Dynamic Insulation
as a strategy for Net-Zero Energy Buildings

Master thesis
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Abstract

The current focus when it comes to size thermal insulation systems is to reach the highest insulation level as possible. Although, this can bring severe overheating problems that need to be solved. This way, dynamic insulation elements appear as a possible solution to this problem as they allow to have an adaptive range of their thermophysical properties, such as thermal conductivity, instead of a static value registered on the conventional insulation systems. Additionally, there are several different materials and systems, with different mechanisms of control and resultant adaptive ranges, that can be used as dynamic insulation elements. Nowadays, in terms of simulation framework, the best software to do this analysis is EnergyPlus, which offers two approaches to predict the performance of dynamic insulation elements: MovableInsulation Actuator and Surface Construction State Actuator (on EMS). After doing a comparison between these two approaches, the second one is the most promising, but due to limitations regarding implementation details, it was not used for the case-study analysis. By using the MovableInsulation Actuator in the case study analysis, for the climate of Lisbon, Portugal, it was concluded that the application of a removable insulation layer (10 cm of EPS), with a proper control strategy, can achieve almost 60% decrease on overheating hours and more than 22% of decrease on the cooling energy demand. Although some of the details of how to assess the dynamic insulation elements become more clear throughout this analysis, there is much more work and research that needs to be done to accelerate the product development and technology implementation of these systems.
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I – Introduction

I.1 – Context about Net-Zero Energy Buildings

Nowadays, in Europe, energy consumption in buildings accounts for around 40% of total primary energy demand and 36% of total greenhouse gases (GHG) emissions (Wehringer et al., 2014). This way, the ‘buildings sector’ has been acknowledge by the European Union (EU) has having a significant potential regarding energy savings (and consequently in GHG emissions) not only in the construction of new buildings but also in the refurbishment of existent ones. This sector is central not only to achieve the EU 20/20/20 targets but also to meet the long term goals defined in the low carbon economy roadmap 2050 (Wehringer et al., 2014). Thereby, the most important action was to launch several regulations to converge the built environment to the concept of Net-Zero Energy Buildings (NZEB). The main legislative document at EU level with the goal to increase the energy efficiency in buildings is the Energy Performance of Buildings Directive – Recast (EPBD Recast, 2010/31/EU), which sets that by 31 December 2020, all new buildings must be nearly-Zero Energy Buildings (nZEB) (EU, 2010).

This NZEB concept is based on covering the energy demand through renewable energy sources (RES), produced on-site or nearby (EU, 2010). However, first it is mandatory to achieve significant savings at the consumption level, applying energy efficiency measures to reduce energy demand. This is the first, and the most important step on the path towards NZEB because it would be financially impossible to cover all the demand just by setting up a massive installed power of renewable energy sources to equal the consumption (Voss, Sartori, & Lollini, 2012). Although, there is a great need to improve buildings performance to meet the requirements of this directive, as a very large percentage of European buildings does not comply with it. Therefore, it is clear that further increasing the energy efficiency in the building envelope elements is of great importance to achieve the Net-Zero Energy concept and develop a whole new generation of buildings in the urban context (U.S. Department of Energy, 2015).

I.2 – Motivation for the application of Dynamic Insulation

The current focus throughout EU national building regulations is on having higher thermal insulation levels and increased air tightness, in order to reduce energy consumption. (IEA, 2013). Despite the fact that having a static higher insulation level will contribute to lower the heat losses from buildings in winter, it will also restrain heat flow across the wall when this is potentially beneficial. An example of that is during nighttime hours in
summer, when it is useful to extract the unwanted heat gains, resultant of internal loads and solar gains through the windows, that were accumulated in the building compartments during the day. Highly insulated dwellings have increased risk of experiencing severe overheating problems, as internal temperature responds more rapidly to the increase of solar and internal gains (Toledo, Cropper, & Wright, 2016).

To avoid overheating, façade elements with switchable U-value could be a possible solution, which would allow to ‘switch off’ the thermal insulation during nighttime in summer (Park, Srubar, & Krarti, 2015a; Pflug et al., 2014). A low U-value would help to keep the heat loads indoors when heating is needed while a high U-value would allow cooling the building when the outdoor temperature is lower than the indoor temperature (Berge, Hagentoft, Wahlgren, & Adl-zarrabi, 2015). To address this, dynamic/adaptive insulation solutions are interesting alternatives to the regular one-dimensional way of only adding more insulation and improving air tightness. This concept can be applied on either in opaque or translucent elements, but the focus of this project will be on the opaque façade. The application of dynamic insulation elements fits into the concept of adaptive façades. This has been seen as a breakthrough approach, not only contributing to improve the energy flexibility of the buildings but also as a way of improving the indoor environment quality for its occupants (Loonen, Favoino, Hensen, & Overend, 2016).

I.3 – Role of the BPS tools

Nowadays, there is a need to assess the performance, to support and accelerate the implementation of these adaptive elements. To do so, Building Performance Simulation (BPS) tools play a major role in the process, as they allow to assess different design and control strategies that maximize building’s performance and support product development (Clarke & Hensen, 2015). However, the application of BPS to study the performance of these elements when integrated at a building level has not been sufficiently explored to reach a point where it is possible to have a clear level of understanding about what are the most important aspects in which the simulation strategy should focus on (Jin, Favoino, & Overend, 2015). The fact that information available on this subject is limited and dispersed, and that current simulation tools were not originally developed for this purpose states a big challenge for a successful design of adaptive façades and leaves limited guidance to the BPS users (Loonen et al., 2016). Loonen et al. (2016) identified that in comparison to conventional static façades, there are two important additional requirements when it is needed to predict the performance of adaptive façade systems: modelling the time varying façade properties and the dynamic operation of façade adaptation.

I.4 – Research goals/Structure of the report

In order to support product development, there is a need to use thermal simulation to better understand how these systems work and how can we optimize them. In addition, it is important to first understand which materials/systems can be integrated at the building level to achieve an adaptive/responsive behavior. Hence, the first goal of the project is to assemble a database of elements which are or can act as dynamic insulation elements, as described in Chapter 2. Furthermore, the next goal is to develop appropriate approaches to predict the performance of dynamic insulation elements. In Chapter 3 those are described and compared, and some preliminary results regarding their use are presented as well. The following goal is to provide insights into the whole-building level performance of dynamic insulation systems. This way, in Chapter 4 an illustrative case study applied to the climate of Lisbon is described where the approaches referred in the previous chapter are applied. Finally, the last goal is to give recommendations for product development and future work. This will be referred in Chapter 5 whereas the main conclusions of the project are outlined.
II – State-of-the-art overview

II.1 – Background

Over the years, several different thermal insulation materials have been developed with the purpose of thermally isolate the inside and outside environments at the building level. The ultimate goal is to achieve significant energy savings while maintaining high levels of indoor thermal comfort. When it comes to select a certain insulation material, the focus is to achieve the highest possible thermal insulation values by picking the ones that have higher thermal resistances. This means materials with lower thermal conductivity in order to reach as low thermal transmittance (U-value) as possible on the building’s façade.

Nowadays, there are numerous static insulation materials that can be applied, from traditional/conventional to state-of-the-art (high-performance) thermal insulation whereas the latter exhibit significantly lower values of thermal conductivity. Current conventional insulation materials such as mineral wool, expanded or extruded polystyrene (EPS, XPS), cellulose, cork and polyurethane (PUR) have relatively high thermal conductivities values, ranging from 20 to 50 mW/(m.K). Although, this range can vary in regard with moisture content, mass density, temperature and possible perforation of the materials (Jelle, 2011; Park, Srubar, & Krarti, 2015b).

To decrease the U-value of the façade without ever increasing the thickness of the insulation layer, new high-performance insulation materials have been developed, which could achieve the lowest thermal conductivity values up-to-date. Vacuum insulation panels (VIP) and aerogels, are examples of some of the solutions that can be applied currently, which can reach values of conductivity as low as 3 mW/(m.K). There are also some future materials and solutions that are being researched such as vacuum insulation materials (VIM), gas insulation materials (GIM) and nano insulation materials (NIM), with an overall thermal conductivity of less than 4 mW/(m.K).

Apart from the solutions previously referred, there is also a relatively new concept that can offer thermal insulation features: phase-change materials (PCM). As the name implies, these materials change from solid state to liquid state when heated, absorbing energy (endothermic process), and from liquid to solid when the temperature drops releasing energy (exothermic process) (Jelle, 2011). Although they are not seen as thermal insulation materials, they can be used for interesting thermal building applications, either being used as separated components in building constructions or impregnated directly into building materials. They make use of the thermal mass to reduce fluctuations in air temperature shifting the cooling loads towards off-peak periods, offering the possibility to store both sensible and latent heat (Sage-Lauck & Sailor, 2014).

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>40-50 mW/(m.K)</td>
</tr>
<tr>
<td>Cork</td>
<td></td>
</tr>
<tr>
<td>Mineral Wool</td>
<td></td>
</tr>
<tr>
<td>Expanded Polystyrene (EPS)</td>
<td>30-40 mW/(m.K)</td>
</tr>
<tr>
<td>Extruded Polystyrene (XPS)</td>
<td></td>
</tr>
<tr>
<td>Polyurethane (PUR)</td>
<td>20-30 mW/(m.K)</td>
</tr>
<tr>
<td>Aerogels</td>
<td>13-14 mW/(m.K)</td>
</tr>
<tr>
<td>Vacuum Insulation Panels (VIP)</td>
<td>3-4 mW/(m.K)</td>
</tr>
<tr>
<td>Vacuum Insulation Materials (VIM)</td>
<td></td>
</tr>
<tr>
<td>Gas Insulation Materials (GIM)</td>
<td>&lt; 4 mW/(m.K)</td>
</tr>
<tr>
<td>Nano Insulation Materials (GIM)</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 - Comparison between traditional and state-of-the-art insulation materials (Jelle, 2011)
However, as introduced in chapter 1, the ideal scenario is to have thermal insulation solutions that not only are able to achieve the lowest thermal conductivity values as possible, but also provide the possibility to control it within a desirable range; thus, it would be possible to control the heat flow through the façade depending on the indoor-outdoor temperature difference (Jin et al., 2015).

II.2 – Dynamic Insulation Solutions

In comparison with the static insulation, dynamic insulation elements can exhibit changeable thermal parameters, such as thermal conductivity and emissivity. These allow buildings’ façades to be responsive elements regarding the surrounding thermal environment. In addition, Loonen et al. (2014) showed that dynamic insulation elements can also be used to achieve variable thermal storage by coupling or decoupling a storage wall from a compartment, as the dynamic insulation layer is able to change between states of low and high conductivity (Loonen, Hoes, & Hensen, 2014).

In this subchapter, several insulation elements are described and classified according to the mechanism used to achieve a dynamic behavior and scale of actuation. In the first place, when the main heat transfer process is convection through air or liquid, the level of actuation is at a macro-scale. On the other hand, when the control is based on controlling the heat conduction by varying the pressure of a gas, changing the path of the gas molecules or its interaction with surface of the insulation panel, the level of actuation is at a micro/nano-scale (Jin et al., 2015). Finally, a movable insulation system is described.

II.2.1 - Macro-scale actuation

This concept is not new, with research dating back to the 1970s and several definitions available from literature. It can be used either in place or in tandem with conventional insulation (Imbabi, 2012). Most of the macro-scale applications for dynamic insulation are achieved by incorporating in the façade a system based on heat convection either through air or liquid, to control the heat transfer (Jin et al., 2015).

II.2.1.1 – Systems based on heat convection through air to control the heat transfer

1 - One of the generic definitions of them is given by Arquis and Langlais, who set that there are three types of generic dynamic insulation systems that can be applied in buildings: parietodynamic, permeodynamic, and thermodynamic insulation (Arquis & Langlais, 1986).

Parietodynamic insulation elements have a channel where the air flow is confined, surrounded by materials impermeable to the airflow. The cold air supplied from outside preheats, by circulating on a cavity within the wall, before entering inside the building, reusing the exhaust air from indoors as a heat exchanger (Elsarrag, Al-Horr, & Imbabi, 2012). This is somewhat similar to a ventilated façade. An example of this insulation solution is called Void Space Dynamic Insulation (VSDI) which can achieve a range of U-values between an average of 0.092 W/m².K in open mode and 0.20 W/m².K in static ‘no airflow’ mode (Imbabi, 2012).
In the case of the permeodynamic insulation (or breathing wall), there is an air porous panel that works as a cross-flow heat-exchanger, with a controllable airflow between inside and outside environments (Fantucci, Serra, & Perino, 2015; Imbabi, 2006). The U-value is a function of the air-flow.

Finally, on the thermodynamic insulation, despite being similar to the permeodynamic, the air circulates in a closed circuit and a separate heat exchanger is necessary.

2 - Pflug et al (2014), proposed and studied a translucent dynamic insulation system denominated FESU (façade element with switchable insulation), which consists on a closed model with one or various insulation panels, where the convection is controlled (Pflug et al., 2014). This element can be in two states, insulating or conduction state (Figure 5).

When it is in insulating state, the translucent panel is at the top avoiding the convection around the panel, existing this way three insulating layers (two of air and one insulation panel). On the other hand, when the system is in conducting state, the panel is a vertical middle position and there is convection around the panel due to a driving pressure difference between the back and front, allowing the heat transfer through the wall. There is a U-value range between 0.7-1.9 W/m².K, depending on the difference of temperatures between indoors and outdoors.
II.2.1.2 – Systems based on heat convection through liquids

There are several systems that use water or other working liquids to control the heat transfer through the buildings' façade. This is not a new concept, with related systems dated back to the 1980s.

1 - Dijk et al. developed a ‘High Performance Passive Solar Heating System’ which allowed not only to transfer the collected solar heat through heat pipes but also to store it in a latent heat storage section. These heat pipes, incorporated on the insulation layer act as thermal diodes, transferring the heat from the collector to the back of the insulation layer but not doing it in the reverse direction. Regarding the latent heat storage, it can be achieved either with a storage section of phase-change materials or water (Dijk, Galen, Hensen, & Wit, 1983).

2 - Numerous researchers have studied and proposed the application of bi-directional thermodiodes (Chun et al., 2009; Chun, Chen, & Kim, 2002; Rylewski, 2005; Varga, Oliveira, & Afonso, 2002). In parallel with the concept of electric diodes, these systems establish a favorable direction of the heat flow, providing insulation on the other direction, with a principle of functioning based on the thermosyphon effect. This allows, for instance, to direct the heat flow to the wall during a warm day and work in the reversed direction when the stored energy in the system is need indoors.

Varga et al. (2002) also tested bi-directional thermodiode panels incorporating heat pipes and obtained a range of apparent conductivities between 0.07 W/m.K in backward mode and a maximum of 0.35 W/m.K in forward mode (being this last one between three to five times higher than in backward mode depending on the temperature difference) (Varga et al., 2002).
3 – Al-Nimr et al. (2009) designed a different solution to what they denominated by a ‘smart thermal insulation system’. The principle of functioning of this system is based on the idea of filling a gap inside a slab wall with rather a very low conductivity fluid (e.g. argon with \( k = 0.0179 \) W/m.K) when it’s needed to provide a good insulation or a very high conductivity fluid (e.g. water with \( k = 0.64 \) W/m.K) when the system is required to be a conductor. As displayed in Figure 9, there is two storage tanks separated by a movable partition which moves to the left or to right depending on the driving forces. When there is a need to have a system in insulating mode, the partition moves to the left in order to fill the gap with the low \( k \) fluid from the storage tank on the right. When the system needs to be in conduction state, it works the other way around, with the movable partition moving to the right (Al-Nimr, Asfar, & Abbadi, 2009).

![Figure 9 - Basic sketch of the smart thermal insulation system (1), in the insulating mode (2) and in the conduction mode (3). Change between modes is achieved via a movable partition on the slab wall (Al-Nimr et al., 2009)](image)

**II.2.1.3 – Active Insulation System**

The Dutch company P&H Advisors proposed the concept of Active Insulation, which has the possibility to turn the insulation between an ‘on’ and ‘off’ functions (KIC InnoEnergy, 2015; P&D Adviseurs, 2015).

![Figure 10 - Principle of functioning of Active Insulation (P&D Adviseurs, 2015)](image)

A structure of air ducts is placed from the top to the bottom on both sides of a convectional hard insulation board. Inside them, two low voltage ventilators are placed, on the top and bottom of the board, to induce forced ventilation which will allow for heat or cold to flow from outside to inside, or the other way around (KIC InnoEnergy, 2015; P&D Adviseurs, 2015). This way, a short circuit is created between the two zones around the system bypassing the actual insulation board. When the sun hits the outside wall, the air inside the ducts gets warmer. If heating is desirable, this air can be pumped by the ventilators towards the inner side of the insulation. For cooling is the other way around. Whenever the ventilator is switched on, the insulation board is turned off and vice-versa. If the ventilators were driven by a temperature sensor, the insulation could become an active element of heating and cooling building systems.
II.2.2 – Micro/Nano-scale actuation

Different approaches have been given either at a micro or nano scale to achieve dynamic insulation level. These solutions control thermal conduction by selecting different strategies: by varying gas pressure, the mean free path of gas molecules or gas-surface interaction in an insulation panel (Jin et al., 2015).

II.2.2.1 – Systems based on varying the pressure of a certain gas to control conduction

1 - This is a concept is not new, having been researched by Xenophou (1976) who submitted a patent about a system which controlled the thermal transfer by regulating the pressure of a partial vacuum between spaced steel panels which form a wall structure. By increasing the pressure of the vacuum, it was possible to decrease the heat flux through the walls, maintaining the ambient temperature in the structure (and the other way around) (Xenophou, 1976).

2 - Benson (1994) studied a variable-conductance vacuum insulation (VCI) material. In this insulation material, there is a small metal hydride connected to the vacuum envelope which reversibly absorbs/desorbs hydrogen, changing its pressure within a range from less than 10⁻⁶ to as much as 1 torr (1 torr ≃ 133.3 Pa), which allow to achieve a variable thermal transmittance (Benson, Potter, & Tracy, 1994).

3 – Horn et al. (2000) designed a switchable insulation system similar to the one developed by Benson. By using a metal hydride to change the pressure of hydrogen gas inside a panel, it is possible to reversibly change the thermal conductivity between 0.14 W/m.K in the conducting state and 0.003 W/m.K on the insulating state (Horn et al., 2000; Horn, Hetfleisch, & Stark, 2003).

Figure 11 - Variation of the thermal conductance through the 20 mm thickness of a VCI panel as a function of the internal hydrogen pressure (Benson et al., 1994)

Figure 12 – Principle of functioning (on the left) (adapted from Burdajewicz, Korjenic, & Bednar, 2011) and range of variation of the thermal conductivity (on the right) (Loonen, 2010)
4 - Berge et al. (2015), developed an insulation system with two different nano-porous materials where its internal pressure is varied to achieve a variable U-value. These materials were aerogel blanket and fumed silica (structure of a Vacuum Insulation Panels, VIP) and measurements of thermal conductivity were made when the air pressure was varied between 1 kPa and the atmospheric pressure (100 kPa) using a vacuum pump (Berge et al., 2015). A variation of the thermal conductivity of around 3 times more for the fumed silica (7-19 mW/m.K) and less than 2 times for the aerogel blanket (11-17 mW/m.K) was measured (Figure 13).

![Figure 13 - Schematic of the equipment for the measurements (on the left). Variation of the apparent thermal conductivity with the increase of air pressure for both materials (on the right) (Berge et al., 2015)](image)

II.2.2.2 – Systems based on varying the gas-surface interaction in an insulation panel

Kimber et al. (2014), performed a conceptual analysis about a ‘smart' multifunctional insulation, where it is possible to switch between insulating (R\textsubscript{ins}) and conducting states (R\textsubscript{cond}), by varying the number of layers of air (N) on a multi-layered polymer membrane. Through each layer of air, there is heat transfer by convection and radiation (R\textsubscript{conv} and R\textsubscript{rad} in parallel) and through the interface between layers there is heat transfer by conduction (R\textsubscript{p}). By collapsing the wall and removing the air, it is possible to change between insulated and conductive states, whereas radiation and convection resistances are no longer present. This way, it is possible to achieve a changeable thermal transmittance (U-value) (Kimber, Clark, & Schaefer, 2014).

![Figure 14 - Illustration of adaptive multilayer wall: (a) is the insulated state, with N layers of air and its equivalent thermal resistance network is displayed below (b); (c) is the configuration for collapsed wall or conductive state whereas (d) is its equivalent thermal resistance (Kimber et al., 2014)](image)

II.2.2.3 - Systems based on varying the mean free path of gas molecules in an insulation panel

Some recent studies have proved that by changing the direction of carbon nanotubes suspensions in a fluid it is possible to reversibly change the thermal conductivity. Wu et al (2014), studied the effect of varying the temperature on the change of direction of the carbon nanotubes. A change in thermal conductivity from 0.4 to 1.2 W/m.K was registered. (Wu, Feng, Sunden, & Wadsoe, 2014). Corinne Baresich et al. studied the effect of applying an external magnetic field to align the carbon nanotubes and consequently achieve a changeable thermal conductivity of the fluids where they are in a suspension (Baresich & Shan, 2011).
II.2.3 – Movable Insulation System: Thermocollect

Thermocollect is a movable insulation system that was developed and tested in Austria by Rudolf Schwarznayr. This is an active-façade system which is constituted by a set of automated movable panels placed in front of a massive wall. The system is automated according to the surrounding indoor and outdoor conditions and can reduce both the heat losses during the winter and the heat gains during the summer.

During the winter, the system is typically closed at night in order to minimize the heat losses. However, during the day, in the presence of solar radiation, the panels are automatically opened to allow the solar heat to be stored in the wall. This heat will take a certain delay time to pass through the wall, but then will allow desirable heat gains inside the dwelling during nighttime (when the panels are closed). During the summer, the system is closed during the day acting as an insulation layer. During the night it can be opened to allow the release of unwanted heat gains accumulated during daytime (Burdajewicz, Korjenic, & Bednar, 2011).
II.2.4 - Comparison

To conclude the state-of-the-art overview, a comparison between the dynamic insulation technologies is presented, in order to compare the range of adaptive control.

Table 2 - Comparison of some of the dynamic insulation technologies based on the range of adaptive control available in the literature

<table>
<thead>
<tr>
<th>Scale</th>
<th>Mechanism of Control</th>
<th>Element Description</th>
<th>Range of adaptive control</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Parietodynamic wall – Void Space Dynamic Insulation (VSDI)</td>
<td>λ: 0.092-0.20</td>
<td>(Imbabi, 2012)</td>
</tr>
<tr>
<td>Macro</td>
<td>Heat convection through air</td>
<td>Permeodynamic wall (Breathing Wall)</td>
<td>U-value: 0.21</td>
<td>(Imbabi, 2006)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Translucent Dynamic Insulation System: Façade element with switchable insulation (FESU)</td>
<td>Re-value: 0.7-1.9</td>
<td>(Pflug et al., 2014)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Active Insulation$^{TM}$</td>
<td></td>
<td>(P&amp;D Adviseurs, 2015)</td>
</tr>
<tr>
<td></td>
<td>Heat convection through liquid</td>
<td>Bi-directional thermodiode</td>
<td></td>
<td>(Varga et al., 2002)</td>
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<tr>
<td></td>
<td></td>
<td>‘Smart thermal insulation system’: low and high conductivity fluid tanks</td>
<td></td>
<td>(Al-Nimr et al., 2009)</td>
</tr>
<tr>
<td>Micro/Nano</td>
<td>Varying the pressure of a gas to control heat conduction</td>
<td>Variable conductance vacuum insulation (VCI) - Adsorption/deabsorption of hydrogen</td>
<td>λ: 0.0-9.0</td>
<td>(Benson et al., 1994)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Variable pressure on aerogel blanket</td>
<td></td>
<td>(Horn et al., 2003)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Variable pressure on fumed silica (VIP)</td>
<td></td>
<td>(Berge et al., 2015)</td>
</tr>
<tr>
<td></td>
<td>Varying the gas-surface interaction</td>
<td>‘Smart’ multifunctional insulation – Variation on the number of layers of air</td>
<td>Re-value: 0.118 – 3.70</td>
<td>(Kimber et al., 2014)</td>
</tr>
<tr>
<td></td>
<td>Varying the mean free path of gas molecules</td>
<td>Change in the temperature to vary the direction of the carbon nanotubes suspension in liquid</td>
<td>λ: 0.4-1.2</td>
<td>(Wu et al., 2014)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>External magnetic field applied to change the direction of the carbon nanotubes</td>
<td></td>
<td>(Baresich &amp; Shan, 2011)</td>
</tr>
</tbody>
</table>

By analyzing the Table 2, it is possible to identify a classification challenge: in some elements the values available in literature for the adaptive range are in terms of $\lambda$ whereas in others they are given in terms of $U$-value. It is really difficult to classify all these elements together because some refer to materials, which can be classified in terms of $\lambda$, or to a whole wall construction, which is classified in terms of $U$-value. Moreover, when it comes to dynamic systems, it all depends on how they are operated, the control strategy and the dynamic conditions. To conclude, the available information about each element is, most of the times, limited, which difficult even more this comparison.
III – Simulation approaches for performance prediction of dynamic insulation elements

III.1 - Background

Throughout the few publications available regarding dynamic insulation modelling, the information accessible to help the BPS users to learn how to model these elements is somehow vague. This is caused by the fact that nowadays most of these BPS tools present some limitations regarding the simulation of time-variant parameters (Loonen et al., 2014). Despite the fact that there is a vast number of different software tools available to assess the performance of buildings, most of them were designed when the dynamicity of building materials/systems was not a central concern. Therefore, once the simulation is running, building shape and thermophysical material properties are not commonly changeable during this period, which difficult the modelling of those dynamic elements (Loonen et al., 2016). This way, it becomes central to develop a simulation assessment strategy to instruct the user on how to model elements which exhibit dynamic thermophysical parameters.

From the software tools available, EnergyPlus is the one which had the most significant improvements in adaptive façade modelling capabilities (Loonen et al., 2016). This whole building energy simulation software, developed by the US Department of Energy (DOE), had notorious developments since the introduction of a simplified programming language denominated as EnergyPlus Runtime Language (ERL), which allows to describe and specify the control algorithms. ERL grants the possibility to replicate a building energy management system (EMS) by means of a simulation tool (Loonen et al., 2016).

III.2 – Tools available in EnergyPlus

When the BPS user wants to simulate a specific building, either in terms of energy demand or thermal comfort assessment, he has to set the material properties of the elements of the several types of constructions on the building. However, by default, once the simulation is running, the user cannot influence or change the input parameters/properties during the process.

![Figure 17 - Display of some of the class lists, in IDF Editor, that the user can edit before running his simulation in EnergyPlus.](image)

In order to model dynamic insulation elements recurring to EnergyPlus software capabilities, there are several approaches that can be followed, depending on the type of insulation material/system which is going to be assessed through the simulation period.
Firstly, EnergyPlus can simulate movable/removable insulation systems, through the use of the Class List *SurfaceControl: MovableInsulation*. Moreover, EnergyPlus also allows to change the thermophysical material properties by using Advanced Control Methods which emulates the behavior of a real building energy management system (EMS). This is possible through the use of a set of sensors, control logics/algorithms and actuators, defined on several Class Lists available on Group Energy Management System (EMS) in EnergyPlus. On the following subchapters, these two approaches will be briefly described whereas some of implementation details will be referred. Moreover, some preliminary results about their application in EnergyPlus will be also outlined. To finish with, a critical comparison will be done in order to inform about some of the limitations of each approach.

### III.2.1 – *SurfaceControl: MovableInsulation* Class List

#### II.2.1.1 – Brief description

The application of movable insulation in a building, has the purpose of either trap heat loads inside or to block heat from coming into the dwelling, at a certain desirable time period. Using the Class List *SurfaceControl: MovableInsulation*, included in Group Advanced Surface Concepts in EnergyPlus, it is possible to schedule when to apply an extra layer of insulation on any construction, either on inside/interior, outside/exterior or even on both of its surfaces (U.S. Department of Energy, 2016b) (as displaced in Figure 18). This can be scheduled for various times of a day, month or year, depending on how the user defines the schedule that control the behavior of these movable insulation elements. Moreover, *MovableInsulation* can only be applied on regular surfaces (wall, floor, roof, etc.), but not on windows, and it has the possibility for the external movable insulation to be transparent (TIM – transparent insulation material).

#### II.2.1.2 – Implementation details

As displayed on Figure 19, there are four fields on this Class List:

- On ‘Insulation Type’, the user chooses if the movable insulation will be applied on either ‘Outside’ or ‘Inside’ of the surface, specified on the next ‘Surface Name’ field (from *BuildingSurface:Detailed* Class List). If it has to be applied on both surfaces, the user has to create two objects: one for the ‘Outside’ layer and another for ‘Inside’ layer.
III – Simulation approaches for performance prediction of dynamic insulation elements

- On ‘Material Name’ field, the user defines which is the material of the movable insulation layer (from: Material or MaterialNoMass Class Lists)
- On ‘Schedule Name’, a schedule is introduced by the user on the IDF Editor or it can be imported from a .txt or .csv file. This schedule should have a real number between 0.0-1.0, at each timestep of the simulation, which works as a fractional multiplier on the thermal resistance (Rc-value) of the material layer defined on the previous field. This way, when it’s 1.0 the layer is added and when it is 0.0 the layer is removed.

<table>
<thead>
<tr>
<th>Field</th>
<th>Obj1</th>
<th>Obj2</th>
<th>Obj3</th>
<th>Obj4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulation Type</td>
<td>Outside</td>
<td>Outside</td>
<td>Outside</td>
<td>Outside</td>
</tr>
<tr>
<td>Surface Name</td>
<td>SouthWall</td>
<td>NorthWall</td>
<td>WestWall</td>
<td>EastWall</td>
</tr>
<tr>
<td>Material Name</td>
<td>SinglePaneOpaque</td>
<td>SinglePaneOpaque</td>
<td>SinglePaneOpaque</td>
<td>SinglePaneOpaque</td>
</tr>
<tr>
<td>Schedule Name</td>
<td>SummerControlPeriod</td>
<td>SummerControlPeriod</td>
<td>SummerControlPeriod</td>
<td>SummerControlPeriod</td>
</tr>
</tbody>
</table>

Figure 19 - Example of an application of the Class List SurfaceControl: MovableInsulation on IDF Editor. In this case, exterior movable insulation, in all surfaces of the building (S, N, W, E) is controlled according to a specific Summer Control schedule.

As referred before, the schedule introduced can take real numbers between 0.0 and 1.0, which can also allow to model systems with changeable conductivity ($\lambda$), and consequently changeable Rc-value, throughout the simulation period.

Knowing that the definition of Rc-value is the thickness ($L$) of the material divided by its conductivity, $(R_c = \frac{L}{\lambda})$, to model an element, with $L$ constant, where it is possible to control its conductivity, between $\lambda_1$ (initial value of the material, introduced before the simulation) and $\lambda_2$, the user have to introduce the fractional multiplier resultant of the ratio $\frac{R_{c,2}}{R_{c,1}} = \frac{\lambda_1}{\lambda_2}$, at the desirable timesteps, on the schedule inputted.

III.2.2 – Surface Construction State Actuator on EMS

II.2.2.1 – Brief description

The second option to model dynamic insulation elements is through a high-level control method available in EnergyPlus: Energy Management System (EMS) (U.S. Department of Energy, 2016b). EMS uses EnergyPlus Runtime programming language to emulate the controls available in digital energy management systems used in real buildings. These real world systems, composed by sensors, control units/logics and actuators (Figure 20), can be used to control several buildings’ systems, which include heating, cooling, ventilation, lighting, on-site power generation, mechanized systems for shading devices, window actuators and façade elements (Peter, Paul, & Drury, 2007).

Figure 20 – Schematic that presents the main components of an Energy Management System (EMS) and displays the way of functioning in order to control a dynamic insulation system.
Making use of sensors, control algorithms and actuators, EMS overrides specific aspects of EnergyPlus behavior (U.S. Department of Energy, 2016b). Firstly, sensors reuse EnergyPlus output variables by measuring a certain parameter regarding the thermal environment. Afterwards, a control algorithm is defined by the user in order to control a certain actuator, based on the information which was provided by the sensors. By means of IF-ELSEIF-ELSE-ENDIF blocks, it will set the behavior of the actuator by proposing a certain action (U.S. Department of Energy, 2016a).

There are several groups of actuators available in EMS, which can be introduced in the class list EnergyManagementSystem:Actuator. The ones which allow to control thermo-optical properties of the materials are regarding the Thermal Envelope (U.S. Department of Energy, 2016a). The actuators available on this group, allow to control and model several building envelope adaptive elements. One of them is the Surface Construction State actuator which is able to model elements with variable thermo-optical material construction properties (U.S. Department of Energy, 2016a). This allow to make insulation changeable in the simulation environment. When modelling a certain element with changeable material properties, the Surface Construction State acts by changing all the existing construction for another which includes a different state of the element, instead of only acting at a material scale. This way, different construction with different thermophysical properties must be created to be used in a sequence defined by the control algorithm.

II.2.2.2 – Implementation details

To the best of our knowledge, there is no simulation strategy available in literature to inform the user of how to model dynamic insulation elements in a simulation environment. This way, a step-by-step procedure of how to use the Surface Construction State Actuator in EMS was given in this subchapter.

Step-by-step procedure of how to use Surface Construction State Actuator to model dynamic insulation elements

Considering a certain insulation element, to be installed on the outside of the exterior walls of a building, that can change its conductivity from \( \lambda_1 \) to \( \lambda_2 \) when the temperature indoors (\( T_{\text{in}} \)) is higher than the temperature outdoors (\( T_{\text{out}} \)).

1\textsuperscript{st} step: Define two different materials on Class List Material: one with conductivity \( \lambda_1 \) and another with \( \lambda_2 \).

2\textsuperscript{nd} step: Define the construction layers’ sequence of the exterior walls on Class List Construction, for both two cases

3\textsuperscript{rd} step: Define which construction is chosen to start the first simulation timestep as the standard for all the wall surfaces (on BuildingSurface:Detailed Class List):

4\textsuperscript{th} step: Define in Class List EnergyManagementSystem:Sensor \( T_{\text{in}} \) and \( T_{\text{out}} \) as sensors for EMS.
5th step: In the Class List EnergyManagementSystem:ConstructionIndexVariable, both constructions defined in step 3 are declared as EMS variables which identify construction states for the program.

6th step: In EnergyManagementSystem:Actuator, the surfaces which have the dynamic insulation element incorporated, are inputted for EMS and this way identified as actuators.

7th step: The control algorithm is introduced in EnergyManagementSystem:Program, which define how the actuator behaves throughout the simulation: IF $T_{in} > T_{out} \Rightarrow$ SET Construction.Actuator = Construction $\lambda_2$; ELSE SET Construction.Actuator = Construction $\lambda_1$.

8th step: Finally, the program created in the previous step is declared and used as an input for EMS controls (on Class List EnergyManagementSystem:ProgramCallingManager).

III.2.3 – Preliminary results

In order to get familiar with the simulation tools and to understand if both approaches work the way it was expected, there is a need to get preliminary simulation results with a simple reference case. This way, the BESTEST Case 600 test building was selected to perform these analyses. This basic test building is a lightweight simple single-zone building which is assessed with a weather file from Denver, Colorado (USA) and has as temperature setpoints 20°C for heating and 27°C for cooling (Henninger & Witte, 2004).

II.2.3.1 – MovableInsulation Actuator

In order to show the transition, in terms of temperature and energy demand, that occurs when MovableInsulation is used to change between insulated and non-insulated states, a simple scenario was designed. Based on schedules previously defined, the goal is to show that it is possible to change from one state to another throughout the simulation.

Two different periods were studied: one in the winter (21st-22nd of December) where the heating rate was assessed and another in the summer (21st-22nd of June). For these two periods, three different scenarios were chosen: Always OFF, where the insulation layer was removed from the wall construction during the chosen period; Always ON, where the insulation layer is placed in the construction the same way as described in BESTEST Construction; 2nd Day OFF, where the insulation was only removed on the second day of the respective period.

![Figure 22 - Example of an application of the Class List EnergyManagementSystem:Actuator which sets each surface as Surface: Construction State Actuators](image)

![Figure 23 - Methodology followed for the 2nd Day OFF Scenario at the summer period. Firstly the schedule described was defined and then it was used on the SurfaceControl:MovableInsulation Class List](image)
After doing this analysis, it is possible to observe the transition between one state and another in both periods (highlighted by the yellow dashed ellipses in Figure 24). On the summer period, the transition between Always ON and Always OFF states can be observed on the temperature graph whereas on the winter period the transition is observed on the heating rate profiles.

III.2.3.2 – Surface Construction State Actuator

In order to illustrate the way how this surface construction state actuator works inside the EMS and the effect it has on the output variables, a specific scenario with a specific control strategy was defined. Once more, it was used the BESTEST Case 600 as an input for the parameters of the model.

As control strategy, it was defined that when the temperature outdoors was higher than 25°C, the actuator would change the standard BESTEST construction with a layer of insulation of 0.04 W/m.K of thermal conductivity (which I named Walls_LowCond) for another construction with a layer of insulation of 0.08 W/m.K (Walls_HighCond), at all the surfaces of the building. The period chosen was between the 24th and 26th of August, and total cooling capacity was limited by 40% in order to allow a more significate variation on the indoor temperature.

**Figure 24** - Results from all the scenarios compared on the same plot. On the left, there are displaced the plots regarding the summer period and on the right regarding the winter period.
A small increase on the indoor temperature is registered on the last two days of the period, when the high conductivity construction overrides the low conductivity one. This way, it is possible to conclude that by having a higher conductivity construction in this period, the overheating problem is accentuated.

### III.2.4 – Critical comparison

Besides the fact that it was proved, in the previous subchapter, that both approaches can be used to predict the performance of dynamic insulation elements, they have some limitations. In addition, there is very limited guidance on how to use them.

When it comes to the use of the MovableInsulation actuator, it offers the advantage of acting at a material level, in contrast with the Surface Construction State Actuator that has to replace the whole construction of the given surface. Although, it is not clear what happens and how is it taken into account the solar heat previously stored in the material layer when this one is removed from the construction. The simplification assumed on this actuator led to different results between having the insulation ON in the MovableInsulation class list or having just having it included in the Construction class list as usual. To finish with, by actuating with schedules, the MovableInsulation actuator cannot take into account the variability of thermophysical parameters of the envelope and its surrounding environment, which is a major limitation.

Regarding the EMS Surface Construction State Actuator, it is much more extensive in terms of control strategies that can be used which makes it more promising than the other approach mentioned. However, it requires that the different constructions to be assigned to have similar thermal/heat storage capacities. If it does not happen, the override action cannot be succeeded and the results can end up being physically inaccurate (U.S. Department of Energy, 2016a). Throughout the simulations, I ran several times into a spatial discretization or nodal placement scheme problem, every time I increased the range of conductivities. This problem would not allow me to put the EMS control rules in practice because it blocked the possibility of overriding the constructions. A solution for this problem was not found, so I decided to carry on with my case study analysis using the MovableInsulation Actuator.
IV – Case study analysis

IV.1 - Introduction

After doing a comparison side-by-side of the approaches available in EnergyPlus to predict the performance of dynamic insulation elements, an illustrative case study is needed to give physical interpretation of what do they mean and how can they be implemented in a real building. BESTEST is a reference case that allows to validate BPS software tools and to get familiar with these tools, but it represents a really simple case building, which is not so realistic and adequate to all the climates. Moreover, a case study should aim to solve a specific problem. On the analysis performed on the previous chapter, an actual problem is not presented because the goal was just to show how each approach works according to a specific control strategy. Thus, the focus on this case study will be on solving an overheating problem that occur in the Summer period, when the capacity of the HVAC systems is limited. As mentioned in the previous chapter, the MovableInsulation actuator will be used on this analysis.

This is chapter will start with a case-study description, where the building details will be given. Next a specific problem will be analyzed and a solution will be proposed by means of a control strategy. Finally, the results from this analysis are presented.

IV.2 – Case study description

IV.2.1 – Building details

In order to get meaningful results, a specific case study building was designed. The chosen climate was Lisbon, Portugal and the location of the building matches the one from the respective weather file (Latitude: 38.73N, Longitude: 9.15W) (INETI, 2006). The goal here was to represent the mild southern European climate. A single-zone residential building with standard Portuguese construction which features increased insulation and improved glazing was chosen (Appendix I). This dwelling has a floor area of 72 m² (6 m depth and 12 m width) and has a height of 3 meters. It is turned south and has 4 windows of 5 m² on that surface. A shading static device, with 1.61 m, was designed in order to guarantee that the windows are fully shaded during the summer (Appendix II). This way, it was placed on the south facade above the windows. The geometry of the building was designed in SketchUp and then it passed to EnergyPlus through the OpenStudio Plugin.
In terms of internal loads, lighting, equipment and occupation profiles were added to EnergyPlus in order to have a realistic case study. In terms of occupation, it was considered that there was one person per 17.70 m² of zone floor area (input from Open Studio model) with a metabolic rate per person of 115 W (70 W sensible and 45 W latent from which 30% is radiant), that corresponds to an adjusted rate (male/female) for a seated person with very light work (ASHRAE, 2009). For lighting and equipment internal loads, a power density of 5W/m², which is regarding residential spaces (single family), was considered for both (Autodesk, 2015). In Appendix III – Internal Loads Schedules an overview of the schedules and other important parameters, regarding the internal loads inputted in EnergyPlus, can be found.

Regarding HVAC systems, constant setpoints of 20°C for heating and 25°C for cooling were considered. The design load for heating and cooling was determined by simulating the building in the design days for Lisbon, being the system dimensioned according to the lowest requirements (Appendix IV –). In terms of infiltration, it was set to 0.5 ACH, being constant throughout the year.

Overheating hours were defined as every hour where the indoor temperature was above 25°C. In order for that to happen, the HVAC cannot be an ideal load system, because it would always meet the temperature requirements. This way, a 60% total cooling capacity was considered for sizing the HVAC. In order to do that, first I ran the simulation with unlimited cooling capacity to determine the maximum capacity. Then a 40% reduction was applied and introduced on the class list HVACTemplate:Zone:IdealLoadsAirSystem, on the field Maximum Total Cooling Capacity.

IV.2.2 – Overheating problem analysis and respective control strategy

IV.2.2.1 – Description of the problem

In the summer, problems regarding overheating are pretty common in some dwellings, especially in a southern European country. In this case study, the application of dynamic insulation by means of using the MovableInsulation actuator have the goal of reducing the overheating problems resultant from not having an ideal load system but with 60% cooling capacity. As the focus of these analysis is to increase the thermal comfort by lowering the overheating, the overheating hours is the main performance indicator. Before applying the control strategy, it was registered a yearly percentage of 16.1% of overheating hours (when T_in > 25°C).

IV.2.2.2 – Control strategy design

To deal with this problem, a control strategy was designed aiming to remove the unwanted heat gains accumulated during daytime, resultant of both solar and internal gains. The goal was to use the MovableInsulation Actuator to remove or add the layer of insulation (10 cm of EPS) to the construction taking into account three control parameters regarding the surrounding thermal environment: outdoor temperature
Dynamic Insulation as a strategy for Net-Zero Energy Buildings

IV – Case study analysis

*Site Outdoor Air Drybulb Temperature*, indoor temperature (*Zone Mean Air Temperature*) and the solar radiation incident on the outside surface (*Surface Outside Face Incident Solar Radiation Rate per Area*).

As the goal of this case study analysis is to reduce the overheating problems, the control strategy should be designed to remove the insulation layer when the temperature is above 25°C. However, it is important to assure that, by removing the insulation layer, the problem will not get worse. So it is of the utmost importance to assure that the outdoor temperature is not above the indoor temperature, and that the solar radiation incident the surfaces is not higher than a reasonable value. In the case study building, there are 4 exterior surfaces, one in each cardinal direction. As the building is situated in the Northern Hemisphere, the south wall is by far the surface the gets more radiation per area than any other surface. This way, the focus was only on the East, West and North walls.

To concretize, the control strategy is the following:

- The insulation layer on the South Wall is ‘Always ON’
- The insulation layer will be removed in a specific surface whenever all of the following conditions are verified:
  - $T_{\text{indoor}} > 25°C$
  - $T_{\text{outdoors}} < T_{\text{indoor}}$
  - Solar radiation incident on the surface $\leq 150$ W/m$^2$
- There is the possibility to remove the insulation only on one of the surfaces, or all of them, depending on the value of the incident radiation on the East, West and North walls.
- If one of the conditions is not verified on that surface, the insulation is set ‘ON’.

As the MovableInsulation approach only works through the use of control schedules, there is a need to run the simulation once to output these three parameters and perform a post-processing analysis in order to understand if all the conditions are verified for each surface. After evaluating the condition for each of the surfaces, a fractional schedule for each surface is imported from a comma separated values file (.csv) to the class list Schedule:File, which will feed the MovableInsulation actuator with the control schedule.

![Figure 30](image)

**Figure 30** - Control strategy applied in EnergyPlus. First the Schedule:File class list imports the control schedule for each surface from the .csv file which will be used as input for the MovableInsulation class list.
IV.3 – Results

After applying the control strategy, described on the previous subchapter, the results obtained were favorable as it was registered a significant decrease in both annual cooling demand and annual percentage of overheating hours, with -22.6% and -59.6% respectively. The control strategy is working the way it was designed to.

![Figure 31](image1.png)

**Figure 31** - Effect of the application of the control strategy on the indoor temperature during the cooling season

![Figure 32](image2.png)

**Figure 32** - Illustration of the effect of the movable insulation during the extreme summer week in Lisbon

![Figure 33](image3.png)

**Figure 33** - Comparison side-by-side of all the parameters taken into account to control the movable insulation layer on the North Façade, for a period of 3 days (15-17 of July). The black dashed line illustrates the state of the movable insulation: when it is 0, the insulation layer is 'OFF' and when it is 1, it is 'ON'. It is important to refer that the T_in_AfterMovable also takes into account the West and East surfaces. By analyzing this graph, it is possible to conclude that the control strategy is working the way it should.
V – Conclusions and future work

Dynamic insulation elements offer plenty of opportunities in comparison with static conventional insulation elements. The idea of “switching off” the insulation allows the possibility of controlling the heat flux through the facades, which brings a significant potential for thermal comfort improvements and energy savings. As presented in Chapter 2, there are so many different possibilities of systems/materials that can be used to achieve different adaptive ranges with different control mechanisms. However, there is very little knowledge of how to turn these opportunities and these potential benefits into real strengths, because the information available is still vague. This lack of information can turn these strengths into weaknesses, because it cannot make the user to conclude that these systems are competitive and cost-effective, which will therefore limit the product development.

When it comes to predict the performance of dynamic insulation elements, there is very little guidance for the user of the BPS tools as there is not any established assessment framework, which constitutes a threat. The goal of this research was to assess how can we use modelling and simulation tools to overcome this threat by predicting how can the dynamic insulation elements be assessed. This way, the weaknesses regarding technology development would be reduced while increasing the strengths.

In chapter 3, two different approaches available in EnergyPlus to predict the performance of dynamic insulation elements were critically compared. Theoretically, the EMS approach using the Surface Construction State seems to show more potential but due to some interface limitations or the way it has been implemented, it has a lot of practical limitations. This led me to pick the MovableInsulation Actuator for the case study analysis. Moreover, in the case study analysis, it was possible to conclude that by using an adequate control strategy, it is possible to achieve significant thermal comfort improvements, by reducing the percentage of overheating hours in almost 60%, and also by lowering the cooling demand by more than 22%. It was also concluded that the control strategy designed to solve the overheating problem was working in the way it should.

Besides the fact that I succeeded partly to eliminate the threats by doing an expositive critical analysis of the different approaches available and its application in the EnergyPlus, there is still much work that needs to be done before it is possible for the concept of dynamic insulation to be a firm reality. To achieve that goal, the weaknesses and the threats, from the technology side and from the simulation side must be eliminated. It is important to better understand how can a user take advantage of the potential of the EMS Surface Construction State Actuator to predict the performance of dynamic insulation elements, as it is way more promising than the MovableInsulation approach, which only works on the basis of schedules. But first, a solution for some of the implementation errors, like the ones I faced throughout the project, must be found.

Moreover, there is also a need to conclude about what are the promising building type for the application of these elements. Additionally, what is the potential of the thermal mass together with dynamic insulation elements and what is the effect of different construction details on the thermal load delay represent some questions that need to be answered in order to assess about what is the best or more appropriate control strategy for dynamic insulation elements. In order to push the application of the concept further, there is a need to do more case study analysis and more measurements in different climates.
References


References


Appendices

Appendix I – Construction details

In terms of construction materials layers, they are based on a standard Portuguese construction (Carrilho da Graça, Augusto, & Lerer, 2012). The order of the materials on the walls was changed in order to make it possible to model using the MovableInsulation approach, as it can only schedule insulation layers on the outside or inside layers of a certain surface but not in the middle. This way, instead of having a sequence, from outside to inside, of plaster (1 cm), hollow brick (11 cm), expanded polystyrene insulation (10 cm), hollow brick (15 cm) and plaster (1 cm), the insulation was chosen as outside layer (10 cm), and then a layer of 26 cm of brick followed by a 1 cm layer of plaster.

Table 3 - Opaque elements for all the constructions (from outside to inside)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Walls: Expanded polystyrene insulation (EPS)</td>
<td>0.10</td>
<td>0.04</td>
<td>25</td>
<td>1500</td>
</tr>
<tr>
<td>Hollow brick</td>
<td>0.26</td>
<td>0.72</td>
<td>1920</td>
<td>835</td>
</tr>
<tr>
<td>Plaster</td>
<td>0.01</td>
<td>0.04</td>
<td>950</td>
<td>840</td>
</tr>
<tr>
<td>Floor: Expanded polystyrene insulation (EPS)</td>
<td>0.08</td>
<td>0.04</td>
<td>25</td>
<td>1500</td>
</tr>
<tr>
<td>Heavyweight concrete</td>
<td>0.15</td>
<td>1.63</td>
<td>2300</td>
<td>800</td>
</tr>
<tr>
<td>Roof: Expanded polystyrene insulation (EPS)</td>
<td>0.15</td>
<td>0.04</td>
<td>25</td>
<td>1500</td>
</tr>
<tr>
<td>Lightweight concrete</td>
<td>0.20</td>
<td>0.38</td>
<td>1200</td>
<td>840</td>
</tr>
<tr>
<td>Plaster</td>
<td>0.01</td>
<td>0.04</td>
<td>950</td>
<td>840</td>
</tr>
</tbody>
</table>

In terms of translucent elements, double-glazed windows with Low-Emissivity were chosen. There are 4 windows, each of them with a U-value of 1.8 W/m².K and a solar factor of g = 0.63. All the windows are shaded by a shading static device of 1.61 m (Appendix II – Shading device width sizing) in order to reduce the solar heat gains during the summer.
Appendix II – Shading device width sizing

The purpose to design a shading device to be used in the case study analysis was to reduce the unwanted solar heat gains through the window during the cooling season. This can be achieved by sizing the width of the shading device for the Autumn Equinox (21st of September) at mid-day. This way, windows will be shaded during the period between Spring and Autumn Equinoxes (21st March – 21st September) (Ecotech Community Wiki, 2016)

To calculate the width of the shading device, it is necessary to calculate the solar altitude $\alpha$ (and consequently the solar declination, $\delta$) for the latitude of Lisbon ($\phi = 38.7^\circ$), at the 21st of September (Julian Day 264) at mid-day (Hour Angle, HRA = 12) (Honsberng & Bowden, 2013). After calculating the solar altitude, the height of the window times the tangent of the complementary angle of the solar altitude gives us the width of the shading device.

![Figure 34 - Desired effect of the shading device during the cooling season](image)

![Figure 35 - Angle geometry to calculate the width of the shading device](image)

```
In[43]= J = 264; HRA = 12; \phi = 38.7 \frac{\pi}{180};

\delta = \text{ArcSin}[0.4093 \text{Sin}[2 \frac{\pi}{365} \frac{284 + J}{365}]]; 
\omega = 15 \text{ (HRA - 12)};
\alpha = \text{ArcSin}[(\cos(\phi) \cos(\delta) \cos(\omega) + \sin(\phi) \sin(\delta))];
\theta = \frac{\pi}{2} - \alpha;
W_{\text{shading}} = 2 \text{Tan}[\theta];

Out[44]= 1.6139
```

![Figure 36 - Calculation of the width of the shading device, on Wolfram Mathematica](image)
Appendix III – Internal Loads Schedules

I - People

In the single-zone residential building designed for the case study analysis there is one person per each 17.70 m² of floor area (EnergyPlus default), which for a floor area of 72 m² is equivalent to approximately four people. Each person as a metabolic rate of 115 W, 70 W sensible and 45 W (ASHRAE, 2009), with a 0.3 fraction radiant. This 115W is set as the activity level for all the year. In terms of the schedule for the occupation profile, it varies from cooling season (1st of July – 31st of September) to heating season (rest of the year).

Table 4 - Occupation profile (Carrilho da Graça et al., 2012)

<table>
<thead>
<tr>
<th>Months</th>
<th>Days</th>
<th>Time of the day</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Through: June, 30</td>
<td>For: Weekdays</td>
<td>Until: 10:00</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Until: 18:00</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Until: 24:00</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>For: Weekends</td>
<td>Until: 24:00</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>AllOtherDays</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Through: September, 30</td>
<td>For: Weekdays</td>
<td>Until: 10:00</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Until: 18:00</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Until: 24:00</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>For: Weekends</td>
<td>Until: 11:00</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>AllOtherDays</td>
<td>Until: 17:00</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Until: 24:00</td>
<td>1</td>
</tr>
<tr>
<td>Through: December, 31</td>
<td>For: Weekdays</td>
<td>Until: 10:00</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Until: 18:00</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Until: 24:00</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>For: Weekends</td>
<td>Until: 24:00</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>AllOtherDays</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

II – Electric Equipment

In terms of electric equipment, for a residential building (single-family) the power density is 5 W/m² (Autodesk, 2015) which is equivalent to 360 W in the single-zone case study building with 72 m² of floor area. This load is 100% sensible and has a radiant fraction of 0.5 (default from the OpenStudio). The fractional schedule for the equipment usage was the same of the occupation profile.

III – Lighting

In terms of lighting, for a residential building (single-family) the power density is 5 W/m² (Autodesk, 2015) which is equivalent to 360 W in the single-zone case study building with 72 m² of floor area. Some additional input parameters for EnergyPlus are 0.4 for the return air fraction, 0.4 for the radiant fraction, 0.2 for the fraction visible and 1 for the fraction replaceable (default from the OpenStudio). In terms of the lighting schedule, an estimation of a standard usage was made.

Table 5 - Lighting usage profile

<table>
<thead>
<tr>
<th>Months</th>
<th>Days</th>
<th>Time of the day</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Through: December, 31</td>
<td>For: Weekdays</td>
<td>Until: 07:00</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Until: 10:00</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>For: Weekends</td>
<td>Until: 18:00</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>AllOtherDays</td>
<td>Until: 24:00</td>
<td>1</td>
</tr>
</tbody>
</table>
Appendix IV – Additional input simulation and system sizing parameters

In this appendix, will be mentioned some of the parameters that were given as input for the simulation, which was performed on EnergyPlus, version 8.4.

Table 6 - Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Convection Algorithm for indoor surface</td>
<td>TARP</td>
</tr>
<tr>
<td>Surface Convection Algorithm for outside surface</td>
<td>DOE-2</td>
</tr>
<tr>
<td>Heat Balance Algorithm</td>
<td>Conduction Transfer Function (CTF)</td>
</tr>
<tr>
<td>Loads Convergence Tolerance Value</td>
<td>0.04</td>
</tr>
<tr>
<td>Temperature Convergence Tolerance Value</td>
<td>0.004</td>
</tr>
<tr>
<td>Solar Distribution</td>
<td>FullInteriorAndExterior</td>
</tr>
<tr>
<td>Maximum Number of Warmup Days</td>
<td>40</td>
</tr>
<tr>
<td>Minimum Number of Warmup Days</td>
<td>6</td>
</tr>
<tr>
<td>Number of Timesteps per Hour</td>
<td>6 (1 per each 10 minutes period)</td>
</tr>
</tbody>
</table>

The site location was the same of the weather data for Lisbon, Portugal (Latitude: 38.73 N, Longitude: 9.15 W, Time zone: GMT (0), Elevation: 71 m). The information about the design days and the ground temperature was also retrieved from the weather data.

Table 7 - Sizing Period: Design Days for Lisbon (INETI, 2006)

<table>
<thead>
<tr>
<th>Date</th>
<th>Winter Design Day</th>
<th>Summer Design Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Dry-Bulb Temperature</td>
<td>4.2°C</td>
<td>34.2°C</td>
</tr>
<tr>
<td>Daily Dry-Bulb Temperature Range (Δ°C)</td>
<td>0</td>
<td>10.1</td>
</tr>
<tr>
<td>Wet bulb or Dew Point at Maximum Dry-Bulb</td>
<td>4.2°C</td>
<td>20°C</td>
</tr>
<tr>
<td>Barometric Pressure</td>
<td>100475 Pa</td>
<td>100475 Pa</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>2.2 m/s</td>
<td>4.4 m/s</td>
</tr>
<tr>
<td>Wind Direction</td>
<td>50°</td>
<td>330°</td>
</tr>
<tr>
<td>Sky Clearness</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 8 - Ground temperature values, for 0.5 m depth, in *GroundTemperature:BuildingSurface* (INETI, 2006)

<table>
<thead>
<tr>
<th>Month</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>13.6</td>
</tr>
<tr>
<td>February</td>
<td>11.8</td>
</tr>
<tr>
<td>March</td>
<td>11.3</td>
</tr>
<tr>
<td>April</td>
<td>11.7</td>
</tr>
<tr>
<td>May</td>
<td>14.2</td>
</tr>
<tr>
<td>June</td>
<td>17.0</td>
</tr>
<tr>
<td>July</td>
<td>19.6</td>
</tr>
<tr>
<td>August</td>
<td>21.4</td>
</tr>
<tr>
<td>September</td>
<td>22.0</td>
</tr>
<tr>
<td>October</td>
<td>21.1</td>
</tr>
<tr>
<td>November</td>
<td>19.0</td>
</tr>
<tr>
<td>December</td>
<td>16.3</td>
</tr>
</tbody>
</table>