ABSTRACT
A virtual experiment is set up in order to assess the impact of building thermal mass in small scale residential architecture. Yearly energy demand for space heating and appreciation of occupant thermal comfort are simulated using whole building simulation tool EnergyPlus in conjunction with Matlab. In order to mimic real life occupant behavior accurately, a stochastic occupant behavior schedule is generated, including a window opening algorithm to reduce overheating. The results for Belgian climatic conditions indicate that on average, a lightweight building demands 4.5% more heating energy compared to a heavy equivalent, and has a level of discomfort which is 20.5% higher. Overall, the impact of thermal inertia is secondary to other design parameters such as insulation level and glazing properties.

INTRODUCTION
Improving the thermal performance of buildings has become a major issue the last decade due to economical, political and ecological motives. In order to estimate the energy consumption of a building during the design phase, simplified calculation methods have been developed. Most of these algorithms focus on the steady state thermal transmittance of the building components, denoted by the U-value [W/m²K]. This is notably the case for most of the national implementations of the European Energy Performance of Buildings Directive.

A steady state calculation allows for a quick and easy application, by neglecting the transient nature of heat transfer phenomena. Due to changing outside temperatures, sun irradiation, internal heat gains, etc., there is an ever changing heat exchange between the building and the environment, as well as between different rooms within a building. Building materials can store and release heat, depending on the temperature difference with their surroundings. The amount of energy stored depends on the mass of the component and the specific heat capacity of the material. A building with a great amount of thermal mass is able to time-shift and flatten out temperature peaks; this is referred to as the thermal inertia of a building. In a steady state calculation, this effect is neglected.

Most research on thermal inertia focuses on offices, for which a high amount of thermal mass can restrict temperature excess, and consequently improve thermal comfort and reduce cooling loads. This is further exploited in low energy concepts such as intensified night ventilation or thermally activated building systems.

Unlike offices, houses are characterized by low internal heat gains and a great spread in comfort demands depending on occupant activities. Furthermore houses are seldom equipped with active cooling equipment, instead people rely on operating windows to avoid overheating. Because of these distinct properties, design rules for offices are not applicable to residential architecture.

In houses a high level of thermal mass can help reducing summer overheating, and thus enhance thermal comfort. During heating season, thermal inertia has two opposite effects on the energy demand. With intermittent heating a less inert building will cool down faster. The reduced temperature leads to lower ventilation and transmission losses. The

![Figure 1 Comparison time series temperature: heavy mass versus lightweight building](image-url)
building will react faster to changing thermostat setpoints; thus a lightweight building could increase occupant satisfaction and reduce energy demand. Conversely, a higher level of accessible thermal mass helps to capture and store heat gains, e.g. from solar radiation during the day, thus reducing the need for additional heat during evening hours.

Scientific literature shows conflicting opinions on the net impact of the level of thermal inertia in residential buildings in the temperate north European climate, where active cooling is generally not needed. Finney (2004) states that overall, a high inertia house will use at least 10% more energy, dependent on the level of insulation. CIBSE Guide F (CIBSE, 2004) suggests that less thermally massive buildings have shorter preheat periods, and use less heating energy. A UK study concludes that the effect of thermal mass varies with insulation standard, climate and occupancy/gains scenario (Tuohy et al., 2005). Hauser concludes that for a german house, the level of thermal inertia has a negligible influence, with a maximum difference of 1.6% on heating energy demand (Hauser, 1997). Conversely, according to a Swedish study, a heavy mass house requires 20% less heating energy compared to a lightweight alternative (Norén et al., 1999).

This objective of this study is to assess the impact of building thermal mass in Belgian temperate climatic conditions, concerning both energy use and thermal comfort throughout the year. Extra attention has been given to the behaviour of the occupants in order to faithfully mimic real life behaviour.

**METHODOLOGY**

**Dynamic Building Simulation**

As stated before, the effect of thermal inertia can not be revealed by a steady state analysis, which solely assesses the thermal transmittances (U-values). Calculating the dynamic behaviour of heat conduction, storage and release processes, requires solving the differential algebraic equations for time dependent heat transport. Literature describes many attempts of analytically or semi-numerically solving these equations, using simplified boundary conditions such as step functions or sinusoidal fluctuating external temperatures. (e.g. Guglielmini et al., 1981 and Tsilingiris, 2006).

These methods become obsolete as several software codes are now capable of simulating a virtual building accurately and swiftly. Unlike the simplified methods, whole building simulation tools are capable of simulating the complex interactions between form and fabric, outside climate, HVAC systems and occupant behaviour. In this study, the freeware EnergyPlus simulation package is deployed (EERE, 2010). Instead of the default conduction transfer functions, the conduction finite difference algorithm is used to have a more accurate calculation of the heat absorb and release processes. All simulations are executed with a 3 minute time step, and span a whole year, for which the weather data are derived from IWEC data set for Brussels, Belgium.

**Building geometry**

Two different building typologies are considered: a two story semi detached dwelling and a free standing bungalow, each comprising 162 m² floor space. The dwellings are subdivided into 4 thermal zones: cooking zone, living zone, sleeping zone, and bathroom zone. Within one thermal zone the air is supposed to be perfectly mixed and thus uniform in temperature. The HVAC system consists of electric baseboard heaters; there is no active cooling system installed.

Throughout the study different variants of the two basic typologies are generated to explore the impact of glazing percentage, building orientation and level of thermal insulation.

The glazed surface can have major impact on energy demand and thermal comfort. Therefore three distinct glazing configurations are considered (see table 1). Apart from the amount of glazing, the orientation of the building can take four values: 0, 90, 180, 270; for which the front of the house is facing respectively North, East, South and West. It is assumed that the houses are not influenced by external shadows.

**Table 2 Glazing Configurations**

<table>
<thead>
<tr>
<th>Glazed Area Semi-detached [m²]</th>
<th>Glazed Area Free standing [m²]</th>
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<tbody>
<tr>
<td>Glass 1</td>
<td>49.75</td>
</tr>
<tr>
<td>Glass 2</td>
<td>34</td>
</tr>
<tr>
<td>Glass 3</td>
<td>21.5</td>
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</table>
Different construction systems are considered, to represent different levels of building thermal inertia: a heavy mass building with brick cavity walls, masonry internal partitions and concrete floor plates versus a lightweight building with wood stud walls and wooden floors. Additionally a medium weight structure is considered, consisting of external wood stud walls and internal brick and concrete partitions. The thermal behaviour of the wood stud walls is modelled according to the equivalent wall method (Kossecka et al., 1997). The thermal mass from furnishing is neglected.

Different levels of thermal insulation are considered: K70, K45, K35 and K20. The names refer to K-level, a concept in Belgian energy standards, which is a measure of global insulation level of a building. K45 is the present legal maximum. The U-values corresponding to a specific K-level are identical for heavy weight and low weight constructions (see table 2). A steady state analysis would thus yield identical heating energy demands.

**Occupant behaviour**

While software tools have made great progress in the simulation of physical processes and HVAC systems, less attention has been given to the behaviour of building occupants. For the latter they have generally relied on fixed profiles of typical occupant presence and associated implications of their presence (Page J., 2007). This may be sufficient for most cases with fairly predictable usage patterns, such as encountered in most offices and schools. House occupants on the contrary show a highly unpredictable behaviour. They change activities throughout the day: sleeping, cooking, going out to work, etc. With these different activities corresponds a different level of internal heat gain, different room occupancy, etc. Furthermore, house inhabitants have many ways to react to unfavorable thermal conditions. Unlike most office workers, they can operate room thermostat control, change their clothing, open or close a window, etc.

In order to represent this real life conditions most faithfully, Matlab scripting language has been used to create a dedicated stochastic model of occupant behavior for this study. This model creates unique occupant behavior schedules for each day of the year with a resolution of 1 minute. The schedules represent the behavior of a family of two working parents and two school children. The activities depend on the type of day (working day, vacation leave, weekend, etc.) and the type of person (e.g. kids may go out to play, father may be preparing dinner). Poisson distributions are used to define duration of activities, and the starting time is distributed normally around its mean value.

The level of internal heat gains has an important effect on the heating demand. Therefore, the energy use associated with some of the activities (e.g. food preparation) is set based on statistical data representing the annual energy use of household equipment in Belgium (Couder et al., 2008).

For each of the 4 thermal zones a heating thermostat schedule with setback during night and working hours has been defined. This setting can be overruled if a person wakes up or comes home earlier, or if all occupants leave the house for a period of more than two hours. Additionally, the room thermostat of the bedrooms can be raised temporarily when someone does schoolwork in this room. In order to estimate the power consumption of artificial light, the time of sunrise and sunset is calculated. Lights are assumed to be on if the azimuth of the sun is lower than 10 degrees and people are present and awake in one of the rooms composing the zone.

The ventilation rate is set to 50% of the installed capacity according to Belgian standard NBN D50-001. The low energy variants K35 and K20 are assumed to be equipped with mechanical ventilation heat recovery. The ventilation rates are divided by 5 to simulate the heat recovery efficiency of 80%. The air exchange between the zones is modeled by a fixed cross ventilation rate.

**Window opening**

The dwelling has no air cooling equipment installed. To prevent overheating, people can increase ventilation by opening windows. If present, heat recovery is automatically switched off if the indoor air temperature exceeds 25°C. EnergyPlus requires a rigid schedule of hvac and occupant behavior before starting the calculation. To simulate the opening of windows and heat recovery bypass, the simulation is executed in an iterative way. The occupants decide to open the windows manually if the indoor temperature is too high. When everybody leaves the house, the windows remain closed. Before going to bed, the occupant can decide to tilt the window. If so, it

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<tbody>
<tr>
<td>K70</td>
<td>0.484</td>
<td>0.822</td>
<td>0.490</td>
<td>2.67</td>
<td>0.703</td>
</tr>
<tr>
<td>K45</td>
<td>0.373</td>
<td>0.482</td>
<td>0.345</td>
<td>1.40</td>
<td>0.568</td>
</tr>
<tr>
<td>K35</td>
<td>0.203</td>
<td>0.341</td>
<td>0.217</td>
<td>1.16</td>
<td>0.488</td>
</tr>
<tr>
<td>K20</td>
<td>0.152</td>
<td>0.203</td>
<td>0.139</td>
<td>0.81</td>
<td>0.461</td>
</tr>
</tbody>
</table>
remains in the same position till the next morning. The indoor air temperatures are obtained by executing an intermediate simulation of the building. This leads to an adapted schedule file, in which an open window is mimicked by an increased ventilation rate.

**Discomfort Indicator**

Energy demand cannot be the only criterion to evaluate a building variant, as the first and foremost function of a dwelling is the creation of a comfortable indoor environment. We are concerned about the human thermal comfort, which depends on characteristics of the person (clothing, metabolism,…) and characteristics of the environment, whereof air temperature and radiant temperature of the surroundings are the most important. As stated before, occupant behavior is far from steady state in dwellings. The desired temperatures depend on the room and the activities, and occupant can react to the thermal environment by changing clothes, operating the thermostat controller, etc. Therefore it is neither feasible nor realistic to evaluate thermal comfort in these simulations by detailed methods like the Fanger PPD/PMV model. Instead, the thermostat temperatures which the occupant has defined are assumed to be sufficient conditions to create a comfortable indoor environment. The level of thermal inertia influences indirectly surface temperature of walls and floors, which in turn affects thermal comfort. In order not to bias the simulation results, the zone heating is controlled by an operative temperature setpoint. The air temperature setpoint fluctuates so that the minimum operative temperature - the average of the zone mean air temperature and the surface weighted mean radiant temperature- is the same in all building variants.

The thermal comfort of the building variants examined in the study is evaluated by a custom created discomfort indicator. A higher number represents less favourable thermal conditions. The discomfort indicator consists of a part which measures overheating burden, and a part which measures cold discomfort because of temperatures below the heating setpoint of a zone. It is assumed that only zones which are occupied contribute to the discomfort indicator, and the severity of discomfort depends on the number of people subject to it.

The indicator of discomfort (1) counts the number of hours a zone is overheated or too cold (ts is the number of simulation timesteps per hour), times the number of people present in the zone npeople,z, times the temperature excess of the zone operative temperature TOP,z above the limit of 26°C, respectively under the heating thermostat setpoint.

$$\text{Discomfort indicator} =$$

$$\sum_{\text{timesteps}} \sum_{\text{zones}} \max(0, (T_{\text{op}, z} - 26^\circ \text{C})) \cdot n_{\text{people}, z} \cdot \text{ts}^{-1} + \sum_{\text{timesteps}} \sum_{\text{zones}} \max(0, (T_{\text{setpoint}, z} - T_{\text{op}, z})) \cdot n_{\text{people}, z} \cdot \text{ts}^{-1}$$

(1)

**Simulation Workflow**

The input for the EnergyPlus simulation engine consists of .idf files which describe the geometry, schedules, HVAC installations, etc. These .idf files of the numerous dwelling variants are automatically generated using Matlab scripts which select all possible combinations of the parameters.

Native EnergyPlus only uses one processor. In order to speed up the simulation process, the Matlab Parallel Computing Toolbox is used to create multiple instances of the EnergyPlus simulator, and run up to eight simulations in parallel.
RESULTS

Insulation versus thermal inertia

Figure 4 presents the simulation results of the 288 house variants, both semi-detached and free standing. It is clear that the annual heating energy demand is mainly governed by the level of thermal insulation of a building variant. The small energy demand of K35 and K20 variants is partly due to the heat recovery system. The average level of discomfort is higher for the lightweight buildings than for heavy weight constructions. However, thermal inertia on its own does not define the level of discomfort. Many lightweight buildings have a lower level of discomfort compared to heavyweight dwellings with less favorable glazing or orientation.

Behaviour models

Figure 5 shows the performance of the same building variants, but with a less detailed model of user behaviour. The user behaviour in figure 5 consists of a deterministic schedule which describes a typical workday and a typical weekend day. Energy use of lights, appliances, etc. is based on the average of the detailed stochastic schedule. A window opening algorithm is not included. The discomfort levels are twice as high compared to the simulation results in figure 4. This stresses the importance of the level of detail applied when modelling reliable user behaviour.

Although the discomfort indicator had dropped by more than 50% by operating windows and heat recovery bypass, the level of discomfort remains high. Figure 6 shows the potential of using sun screens to diminish the summer overheating risk. Every window is equipped with a sun screen, and these are lowered automatically if the indoor air temperature in a zone raises too high. The overheating risk is reduced dramatically, and the energy demand raises a little bit. The correlation between discomfort indicator and level of thermal insulation is much smaller compared to figure 4 and figure 5.
Finally a very basic schedule reduces all user behavior and hvac setpoints to one average value, steady throughout the year, and describes the house as one thermal zone instead of four.

The values in table 3 denote the change in heating energy demand and discomfort indicator of lightweight buildings relative to their identical massive counterpart. The values in italic denote the change of medium weight versus massive constructions. The values represent the average augmentation for both typologies, the four main building orientations and three glazing configurations.

On average, the heating energy use rises with 4.5% if a massive building is replaced by its lightweight counterpart, and the discomfort augments with 20.4%, both assuming the most realistic stochastic schedule with window opening capabilities. Contrary to the simplified basic and deterministic schedules, the detailed stochastic schedule indicates that the performance of houses with lightweight outer skin and heavy internal partitions does not differ greatly from the performance of heavy weight houses. This shows that a moderate amount of thermal mass suffices to make the building profit from the ‘thermal flywheel effect’.

The rise in energy use when applying lighter constructions is consistent for all four considered occupancy schedules, except for the simplified deterministic schedule with K45 and K70 insulation. The rise in discomfort is more pronounced than the augmentation of the energy use, with the exception of the less insulated K45 and K70 variants with solar shading.

Overall, the deterministic schedule is not able to make reliable predictions on energy demand and discomfort, compared to the results of the more realistic stochastic schedule.

### Glass and orientation

Figure 7 and 8 show the simulation results of 72 variants of the K45 dwellings. Overall, the spread in discomfort values is far greater than the spread in energy demand. Every heavy weight variant performs better on both criteria than its lightweight counterpart. Again, the results of the medium heavy buildings don’t differ much from the heavy weight buildings. For this

<table>
<thead>
<tr>
<th>Detailed stochastic schedule with window opening</th>
<th>Detailed stochastic schedule with sun shading</th>
<th>Deterministic schedule</th>
<th>Basic schedule, 1 zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>K20</td>
<td>2.3%</td>
<td>18.0%</td>
<td>0.8%</td>
</tr>
<tr>
<td>K35</td>
<td>2.2%</td>
<td>19.9%</td>
<td>2.7%</td>
</tr>
<tr>
<td>K45</td>
<td>7.8%</td>
<td>26.2%</td>
<td>3.6%</td>
</tr>
<tr>
<td>K70</td>
<td>5.7%</td>
<td>17.5%</td>
<td>3.6%</td>
</tr>
<tr>
<td></td>
<td>1.3%</td>
<td>-0.2%</td>
<td>1.2%</td>
</tr>
</tbody>
</table>

Note: Positive values denote an increase in energy demand or discomfort if a heavy weight building is changed to a light weight timber structure. The values in italic refer to a change from heavy weight to medium weight constructions.
particular building, orientation 270 yields the best results. A higher glazing percentage yields to lower energy demand: the extra solar heatgains outweigh the increased transmission losses. As expected, the higher gains lead to a higher discomfort indicator due to summer overheating. The decision on the optimal amount of glazing will thus depend on the relative importance of the energy and comfort criteria.

When optimizing the performance of a building design, the amount of glazing can not be treated separate from the building orientation. For instance, increased glazing (glass 1) generally yields a lower heating energy demand, but buildings with low glazing amount and orientation 0 perform better on both criteria compared to buildings with increased glazing and orientation 90. The relative impact of changing thermal mass is fairly constant for the 3 glazing configurations. Comparing nominal change of the discomfort indicator indicates that thermal mass is most needed for variants with higher glazing percentages.

**CONCLUSION**

Dynamic simulations of different dwelling variants in Belgian climatic conditions show the influence of building thermal mass on heating energy demand and thermal comfort. On average, a woodframe house demands 4.5% more heating energy compared to a heavy weight brick and concrete structure. This effect is very small compared to the impact of the level of thermal insulation.

The impact of thermal mass on discomfort is more pronounced, with an average 20.4% increase for lightweight buildings. A combination of lightweight outer skin, and heavy weight internal partitions performs much like a heavy weight building.
Thermal inertia on its own does not define the level of discomfort. Many heavy weight design alternatives have a higher level of discomfort compared to light weight buildings with less glazing or a more favorable building orientation.

In order to obtain more reliable simulation results, the quality of the model of occupant behaviour proved to be very important. User interactions such as opening windows or operating sun shading have a greater effect on thermal comfort than the level of thermal inertia.

Further research will focus on the incorporation of sun shading devices and a more detailed model to incorporate inertia of the heating equipment.

ACKNOWLEDGEMENT
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