectively. Design alternative 1 is an uninsulated concrete wall with an R-value of 0.34 m^2 K/W, which is considered as a reference case. Design alternatives 2 to 8 present the same amount of insulation (R-value = 5 m^2 K/W) distributed as follows:

2. on both sides of the thermal mass layer (2.5 m^2 K/W external and 2.5 m^2 K/W internal);
3. on both sides of the thermal mass layer (5 m^2 K/W external and 5 m^2 K/W internal);
4. wholly on the external side of the thermal mass layer;
5. wholly on the internal side of the thermal mass layer;
6. and 7. in the middle of the thermal mass layer (7. presents an additional air cavity and external masonry wall);
8. in the middle of two glass layers, representing a spandrel panel in a curtain wall construction.

The insulation layer, wherever present, can be either a conventional "static" insulation, or be actively controlled according to a specific control strategy. In particular, the insulation can switch from its maximum value (from Table 2) to its minimum value (no insulation at all), corresponding to a value of 1 or 0, respectively. Although different switching ranges are tested, the maximum insulation level achievable is kept constant and the minimum value is varied according to Table 2. The comparison between the adaptive insulation switching ranges adopted in this study and the switching ranges of the technologies available in literature is shown in Fig. 2 (switching ranges A to E). For each alternative design of opaque wall and switching range, six different control strategies are compared. The control strategies for adaptive insulation commonly available in literature are all based on control rules considering past and present states of the building and/or building envelope system (rule based control), such as heating and cooling demand [9], difference between indoor and outdoor temperature [10], difference between wall surface temperature and indoor heating and cooling set-point [11,12]. More advanced control strategies could be considered which minimise a cost function (such as energy use and/or thermal discomfort) [13]. In the present paper the following control strategies are compared for each design alternative:

C1 - Conventional "Static" insulation, according to the thermal characteristics presented in Table 1. This control alternative is considered as a reference for the other adaptive insulation options;

C2 - Adaptive insulation with demand control: the insulation is switched to its minimum value when cooling demand is present in the indoor environment: if $Q_{cool} > 0$ W/m^2 ($T_{\_room} > 26$ °C), then INS = MIN;

C3 - Adaptive insulation with demand and temperature control: if $Q_{cool} > 0$ W/m^2 & $T_{\_room} > T_{\_out}$, then INS = MIN; if else $Q_{heat} > 0$ W/m^2 & $T_{\_room} < T_{\_out}$, then INS = MIN:if else $Q_{heat} = 0$ &

Table 2
Adaptive Insulation switching range.

Case		U-value of the construction	R-value of the construction	R-value insulation	λ[a]	Insulation schedule	Switching range
Unit		(W/m^{2}K)	(m^{2}K/W)	(m^{2}K/W)	(W/mK)	(–)	
Max	R-Static	0.193	5.181	5.00	0.005	1.00	0%
Min	RA	0.373	2.681	2.50	0.010	1.00–0.50	50%
	RB	1.468	0.681	0.50	0.050	1.00–0.10	90%
	RC	2.320	0.431	0.25	0.100	1.00–0.05	95%
	RD	4.329	0.231	0.05	0.500	1.00–0.01	99%
	RE	5.525	0.181	0.00	260.00	1.00–0.00	100%

[a] The λ value is calculated based on 0.025 m thickness of the insulation layer.

$Q_{cool} = 0$ &$T_{\_room} < T_{\_out}$, then INS = MIN; in all the other cases INS = MAX. This control strategy considers the presence of heating and cooling loads, but also the temperature difference between indoor and outdoor;

C4 - The control strategy C3 is modified in order to take into account the presence of internal solar and endogenous loads, so that the reference external temperatures considered are reduced: if $Q_{cool} > 0$ W/m^2 & $T_{\_room} -10 > T_{\_out}$, then INS = MIN; if else $Q_{heat} > 0$ W/m^2 & $T_{\_room} -5 < T_{\_out}$, then INS = MIN; if else $Q_{heat} = 0$ & $Q_{cool} = 0$ & $T_{\_room} -10 < T_{\_out}$, then INS = MIN; in all the other cases INS = MAX;

C5 – This control strategy takes into account the outdoor and indoor surface temperature of the wall and the heating and cooling demand: if $Q_{cool} > 0$ W/m^2 & $T_{\_S\_out} < T_{\_S\_in} < 25$, then INS = MIN; if else $Q_{heat} > 0$ W/m^2 & $T_{\_S\_out} > T_{\_S\_in} > 20$, then INS = MIN; if else $Q_{heat} = 0$ & $Q_{cool} = 0$ & $20 < T_{\_S\_out} < T_{\_S\_in} < 25$, then INS = MIN; in all the other cases INS = MAX;

C MPC - Adaptive insulation with optimised control sequence: the control sequence of the adaptive insulation is optimised based on the minimisation of one or more cost functions, which in this study are the performance objectives described in Section 2.2. This control technique is usually referred as Model Predictive Control (MPC) or Receding Horizon Control (RHC) [13]. In particular RHC is a feedback non-linear control technique, that solves an optimisation problem at each time step of the simulation/operation to determine the control sequence (sequence of optimal adaptive building envelope properties) over a certain time horizon (planning horizon), by minimizing a specified objective function on a certain cost horizon. The cost horizon comprises the planning horizon and a prediction horizon. The prediction horizon is used to include the effect of varying material properties during the planning horizon on building performance in the subsequent period. This is due to the delayed thermal response of the building to a control action on the adaptive insulation. Details of the implementation of MPC to adaptive insulation can be found in Section 3.1 of Part 1, while the main parameters for its implementation are described in Section 3.2.1 and 3.2.3 of Part 1. Particularly, the days with the highest hourly variation of climate boundary conditions (temperature and perpendicular solar radiation) during the year are chosen to give a deeper insight into the performance of the different control strategies simulated.

The combination of all the design variables (position of adaptive insulation, amount of thermal mass and switching range of adaptive insulation), control strategies and reference cases amounts to a variable space of 175 analysis, of which 30 require a control optimisation (C MPC) to be performed. In addition, a zone energy balance analysis is also performed for design alternative 4 with static performance properties and MPC on a seasonal basis to investigate the effectiveness of adaptive insulation.

2.2. Performance objectives

The two main objectives of adopting an adaptive insulation are to reduce total primary energy use and to improve global thermal comfort:

1. Objective One is to minimise the primary energy use E_{tot}, as a sum of heating, cooling and lighting primary energy use (E_h, E_c, E_l respectively). E_{tot} is calculated according to Eq. (1), taking into account the HVAC efficiencies and the fuel factors detailed in the previous section:

$$E_{tot} = \eta_h \cdot E_h \cdot f_{NG} + \left(\frac{E_c}{SEER} + E_l\right) \cdot f_{El} \quad [\mathrm{kWh/m2y}] \tag{1}$$

2. Objective Two is to maximise global thermal comfort of the office room. This is evaluated according to the Long-term Percentage of Dissatisfied (LPD) developed in Ref. [14]. The objective is to minimise LPD. The use of different possible and more immediate comfort indexes for the parametric design evaluation and the control optimisation was evaluated (such as indexes considering operative temperature or PMV ranges unmet hours [15]). Even though these could provide a better understanding of the effect of the use of an adaptive insulation, their intrinsic characteristics (such as discontinuity and asymmetry [16]) and the need to define threshold temperatures to take into account for overheating and overcooling phenomena, make them unsuitable for the control optimisation task. The LPD index is a symmetric and continuous index, and it better estimates predicted thermal response of a typical individual based on Fanger's comfort theory [17], making into suitable for the control optimisation task [18]. It measures the average Percentage of People Dissatisfied (PPD) by the thermal perception by weighting the PPD on the number of occupied rooms in a building, the occupation rate of each room (*occ*) and the duration of the evaluation (*h* is the single time step, *T* is the total number of time step for each evaluation). The use of comfort indexes (i.e. LPD, PMV or unmet operative temperature hours) implies different assumptions over physical variables not calculated by the simulation engine (such as air speed), but also physiological and behavioural occupants' parameters (such as metabolic activity and clothing). Within the present case study parameters generally adopted by literature and other researchers are considered. A metabolic rate for office activity of

1.2 met, clothing insulation level of 0.5 between May and September and 1.0 for the rest of the year [19] are considered. Air velocity is modelled with uniform distribution within the room and considered constant for the entire year (0.137 m/s) during the occupied period, given that a minimum primary ventilation flow rate need to be maintained during occupation hours by means of the mechanical ventilation, as detailed in Section 5.1 of Part 1. For a single office room the LPD can be expressed by Eq. (2):

$$LPD = \frac{\sum_{t=1}^{T} occ_t \cdot PPD \cdot h_t}{\sum_{t=1}^{T} occ_t \cdot h_t} \quad [\%] \tag{2}$$

For the present case study, from a thermal comfort perspective the use of the adaptive insulation compared to a static one, as documented in the following Section 3.1 in Part 1 and Section 3.2 in this paper, has effect only on the internal surface temperature of the controlled wall and the internal air temperature. Therefore to have a better understanding of the performance of an adaptive insulation, along with the LPD which is adopted for its suitability for the sake of the control optimisation, other indoor environment local discomfort indicators are reported with the results (Table 4 and Table A.1). These are the number of occupied hours in which the operative temperature is below the heating set point (3) and above the cooling set point (4), multiplied by the intensity of this deviation from the set point temperatures, as described in Ref. [20]. Moreover it was established that radiant temperature asymmetry thresholds of 23 °C for warm walls and 10 °C for cold walls were not exceeded [21].

$$OH_h = \sum_{t=1}^{T} wf_{OH} \cdot h_t \ [\text{hrs}] \tag{3}$$

$$OC_h = \sum_{t=1}^{T} wf_{OC} \cdot h_t [\text{hrs}] \tag{4}$$

$$\text{where } wf_{OH} = \left| T_{op} - T_{heating} \right| \text{ and } wf_{OH} = \left| T_{op} - T_{cooling} \right| \tag{5}$$

These performance objectives are evaluated for a whole year of building operations (from 1st January to 31st December), by means of the building simulation tool detailed in Section 3.1 of Part 1.

2.3. Parameters for the implementation of optimised control strategies

2.3.1. Time horizons

In order to establish the optimal length of the pre-conditioning horizon a parametric study was carried out to quantify the influence of the length of pre-conditioning on the energy balance of typical days in the four different seasons. For this case, since no window solar/visible properties were changed during the simulation runtime [22,23], 10 days preconditioning horizon was sufficient to ensure convergence of the energy balance of the room in different seasons. The total horizon for the moving horizon building performance simulation (level 4) for each control optimisation is given by the sum of preconditioning, planning and termination horizons, which for the present study is 13 days.

2.3.2. Population size and number of generations

The NSGA II algorithm [24] was used to solve the control optimisation problem. Mutation and crossover probability advised in Ref. [24] are not changed from the original formulation of the NSGA II algorithm. A convergence test was carried out to find the optimal population size (Pop) and number of generation (Gen) for the optimisation analysis by running multiple one-day simulations (on the same day) and study the convergence of the Pareto Front by means of the hyper volume indicator, for different sizes of the variable space. Each test was run for three times to ensure the convergence at the corresponding Gen. The results are shown in Table 3. Pop = 50, Gen = 10 and Pop = 100, Gen = 15 are selected for 12- and 24-variable models, respectively, to minimise the total computational time while obtaining a good approximation of the Pareto Front. Therefore, the total computational time for 12-variable and 24 variable models are 34 h and 98 h, respectively, using a Windows-based PC with a 1.70 GHz processor and 8GB of RAM.

2.3.3. TOPSIS approach and frequency of controlling the adaptive insulation

For each planning horizon (1 day) a Pareto Front (PF) is generated. The TOPSIS approach (Technique for Order Preference by Similarity to the Ideal Solution) [25] was adopted to choose one control solution according to more than one performance objectives, in order to move the simulation forward in time.

The optimisation problem to be solved for each cost horizon can therefore be written as:

$$\begin{cases} \min E_{TOT} \\ \min LPD \\ with\ R_{INS,t} = [R_{min}, R_{max}] \end{cases} \tag{6}$$

where $R_{INS,t}$ is the variable adaptive insulation layer resistance for each time interval of the planning horizon, that can vary between $R_{\min}$ and $R_{\max}$, defined in Section 2.1 (cf. Fig. 2); t is the number of control actions (optimisation variables) in one planning horizon (1 day), a higher value of t will require longer optimisation computational time for each planning horizon, and consequently for the whole yearly simulation to be completed.

Therefore, a parametric study was carried in order to: a) identify the most effective frequency of controlling the adaptive insulation when MPC is adopted; b) assess the effect of the control decision making criteria on the building performance when dealing with conflicting requirements; c) explore how to reduce the computational time for simulating the yearly performance of the MPC control without affecting the final results (maximum building performance achievable).

The control parameters varied in this parametric study are: a) the adaptive insulation frequency, from 1 control action per day (Daily frequency = 1) to one control action per hour (Daily frequency = 24); b) the Decision Making Criteria (DMC) for selecting one control solution in the Pareto Front, either lowest energy consumption (DMC1), or highest thermal comfort (DMC2), or the multi criteria TOPSIS approach (DMC3).

For each insulation adaptive frequency, except the hourly one, an exhaustive search of the optimal control sequence is performed in order to produce results which are independent of the optimisation algorithm parameters. While for the hourly frequency an optimisation was carried out adopting NSGA II. This study was carried out for the largest adaptive insulation switching range (RE),

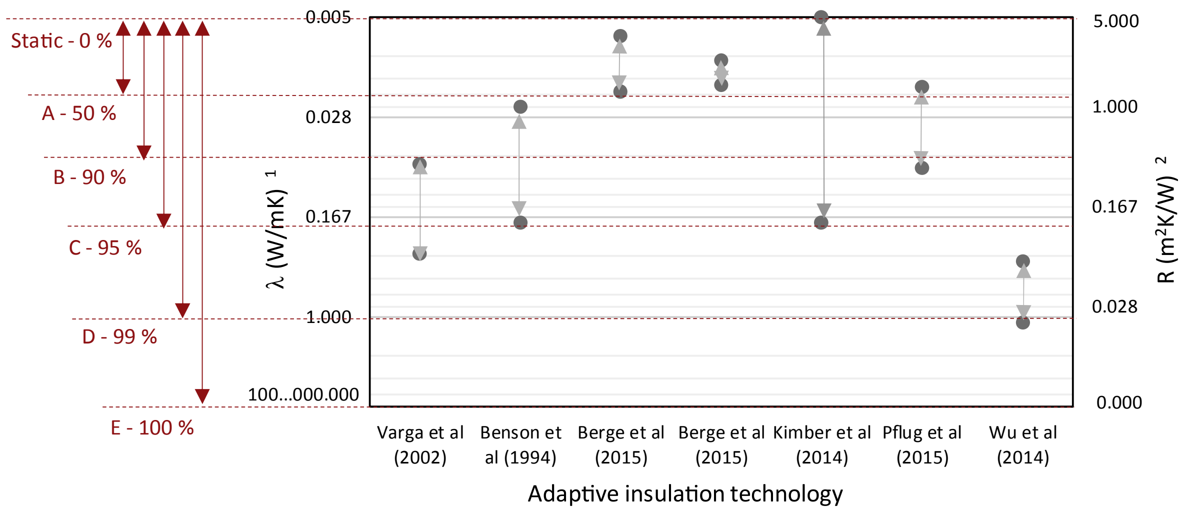


Fig. 2. Adaptive Insulation switching range (in terms of λ[1] and R[2]) compared to available technologies.

Table 3
Convergence test.

Test models		Pop	Gen	Converge at Gen	Time for convergence (minutes)
12-variable model	Test 1	100	30	7	7.5
	Test 2	50	20	10	5.7
	Test 3	30	30	25	8
24-variable model	Test 1	50	50	30	16.5
	Test 2	100	20	15	16
	Test 3	150	50	15	25

as shown in Fig. 2. Fig. 3 and Table 4 show the results of this parametric analysis for three consecutive days in winter (31 Jan – 2 Feb). These 3 days are chosen as they have the largest hourly variation in terms of boundary conditions (i.e. outdoor temperature and total solar radiation perpendicular to the South oriented wall), and will therefore generate the largest benefit from a faster adaptive frequency.

The three trends in Fig. 3 represent the three criteria for selecting a control sequence: on the x-axis the alternative adaptive frequencies are represented, the building energy use is represented on the primary y-axis, while the long-term percentage of dissatisfied from the thermal comfort is represented on the secondary y-axis. Each bar represents the performance variation of a specific adaptive frequency according to the relative performance criteria analysed. For example, for the objective of reducing energy use, the lowest energy use is achieved by DMC1 which minimises energy use, while the highest by DMC2 which maximises thermal comfort. DMC3 achieves a trade-off between the two conflicting performance objectives.

As far as the frequency is concerned, for all the DMCs analysed, there is no significant performance improvement for a control frequency higher than daily frequency = 12. The lowest E_{TOT} is achieved by DMC1 with daily frequency = 12, while no further improvement is achieved with higher frequencies. The lowest LPD is achieved for daily frequency = 12 with DMC2. Therefore, for the parametric study in this paper, one control action every 2 h is performed for the MPC control, because it reduces energy use to the lowest extent and long-term thermal discomfort without increasing computational time.

As far as the decision making criteria is concerned, the difference between DMC1, 2 and 3 is an indication of the difference of MPC performance adopting either single objective optimisation (minimizing energy use, DMC1, or thermal discomfort only, DMC2), or a multi-objective one. As expected the lowest energy use is given by DMC1, and lowest thermal discomfort by DMC2. Analogously the highest energy use is given by DMC2, and highest thermal discomfort by DMC1. Even if the evaluation is presented for a winter scenario (31st Jan – 2nd Feb) when the two objectives are not expected to conflict, adopting DMC1 (minimisation of energy) increases the average percentage of people dissatisfied during the occupied period. On the other hand DMC2 (maximisation of global thermal comfort) does not decrease building energy use compared to the slower adaptive case (daily frequency = 1), even with high adaptive insulation frequency. This difference is expected to increase when the two objectives are in conflict more a larger amount of time (i.e. mid-season and summer). DMC3, in contrast, is able to provide, by applying the TOPSIS decision making approach to the specific multi-objective control optimisation, a good trade-off between reduction of energy use and improvement of thermal comfort, even if a higher performance could be achieved as far as each individual objective is considered. In fact DMC3 presents a significant reduction of total energy use, without decreasing the thermal

[1] The thermal conductivity λ and thermal resistance R refers to the insulation layer(s) only.

[2] To obtain the R-value of the opaque building envelope, not only of the insulation layer(s), an additional 0.34 m^2K/W need to be added to the values in Fig. 2 (0.17 for the total external and internal surface resistances and 0.17 for the concrete layer). Therefore when the insulation layer is switched off and has 0 m^2K/W thermal resistance (infinite thermal conductivity - λ) the thermal resistance R of the opaque wall is in reality 0.34 m^2K/W. Equally when the insulation has its maximum resistance value (R = 5.00 m^2K/W, λ = 0.005 W/m^2K) the thermal resistance of the opaque construction is in reality 5.34 m^2K/W.

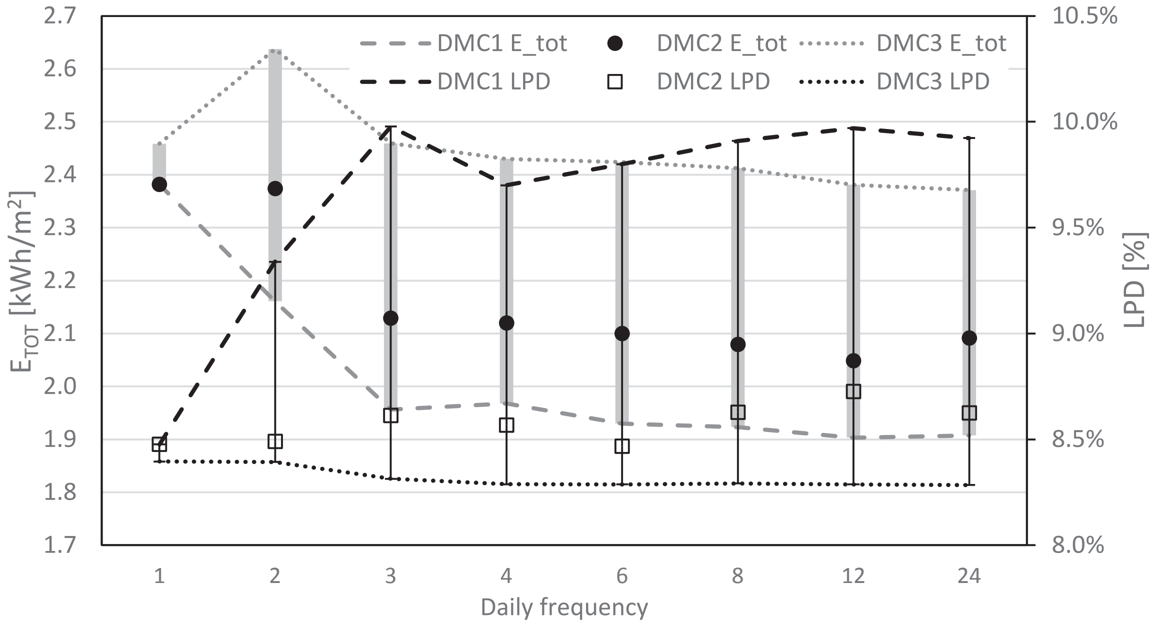


Fig. 3. Effect of adaptive frequency and decision making criteria.

comfort performance. The lowest E_{TOT} is achieved with daily frequency = 12, although with the highest thermal discomfort for DMC3, which is anyway only 0.5% higher than the static insulation performance for those days (daily frequency = 1). Therefore for the MPC control DMC3 will be adopted for the design and control optimisation case study.

3. Results

The results of the design and control parametric evaluation of an adaptive insulation systems are divided into three parts: a) the analysis of the performance of the static insulation design alternatives (Control C1) aims at evaluating the building performance of the static reference design alternatives, and specifically the relationship between the two performance objectives when a conventional static solution is adopted (Section 3.1); b) the comparison between static insulation (C1) and adaptive insulation with different control strategies (Control C2 to MPC) (Section 3.2) provides a closer insight into the differences between static and adaptive insulation, as well as the differences in performance between control strategies; c) the effect of different design alternatives, control strategies and switching ranges of energy use and thermal comfort (Section 3.3), provides a detailed account of the case study with the aim of optimising both design characteristics and control aspects of an opaque wall integrated with adaptive insulation.

3.1. Performance of static insulation design alternatives - reference cases

In Fig. 4 the long term thermal discomfort (LPD) is compared with the total energy use, while additional information is available in Table 5, such as the break down between primary energy use for heating, cooling and lighting, the overheating and overcooling indexes. The variability of the performance due to a change in the amount of static insulation is also presented in Fig. 4 and Table 5. In Fig. 4, The insulation thickness is varied from 0% (1 UN_INS), to 50% (smaller data points), 100% and 200% (larger data points) compared to the cases in Table 1, for each design alternative.

Depending on the amount and position of the static insulation layer relative to the thermal mass, as well as the amount of thermal mass the total energy use of the office building can vary between 78 and 112 kWh/m^2 (lighting energy demand is constant at 21.9 kWh/m^2), while the long term discomfort index can vary between 10 and 23%. The variability of the total energy use is due to the sensitivity of the heating and cooling energy use to the design of the exposed opaque wall (amount of insulation and thermal mass, and their position). For heavy weight walls, when the insulation is exposed to the outdoor environment the heating energy use varies between 62 and 20 kWh/m^{2}y, conversely the cooling energy use varies between 12 and 38 kWh/m^{2}y. This sensitivity is reduced significantly for both heating and cooling, if the insulation is not exposed externally, or insufficient thermal mass is exposed internally.

Table 4
Effect of adaptive frequency and decision making criteria.

Daily Frequency	DMC1 $_{E\_tot}$ (kWh/m^2)	DMC1 $_{LPD}$ (%)	DMC2 $_{E\_tot}$ (kWh/m^2)	DMC2 $_{LPD}$ (%)	DMC3 $_{E\_tot}$ (kWh/m^2)	DMC3 $_{LPD}$ (%)
1	2.38	8.5%	2.38	8.5%	2.46	8.4%
2	2.16	9.3%	2.37	8.5%	2.64	8.4%
3	1.96	10.0%	2.13	8.6%	2.46	8.3%
4	1.97	9.7%	2.12	8.6%	2.43	8.3%
6	1.93	9.8%	2.10	8.5%	2.42	8.3%
8	1.92	9.9%	2.08	8.6%	2.41	8.3%
12	1.90	10.0%	2.05	8.7%	2.38	8.3%
24	1.91	9.9%	2.09	8.6%	2.37	8.3%

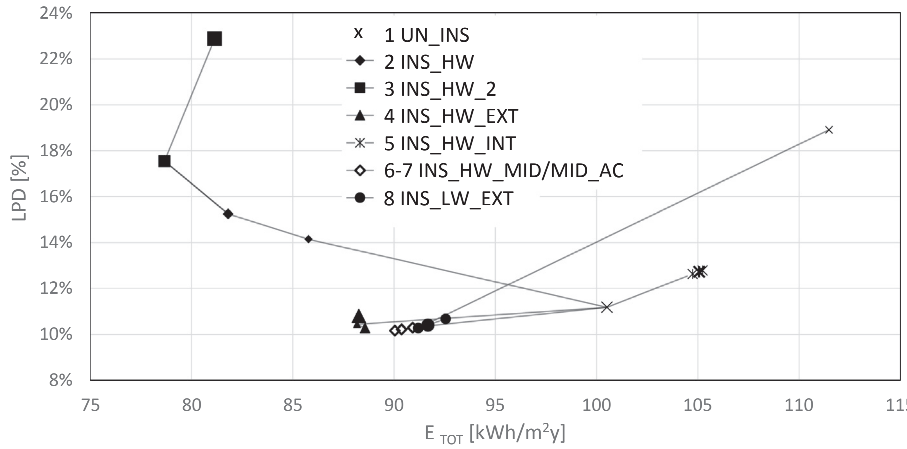


Fig. 4. Static insulation performance for the different 8 design alternatives (+100% and −50% of the insulation thickness).

The sensitivity of LPD is similarly affected by the position and amount of the insulation layer. Whenever the insulation is external, the amount of hours with overheating risk (OH_h) increases due to an increase in the exposed wall surface temperature during summer (also resulting in higher cooling energy use), although the number of hours with overcooling risk (OC_h) decrease slightly. Instead when thermal mass is exposed to the external environment, the LPD is much less sensitive to the variation of the amount of static thermal insulation, analogously to heating and cooling energy use, as more stable internal wall surface temperatures are present.

The best case as far as LPD and energy use among the design alternatives with only one static insulation layer is represented by case 4, i.e. insulation on the external side of the thermal mass. When the insulation is distributed on both sides of the thermal mass (2 INS_HW and 3 INS_HW_2), the reduction in heating energy use is larger, in absolute terms, than the increase in cooling energy use. This results in a simultaneous significant decrease in total primary energy use, and a higher increase in LPD (due to higher overheating risk).

In general a larger amount of insulation does not necessarily produce lower yearly energy use and higher year-long thermal comfort, as the two objective may be conflicting. A closer analysis reveals that increasing the amount of static thermal insulation results in lower heating energy use, but above a certain threshold, cooling energy use and overheating risk are increased (such as for design alternative 2 and 3). Although the amount of insulation, thermal mass and their relative position could be optimised to reduce the yearly performance in terms of energy use and thermal comfort, inevitably, above a certain threshold depending on local conditions, an increase in the amount of insulation, wherever it is placed, although decreasing heating energy use will result in larger cooling loads and overheating risk due to the increased internal surface temperature of the exposed wall. Therefore improvements in energy use and thermal comfort could arise from adaptive thermal insulation, this will be documented in the next sections.

Table 5
Static insulation performance for the different 8 design alternatives (+100% and −50% of the insulation thickness).

Case #	Description	Ep (kWh/m^2)	Ep heat (kWh/m^2)	Ep cool (kWh/m^2)	Ep light (kWh/m^2)	LPD [%]	OH_h [hrs]	OC_h [hrs]
1	UN_INS_HW	100.51	62.16	16.45	21.90	0.11	1480	790
1.1	UN_INS_LW	111.47	59.82	29.44	21.90	0.19	1930	590
2	INS_HW	81.81	34.00	25.91	21.90	0.15	2049	379
2.1	INS_HW −50%	85.78	40.05	23.83	21.90	0.14	1908	487
2.2	INS_HW +100%	81.14	20.63	38.61	21.90	0.23	2582	202
3	INS_HW_2	78.67	26.87	29.90	21.90	0.18	2261	257
3.1	INS_HW_2−50%	81.80	34.00	25.90	21.90	0.15	2049	379
3.2	INS_HW_2 +100%	81.10	20.60	38.60	21.90	0.23	2582	202
4	INS_HW_EXT	88.60	54.00	12.70	21.90	0.10	1432	759
4.1	INS_HW_EXT −50%	89.40	50.70	16.80	21.90	0.11	1477	738
4.2	INS_HW_EXT +100%	88.30	51.20	15.20	21.90	0.11	1540	698
5	INS_HW_INT	105.06	63.45	19.71	21.90	0.13	1553	810
5.1	INS_HW_INT −50%	104.75	63.34	19.51	21.90	0.13	1547	811
5.2	INS_HW_INT +100%	105.23	63.51	19.83	21.90	0.13	1556	811
6	INS_HW_MID	90.38	56.31	12.17	21.90	0.10	1388	800
6.1	INS_HW_MID−50%	90.90	56.60	12.50	21.90	0.10	1397	797
6.2	INS_HW_MID +100%	90.10	56.20	11.90	21.90	0.10	1381	802
7	INS_HW_MID_AC	90.38	56.33	12.15	21.90	0.10	1388	802
7.1	INS_HW_MID_AC −50%	90.92	56.54	12.48	21.90	0.10	1397	797
7.2	INS_HW_MID_AC +100%	90.04	56.20	11.94	21.90	0.10	1381	802
8	INS_LW_EXT	91.67	56.28	13.17	21.90	0.10	1482	675
8.1	INS_LW_EXT −50%	91.20	56.29	12.69	21.90	0.10	1459	679
8.2	INS_LW_EXT +100%	92.55	56.27	14.07	21.90	0.11	1524	661

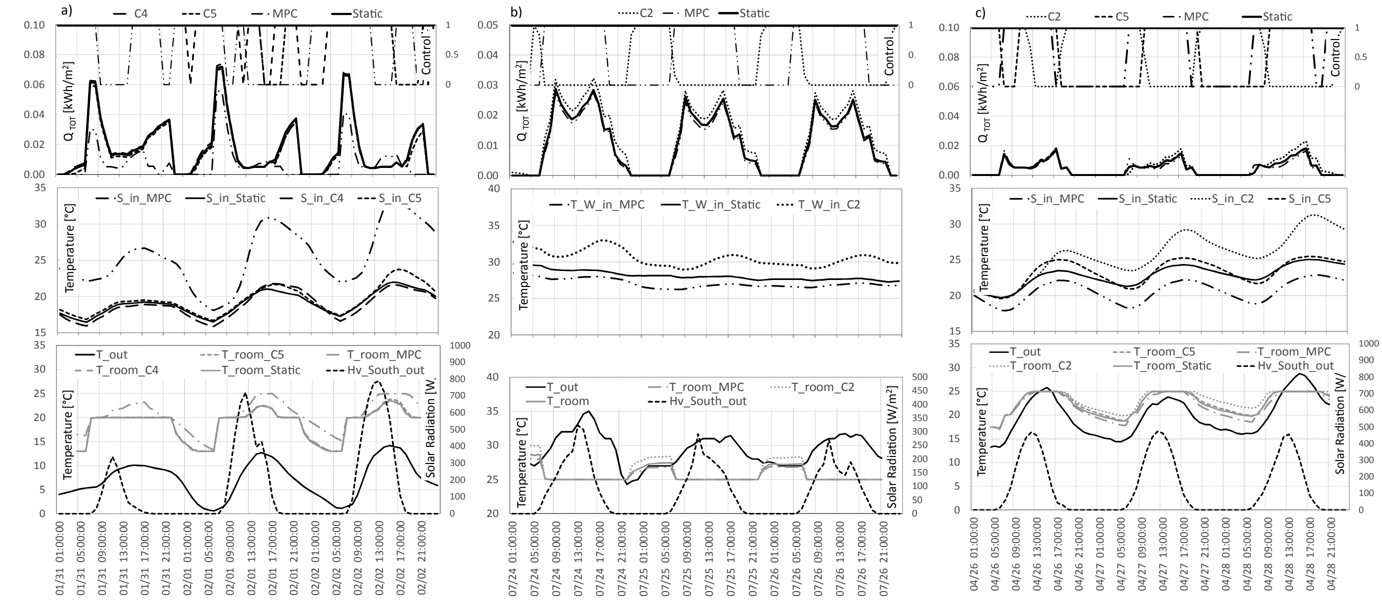


Fig. 5. Design alternative 4: boundary conditions (lower graphs), wall temperatures (middle graphs), building loads and control (top graphs) for a) 3 winter days (31st January – 2nd February) with high solar radiation and low temperatures, b) 3 summer days (24th to 26th July) with high solar radiation and high temperatures, c) 3 mid-season days (26th to 28th April) with high variability of outdoor temperature and high solar radiation.

3.2. Reference of alternative control strategies

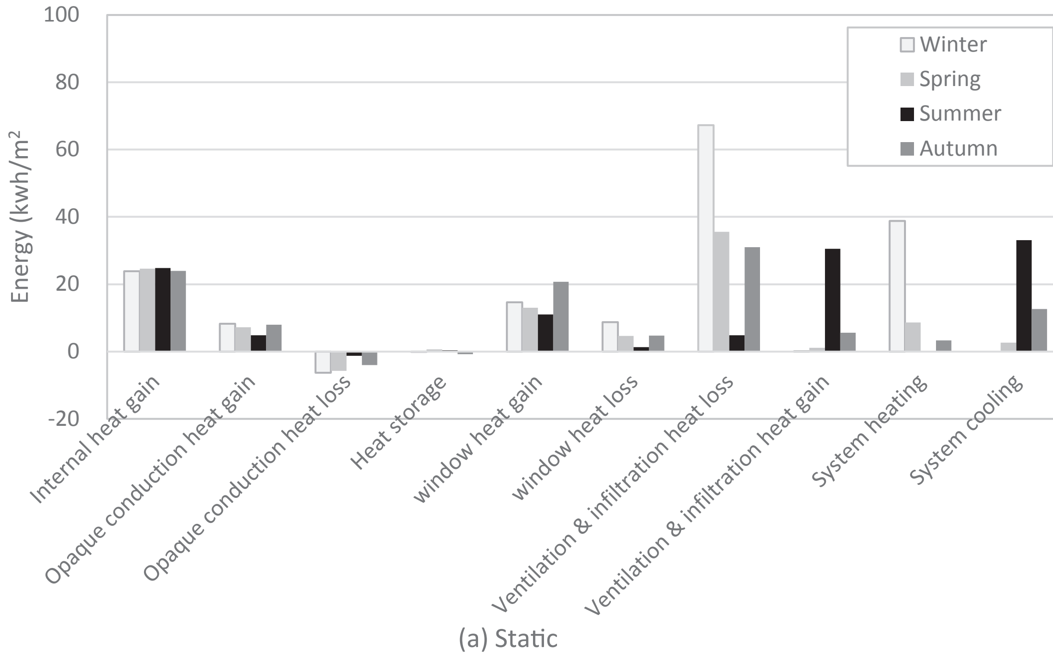
In general the effect of controlling the level of insulation in the sun-exposed opaque wall is to modulate its thermal resistance. This has the effect of decreasing the unwanted heat losses (during winter) or gains (during summer), but also to increase the desirable heat gains (in winter) and losses (in summer). Another very significant effect is to control the amount of solar energy that can be stored in the thermal mass of the opaque wall construction and that can be released to the internal environment when needed. From the internal environment perspective, all these effects cause a variation of the wall internal surface temperatures, which can modulate the radiant and convective heat exchange between the wall and the indoor environment (affecting the energy use for heating and cooling of the building), but also the thermal sensation of the building occupants. This capability of the adaptive insulation, and the extent of building performance improvements depends on design parameters of the adaptive insulation system and the control strategy adopted.

This section focuses on the comparison between alternative control strategies, in order to understand the behaviour and performance of an opaque wall with adaptive insulation. Six control strategies are compared in detail for design alternative 4, while some information about other design alternatives is provided at the end of this section.

In Fig. 5 three days in winter (5.a), summer (5.b) and mid-season (5.c) are compared. In the top tier graphs of Fig. 5 the control strategy is shown (on the secondary y-axis, 0 for no insulation and 1 for maximum insulation), together with the total building loads (heating, cooling and lighting). In the middle tier graphs the temperatures of the indoor surface of the adaptive insulation wall are represented, in order to provide a better understanding of the main factors influencing the performance of the adaptive insulation system. In the bottom tier graphs the corresponding outdoor (temperature and South vertical solar radiation) and indoor (air temperature) boundary conditions are shown. In Fig. 5, depending on the season, some results of specific control strategies are omitted as identical to others: during winter, C2 and C3 control strategies are identical to the static control; in summer C3, C4 and C5 are similar to the static control; in the mid-season C2, C3 and C4 operate the adaptive insulation in the same way.

During winter negligible differences are present for the building loads and for the internal wall temperatures between the static alternative and rule based controls, even though C4 and C5 vary the level of insulation during day 2, when the outdoor temperature or the wall internal temperature are above a certain threshold. Control C2 and C3 do not differ from the Static one, i.e. the insulation is always at its maximum level (1). In contrast MPC control lowers the insulation level whenever the incident solar radiation heats up the thermal mass above the heating set-point and below an upper threshold (to avoid the occurrence of discomfort due to overheating), as visible from the wall internal surface temperature trend. In fact, switching off the external insulation whenever solar radiation is available allows storage of solar energy in the heavyweight construction, thereby increasing the wall temperature (Fig. 5a, middle tier graph) and the radiant temperature of the room, significantly reducing heating energy use and improving global thermal comfort. More specifically, heating demand is eliminated (except for morning hours) but some cooling need is introduced in the afternoon of the second and third days, as visible from the air temperature trends of the MPC control.

During summer the adaptive insulation in C2 control is operated in a completely opposite way compared to MPC control. In fact C2 switches off the adaptive insulation whenever cooling loads occur in the room regardless of outdoor boundary conditions; while it is switched on during the setback period of the cooling system, even though the adaptive insulation wall internal temperature is still higher than the cooling set point, thereby increasing internal air temperatures during the night and morning and afternoon peak cooling loads, while decreasing occupant thermal comfort. In contrast, C3, C4 and C5 maintain the insulation switched on because the outside temperature and/or incident solar radiation on the South wall cause a rise of surface temperature above the cooling set point, or because of the occurrence of cooling loads. MPC, instead, increases the level of insulation during the day, preventing the heat from entering the room, while switching the insulation off



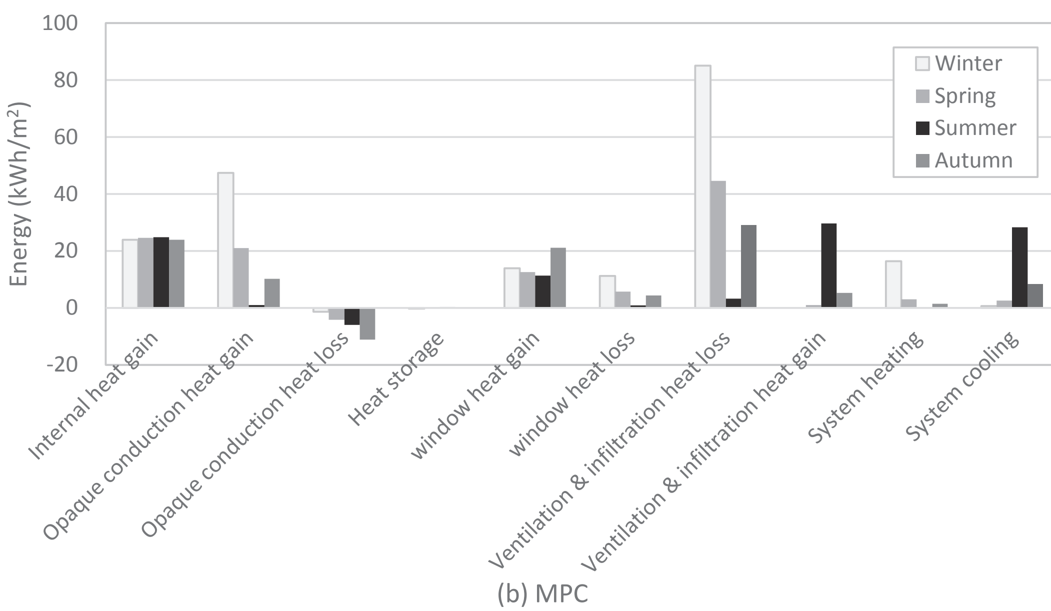


Fig. 6. Zone energy balance for Design Alternative 4 with (a) static performance properties and (b) Control Strategy MPC.

when solar radiation is not present and when the outside temperature is below the wall temperature, thereby reducing cooling loads and wall internal surface temperatures.

During the mid-season, unlike for summer days, C2, C3 and C4 strategies operate the adaptive insulation in a similar manner, i.e., the insulation is switched off whenever cooling loads occur in the room regardless of outdoor boundary conditions. This results in a wall internal temperature that is up to 5–6 °C higher than the static insulation design alternative, and higher free running temperatures during the day thereby, decreasing global thermal comfort. On the other hand, C5 switches the insulation off whenever the wall internal temperatures are between the heating and cooling set-points, resulting in sinusoidal internal surface wall temperatures between these two thresholds, which are anyway higher than the corresponding static case during the day and lower during night. MPC operates the adaptive insulation similarly to its summer operations, increasing the insulation level during the day thereby preventing cooling demand and overheating risk, and decreasing it during the night thereby lowering the internal wall surface and air temperatures and reducing the following morning cooling demand.

Additionally, whenever an additional layer of independently controllable adaptive insulation is present on the internal side (design alternatives 2 and 3), this is operated most of the time by MPC to reduce the temperatures of the wall preventing overheating during day time, while the level of insulation is decreased at night

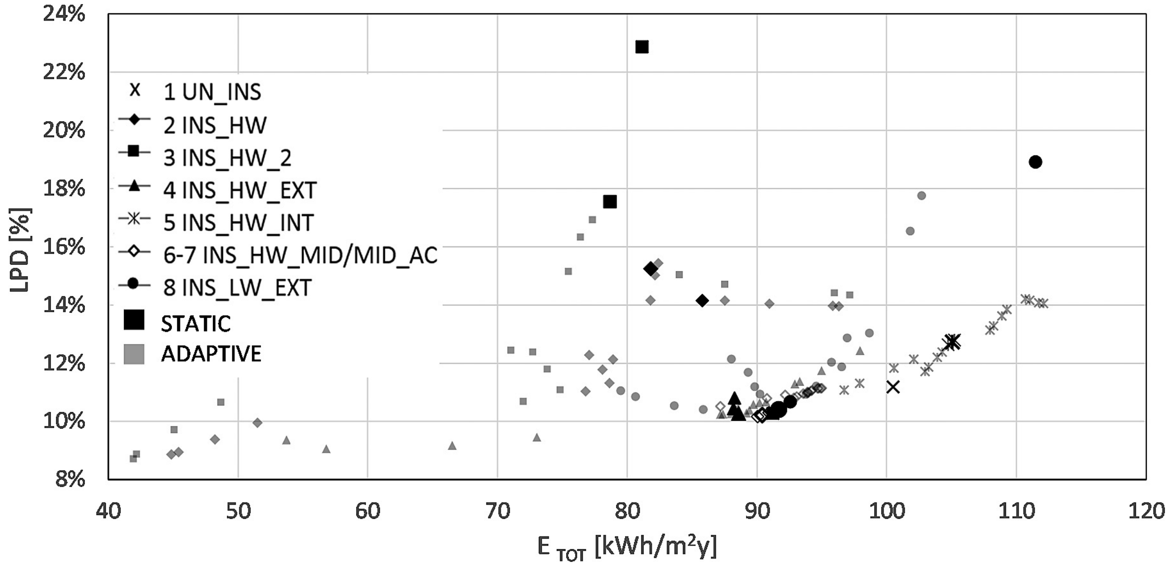


Fig. 7. Performance of all design alternatives analysed, across the variations in construction design alternatives, control strategies, and switching ranges.

to increase the access to the building envelope thermal mass. Conversely during winter the insulation is switched off during the day to allow solar energy stored in the sun exposed wall to enter the indoor environment, while it is increased at night to prevent heat losses. When instead a lightweight construction is analysed (8), although operated in a similar way, the thermal comfort can only be marginally increased due to the high temperatures reached by the light weight wall when solar radiation is present, while simultaneously decreasing the amount of energy used for heating.

A zone energy balance analysis is performed for Design Alternative 4 with static performance properties and Control MPC on a seasonal basis (Fig. 6). Although the energy balance is dominated by convective heat transfer (losses in winter and gains in summer), the use of adaptive insulation is nevertheless beneficial to heating and cooling energy demand. In winter, adaptive insulation is able to obtain nearly 6 times the heat gain and reduce heat loss by nearly 5 times, which reduces heating energy demand by 58%. Similar situation happens to spring, when the heating energy demand is reduced by 65%. In autumn, the adaptive insulation also works effectively to remove undesirable heat in the room and hence reduces cooling energy demand by 35%. In summer, since the internal heat gain and infiltration heat gain are dominating and the amount of energy that the adaptive insulation could remove is much less, cooling energy demand could only be saved by 14%. This result shows that overall adaptive insulation could significantly reduce energy demand by effectively transmitting desirable heat and block undesirable heat.

3.3. Effect of design alternatives, control strategies and switching ranges

The choice of the best control strategy for an adaptive insulation system is linked to the specific design adopted (i.e. amount of insulation and thermal mass, their relative position, adaptive insulation switching range etc.). Fig. 7 summarises the performance of all cases analysed, across the variations in construction design

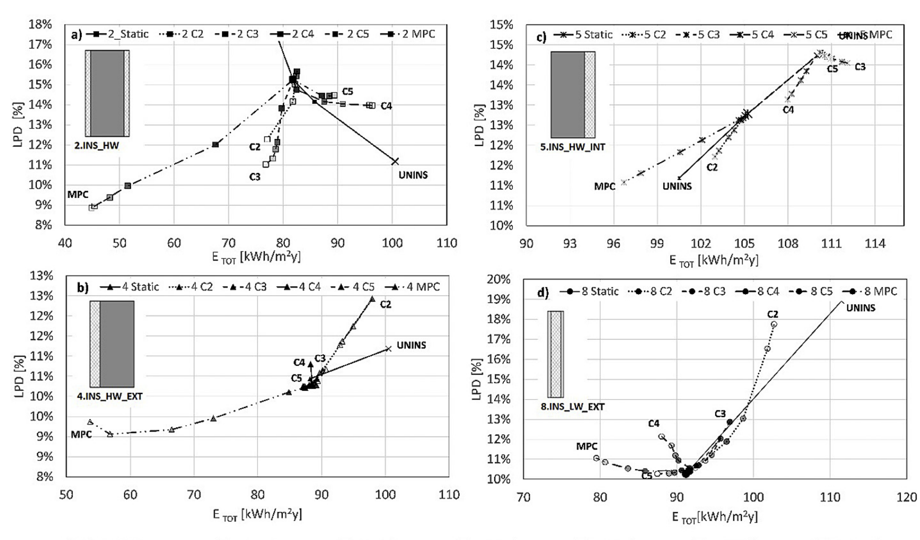


Fig. 8. Effect of control strategies for design alternatives: a) 2; b) 4; c) 5; d) 8.

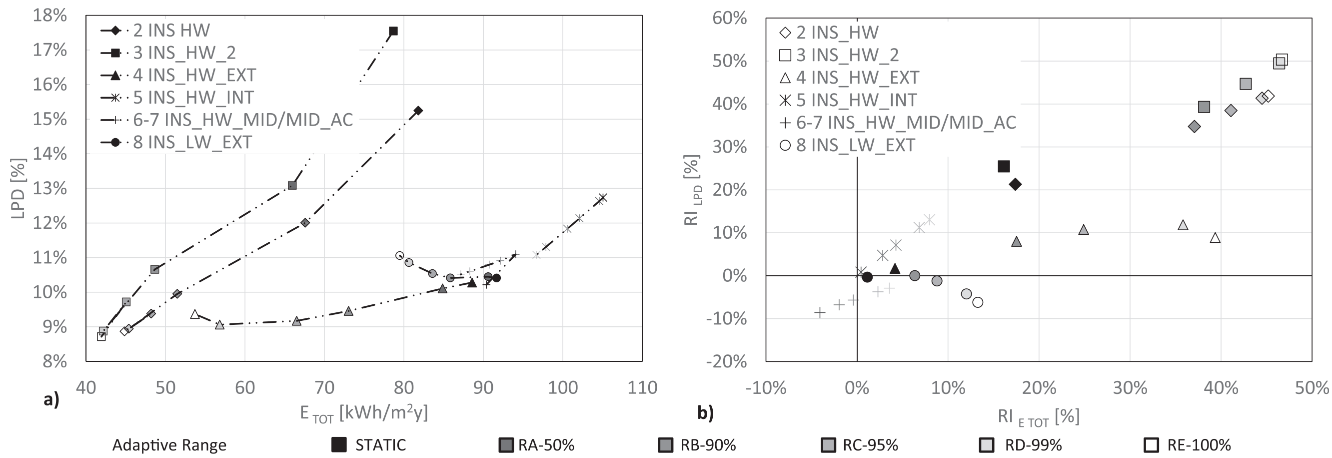


Fig. 9. Performance improvement of design alternatives adopting model predictive control: a) absolute and b) relative.

alternatives, control strategies, and switching ranges, but keeping fixed the frequency of control action (1/2 h) and the use of multi-objective decision making criteria (TOPSIS) for the MPC control. For non-predictive control (C2, 3, 4 and 5) one control state per simulation time step is performed (1/15 min). The performance data for each design alternative are summarised in Table A1 in the appendix (including heating, cooling and lighting energy use). The colour of the table cells indicate a performance improvement (blue) or a performance decrease (red) compared to the corresponding baseline static insulation scenario. Moreover the colours are used in order to detect whether the two objectives (low energy use and low long term thermal discomfort) are in agreement for each control strategy and design alternative compared to the reference static insulation case. For example if both energy use and LPD entries are highlighted in blue, it means that both energy use and LPD are lower than the static reference case; if energy use is coloured in blue and LPD is red, it means that energy use is improved, while LPD is increased. The relative performance improvement compared to the static reference case is summarised in Table A2, for both objectives, and for heating and cooling energy uses, making the same use of conditional formatting. Fig. 8 compares the performance of 4 design alternatives singularly. When comparing the variation of total energy demand in Figs. 7 and 8, it should be noted that the lighting energy demand for all cases is always constant at 21.9 kWh/m^2.

From Fig. 7 it is observed that for the investigated variable space, although the two performance objectives of reducing thermal discomfort and energy use may be conflicting when optimising a conventional static insulation systems (larger data points), it is possible to improve both objectives simultaneously by using actively controlled adaptive insulation (smaller data points). This is due to the fact that energy use and thermal comfort are not always conflicting objectives at all times, but whenever it is so, the decision making criteria TOPSIS is able to minimise both objectives. Moreover it is clearly visible that some adaptive insulation design solutions (i.e. 2, 3 and 4) yield higher performance improvements than others when they are optimally controlled. It is therefore pertinent to take a closer look as far as the performance of the different control strategies and switching ranges are concerned for each design alternative.

Fig. 8 analyses the performance of design alternatives singularly (Fig. 8a, design alternative 2; Fig. 8b, 4; Fig. 8c, 5; Fig. 8d, 8; design alternatives 3 and 6 were excluded as they have a similar behaviour to 2 and 5 respectively). Each data point represents the performance of a specific design solution: design solutions with similar control strategy are on the same line (discontinuous lines), while the grey-scale colour of the data point indicate the switching range (the lighter the colour, the larger the switching range). The sensitivity of the yearly performance due to the amount of static insulation is shown as a continuous line (from 100% additional insulation to uninsulated), in the graphs related to each specific design alternative.

Several considerations can be drawn by comparing alternative control strategies and insulation switching ranges for each design alternative. When the adaptive insulation is placed on the outside of a heavy weight sun exposed wall (Fig. 8b), rule based control strategies (C2, 3, 4 and 5) are largely unable to improve building performance as far as both objectives are concerned. In particular C2, which is only based on heating and cooling loads, causes an increase in both energy use and thermal discomfort, while C3, C4 and C5 although based on more boundary conditions (i.e. outdoor, indoor and wall surface temperatures) are unable to increase significantly the performance of the static insulation. This could be due to the thermal inertia of the building introducing a delay between the control action and the thermal response of the building. It should also be noted that since C1-C4 are not controlled by parameters directly related to thermal comfort (such as wall surface temperature in C5), LPD may not be minimized effectively. In contrast, adopting MPC decreases the energy use by up to 40% and improves global thermal comfort by a more modest amount (up to 10%). Increasing the switching range does not necessarily result in an improvement of both objectives, in fact increasing the switching range to a value higher than 95% (RC) can decrease global thermal comfort, caused by higher or lower surface temperatures on the wall, which might be due to a sub-optimal control strategy adopted or/and decision making (balancing out energy efficiency and thermal comfort). Moreover smaller switching ranges (i.e. 90%, RB, or 95%, RC), which are comparable with a prototype-stage technology [26], can yield important performance improvements compared to the conventional static insulation (up to 20–25% energy use reduction and 10% comfort improvement).

If the same amount of insulation is distributed equally between two independently controllable adaptive insulation layers, on either side of the heavy weight construction (design alternative 2 and 3, Fig. 8a) control C2 and C3 are able to increase global thermal comfort for a much larger extent than energy efficiency, while C4 and C5 are only able to increase thermal comfort, reducing mainly overheating. Compared to the design option that adopts external insulation only, design alternatives 2 and 3 with MPC are able to improve thermal comfort to a greater extent, but this is due to the poor thermal comfort performance of the corresponding static insulation reference case. Moreover with the first two modulation ranges of adaptive insulation (50%, A and 90%, B) this design alternative is able to achieve high performance improvements (25–40% for both objectives), while increasing further the insulation switching range to C, D and E yields limited additional performance improvements. Doubling the maximum insulation level achievable by the adaptive insulation (difference between design alternative 2 and 3) has a very low effect on the performance improvement. Therefore even when adaptive insulation is adopted, increasing the maximum insulation level achievable beyond a certain level has a very low effectiveness.

If no thermal mass is adopted together with the adaptive insulation (design alternative 8, Fig. 8d), only C4 and C5 are able to decrease energy use among the rule-based control strategies, but, as MPC, they are unable to increase global thermal comfort. Moreover predictive control is far less effective at reducing energy compared to when used in conjunction with thermal mass.

When the adaptive insulation layer is placed internally (5) or in the middle of the thermal mass (7), as shown in Fig. 8c, none of the control strategies considered is able to improve either energy or comfort, unless a wider range is used for MPC (i.e. MPC with RD or RE).

By comparing different design alternatives it is clear that design solutions adopting an adaptive insulation layer on the external side of a heavy weight opaque construction (2, 3 and 4) are by far the best solutions in terms of both reduction in energy use and improved global thermal comfort.

As far as the best rule-based control strategies are concerned (C2, C3, C4 and C5), which are the most adopted one in both simulation studies [7–10] and in real building applications [11], the choice depends on the design alternative considered very different considerations could be done. For example if thermal mass is placed between two adaptive insulation layers the best control strategies are C2 and C3 (the one adopting considering only cooling/heating energy loads and/or different between outdoor and indoor temperature, respectively). Although if no thermal mass is adopted control strategies considering also the presence of solar radiation and internal loads (C4 and C5) present a higher performance.

Compared to rule based control strategies adopted in this study, MPC presents by far the best performance achievable in terms of building energy use and thermal comfort. In Fig. 9 the performance of only MPC controlled design alternatives is shown, for each different design alternative (represented by a different line) and for the different switching ranges (represented by the grey-scale colour of the data point) in absolute and relative terms compared to the static reference (Fig. 9a and b respectively). By comparing for the same range (i.e. RE, white coloured data points) different design alternatives, it is possible to assess the effect of: a) doubling the maximum insulation level achievable (difference between design alternative 2 and 3); b) adopting only one external adaptive insulation rather than two independent ones (difference between 2 and 4); c) using the adaptive insulation in conjunction with thermal mass or not (difference between 4 and 8). In particular placing the controllable insulation externally to the thermal mass (design alternatives 2, 3 and 4) increases the energy saving potential of the adaptive insulation system to the greatest extent. While comfort improvements are possible only if a sufficient amount of thermal mass is present; in fact, when no thermal mass is available, the ability to control the insulation level results in lower global thermal comfort than the static alternative. The high relative improvement in thermal comfort for design alternative 2 and 3, depends largely on the low performance of the reference static design alternative, but in absolute terms the thermal comfort performance is not significantly higher than design alternative 4.

The conditional formatting of Table A1 and A2 highlights that with rule based control strategies investigated in this study, it is not possible to achieve a good trade-off between energy use and thermal comfort, and most of them are only able to improve one performance objective at a time. Although C5 did take into account wall surface temperature, it still failed to outperform MPC. In contrast MPC adopting multi-objective optimisation is able to provide whenever possible (due to the position of the adaptive insulation and the amount of thermal mass) a performance improvement for both energy use and global thermal comfort.

Generally a wider switching range always results in a larger difference between the static insulation performance and an adaptive one irrespective of the control strategy considered, except in the case where the adaptive insulation is placed internally, as in this case an uninsulated construction yields better yearly performance than an insulated one. The relationship between adaptive modulation range and performance improvement can vary with the position of the adaptive insulation relative to the thermal mass and to the amount of thermal mass, in fact, with the same amount of insulation distributed between two independently controllable insulation layers (one internal and one external to the thermal mass), a higher performance improvement is achievable with lower modulation ranges compared to when the adaptive insulation is all located in an external layer (Fig. 9b).

4. Discussion

In the current case study, MPC presents an advantage over rule-based control strategies. During the design process, considering only one or few rule based control strategies may bias the results of the performance evaluation of an adaptive building component. The use of more advanced simulation strategies which allows to simulate and optimise advanced control strategies, like MPC, could have a significant difference on the final product performance.

However, the real-world implementation of MPC would involve a higher cost compared to rule base one, as well as a bigger challenge in ensuring the accuracy of predicted performance. The fact that different parts of the building usually adopt different control strategies even increases the complexity further. In order to implement real-time MPC, compared to rule based control, a calibrated building model, correct estimates of weather and endogenous loads, and a larger number of sensors for updating the model according to the acquired measurements are required [27]. Additionally, real-time MPC requires much longer computational time, but parallel computing techniques and high-speed computer could effectively compensate. Although it is observed that the MPC operated adaptive insulation presents a number of controlled actions per day which is lower than rule based control strategies (C2, 3 and 4). From a frequency analysis on the control actions, it appears that a maximum of 3 actions per day are performed for all different design alternatives and control ranges for 80% of the time. In particular during winter and summer an average of 2 ± 1 (CI 95%) control actions per day are recorded, while during part of the mid-season an average of 4 ± 1 (CI 95%) control actions per day are observed for the MPC control. From the previous analysis (Section 3.3) it was observed that these control actions may be related, depending on the season, to external boundary conditions, such as outdoor temperature and incident solar radiation, internal boundary conditions, such as occupation, endogenous loads and air temperature set points, and/or to building states, such as indoor air temperature and wall internal surface temperature. Therefore it may be possible to use the simulated deterministic MPC to extract simpler rules to bridge the gap between MPC and simple rule based control strategies, although a small decrease in operational performance compared to the simulated MPC may be expected. The effectiveness of an MPC rule extraction technique has already been proven by simulation [28] and with experiments [29] for thermally active buildings. Therefore, further research is needed to verify its applicability to adaptive insulation integrated with the thermal mass of an opaque wall. Once this is done, a more comprehensive comparison between rule-based control (with rules extracted from MPC) and MPC strategies could be performed. In this way it is possible to eliminate the need for a calibrated building model and on-line optimisation during building operations, and to reduce the number of sensors needed.

The MPC strategy presented in this study is a virtual construct. No weather forecast uncertainties and occupant influences are assessed at this stage. However, the implementation of MPC in real buildings (as well as RBC extracted from MPC) may suffer from the dependency on input data (weather, endogenous loads and occupant actions) and their uncertainty, compared to simulated MPC [29]. Therefore future work with the aim of improving the accuracy of weather predictions, endogenous loads and occupant actions and interaction with building elements, and quantifying their uncertainty would be very worthwhile.

The way the MPC and the rule based control strategies are operated and perform in this building context are due not only to the specific climatic boundary conditions, but also to the specific type of building analysed (office building with pre-defined day time occupation, specified endogenous loads, air temperature set points, etc). It should be noted that if any of these design conditions change, the results may be different. For example, in a residential building, characterised by endogenous loads (and indoor air set points) patterns which are often non contemporary to high solar radiation, different control patterns may be present for the MPC, and a different performance level may be achievable. Therefore the impact of the different control strategies on other types of climates and building types are yet to be addressed.

The present simulation case study relies on the accuracy and reliability of the simulation model adopted for the adaptive insulation. Although a qualitative validation of this model for the present case study is provided in Part 1, this is only partial and a complete and experimental validation of the “SurfaceControl:MovableInsulation” model of EnergyPlus would be needed.

In terms of design parameters, only some of them are explored, such as the amount and position of thermal insulation and thermal mass, and the range of adaptive insulation achievable. Although other design aspects need to be investigated, such as the influence of external surface solar absorption and emissivity and the variability of the maximum value of adaptive thermal insulation achievable.

5. Conclusions

This paper presents a parametric study on the performance of adaptive insulation envelope systems for an office room application in a temperate climate of Shanghai, using an optimisation system developed for adaptive insulation in Part 1. The parametric study analysed both design and control parameters of an adaptive insulation system, to optimise the building performance in terms of total energy use and global thermal comfort. Parameters such as the amount and position of the adaptive insulation with respect to the thermal mass of the opaque wall, the amount of thermal mass exposed to the indoor environment, different rule based and predictive control strategies, different modulation ranges of the adaptive insulation, are varied. The following major conclusions could be drawn from the results:

(1) The use of adaptive insulation, if properly controlled and designed, can effectively modulate heat gains and losses between the outdoor and indoor environment, also enhancing the exploitation of available solar radiation in the indoor environment, contributing to reducing heating and cooling energy use, and improving occupant global thermal comfort;
(2) a careful selection of the amount of thermal mass and position of the adaptive layer is needed at the design stage, together with an optimisation of the control strategy. In particular, the design alternatives in which the adaptive insulation layer is placed on the external side of the thermal mass of the opaque construction coupled with predictive control, present high performance in terms of heating and cooling energy use, as well as global thermal comfort. In fact, the two aspects, design and control, are mutually interrelated if rule based control is adopted;
(3) a wider switching range generally results in higher performance, whenever the correct control strategy is adopted;
(4) the control strategy adopted has a major impact on the energy and thermal comfort performance. When adopting an MPC control strategy, 10–50% energy saving and thermal comfort improvement could be achieved, depending on the adaptive insulation design (thermal mass, position on the adaptive insulation, modulation range of insulation), compared to the performance of the relative static insulation. Moreover, if an incorrect control strategy is adopted, the building performance could be decreased with respect to the corresponding static case, and the potential of an adaptive insulation could be underestimated;
(5) the best control strategy investigated in this study for all design alternatives is the MPC. This control strategy has the advantage of optimising both energy use and thermal comfort if multi-objective optimisation is adopted. This is because MPC is the result of an optimisation process, while the rule-based control strategies used for comparison could be sub-optimal in the specific climate and building under investigation. Although these results quantify the maximum achievable performance of an adaptive insulation system and, as it maximises the energy saving achievable, it may make adaptive insulation system more financially viable;
(6) the adaptive insulation for similar type of building in climates where heating and cooling loads are balanced may outperform the intrinsic limitation of static insulation systems at improving energy use and thermal comfort simultaneously. Although the magnitude of the performance improvement is case specific and largely depends on design and control parameters of the adaptive insulation.

Acknowledgements

The Chinese author would like to acknowledge the financial supports from the National Natural Science Foundation of China (Grant No. 51408427). The British authors would like to acknowledge support from EPSRC Doctorial Training Grant (EP/503009/1) and project RG70518, funded by Wintech ltd. The authors would like to thank EU Cost Action TU1403 "Adaptive Facades Network" for providing excellent research networking.

Appendix A. Complete set of simulation results.

Table. A1
Effect of design, control and switching range.

RA

#		Control	LPD (%)	E_{TOT} (kWh/m^2)	E_{HEAT} (kWh/m^2)	E_{COOL} (kWh/m^2)	E_{LIGHT} (kWh/m^2)	OH_h [hrs]	OC_h [hrs]
2	INS_HW	C2	15.7%	82.5	33.5	27.2	21.9	2114	372
3	INS_HW_2	C2	17.6%	78.7	26.4	30.3	21.9	2295	253
4	INS_HW_EXT	C2	10.4%	89.3	53.9	13.4	21.9	1466	759
5	INS_HW_INT	C2	12.7%	104.9	63.5	19.6	21.9	1553	810
7	INS_HW_MID_AC	C2	11.1%	94.4	56.5	15.8	21.9	1506	795
8	INS_LW_CW	C2	10.7%	92.9	56.5	14.1	21.9	1534	645
2	INS_HW	C3	13.8%	79.7	34.9	22.9	21.9	1938	390
3	INS_HW_2	C3	15.0%	75.0	28.2	24.9	21.9	2090	265
4	INS_HW_EXT	C3	10.3%	88.8	54.0	12.9	21.9	1461	759
5	INS_HW_INT	C3	14.2%	110.0	66.4	21.7	21.9	1550	861
7	INS_HW_MID_AC	C3	11.1%	94.4	56.5	15.8	21.9	1505	795
8	INS_LW_CW	C3	10.6%	92.4	56.6	13.6	21.9	1528	646
2	INS_HW	C4	14.8%	82.4	35.2	25.3	21.9	1981	401
3	INS_HW_2	C4	16.4%	79.4	29.2	28.3	21.9	2120	282
4	INS_HW_EXT	C4	10.3%	88.3	53.7	12.7	21.9	1432	754
5	INS_HW_INT	C4	14.3%	110.2	66.5	21.8	21.9	1546	865
7	INS_HW_MID_AC	C4	11.1%	94.5	56.5	15.9	21.9	1509	795
8	INS_LW_CW	C4	10.6%	91.6	56.1	13.4	21.9	1538	642
2	INS_HW	C5	14.4%	88.5	41.5	25.1	21.9	1991	478
3	INS_HW_2	C5	17.3%	83.0	31.4	29.7	21.9	2184	344
4	INS_HW_EXT	C5	10.3%	88.1	53.4	12.7	21.9	1449	752
5	INS_HW_INT	C5	14.3%	110.2	66.4	21.9	21.9	1550	864
7	INS_HW_MID_AC	C5	11.1%	94.5	56.6	15.9	21.9	1509	795
8	INS_LW_CW	C5	10.5%	91.5	55.9	13.3	21.9	1519	638
2	INS_HW	MPC	12.0%	67.6	27.2	18.5	21.9	1754	307
3	INS_HW_2	MPC	13.1%	66.0	24.0	20.1	21.9	1886	230
4	INS_HW_EXT	MPC	10.1%	84.9	50.5	12.5	21.9	1417	699
5	INS_HW_INT	MPC	12.6%	104.6	63.2	19.5	21.9	1527	795
7	INS_HW_MID_AC	MPC	11.1%	94.1	56.2	15.7	21.9	1488	788
8	INS_LW_CW	MPC	10.4%	90.6	55.1	13.3	21.9	1499	624

RB

#		Control	LPD (%)	E_{TOT} (kWh/m^2)	E_{HEAT} (kWh/m^2)	E_{COOL} (kWh/m^2)	E_{LIGHT} (kWh/m^2)	OH_h [hrs]	OC_h [hrs]
2	INS_HW	C2	15.4%	82.4	32.7	27.8	21.9	2132	358
3	INS_HW_2	C2	16.9%	77.3	25.6	29.8	21.9	2313	238
4	INS_HW_EXT	C2	11.3%	92.9	53.8	17.2	21.9	1584	752
5	INS_HW_INT	C2	12.4%	104.3	63.5	18.9	21.9	1546	810
7	INS_HW_MID_AC	C2	11.0%	93.9	56.5	15.3	21.9	1491	795
8	INS_LW_CW	C2	11.9%	96.5	56.2	18.0	21.9	1579	640
2	INS_HW	C3	12.1%	78.9	37.6	19.4	21.9	1709	448
3	INS_HW_2	C3	12.4%	72.7	31.2	19.6	21.9	1838	308
4	INS_HW_EXT	C3	10.6%	89.7	54.0	13.8	21.9	1525	759
5	INS_HW_INT	C3	13.8%	109.3	66.5	20.8	21.9	1523	871
7	INS_HW_MID_AC	C3	11.1%	94.2	56.5	15.6	21.9	1497	795
8	INS_LW_CW	C3	10.9%	93.7	56.6	14.9	21.9	1539	651
2	INS_HW	C4	14.2%	87.5	41.2	24.4	21.9	1852	520
3	INS_HW_2	C4	15.0%	84.0	35.8	26.3	21.9	1938	417
4	INS_HW_EXT	C4	10.2%	87.4	52.8	12.7	21.9	1434	745
5	INS_HW_INT	C4	14.2%	110.7	67.1	21.7	21.9	1535	879
7	INS_HW_MID_AC	C4	11.1%	94.6	56.7	15.9	21.9	1509	794
8	INS_LW_CW	C4	10.9%	90.2	54.3	13.7	21.9	1626	623
2	INS_HW	C5	14.4%	89.4	42.4	25.1	21.9	1807	596
3	INS_HW_2	C5	16.5%	88.8	38.2	28.7	21.9	1999	516
4	INS_HW_EXT	C5	10.2%	87.1	52.5	12.7	21.9	1437	745
5	INS_HW_INT	C5	14.3%	110.4	66.6	21.8	21.9	1548	876
7	INS_HW_MID_AC	C5	11.1%	95.1	57.1	15.9	21.9	1510	806
8	INS_LW_CW	C5	10.3%	89.7	54.6	12.8	21.9	1498	614
2	INS_HW	MPC	9.9%	51.5	16.8	12.7	21.9	1482	152
3	INS_HW_2	MPC	10.7%	48.7	13.3	13.4	21.9	1648	87
4	INS_HW_EXT	MPC	9.5%	73.0	39.5	11.7	21.9	1344	558
5	INS_HW_INT	MPC	12.1%	102.1	61.7	18.5	21.9	1505	784
7	INS_HW_MID_AC	MPC	10.9%	92.2	55.0	15.0	21.9	1478	772
8	INS_LW_CW	MPC	10.4%	85.8	50.6	13.0	21.9	1499	577

RC

#		Control	LPD (%)	E_{TOT} (kWh/m^2)	E_{HEAT} (kWh/m^2)	E_{COOL} (kWh/m^2)	E_{LIGHT} (kWh/m^2)	OH_h [hrs]	OC_h [hrs]
2	INS_HW	C2	15.0%	82.1	32.8	27.5	21.9	2119	356
3	INS_HW_2	C2	16.3%	76.4	25.3	29.1	21.9	2291	236
4	INS_HW_EXT	C2	11.7%	94.9	53.7	19.4	21.9	1628	752
5	INS_HW_INT	C2	12.2%	103.9	63.5	18.5	21.9	1544	810
7	INS_HW_MID_AC	C2	11.0%	93.6	56.5	15.0	21.9	1489	795
8	INS_LW_CW	C2	13.0%	98.6	56.1	20.4	21.9	1600	636
2	INS_HW	C3	11.8%	78.1	37.5	18.7	21.9	1650	458
3	INS_HW_2	C3	11.8%	73.8	33.5	18.5	21.9	1720	361
4	INS_HW_EXT	C3	10.6%	90.2	54.1	14.2	21.9	1522	763
5	INS_HW_INT	C3	13.6%	108.9	66.7	20.3	21.9	1512	877
7	INS_HW_MID_AC	C3	11.0%	94.1	56.5	15.5	21.9	1493	795
8	INS_LW_CW	C3	11.2%	94.5	56.6	15.7	21.9	1533	654
2	INS_HW	C4	14.0%	90.9	44.9	24.1	21.9	1811	586
3	INS_HW_2	C4	14.7%	87.5	39.9	25.7	21.9	1864	487
4	INS_HW_EXT	C4	10.2%	87.2	52.6	12.7	21.9	1434	742
5	INS_HW_INT	C4	14.2%	111.0	67.5	21.7	21.9	1522	886
7	INS_HW_MID_AC	C4	11.1%	94.7	56.7	15.9	21.9	1510	797
8	INS_LW_CW	C4	11.2%	89.8	53.5	14.1	21.9	1666	614
2	INS_HW	C5	14.4%	88.5	41.5	25.1	21.9	1806	594
3	INS_HW_2	C5	16.2%	90.0	39.7	28.4	21.9	1911	559
4	INS_HW_EXT	C5	10.2%	87.1	52.6	12.7	21.9	1427	747
5	INS_HW_INT	C5	14.2%	110.5	66.8	21.8	21.9	1547	879
7	INS_HW_MID_AC	C5	11.2%	95.5	57.5	15.9	21.9	1513	809
8	INS_LW_CW	C5	10.3%	89.0	53.9	12.8	21.9	1467	600
2	INS_HW	MPC	9.4%	48.2	14.9	11.4	21.9	1301	151
3	INS_HW_2	MPC	9.7%	45.1	11.7	11.5	21.9	1398	74
4	INS_HW_EXT	MPC	9.2%	66.5	33.4	11.2	21.9	1296	505
5	INS_HW_INT	MPC	11.8%	100.6	60.8	17.9	21.9	1496	770
7	INS_HW_MID_AC	MPC	10.8%	90.7	54.0	14.6	21.9	1470	761
8	INS_LW_CW	MPC	10.5%	83.6	48.4	12.9	21.9	1539	566

RD

#		Control	LPD (%)	E_{TOT} (kWh/m^2)	E_{HEAT} (kWh/m^2)	E_{COOL} (kWh/m^2)	E_{LIGHT} (kWh/m^2)	OH_h [hrs]	OC_h [hrs]
2	INS_HW	C2	14.2%	81.8	33.2	26.7	21.9	2002	362
3	INS_HW_2	C2	15.2%	75.5	25.7	27.9	21.9	2192	244
4	INS_HW_EXT	C2	12.4%	97.9	53.5	22.5	21.9	1653	750
5	INS_HW_INT	C2	11.9%	103.2	63.5	17.8	21.9	1541	811
7	INS_HW_MID_AC	C2	10.8%	93.0	56.5	14.4	21.9	1476	795
8	INS_LW_CW	C2	16.5%	101.8	55.8	23.9	21.9	1619	630
2	INS_HW	C3	11.3%	78.6	38.9	17.9	21.9	1549	491
3	INS_HW_2	C3	11.1%	74.8	35.5	17.4	21.9	1566	403
4	INS_HW_EXT	C3	10.7%	90.7	54.1	14.7	21.9	1490	765
5	INS_HW_INT	C3	13.3%	108.2	66.8	19.5	21.9	1498	879
7	INS_HW_MID_AC	C3	11.0%	93.9	56.5	15.3	21.9	1485	794
8	INS_LW_CW	C3	12.0%	95.7	56.5	17.0	21.9	1524	652
2	INS_HW	C4	14.0%	96.3	50.7	23.7	21.9	1761	690
3	INS_HW_2	C4	14.4%	96.0	49.3	24.8	21.9	1778	645
4	INS_HW_EXT	C4	10.3%	88.0	53.4	12.7	21.9	1433	756
5	INS_HW_INT	C4	14.1%	111.7	68.3	21.5	21.9	1505	894
7	INS_HW_MID_AC	C4	11.1%	94.9	56.9	15.9	21.9	1510	799
8	INS_LW_CW	C4	11.7%	89.3	52.2	14.9	21.9	1700	601
2	INS_HW	C5	14.4%	87.0	40.1	25.0	21.9	1805	593
3	INS_HW_2	C5	16.2%	90.0	39.7	28.4	21.9	1911	559
4	INS_HW_EXT	C5	10.2%	87.1	52.6	12.7	21.9	1427	747
5	INS_HW_INT	C5	14.2%	110.5	66.8	21.8	21.9	1547	879
7	INS_HW_MID_AC	C5	11.2%	95.5	57.5	15.9	21.9	1513	809
8	INS_LW_CW	C5	10.3%	87.5	52.0	13.3	21.9	1512	575
2	INS_HW	MPC	8.9%	45.4	13.3	10.2	21.9	1113	180
3	INS_HW_2	MPC	8.9%	42.2	10.6	9.6	21.9	1085	122
4	INS_HW_EXT	MPC	9.1%	56.8	24.5	10.5	21.9	1213	396
5	INS_HW_INT	MPC	11.3%	97.9	59.2	16.8	21.9	1475	745
7	INS_HW_MID_AC	MPC	10.6%	88.3	52.2	14.0	21.9	1448	736
8	INS_LW_CW	MPC	10.9%	80.6	45.2	13.2	21.9	1558	548

RE

#		Control	LPD (%)	E_{TOT} (kWh/m^2)	E_{HEAT} (kWh/m^2)	E_{COOL} (kWh/m^2)	E_{LIGHT} (kWh/m^2)	OH_h [hrs]	OC_h [hrs]
2	INS_HW	C2	12.3%	77.1	35.0	20.2	21.9	1846	388
3	INS_HW_2	C2	12.4%	71.0	28.6	20.6	21.9	1918	267
4	INS_HW_EXT	C2	11.4%	93.3	53.7	17.6	21.9	1551	752
5	INS_HW_INT	C2	11.7%	103.0	63.6	17.5	21.9	1537	813
7	INS_HW_MID_AC	C2	10.8%	92.8	56.5	14.2	21.9	1468	796
8	INS_LW_CW	C2	17.8%	102.7	55.5	24.9	21.9	1638	627
2	INS_HW	C3	11.0%	76.8	38.6	16.3	21.9	1480	483
3	INS_HW_2	C3	10.7%	72.0	34.5	15.6	21.9	1484	387
4	INS_HW_EXT	C3	10.4%	89.4	54.2	13.3	21.9	1406	768
5	INS_HW_INT	C3	13.1%	108.0	66.9	19.1	21.9	1496	884
7	INS_HW_MID_AC	C3	11.0%	93.9	56.5	15.3	21.9	1480	795
8	INS_LW_CW	C3	12.9%	96.9	56.1	18.6	21.9	1601	639
2	INS_HW	C4	14.0%	95.8	50.1	23.8	21.9	1751	675
3	INS_HW_2	C4	14.3%	97.1	50.6	24.6	21.9	1738	682
4	INS_HW_EXT	C4	10.3%	89.2	54.6	12.7	21.9	1429	765
5	INS_HW_INT	C4	14.0%	112.1	68.7	21.5	21.9	1501	899
7	INS_HW_MID_AC	C4	11.1%	95.0	57.0	15.9	21.9	1511	799
8	INS_LW_CW	C4	12.1%	88.0	50.3	15.5	21.9	1729	587
2	INS_HW	C5	14.5%	91.5	44.6	25.0	21.9	1779	633
3	INS_HW_2	C5	16.2%	92.1	42.0	28.2	21.9	1868	593
4	INS_HW_EXT	C5	10.2%	87.4	53.0	12.5	21.9	1395	755
5	INS_HW_INT	C5	14.1%	110.9	67.3	21.8	21.9	1544	884
7	INS_HW_MID_AC	C5	11.2%	96.7	58.7	15.9	21.9	1517	825
8	INS_LW_CW	C5	10.3%	87.5	52.0	13.3	21.9	1545	576
2	INS_HW	MPC	8.9%	44.8	13.1	9.8	21.9	1060	192
3	INS_HW_2	MPC	8.7%	41.9	10.9	9.1	21.9	978	164
4	INS_HW_EXT	MPC	9.4%	53.7	21.4	10.4	21.9	1296	354
5	INS_HW_INT	MPC	11.1%	96.7	58.4	16.4	21.9	1472	729
7	INS_HW_MID_AC	MPC	10.5%	87.2	51.4	13.7	21.9	1439	731
8	INS_LW_CW	MPC	11.1%	79.5	43.9	13.4	21.9	1564	537

Table. A2
Relative improvement compare to the static design solution for different design alternatives, controls and switching ranges.

			RA				RB				RC				RD				RE			
#		Control	LPD (%)	E_{TOT} (kWh/m^2)	E_{HEAT} (kWh/m^2)	E_{COOL} (kWh/m^2)	LPD (%)	E_{TOT} (kWh/m^2)	E_{HEAT} (kWh/m^2)	E_{COOL} (kWh/m^2)	LPD (%)	E_{TOT} (kWh/m^2)	E_{HEAT} (kWh/m^2)	E_{COOL} (kWh/m^2)	LPD (%)	E_{TOT} (kWh/m^2)	E_{HEAT} (kWh/m^2)	E_{COOL} (kWh/m^2)	LPD (%)	E_{TOT} (kWh/m^2)	E_{HEAT} (kWh/m^2)	E_{COOL} (kWh/m^2)
2	INS_HW	C2	-2.7%	-0.9%	1.6%	-4.8%	-1.2%	-0.7%	3.7%	-7.1%	1.4%	-0.4%	3.6%	-6.0%	7.1%	0.0%	2.4%	-3.0%	19.5%	5.8%	-2.9%	22.2%
3	INS_HW_2	C2	0%	0%	2%	-1%	4%	2%	5%	0%	7%	3%	6%	3%	14%	4%	4%	7%	29%	10%	-6%	31%
4	INS_HW_EXT	C2	-2%	-1%	0%	-6%	-10%	-5%	0%	-36%	-14%	-7%	1%	-53%	-21%	-11%	1%	-77%	-11%	-5%	0%	-39%
5	INS_HW_INT	C2	0%	0%	0%	1%	3%	1%	0%	4%	4%	1%	0%	6%	7%	2%	0%	10%	8%	2%	0%	11%
7	INS_HW_MID_AC	C2	-9%	-4%	0%	-30%	-8%	-4%	0%	-26%	-7%	-4%	0%	-23%	-6%	-3%	0%	-19%	-6%	-3%	0%	-17%
8	INS_LW_CW	C2	-3%	-1%	0%	-7%	-14%	-5%	0%	-37%	-25%	-8%	0%	-55%	-59%	-11%	1%	-81%	-71%	-12%	1%	-89%
2	INS_HW	C3	9%	3%	-3%	12%	20%	4%	-11%	25%	23%	5%	-10%	28%	26%	4%	-14%	31%	28%	6%	-13%	37%
3	INS_HW_2	C3	15%	5%	-5%	17%	29%	8%	-16%	34%	33%	6%	-25%	38%	37%	5%	-32%	42%	39%	8%	-29%	48%
4	INS_HW_EXT	C3	-1%	0%	0%	-2%	-3%	-1%	0%	-9%	-4%	-2%	0%	-12%	-4%	-2%	0%	-16%	-1%	-1%	0%	-5%
5	INS_HW_INT	C3	-12%	-5%	-5%	-10%	-9%	-4%	-5%	-6%	-7%	-4%	-5%	-3%	-4%	-3%	-5%	1%	-3%	-3%	-6%	3%
7	INS_HW_MID_AC	C3	-9%	-4%	0%	-30%	-8%	-4%	0%	-29%	-8%	-4%	0%	-28%	-8%	-4%	0%	-26%	-7%	-4%	0%	-26%
8	INS_LW_CW	C3	-2%	-1%	-1%	-3%	-5%	-2%	-1%	-13%	-8%	-3%	-1%	-19%	-16%	-4%	0%	-29%	-24%	-6%	0%	-42%
2	INS_HW	C4	3%	-1%	-4%	2%	7%	-7%	-21%	6%	8%	-11%	-32%	7%	8%	-18%	-49%	8%	8%	-17%	-47%	8%
3	INS_HW_2	C4	7%	-1%	-9%	5%	14%	-7%	-33%	12%	16%	-11%	-49%	14%	18%	-22%	-83%	17%	18%	-23%	-88%	18%
4	INS_HW_EXT	C4	0%	0%	0%	0%	0%	1%	2%	0%	0%	2%	3%	0%	0%	1%	1%	0%	0%	-1%	-1%	0%
5	INS_HW_INT	C4	-12%	-5%	-5%	-11%	-12%	-5%	-6%	-10%	-11%	-6%	-6%	-10%	-11%	-6%	-8%	-9%	-10%	-7%	-8%	-9%
7	INS_HW_MID_AC	C4	-9%	-5%	0%	-31%	-9%	-5%	-1%	-31%	-9%	-5%	-1%	-31%	-9%	-5%	-1%	-31%	-9%	-5%	-1%	-31%
8	INS_LW_CW	C4	-1%	0%	0%	-1%	-5%	2%	4%	-4%	-8%	2%	5%	-7%	-12%	3%	7%	-13%	-17%	4%	11%	-18%
2	INS_HW	C5	-8%	-22%	3%	5%	-9%	-25%	3%	5%	-8%	-22%	3%	5%	-6%	-18%	3%	5%	-12%	-31%	3%	5%
3	INS_HW_2	C5	-6%	-17%	1%	1%	-13%	-42%	4%	6%	-14%	-48%	5%	7%	-14%	-48%	5%	7%	-17%	-56%	6%	8%
4	INS_HW_EXT	C5	1%	1%	0%	0%	2%	3%	0%	0%	2%	3%	0%	0%	2%	3%	0%	0%	1%	2%	1%	1%
5	INS_HW_INT	C5	-5%	-5%	-11%	-12%	-5%	-5%	-11%	-12%	-5%	-5%	-11%	-12%	-5%	-5%	-11%	-12%	-6%	-6%	-11%	-11%
7	INS_HW_MID_AC	C5	-5%	0%	-31%	-9%	-5%	-1%	-31%	-9%	-6%	-2%	-31%	-9%	-6%	-2%	-31%	-9%	-7%	-4%	-31%	-10%
8	INS_LW_CW	C5	0%	1%	-1%	0%	2%	3%	2%	1%	3%	4%	3%	1%	5%	8%	-1%	1%	5%	8%	-1%	1%
2	INS_HW	MPC	21%	17%	20%	29%	35%	37%	50%	51%	38%	41%	56%	56%	41%	45%	61%	61%	42%	45%	61%	62%
3	INS_HW_2	MPC	25%	16%	11%	33%	39%	38%	50%	55%	45%	43%	57%	62%	49%	46%	60%	68%	50%	47%	59%	69%
4	INS_HW_EXT	MPC	2%	4%	7%	1%	8%	18%	27%	8%	11%	25%	38%	12%	12%	36%	55%	18%	9%	39%	60%	18%
5	INS_HW_INT	MPC	1%	0%	0%	1%	5%	3%	3%	6%	7%	4%	4%	9%	11%	7%	7%	15%	13%	8%	8%	17%
7	INS_HW_MID_AC	MPC	-9%	-4%	0%	-29%	-7%	-2%	2%	-24%	-6%	0%	4%	-20%	-4%	2%	7%	-15%	-3%	4%	9%	-13%
8	INS_LW_CW	MPC	0%	1%	2%	-1%	0%	6%	10%	1%	-1%	9%	14%	2%	-4%	12%	20%	0%	-6%	13%	22%	-2%

References

[1] Pflug T, Kuhn TE, Nörenberg R, Glück A, Nestle N, Maurer C. Closed translucent façade elements with switchable U-value—a novel option for energy management via the facade. Energy Build 2015;86:66–73. http://dx.doi.org/10.1016/j.enbuild.2014.09.082. ISSN 0378-7788.

[2] Berge A, Hagentoft CE, Wahlgren P, Adl-Zarrabi B. Effect from a variable U-Value in adaptive building components with controlled internal air pressure. Energy Procedia 2015;78:376–81. http://dx.doi.org/10.1016/j.egypro.2015.11.677. ISSN 1876-6102.

[3] Assimakopoulos MN, Tsangrassoulis A, Santamouris M, Guarracino G. Comparing the energy performance of an electrochromic window under various control strategies. Build Environ 2007;42:2829–34. http://dx.doi.org/10.1016/j.buildenv.2006.04.004.

[4] Jonsson A, Roos A. Evaluation of control strategies for different smart window combinations using computer simulations. Sol Energy 2010;84(1):1–9. http://dx.doi.org/10.1016/j.solener.2009.10.021. ISSN 0038-092X.

[5] Warwick M, Ridley I, Binions R. The effect of transition hysteresis width in thermochromic glazing systems. Open J Energy Effic 2013;2:75–88. http://dx.doi.org/10.4236/ojee.2013.22011.

[6] Favoino F, Fiorito F, Cannavale A, Ranzi G, Overend M. Optimal control and performance of photovoltachromic switchable glazing for building integration in temperate climates. Appl Energy 2016;178:943–61.

[7] Energy Research Institute of National Development and Reform Commission of China (ERINDRCC). General principles for calculation of total production energy consumption (GB/T 2589-2008). China. 2008.

[8] Evins R. Multi-level optimization of building design, energy system sizing and operation. Energy 2015;90:1775–89.

[9] Gan G. Numerical evaluation of thermal comfort in rooms with dynamic insulation. Build Environ 2000;35:445–53.

[10] Nielsen MV, Svendsen S, Jensen LB. Quantifying the potential of automated

dynamic solar shading in office buildings through integrated simulations of energy and daylight. Sol Energy 2011;85(5):757–68.
[11] Bionda D, Menti UP, Manz H. Kann eine Gebaüdehülle Mit Steuerbarem U-Wert Zur Reduktion Des Kühlenenergiebedarfs Beitragen?. In: Proceedings of BauSIM2014, the fifth German-Austrian IBPSA conference; 2014. p. 649–55.
[12] Burdajewicz F, Korjenic A, Bednar T. Bewertung Und Optimierung von Dynamischen Dämmsystemen Unter Berücksichtigung Des Wiener Klimas. Bauphysik 2011;33(1):49–58.
[13] Corbin CD, Henze GP, May-Ostendorp P. A model predictive control optimization environment for real-time commercial building application. J Build Perform Simul 2013;6(3):159–74.
[14] Wang S, Ma Z. Supervisory and optimal control of building HVAC systems: a review. HVAC&R Res 2008;14(1):3–32.
[15] Jin Q, Favoino F, Overend M. The potential opaque adaptive façades for office buildings in a temperate climate. In: Proceedings of building simulation 2015 conference; 2015. p. 98–105.
[16] Carlucci S, Pagliano L. A review of indices for the long-term evaluation of the general thermal comfort conditions in buildings. Energy Build 2012;53: 194–205. http://dx.doi.org/10.1016/j.enbuild.2012.06.015. ISSN 0378-7788.
[17] Carlucci S, Cattarin G, Causone F, Pagliano L. Multi-objective optimization of a nearly zero-energy building based on thermal and visual discomfort minimization using a non-dominated sorting genetic algorithm (NSGA-II). Energy Build 2015;104:378–94.
[18] Carlucci S. Thermal comfort assessment of buildings. Springer; 2013.
[19] EN ISO 7730. 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. 2005.
[20] EN ISO 15251. Indoor environmental parameters for assessment of energy performance of buildings- addressing indoor air quality, thermal environment, lighting and acoustics. 2007.
[21] ANSI/ASHRAE Standard 55. Thermal environmental conditions for human occupancy. 2010.
[22] Ashouri A, Fux SS, Benz MJ, Guzzella L. Optimal design and operation of building services using mixed-integer linear programming techniques. Energy 2013;59:365–76.
[23] Fanger PO. Thermal comfort: analysis and applications in environmental engineering. Copenhagen: Danish Technical Press; 1970.
[24] Deb K, Pratap A, Agarwal S, Meyarivan T. A fast and elitist multiobjective genetic algorithm: NSGA II. IEEE Trans Evol Comput 2002;6(2):182–97.
[25] Lee WS, Lin YC. Evaluating and ranking energy performance of office buildings using Grey relational analysis. Energy 2011;36(5):2551–6.
[26] Kimber M, Clark WW, Schaefer L. Conceptual analysis and design of a partitioned Multifunctional smart insulation. Appl Energy 2014;114:310–9.
[27] MOHURD (Ministry of Housing and Urban-Rural Development of China). Design standard for energy efficiency of public buildings GB50189-2005.China. 2005.
[28] May-Ostendorp P, Henze GP, Corbin CD, Rajagopalan B, Felsmann C. Model-predictive control of mixed-mode buildings with rule extraction. Build Environ 2011;46(2):428–37.
[29] May-Ostendorp PT, Henze GP, Rajagopalan B, Kalz D. Experimental investigation of model predictive control-based rules for a radiantly cooled office. HVAC&R Res 2013;19(5):602–15.