Performance prediction of buildings with responsive building elements challenges and solutions

Citation for published version (APA):
Loonen, R. C. G. M., Hoes, P., & Hensen, J. L. M. (2014). Performance prediction of buildings with responsive building elements challenges and solutions. In L. Malki-Epshtein, C. Spataru, L. Marjanovic Halburd, & D. Mumovic (Eds.), *Proceedings of the 2014 Building Simulation and Optimization Conference (BSO14), 23-24 June 2014, London, United Kingdom* (pp. 1-8)

Document status and date:
Published: 01/01/2014

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
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PERFORMANCE PREDICTION OF BUILDINGS WITH RESPONSIVE BUILDING ELEMENTS: CHALLENGES AND SOLUTIONS

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ABSTRACT

Modelling and simulation can play an important role for design support and product development of responsive building elements (RBEs). There is, however, limited guidance on how to model such adaptable construction elements in an appropriate way. This paper investigates two different strategies for representing the dynamic aspects of RBEs using whole-building performance simulation tools. Simulations are performed for two case studies: (i) a coating with variable emissivity/absorptivity properties, (ii) a storage wall with switchable insulation. The results show that a simplified simulation strategy is not always capable of accurately capturing the relevant physical phenomena in RBEs. Especially when thermal storage effects are involved, the adaptation needs to take place during simulation run-time, to prevent significant errors in the results.

INTRODUCTION

Traditionally, buildings have been designed as static objects. They provide shelter and protection, and once constructed, their main components usually do not change anymore. Recently, however, a new trend towards design and development of responsive building elements (RBEs) has been observed (Wigginton and Harris 2002; Heiselberg 2009). Such buildings try to take advantage of the variability in ambient conditions and occupants' requirements, by changing their shape or physical properties over time in response to these transient conditions.

Innovative materials and components such as switchable windows (Baetens et al. 2010), variable emissivity coatings (Agrawal and Loverme 2011; Karlessi et al. 2009) and dynamic insulation systems (Kimber et al. 2014; Burdajewicz et al. 2011) can now facilitate the design of dynamic facades (Loonen et al. 2013) or building constructions with adaptable thermal storage capacity (Hoes et al. 2011; Hoes et al. 2013). The application of such RBEs is gaining popularity because they can help realise energy savings, while maintaining high levels of indoor environmental quality. This makes them useful components for the design and operation of nearly zero energy buildings with comfortable indoor conditions.

Successful design of buildings with RBEs is, however, a challenging task. The performance of RBEs is very case-specific, and largely determined by dynamic interactions between building structure, occupants, weather conditions and HVAC systems. Prescription-based, traditional design methods, rules-of-thumb and simplified calculations have only limited value in supporting decision-making in the complex design process of buildings with RBEs. Dynamic simulations on the other hand are able to provide insights into building performance aspects of RBEs throughout the various stages of the building design process (Ochoa and Capeluto 2009; Andresen et al. 2009). Simulation-based support can also be a helpful tool in the product development process of innovative RBE concepts.

Currently, however, there is a lack of models for performance prediction of buildings with RBEs in most building performance simulation (BPS) software tools. Whereas extensive quality assurance procedures are in place for ensuring the accuracy and credibility of BPS predictions in general (Franconi 2011), there is hardly any guidance on such issues in the context of performance prediction of buildings with RBEs.

The aim of this paper is to develop a better understanding of different modelling approaches and their consequences in the context of RBEs. After an initial overview of the potential and current limitations of modelling and simulation for RBE, this is done by analysis of two different RBE case studies: (i) a building envelope construction with variable absorptivity and emissivity properties, and (ii) an internal wall with variable thermal storage by means of dynamic insulation.

MODELING AND SIMULATION OF RESPONSIVE BUILDING ELEMENTS

Most state-of-the-art building energy simulation (BES) tools (e.g. ESP-r, EnergyPlus, TRNSYS, IES-ve) are legacy software, which stem from a time when adaptability of building components was not a primary consideration (Ayres and Stamper 1995). The building's shape and thermophysical material properties in these tools are therefore usually not changeable over time. Some tools have application-oriented capabilities for modelling e.g. phase change materials or switchable windows, but in general, the options for performance prediction of buildings with RBEs are limited (Loonen 2010; Crawley et al. 2008). There are three main reasons for the present difficulties:

1. User interface. Input for constructions and material properties to BPS programs is normally given in the form of *scalar* values (typical exceptions are solar shading properties and window openings for natural ventilation, both of which can be *functions* or *time series*). This information is then processed once, prior to the actual simulation run, and is not updated in the simulation engine afterwards. Users of the (usually proprietary) simulation tools have limited flexibility to extend the functionality for modelling RBEs through the non-modifiable user interface.

2. Solution routines for energy balance equations. Many of the widely used methods for solving the differential equations in BES tools can only work with time-invariant parameters (Clarke 2001). For example, the Conduction Transfer Function method in TRNSYS' multi-zone building model is optimized for computational performance, but has shortcomings that prohibit modelling the transient aspects of modern construction types, such as phase change materials (Delcroix et al. 2012). EnergyPlus was recently extended with a new finite difference scheme for conduction, to allow for modelling temperature- or time-dependent material properties (Pedersen 2007; Tabares-Velasco and Griffith 2012). Practical use of these new algorithms is still limited, and its potential largely unexploited.

3. Control strategies. Most BES tools use simplified expressions for building systems control algorithms, and have a limited range of sensor and actuator options (Hoes et al. 2012). Advanced control is one of the major elements needed for performance assessment of RBEs. The lack of options is currently a significant barrier for performance prediction of advanced operation strategies with RBE as time-varying actuators.

Despite the limitations in existing software tools, researchers and engineers have developed numerous customized simulation strategies for predicting the performance of RBEs in whole-building performance simulation programs (Loonen et al. 2010). So far, most of these attempts have used workarounds, which tend to rely on approximations or simplifications.

The simplest approach for representing RBEs is by subdividing the year into smaller periods (e.g. seasons), each with distinct building properties (Joe et al. 2013; Hoes et al. 2011; Loonen et al. 2011). The downside of this approach is that the correctness of thermal history effects cannot be guaranteed due to the absence of methods for explicit state initialization (Hoes et al. 2012). With short-term adaptation cycles (e.g. hours), in particular, this can lead to significant prediction errors, as it would almost defeat the purpose of dynamic simulations. The approach is also limited for implementing feedback-based control strategies, which cannot be calculated a priori but depend on simulation variables.

A second approach uses separate models to represent different states of the RBE. For example, DeForest et al. (2013) used simulations to predict the performance of smart windows that switch optical properties in the infrared wavelength range. The lack of capabilities to model the behaviour of the window in COMFEN was circumvented by running two separate annual simulations with static window properties (a reflecting and a normal state), and reassembling them in the post-processing phase to resemble dynamic switching. This method captures switching of instantaneous solar gains, but fails to account for effects of delayed thermal response due to capacitance. Using a similar technique in cases where thermal mass is involved in RBE operation, without respecting transient thermal energy storage effects during their transitions, would probably lead to significant errors in the results (Erickson 2013). The discrete nature of this method also introduces problems in modelling RBEs with intermediate states, and hysteresis effects during transitions. These inaccuracies may eventually compromise decision-making based on simulation outcomes, but little is known about these effects. One of the goals of this paper is to quantify such effects, by contrasting the simplified approach to one that more closely resembles reality by updating RBE operation within a simulation. This latter approach is done using ESP-r (Clarke 2001).

RESPONSIVE BUILDING ELEMENTS IN ESP-r

Similar to other simulation tools, ESP-r, by default, assumes constructions with time-invariant properties. However, the finite difference control-volume approach that forms the numerical foundation of ESP-r does not pose fundamental limitations for making the properties vary with time. ESP-r's modular structure and open source distribution moreover enables users to accomplish this with relatively few code modifications.

The implementation that is used in the present research reuses existing features from the *variable thermophysical properties* and *material property substitution* facilities which were developed two decades ago (Nakhi 1995; MacQueen 1997).

The key difference with normal ESP-r is that in this implementation, not only such factors as incident solar radiation, internal gains and ventilation exchange, but also nodal coefficients of equations in the transient heat conduction model are updated at every time-step of the simulation. These coefficients, contained in subroutine `MZCOE1`, are used to establish the building-side matrix equations. For reasons of computational efficiency, this is normally only done at the beginning of each simulation, but here we extended this capability using simulation control subroutine `MZNUMA` to recalculate at any desired time step. The change of dynamic construction properties is controlled by user-defined expressions in the Fortran code, and can for example be based on (i) time, (ii) external boundary conditions (e.g. incident radiation), (iii) simulation variables (e.g. surface temperature), or (iv) signals received from the Buildings Control Virtual Test Bed (BCVTB) (Wetter, 2011; Hoes et al. 2012).

CASE STUDY DESCRIPTION

In this paper, we simulate the building performance of two RBE concepts using a simplified modelling approach and a more advanced modelling approach. For each RBE concept, we compare the simulated building performance of both modelling approaches to quantify the effect of the modelling approach.

We investigated the following two RBE concepts: building elements with thermotropic coatings (Case 1) and building elements with switchable thermal insulation (Case 2). We applied these two RBE concepts to a residential case study building, located in the Netherlands. The case study building consists of five zones (Figure 1): a living space (zone A, south facing) and a kitchen (zone B, north orientated) on the ground floor, and two bedrooms and a study room (zone C and D, south orientated and zone E, north orientated) on the first floor. The north and south façades consist of large (identical sized) windows. The south façade has an external shading device (horizontal venetian blinds). The external walls and roof constructions have R_c values of 5 m^2K/W; the windows have U-values of 1.1 W/m^2K. The building has a balanced mechanical ventilation system. The temperature set points are 21^oC for an occupied house and 14^oC for when the house is not occupied. No mechanical cooling is available in the building.

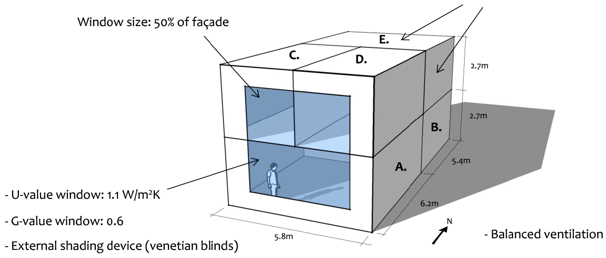


Figure 1: Geometry of the case study building with several building characteristics. Facing the south façade.

Performance indicators

We used two performance indicators to assess the building's performance: energy use for heating and thermal comfort.

The first indicator, the heating energy use, is based on the calculated heating energy demand by ESP-r. The energy use by the heating system is calculated using the following efficiency factors: for heat generation $\eta_{generation} = 0.95$, heat distribution $\eta_{distribution} = 1.0$ (no losses since it is assumed that the heat distribution takes place within the thermal zone) and heat supply $\eta_{supply} = 0.95$. The second indicator, the weighted discomfort hours (wPPDhrs), is based on the calculated average PPD for each hour. Each hour with a $PPD > PPD_{limit}$ is regarded as discomfort hour and weighted with the factor PPD/PDD_{limit}. The PPD_{limit} is set to 10%, following climate category B of NEN-ISO 7730. In the calculation of the PMV/PPD, we assumed that people in their own homes have a stronger tendency to change their clothing to reach their preferred comfort level than in offices and other public spaces. Therefore, defining a fixed clothing (clo) value in the PMV/PPD equation for winter and summer is not realistic. We defined, instead, an upper and a lower limit for the clo-value per season, resulting in a bandwidth of acceptable temperatures.

The next sections describe the results for each case in detail.

CASE 1 – SURFACE COATING WITH SWITCHABLE PROPERTIES

Introduction

Properties of the interior and exterior finishing of building envelope constructions have a large impact on the building's overall energy balance and thermal comfort conditions. Although c*ool materials*, with high solar reflectance and high thermal emissivity are considered a good strategy for reducing cooling load and mitigating the urban heat island effect, they may also increase energy demand in the heating season (Synnefa et al. 2007). Thermotropic coatings, which can change the surface properties of a material depending on temperature, are therefore regarded as a promising alternative (Karlessi et al. 2009). At low temperatures, the thermotropic layer absorbs most of the incoming solar radiation, whereas at high temperatures, the coating helps reduce cooling load via reflection and enhanced longwave radiation exchange. Different thermotropic technologies are currently under development, but most of them are still in the earlier phases of the innovation process (Agrawal and Loverme 2011; Bergeron et al. 2008).

Several variables influence the potential performance of thermotropic coatings, such as: spectral selectivity (shortwave/longwave), switching temperature, application surfaces (inside/outside), thermal resistance of the construction, weather conditions, etc. BPS is a powerful tool to investigate the impact of these interrelated effects, and can be useful for giving direction in the product development process of new materials.

This demonstration example focuses on the applicability and credibility of different simulation methods, but also presents an assessment of thermotropic coatings with different switching temperatures and responsive wavelength ranges.

Methodology

In this case study, we investigated two types of thermotropic coatings, by changing:

I Solar absorptivity (α) (λ: 0.28 – 2.8 µm)
II Thermal longwave emissivity (ε) (λ > 3 µm)

Because the variability of these properties has an influence on different energy flow paths, we expect that they will lead to different performance.

The coating is modelled to switch instantaneously, but only one of the properties at a time. This means that when the case with variable absorptivity is investigated, the value for emissivity is left in the default state. Table 1 shows the material properties that were analysed. Unless noted otherwise, the threshold surface temperature for switching states is 20°C. Depending on the application area, the coating is applied to all opaque interior or exterior surfaces.

We investigated two modelling strategies, (A) discontinuous, where the behaviour of the coating is approximated by two simulation runs with fixed properties, and (B) run-time, where changes are implemented during the course of one simulation.

Table 1: Material properties thermotropic coating.

	Low	High	Default
Absorptivity (α)	0.3	0.7	0.65
Emissivity (ε)	0.3	0.9	0.84

Results – outdoor application

Figure 2 shows the surface temperature of the exterior roof layer for three days in summer (4-6 July). In the situation with fixed high absorptance (dashed line), higher temperatures are reached than is the case for fixed low absorptance (solid black line). Temperature of the thermotropic coating closely follows one of the two states with static properties around the switching point of 20°C.

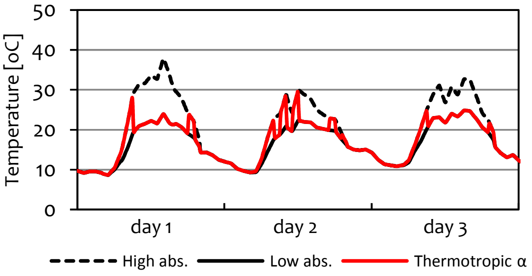


Figure 2: Exterior surface temperature. Thermotropic α coating and fixed low and high absorptivity, (4-6 July).

The same type of behaviour is observed in the results with variable emissivity (Figure 3, period: 30 Aug.–1 Sep.). In this situation, a temperature difference between the high and low case is not only present during the day, but also at night when the radiant heat transfer coefficient from the roof to the sky and surroundings differs with emissivity.

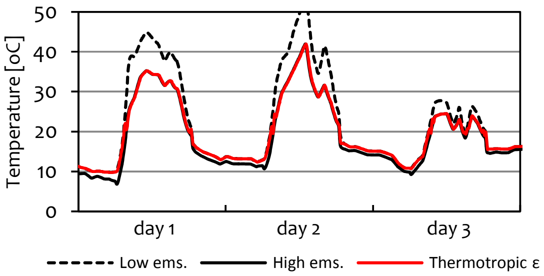


Figure 3: Exterior surface temperature. Thermotropic ε coating and fixed low and high emissivity, (30 Aug-1 Sep).

To evaluate the effect of different modelling strategies, a comparison of heating energy consumption and thermal comfort, predicted by the two methods is presented in Table 2. The differences in heating energy consumption are very small (less than three percent). The difference in discomfort hours is also negligible. Use of the simplified, discontinuous, modelling approach in this case could therefore be justified, because the predicted difference will likely not lead to a different design decision.

This result is not unexpected because the coating is applied outside of the thermal insulation layer. Therefore, temperature changes immediately follow switching actions, because almost no thermal energy is stored in the construction.

Table 2: Comparison of results for the two modelling approaches (discontinuous and run-time).

	Discont.	Run-time
Heating Energy (kWh)		
Thermotropic α	2492	2525
Thermotropic ε	2321	2393
Thermal Comfort (wPPDh)		
Thermotropic α	65	67
Thermotropic ε	74	76

In Figure 4, we compare the results of coating designs other than the two from Table 2. Open squares and triangles represent cases with fixed surface absorptivity and emissivity, respectively. From left to right, the results move from 0.9 to 0.1 (absorptivity) and 0.1 to 0.9 (emissivity) in increments of 0.1. Results in purple and blue indicate thermotropic coatings α and ε, and show that dynamic properties can always perform better than the best static design solutions. The colour tints indicate the switching temperature from 0°C (dark) to 50°C (bright) in steps of 10°C. By tuning this parameter in the materials development phase, it is possible to establish a clear effect on the energy versus comfort trade-off. In future research, the effects of tuning coating specifications could be investigated in response to a wider range of specific design conditions.

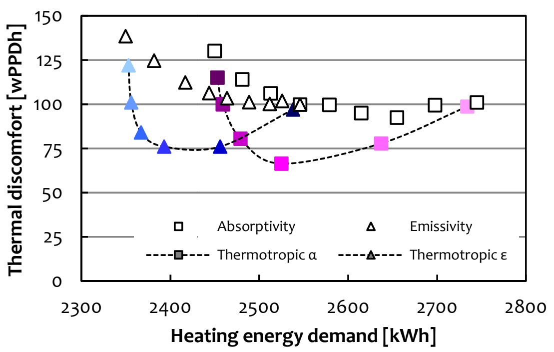


Figure 4: Annual performance comparison of different coating designs. Exterior application.

Results – indoor application

Thermotropic coatings are not only applied to the exterior surfaces of buildings, but can also be useful for indoor applications, especially to control the release of energy to/from constructions with thermal mass. Figure 5 shows the indoor surface temperature for the case with an internal thermotropic emissivity coating for the period 7-10 March. In contrast to the exterior application, the thermotropic coating is in direct contact with materials that have high thermal storage capacity. Because the switching of surface properties in this case significantly influences the thermal history of the construction, there is hardly any overlap with any of the two static surface temperature curves. In terms of surface temperature, the thermotropic coating is therefore not well-represented by either one of the static cases. A discontinuous modelling approach would therefore not lead to reliable results.

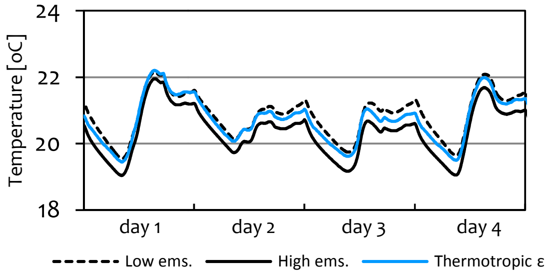


Figure 5: Interior surface temperature. Thermotropic ε coating and fixed low and high emissivity, (7-10 Mar).

Figure 6 shows that the thermal mass phenomenon can even lead to more unexpected effects (27-29 April). In several periods in this interval, the temperature of the thermotropic layer rises higher than what would have happened in the static case. The exact reason for such effects is hard to identify, but comes from multimode heat transfer effects, including non-linearities of longwave heat transfer and convection regimes. It also depends on whether the construction is already charged with energy, relative to its surroundings and heating system operation.

This effect is not reproducible with discontinuous simulations. Only when adaptation of construction properties takes place during simulation run-time, it is possible to analyse and quantify the impacts of this effect.

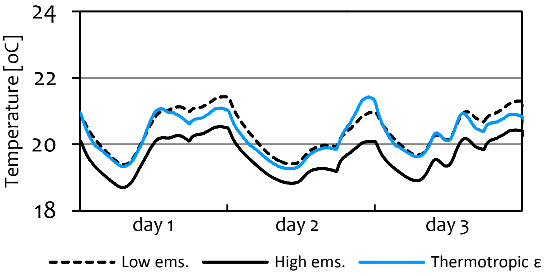


Figure 6: Interior surface temperature. Thermotropic ε coating and fixed low and high emissivity, (27-29 Apr).

CASE 2 - STORAGE WALL WITH SWITCHABLE INSULATION

Introduction

The thermal mass of a building has a strong influence on the building's heating energy demand and level of thermal comfort. Hoes et al. (2011) show that the optimal thermal mass of a building changes during the year depending on the seasons and occupant behaviour. Therefore, they investigated the potential of concepts that enable the building to change its thermal mass by using adaptable thermal storage concepts (Hoes et al. 2013). In this section, such a concept is further investigated. The concept consists of a concrete storage wall with an interface construction of a dynamic thermal insulation layer and a coated metal sheet (Figure 7). The *dynamic insulation* layer is able to switch between states of low and high conductivity, thus thermally *coupling* or *decoupling* the storage wall from the room. The dynamic insulation layer is applied on the inside face of the west and east walls and of the partition walls between the rooms.

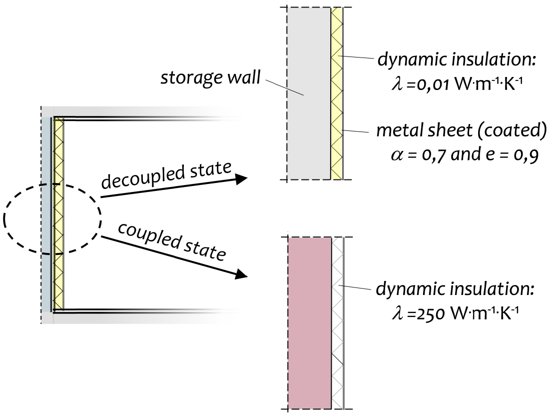


Figure 7: Schematic representation of the wall with dynamic thermal insulation in decoupled state (top) and coupled state (bottom).

Several researchers have investigated dynamic insulation concepts. For example, Chun and Chen (2002) and Rylewski (2005) propose bi-directional thermodiodes (based on the thermosyphon effect), which make it possible to change the direction of heat transfer in a construction from conducting to insulating. This makes it possible to direct the heat flow to the wall during a summer day and reverse the heat flow when the stored energy is needed in the building. Al-Nimr et al. (2009) propose a 'smart insulation' system based on fluids and a movable partition. Another dynamic system is the 'switchable insulation' proposed by Horn et al. (2000). Their system changes the thermal conductivity by using a metal hydride to change the pressure of hydrogen gas inside a panel. They show that the conductivity of the panel can be changed by about a factor of 50.

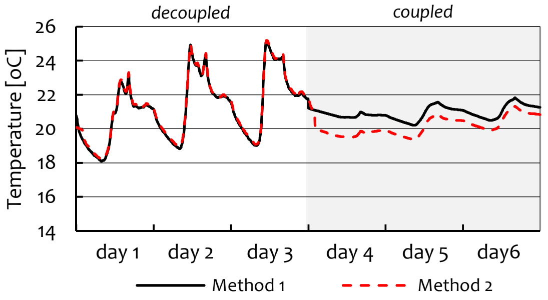
Methodology

In this case study, we investigated two modelling strategies, method 1, discontinuous (*cut 'n paste*), where the behaviour of the dynamic insulation is approximated by two simulation runs with a fixed insulation state (*coupled* or *decoupled*), and method 2, *run-time*, where the insulation material is changed during the simulation. One full month (October) is simulated to investigate the differences between both methods. Every three days the wall changes from insulation state without time delay. The simulation time step is 10 minutes.

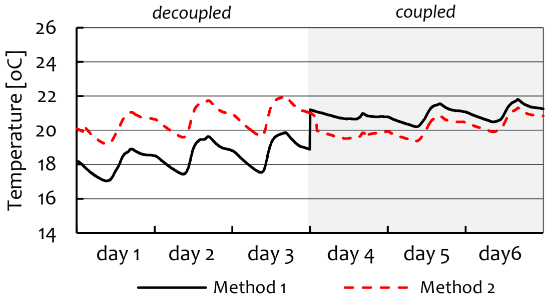
Results

Figure 8 shows the simulated surface temperatures of the partition wall in zone A for the fixed insulation states (coupled and decoupled). The coupled state (insulation layer with high conductivity; thin solid line) shows less temperature fluctuations than the decoupled state (insulation layer with low conductivity; thin dashed line), since the concrete wall is able to store the solar gains and other internal gains. As mentioned, for method 1 and 2, every three days the wall switches to the other insulation state. In Figure 8, the state of the dynamic insulation is indicated with different shades: grey shade indicates the coupled state and no shade indicates the decoupled state. Method 1 (*cut 'n paste*) is composed of the results for the fixed insulation states and thus matches those lines exactly. This is not the case for method 2 in which the history effect of the storage capacity is taken into account. The influence of this history effect is clear from the graphs in Figure 9. The graphs show the temperatures of the construction layers in the partition wall for a period of 6 days (indicated with the dashed box in Figure 8).

Temperature; surface:



Temperature; insulation material:



Temperature; storage wall:

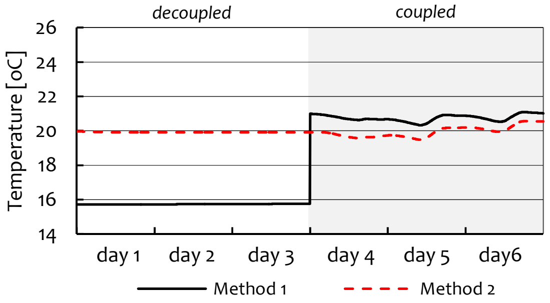


Figure 9: Surface temperature and construction temperatures of the partition wall with dynamic insulation.

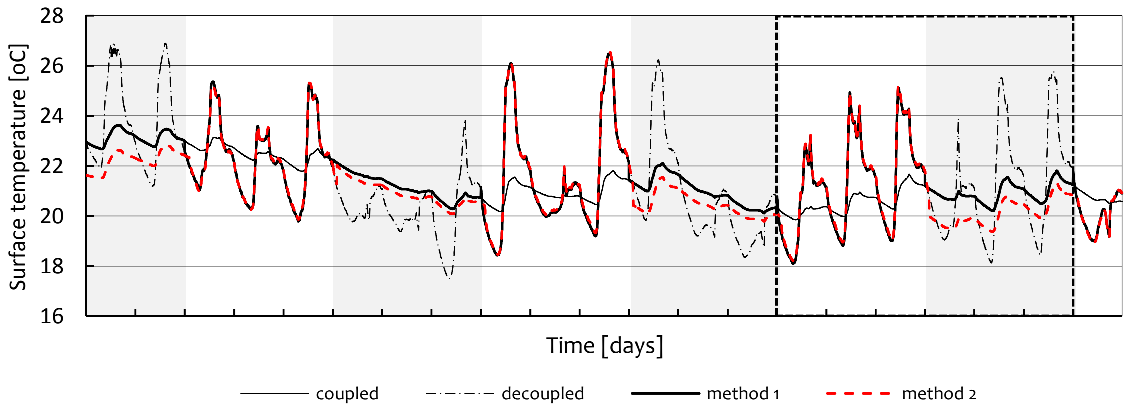


Figure 8: Surface temperature of partition wall (zone A) for coupled sequence, decoupled sequence, method 1(cut 'n paste; grey background indicates 'coupled', white background indicates 'decoupled') and method 2 (advanced). Simulation period: 16-31 October; the dashed box indicates the six days which are analysed in detail in Figure 9.

The bottom graph of Figure 9 shows, for method 1, a clear jump in the temperature of the storage wall during the switch from decoupled to the coupled state. This jump is not visible for method 2. It is clear that this jump might cause differences in the simulated performance indicators between the two methods. We investigated the potential effect of this on the energy use for heating (no discomfort occurred during this month). Figure 10 shows the cumulative heating energy use for method 1 and method 2 for the whole month; indicating a 27% difference between the two methods towards the end. Depending on the number of switches and the amount of energy stored during each state, this difference will likely grow. It is safe to assume that method 2 results in more accurate results since history effects are taken into account.

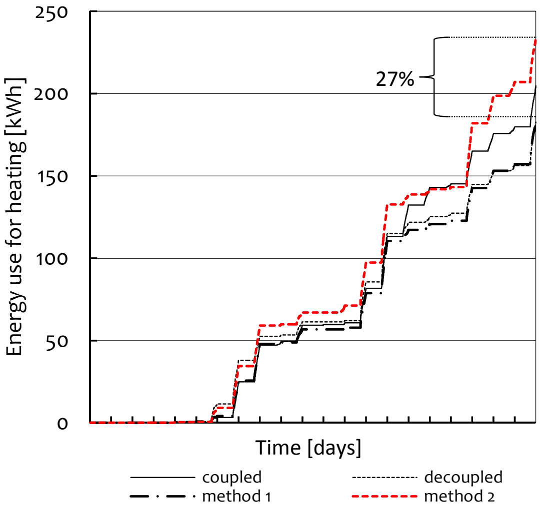


Figure 10: Cumulative heating energy for the simulation period (16-31 October); a difference of 27% is observed between method 1 (cut 'n paste) and method 2 (run-time).

CONCLUSIONS

This paper has introduced the current limitations and highlighted some potential advantages of more widespread use of modelling and simulation to support informed decision-making in the design of buildings with responsive building elements (RBE). We have analysed two simulation strategies to represent RBE in whole-building simulation tools. The simple, discontinuous approach combines the results from separate simulation runs with fixed properties. The more advanced run-time approach, on the other hand, effectively models state transitions during one simulation, but required code modifications, and is less user-friendly. With respect to these different modelling approaches, this paper has shown that:

- Thermal mass has a big influence on the proper selection of performance prediction strategies for RBEs.
- In cases where RBE operation is decoupled from thermal storage (e.g. exterior coatings with varying surface properties), a decoupled simulation approach is adequate.
- When the RBE operation does affect the amount of energy stored in the thermal mass (e.g. storage walls with switchable insulation), these dynamic effects have to be taken into account during simulation run-time.
- The simplified approach is not always able to capture all heat transfer phenomena during RBE state transitions.
- Choosing a non-appropriate simulation strategy can lead to significant prediction errors that, in turn, can result in sub-optimal design decisions.

ACKNOWLEDGEMENTS

This research was carried out under the project number M81.1.08319 in the framework of the Research Program of the Materials innovation institute (M2i) and under the project FACET in the framework of Agentschap-NL EOS-lt.

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