Simplified calculation model for predicting overheating in early design phases. A trade-off between simplicity and accuracy

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Abstract: Early design support for summer comfort is increasingly important, considering the trend towards highly insulated buildings together with the importance of glass in contemporary architecture and the probability of higher outdoor temperatures due to climate change. From this perspective, this paper focuses on the integration of summer comfort evaluations of dwellings in early design phases. The reliability of a simple heat-balance based calculation model for an early indication of overheating was extensively tested in a comparative analysis with a multi-zone dynamic simulation in TRNSYS. A parametric study was conducted for both the simplified approach and TRNSYS, to evaluate the most important simplifications assumed in the model and to determine the impact of reduced data-input and complexity on the accuracy.

Keywords: Summer comfort, early design phase, architects, simplified model, parametric study

1 Introduction

Buildings are increasingly insulated to reduce energy use and greenhouse gas emissions. This positively influences thermal comfort in winter, but might result in higher indoor temperatures in summer. Further, due to climate change, outdoor temperatures are expected to rise (IPCC, 2007). Along with the importance of glass in contemporary architecture, overheating might thus become a growing problem in future buildings, even in moderate climates.

This creates enormous challenges to architects when designing new buildings. Architects should not only be aware of this important problem, they should also know how to anticipate to it with their designs. Considering that the sketch design creates the foundation for a good thermal design (Ellis and Mathews, 2001), early design support for architects on summer comfort becomes increasingly important, especially for small projects that lack engineering support due to limited budgets.

Therefore, this paper focuses on the integration of summer comfort evaluations of dwellings in early design phases (EDP). The current research starts from the assumption that for a simple and quick evaluation of summer comfort it is more important to provide a clear indication of possible problem areas in the design than very detailed and accurate results, taking into account the target audience (architects), the type of projects (dwellings) and the design phase (sketch design) the evaluation is intended for. Other important aspects concern a direct coupling between design and
evaluation enabling designers to assess the impact of architectural design parameters on the building performance, and simple straightforward output.

In the past, several calculation procedures and simulation tools have been developed for thermal comfort evaluations of buildings, ranging from very simple design rules to highly detailed calculation procedures. Maeyens (2001) outlines several existing design rules to test a design for summer overheating. These design rules differ in their degree of detail from simply providing a maximum allowable value for the product of g-value and glazing percentage to more analytical methods. The former tend to be rather prescriptive and lack a clear link with the architectural design. Hence, their applicability in the design process is limited. Meanwhile, more detailed methods, such as advanced dynamic multi-zone building performance simulation tools (BPST) like TRNSYS\(^1\) or EnergyPlus\(^2\) are too detailed and complex for use by architects in EDP. In this regard, several researchers have proposed and validated simplified methods for building designers to evaluate the thermal performance of their designs (Mathews et al., 1994; Ellis and Mathews, 2001; Nielsen, 2005; NBN EN ISO 13792; Schultz and Svendsen, 1998). These models often adopt a middle course between the simple design rules and the advanced BPST. Some of these models were subjected to extensive validation tests and provide reasonably accurate results, but still tend to be rather detailed for a quick evaluation of the summer performance in EDP by architects (Mathews et al., 1994; NBN EN ISO 13792). Other models require less detailed data-input but the validation tests were only performed for a small number of variants (Nielsen, 2005, Schultz and Svendsen, 1998). Finally, the Flemish energy performance legislation includes the use of an overheating indicator to ensure acceptable comfort levels in summer (EPB Besluit Bijlage I, 2005). This provides Flemish architects with easily interpretable feedback on the summer performance of their design. The calculation model however consists of a monthly based steady-state one zone approach and is therefore too limited for a good summer comfort evaluation, as problem zones cannot be detected.

In this context, the current research investigates the potential of a simplified calculation model to predict overheating of dwellings in EDP. The quasi-steady-state calculation model is based on the basic heat balance to determine hourly indoor temperatures for a room. Each room is treated separately and inter-zonal heat gains are ignored. A description of the model and its simplifications is given in section 2. The model only requires very limited and architect oriented data-input, and thus is adapted to EDP. The output consists of hourly temperatures during one summer month and is therefore easily adjustable to architects. However, the simplifications also lead to less accurate results.

Therefore, the objective of the research is twofold. The first purpose consists of determining which assumptions and simplifications in a simplified calculation model legitimate less accurate results in favour of reduced data-input and reduced complexity of the model. The second aim relates to identifying the applicability and the reliability of the simplified model for a simple evaluation of summer comfort in EDP, considering the important issues identified earlier. This was extensively tested in a comparative analysis with a multi-zone simulation in TRNSYS.

A parametric study was conducted for both models and the results were compared to evaluate the most important simplifications assumed in the model. This paper first presents the methodology (section 2). Then the most important results of this parametric analysis are documented, showing to what extent the simplifications of the model justify a more limited and architect oriented data-input against less accurate results. The results in general show that the quasi-steady-state method provides a

\(^1\) [http://sel.me.wisc.edu/trnsys/](http://sel.me.wisc.edu/trnsys/)

good indication for EDP of problem areas in the design regarding overheating, despite extensive simplifications.

2 Methodology

2.1 Simplified quasi-steady-state model

In this approach, summer comfort is estimated by calculating the indoor temperature for each zone separately on an hourly basis during one summer month (i.e. July), based on the heat-balance in its basic form. The indoor temperature depends on the outdoor temperature, the heat gains (internal ($\Phi_i$) and solar gains ($\Phi_s$)), the heat losses (conduction ($\Phi_T$) and ventilation ($\Phi_V$)) and the heat capacity of the building ($\sum \rho \cdot c \cdot d \cdot A$). Considering the focus of the research on dwellings, active cooling is not taken into account. In moderate climates such as the Belgian climate, passive design measures can make mechanical cooling redundant for dwellings, which should be stimulated during the design. Hence, the calculated indoor temperature concerns the free floating temperature.

In this model, the different zones of multi-zone dwellings are analysed separately, thus, ignoring heat gains from adjacent zones (i.e. inter-zonal gains). The model uses a fixed thermal capacity, which explains the term ‘quasi-steady-state’. Further, an initial indoor temperature of 20°C was assumed. The hourly climate data were derived from the Test Reference Year from Uccle, as used in TRNSYS.

Heat balance:

$$\Phi_s + \Phi_i + \Phi_h = \Phi_T + \Phi_V + \frac{dU}{dt}$$

With:

$$\frac{dU}{dt} = \sum \rho_i \cdot c_i \cdot d_i \cdot A_i \cdot \frac{\Delta \theta_i}{\Delta t}$$

Indoor temperature at a given time:

$$\theta_{in} = \left( \frac{\Phi_T + \Phi_V}{\sum \rho_i \cdot c_i \cdot d_i \cdot A_i} \cdot 3600 \right) + \theta_i$$

2.2 Assumptions and simplifications

The model is based on following simplifications:

- Only the indoor air temperature is calculated;
- Solar gains are directly injected into the room air temperature, instead of first being absorbed by construction components
- The capacity of the construction is integrated, but simplified as a fixed value. A thickness of maximum 10cm was considered to determine the thermal capacity
- Indirect solar gains through opaque construction elements are ignored
- A mean U-value is used for the calculation of transmission losses and heat losses to the ground are simplified through a reduction factor applied on the U-value
- Each zone of a multi-zone building is analyzed independently; inter-zonal heat gains/losses are ignored
- A fixed value is used for the dependency of the solar energy transmittance on the incidence angle
2.3 Parametric study

From the outline above, it is clear that the simplifications lead to less accurate results. However, since the objective of the research is to develop a method that allows to give a quick and easy indication of the performance of the design during EDP, this research aims at examining which simplifications are (not) justified in this context.

Therefore, the inherent simplifications of this method compared to an advanced dynamic simulation are investigated in a parametric study, in which the reliability of this simplified approach was extensively tested through a comparative analysis with multi-zone dynamic TRNSYS simulations.

Two cubes (3x3x3m and 10x10x10m), each representing a single thermal zone, were used to simulate multiple variants in the quasi steady-state method and in TRNSYS. In addition to building volume, parameters such as window-to-floor-ratio, orientation, thermal mass and U-values of construction components were included. The examined variants are based on the assumptions and simplifications discussed earlier, to analyze the impact of these simplifications.

The simulations were conducted for one summer month, i.e. July, with a time-step of one hour.

\[
\begin{array}{|c|c|}
\hline
\text{Volume:} & 27m^3 & 1000m^3 \\
\text{Total loss area:} & 54m^2 & 600m^2 \\
\text{Compactness:} & 0.5m & 1.67m \\
\hline
\end{array}
\]

**Figure 1: Two cubes as basis for the parametric study**

The following assumptions and fixed values were employed for the parametric study:
- A fixed ventilation rate of n=1/h was assumed
- No internal gains were considered
- Calculations were based on external dimensions
- The maximum U-values of the construction components are based on the Flemish energy code, i.e. a maximum U-value of 0.4W/m²K; only values equal to or lower than 0.4W/m²K were considered
- Windows consist of 100% glass area, i.e. window frames are neglected
- The isotropic sky model is used for calculating solar gains in both models
- The composition of construction components is summarized in table 1
- Other inputs are shown in table 2

Matlab was used to automate the simulations in TRNSYS. The calculations for the simple model were conducted and automated in MS Excel.

The simple model calculates the indoor air temperature. In TRNSYS the operative temperature was calculated, as this provides a more accurate indicator for thermal comfort.

The impact of the simplifications is studied by calculating the mean difference between the temperatures from TRNSYS and from the simplified model for each parameter combination. First, the hourly difference in temperature between TRNSYS and the quasi-steady-state model was calculated during the entire month. Then, the mean and standard deviation (stdev) of these differences over the entire calculation period (one month) were determined for the particular parameter combination.
Furthermore, to examine whether the simplified model is able to provide a good indication of summer comfort in EDP, the maximum, mean and mean+stdev of the hourly temperatures over the entire month obtained from TRNSYS and the quasi-steady-state method are compared for the different combinations.

**Table 1: Composition of construction components**

<table>
<thead>
<tr>
<th>COMPOSITION OF CONSTRUCTION COMPONENTS</th>
<th>Thickness [m]</th>
<th>$\lambda$ [W/mK]</th>
<th>$\varepsilon$ [kJ/kgK]</th>
<th>$\rho$ [kg/m$^3$]</th>
<th>Umean [W/m²K]</th>
<th>absorption coefficient inside</th>
<th>outside</th>
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<tbody>
<tr>
<td><strong>WALLS</strong></td>
<td></td>
<td></td>
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<tr>
<td>TRNSYS:</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gypsum plaster</td>
<td>0.01</td>
<td>0.52</td>
<td>1</td>
<td>1100</td>
<td>0.3</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>building brick</td>
<td>0.14</td>
<td>0.419</td>
<td>1</td>
<td>1200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>insulation</td>
<td>0.047</td>
<td>0.025</td>
<td>1.4</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>facing brick</td>
<td>0.09</td>
<td>0.985</td>
<td>1</td>
<td>1400</td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
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<tr>
<td><strong>ROOF</strong></td>
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<tr>
<td>Gypsum plaster</td>
<td>0.01</td>
<td>0.52</td>
<td>1</td>
<td>1100</td>
<td>0.2</td>
<td>0.9</td>
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<tr>
<td>Concrete</td>
<td>0.15</td>
<td>1.7</td>
<td>1</td>
<td>2400</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light concrete</td>
<td>0.049</td>
<td>0.21</td>
<td>1</td>
<td>650</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation</td>
<td>0.05</td>
<td>0.025</td>
<td>1.4</td>
<td>40</td>
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<td></td>
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<tr>
<td>SIMPLIFIED MODEL:</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>FLOOR ON GROUND</strong></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>TRNSYS:</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>ceramic tile</td>
<td>0.02</td>
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<td>1</td>
<td>1700</td>
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<tr>
<td>Light concrete</td>
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<td>0.21</td>
<td>1</td>
<td>650</td>
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<tr>
<td>concrete</td>
<td>0.15</td>
<td>1.7</td>
<td>1</td>
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<tr>
<td>insulation</td>
<td>0.021</td>
<td>0.025</td>
<td>1.4</td>
<td>40</td>
<td></td>
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<td></td>
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</table>

* ground temperature calculated with simplified ground temperature model (type 77)

| SIMPLIFIED MODEL:                      | -             | -                | -                      | -                | 0.4          | -                           | -       |

**Table 2: Other input parameters**

<table>
<thead>
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<th></th>
<th>TRNSYS</th>
<th>SIMPLIFIED MODEL</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>internal heat gains</td>
<td>0</td>
<td>0</td>
<td>W</td>
</tr>
<tr>
<td>Air-change ventilation</td>
<td>0.609</td>
<td>0.609</td>
<td>/h</td>
</tr>
<tr>
<td>g-value glass</td>
<td>1.1</td>
<td>1.1</td>
<td>W/m²K</td>
</tr>
<tr>
<td>schedules</td>
<td>no schedules</td>
<td>no schedules</td>
<td>-</td>
</tr>
<tr>
<td>shading factor</td>
<td>no shading</td>
<td>no shading</td>
<td>-</td>
</tr>
<tr>
<td>climate data</td>
<td>test reference year Uccle</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>heating</td>
<td>-</td>
<td>-</td>
<td>heating</td>
</tr>
<tr>
<td>cooling</td>
<td>-</td>
<td>-</td>
<td>cooling</td>
</tr>
</tbody>
</table>

**3 Results**

In this section, a small fraction of the results of the parametric study are summarized. Depending on the variant, the impact of the simplifications outlined earlier was entirely studied in TRNSYS or both in TRNSYS and the simplified model. The first approach was used to study the impact of general assumptions or simplifications, whereas the latter was used for both studying the impact of specific simplifications as well as determining the applicability of the simplified model for an indication in EDP.

**3.1 Variation 1: one versus multi-zone model**

In this variant, the importance of modelling a building on a multi-zone against a one-zone level was studied in TRNSYS.

**Figure 2: Configuration of cubes for variant 1**
Two cubes were placed on top of each other, representing two rooms (figure 2). The configuration on the left consists of two zones, while the model on the right consists of a single zone. The upper cube (zone 2) remains fully opaque during the entire parametric study, while the window-to-floor-ratio (WFR) of the lower cube (zone 1) varies from 100% to 0%, in steps of 10%. The glazing area was uniformly distributed over the 4 orientations. In total, 176 parameter combinations were simulated in TRNSYS. The different parameter ranges are outlined in table 3. To investigate the impact of the floor separating both rooms, two densities and thermal conductivities were included. The floor was simplified as a single layer with a thickness of 20cm. The heat capacity of this floor (c) remained 1000 J/kgK for all variants.

Table 3: Parameter ranges for variant 1

<table>
<thead>
<tr>
<th>PARAMETER:</th>
<th>VALUES OR RANGES:</th>
<th>N°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (single cube)</td>
<td>3x3x3; 10x10x10</td>
<td>m³</td>
</tr>
<tr>
<td>U opaque</td>
<td>0.4; 0.1</td>
<td>W/m²K</td>
</tr>
<tr>
<td>WFR zone 1</td>
<td>100% to 0%; in steps of 10%</td>
<td>%</td>
</tr>
<tr>
<td>Density intermediate floor</td>
<td>2000; 500</td>
<td>kg/m³</td>
</tr>
<tr>
<td>λ intermediate floor</td>
<td>1.7; 0.15</td>
<td>W/mK</td>
</tr>
<tr>
<td>TOTAL NUMBER OF COMBINATIONS</td>
<td></td>
<td># 176</td>
</tr>
</tbody>
</table>

The results for cube 3x3x3 with a U-value for opaque constructions of 0.4 W/m²K are displayed in the graphs below (figure 3). The upper graphs show the maximum temperature, whereas the lower graphs give the mean temperature and the mean+stdev as a function of the WFR in zone 1. The graphs on the left show the results for the intermediate floor with the highest thermal conductivity, and the graphs on the right for the lower thermal conductivity. All graphs provide the temperatures for zone 1 and zone 2 modeled as two separate zones, as well as for the configuration with both rooms considered as a single zone (zone 1+2). The dotted line in the graphs highlights a temperature of 27°C and is used to indicate overheating problems.

Cubes 3x3x3; U opaque 0.4W/m²K

Figure 3 shows that highest temperatures are reached in zone 1 (blue marks). While zone 2 (green marks) remains opaque, the temperature in this zone is influenced by heat transfer from zone 1 and thus slightly increases with increasing WFR in zone 1.
When both rooms are modeled as a single zone, i.e. zone 1+2 (red marks), the temperatures fall in between these of zone 1 and 2. The results are more pronounced for the better insulated intermediate floor (graphs on the right), as the heat transfer from zone 1 to 2 is more obstructed. Further, there is only a very small difference between the light and heavy intermediate floor. Similar tendencies are found for the maximum temperature as for the mean and mean+stdev temperatures. Overall, the results reveal that for a good indication of summer comfort, a multi-zone model is more appropriate to detect problem areas with regard to overheating. Overheating occurs faster and more pronounced in zone 1 than for both rooms modeled as a single zone. The results for an opaque U-value of 0.1 were similar but more pronounced. Also, similar findings were examined for cube 10x10x10.

3.2 Variation 2: impact of inter-zonal gains/losses

The previous variant revealed the importance of multi-zone modeling, to identify important problem zones. Subsequently, this variant investigates the assumption that for an early indication of summer comfort it might be sufficient to simulate multiple zones of a dwelling independently from each other. In other words, the impact of inter-zonal heat transfer is examined in TRNSYS. The same arrangement, with two cubes on top of each other, was used for this analysis. Two configurations as shown in figure 4, were compared. In the left configuration both zones are simulated as a multi-zone model including inter-zonal heat transfer, while in the right configuration the two zones are modeled separately from each other and the intermediate floor is adiabatic. The same combinations were considered as in the previous variant (table 3) and zone 2 remains opaque.

**Figure 4: Configuration of cubes for variant 2**

Figure 5 shows the results for cubes 3x3x3 with a Uopaque of 0.4W/m²K and displays the maximum temperature (upper graph) and the mean temperature and the mean+stdev (lower graph) for zone 1 and 2. The dotted line represents a temperature of 27°C and is used as an indication for overheating. The marks in black show the results for both zones modeled separately. The marks in red display the results for the multi-zone model with the higher conductivity for the heavy intermediate floor, while the marks in blue demonstrate the results for the heavy floor with lower conductivity. In practice the conductivity of the intermediate floor will usually lie in between both values. The graphs only include the results for the heavy floor (density of 2000kg/m³), as there was only a very small difference for the light floor. Figure 5 reveals a clear impact of heat transfer from zone 1 to zone 2. The temperature in zone 1 increases when modeling the zones separately. The maximum and mean temperature rise up to 5°C more compared to the multi-zone model with the high conductivity floor for a WFR of 100%. The difference with the low conductivity floor is very limited. The temperature difference decreases with a lower WFR in zone 1. When considering a realistic difference in glazing percentage between both zones (0-30%), the impact of inter-zonal heat transfer decreases and is rather limited (up to 2.4°C for zone 1). In general, the separated model overestimates the temperature in zone 1 and overheating problems occur at a lower WFR than in the multi-zone model. The maximum temperature in the separated zone just exceeds the limit of 27°C at a
WFR of 30%, while the multi-zone model approximates this limit at a WFR of 40% (figure 5, upper graph). Nonetheless, the maximum temperature alone does not indicate the frequency of time above 27°C and thus is not sufficient for an indication of overheating. Looking also at the mean+stdev temperature (figure 5, lower graph) it appears that overheating is likely to occur at a WFR of 40% for the separated zone and at a WFR of 50% and 60% for the multi-zone model with the low conductivity floor and the high conductivity floor respectively. Overall, this difference in WFR is rather limited, especially considering the focus of the research on EDP. Besides, these results concern a high difference in WFR between zone 1 and 2, compared to current dwelling designs. Similar results were observed for an opaque U-value of 0.1 W/m²K, but the temperatures reach higher values because heat transfer through outdoor walls is significantly impeded. Also, similar trends appeared for cubes 10x10x10, but the impact of inter-zonal gains is much smaller as the initial temperatures remained lower probably due to its higher volume compactness.

CUBES 3x3x3; Uopaque 0.4 W/m²K

![Graph showing temperature variations across different WFR values](image)

Figure 5: Maximum temperature (upper graph), mean temperature and mean temperature+stdev (lower graph) in TRNSYS for cubes 3x3x3 and Uopaque 0.4 W/m²K; LC = low conductivity

Considering zone 2, the temperatures drop and remain constant when modeled separately, as they no longer depend on the WFR of zone 1 (figure 5). In this case, the separated model underestimates the zone temperature. However, overheating is not likely to occur in this zone only as a result of heat transfer from zone 1. In the multi-zone model, the maximum temperatures remain below the limit of 27°C, even for high glazing percentages in zone 1 (figure 5, upper graph). In practice, the difference in WFR between adjacent zones will be smaller. Consequently, the temperature difference between the zones will be smaller resulting in a lower impact of inter-zonal
heat transfer. Similar results were achieved for cubes 10x10x10, but with a much smaller impact.

Overall, the results show that it is acceptable to simulate multiple zones of a dwelling independently from each other for a first indication of overheating in EDP. Although the temperature is overestimated in zone 1, the impact is relatively small as both configurations predict overheating problems at almost similar boundary conditions. Summarized, problem zones can clearly be detected using the separated configuration, which will draw the attention of building designers to these particular zones.

### 3.3 Variation 3: impact of direct solar gains

The previous variant proved that the simplification of considering different zones of a dwelling separately is justified to significantly reduce the complexity of the model, while remaining a valuable indication for summer comfort in EDP. This variant examines the specific simplification of the simplified model in which solar gains are directly injected into the air temperature. The reliability of the simplified model for a first indication of problem zones in EDP is further examined by comparing different parameter combinations simulated in the simplified model and in TRNSYS (table 4).

The configuration consists of a single cube. The WFR increases from 0 to 100% for a uniform distribution among the four orientations. Besides, the impact of the orientation was also taken into account, by simulating several WFRs distributed among one main orientation.

#### Table 4: Parameter ranges for variant 3

<table>
<thead>
<tr>
<th>PARAMETER:</th>
<th>VALUES OR RANGES:</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>3x3x3; 10x10x10</td>
<td>m³</td>
</tr>
<tr>
<td>U opaque</td>
<td>0.4; 0.1 W/m²K</td>
<td>#2</td>
</tr>
<tr>
<td>WFR, uniform</td>
<td>0-100 % in steps of 10%</td>
<td>%</td>
</tr>
<tr>
<td>WFR per orientation</td>
<td>10; 30; 50; 70; 90%</td>
<td>%</td>
</tr>
<tr>
<td>orientation: N/O/Z/W</td>
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</table>

**TOTAL NUMBER OF COMBINATIONS #124**

**Figure 6:** Average temperature difference between the simplified model and TRNSYS for cube 3x3x3 (left) and cube 10x10x10 (right)

Figure 6 shows the average difference between the air temperature of the simplified model and the operative temperature of TRNSYS for both cubes. This difference increases to approximately 3°C and 4°C for an opaque U-value of 0.4 and 0.1 W/m²K respectively for cube 3. The difference thus is slightly higher for well insulated constructions. The temperature difference clearly increases with increasing WFR and
also the STDEV ranges from 0.2 and 0.8°C for a WFR of 20% to 4.5 and 7°C for a WFR of 100% for a Uopaque of 0.4 and 0.1 W/m²K respectively. The impact of the orientation is very limited. Southern orientations show a slightly higher difference, probably due to higher solar radiation. Considering realistic WFRs (up to 40%), the difference between the simplified model and TRNSYS is rather small (0.2°C ± 0.8°C; for Uopaque 0.4 W/m²K) and even negative for glazing percentages up to 20%. Negative values represent higher temperatures in TRNSYS than in the simplified model. This is probably due to indirect solar gains, which are not considered in the simplified model.

Cube 10 (figure 6; right graph) shows similar trends, but the average difference with TRNSYS is much smaller (up to approximately 2°C), even for high WFRs. This is probably due to the higher volume compactness.

**Figure 7:** Maximum temperature (left) and mean temperature and mean+stdev (right) for cube 3x3x3 in TRNSYS and the simplified model for a uniform glazing distribution

To examine the applicability of the simplified model for EDP, the maximum temperature, the mean and the mean+stdev temperature were compared with the results obtained in TRNSYS (figure 7). The temperatures are higher in the simplified model than in TRNSYS. The opaque U-value of 0.1W/m²K reaches higher temperatures than 0.4 W/m²K, in both models and the difference between the models slightly increases.

Although there is a difference between both models in absolute values, which clearly increases with larger WFRs, tendencies are similar between TRNSYS and the simplified model when looking at the WFR for which both models predict overheating. For large WFRs with a large difference in absolute temperatures both models clearly predict overheating problems. For smaller WFRs, where the difference between the models is limited, the simplified model predicts overheating slightly earlier than TRNSYS. In particular, for a Uopaque of 0.4W/m²K, the maximum temperature exceeds the limit of 27°C at a WFR of 40% in both TRNSYS and the simplified model, with a temperature difference about 1°C between the models. However, the corresponding mean+stdev merely approximates 25°C, which does not indicate overheating. Looking at both the maximum temperature and the mean+stdev, it appears that the simplified model shows overheating problems around 50% WFR and TRNSYS around 60%. This is only a margin of 10% which is an acceptable accuracy for EDP. Similar trends are found for a Uopaque of 0.1W/m²K, but overheating occurs at a lower WFR (figure 7).

Similar results were also shown for cube 10x10x10, but temperatures remained much lower, for both TRNSYS and the simplified model. Also, the temperature difference between the two models was much smaller.
3.4 Variation 4: impact of indirect solar gains

While the simplification of direct solar gains was analyzed in the former variant, this variant investigates the impact of indirect solar gains. This analysis was conducted in TRNSYS and as a comparison between TRNSYS and the simplified model. This paper only presents the results obtained from TRNSYS. The same combinations and parameter ranges were applied as in the previous variant (table 4). In addition, the absorption coefficients of the roof and the walls were varied for this particular variant (table 5). In total, 372 combinations were simulated in TRNSYS. Figure 8 demonstrates the average temperature difference in TRNSYS between the combinations with the absorption coefficient of the starting situation and the other absorption coefficients (see also table 5).

**Table 5: Absorption coefficients for the walls \((\alpha_w)\) and the roof \((\alpha_R)\)**

<table>
<thead>
<tr>
<th>Starting situation:</th>
<th>(\alpha_w=0.9, \alpha_R=0.9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other combinations:</td>
<td>(\alpha_w=0.6, \alpha_R=0.9)</td>
</tr>
<tr>
<td></td>
<td>(\alpha_w=0.6, \alpha_R=0.6)</td>
</tr>
</tbody>
</table>

The results for cube 3x3x3 (figure 8) show that there is only a very small average temperature difference and a small STDEV between the different absorption coefficients. The difference is smaller for a Uopaque of 0.1 than 0.4 W/m²K and for larger WFRs (reduced wall area). Consequently, the impact of indirect solar gains is limited. Similar conclusions appeared from the comparison between TRNSYS and the simplified model. Nonetheless, these results specifically apply to the moderate climate of Belgium and well insulated constructions. The impact would probably be higher for less insulated constructions. Similar results were found for cube 10x10x10, but the impact appeared to be even smaller.

![Figure 8: Average temperature difference in TRNSYS against the starting situation with an absorption coefficient of the walls \((\alpha_w)=0.9\) and the roof \((\alpha_R)=0.9\)](image)

3.5 Variation 5: impact of the mean U-value

In this variation, the impact of the mean U-value is studied. In particular, this variation analyses whether it would be acceptable for an indication in EDP to use the mean U-value of a zone instead of the U-values of the individual construction components. Unlike TRNSYS, the simplified model does not distinguish between the U-values of individual components. The impact was studied in TRNSYS, but also as a comparison between TRNSYS and the simplified model. This paper only reports on the analysis in TRNSYS.
This analysis started from several fixed mean U-values. For each mean U-value the U-values of the walls, the roof and the floor were varied. Fixed values were used for the roof and the floor. The U-value of the walls was calculated as function of the mean U-value, the U-values of the floor, the roof and the windows. A number of combinations were analyzed for 3 different glazing percentages (table 6).

**Table 6: Parameter ranges for variant 5**

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUES OR RANGES:</th>
<th>N°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>3x3x3; 10x10x10</td>
<td>m³</td>
</tr>
<tr>
<td>Window-to-wall ratio</td>
<td>5%; 10%; 15%</td>
<td>%</td>
</tr>
<tr>
<td>Mean U-value</td>
<td>0.7-0.6-0.5-0.4-0.3</td>
<td>W/m²K</td>
</tr>
<tr>
<td>U-roof</td>
<td>0.7-0.6-0.5-0.4-0.3-0.2-0.1</td>
<td>W/m²K</td>
</tr>
<tr>
<td>U-floor</td>
<td>0.7-0.6-0.5-0.4-0.3-0.2-0.1</td>
<td>W/m²K</td>
</tr>
<tr>
<td>U-wall</td>
<td>function of U-floor/roof</td>
<td>W/m²K</td>
</tr>
<tr>
<td>TOTAL NUMBER OF COMBINATIONS</td>
<td>#1402</td>
<td></td>
</tr>
</tbody>
</table>

Figure 9 shows the results for cubes 3x3x3 and 10x10x10 with a window-to-wall ratio (WWR) of 5%, which corresponds to a WFR of 20%. The graphs demonstrate the temperature range for each mean U-value. This was obtained by calculating the average temperature difference between the different combinations and a reference case. For each mean U-value the reference case differs and corresponds to the combination with highest U-values for the floor and the roof. Basically, the choice of the reference case is arbitrary as this analysis specifically concerns the distribution of the results. The results presented in the graphs only concern combinations that meet current regulatory requirements for the U-values of the floor (maximum 0.4 W/m²K) and the roof (maximum 0.3W/m²K).

The entire spread on these results varies between 0.35°C (for a Umean=0.7W/m²K) and 0.6°C (Umean= 0.3W/m²K) for cube 3x3x3 (left graph) and situates around 0.3°C for cube 10x10x10 (right graph). This however still includes U-values of the wall that do not meet current regulatory requirements. The lower the mean U-value the higher the spread. Furthermore, the spread on the results is larger when varying the U-value of the floor at a constant U-value of the roof (black arrow) than the other way around (dotted arrow). This is probably due to heat losses to the ground. In summer, the ground has a cooling effect, but this effect decreases with better insulated constructions.

Overall, the spread in results is rather limited. This indicates that mean U-values are acceptable for an indication of summer comfort in EDP. Besides, as regulations become stricter in future, the effect of the mean U-value will further decrease, as the difference between the U-values of the distinctive components decreases. The results were similar for the other glazing percentages.

**Figure 9:** Average temperature difference in TRNSYS against a base case per mean U-value for a WWR of 5%; U-values of the floor and roof that do not meet current regulatory requirements are excluded (left: cube 3x3x3; right: cube 10x10x10).
Figure 10 displays the maximum temperature (left graph) and the mean temperature +stdev (right graph) for cube 3x3x3 and a WWR of 5%. Only combinations that meet current regulatory requirements for the U-values of the floor and the roof are included in the graphs.

The tendencies are similar as in figure 9. The spread is rather limited and is slightly larger at lower mean U-values. Nonetheless, overheating is not likely to occur only as a result of a difference in U-value of the distinctive construction components and the mean U-value. Similar results were observed for cube 10x10x10.

The comparison between TRNSYS and the simplified model corresponded to the former results. Largest temperature deviations between both models appeared for the variations in the U-value of the floor. This is probably due to the difference in calculating heat losses to the ground. The results of this comparison further revealed that the WFR largely determines the temperature difference between both models, followed by the mean U-value. The better insulated the building, the larger the temperature deviation, as indicated previously. Ultimately, the deviation is defined by the difference in mean U-value versus the U-values of the construction components.

Figure 10: Maximum temperature (left) and mean temperature and mean+stdev (right) in TRNSYS for cube 3x3x3 and a WWR of 5%, with exclusion of U-values of the floor and roof that do not meet current regulatory requirements

3.6 Other variations

Due to the extensiveness of the study it is not possible to report on all variants analyzed. Therefore, this section summarizes some results of other variations. The simplification of the air versus the operative temperature was studied in TRNSYS. Only a very small temperature deviation appeared between both factors, which might be due to the specific focus on the summer situation. Hence, the air temperature can be used for a first evaluation of summer comfort in EDP.

The thermal mass was also included in a variation. Three different types were considered ranging from light to heavy structures. A comparison was made between TRNSYS and the simplified model. The average temperature difference between both models was equal for all three construction types, but the STDEV of the temperature differences increased with lower thermal mass. For lighter constructions, the maximum temperature raised in both models, but the deviation in the maximum temperature also increased. This might be explained by the fact that the simplified model overestimates the thermal mass, as it uses a fixed value that is continuously available. Consequently, the indoor temperature is lowered. This simplification partly neutralizes the simplification of injecting solar gains directly into the air temperature and has a larger impact for high thermal mass. Nevertheless, both models predict similar trends for summer comfort. Largest deviations between both models occurred at high WFRs, but at this point both models clearly predict overheating. Considering more realistic WFRs, the temperature deviations were much smaller, but then the
simplified model points out overheating slightly earlier than TRNSYS. However, regarding the focus of this research on EDP, this small safety margin is acceptable. Finally, the impact of internal gains was analyzed in a comparison between TRNSYS and the simplified model. They have no impact on the difference between both models, as the temperatures increased equally when adding internal gains.

4 Discussion and conclusions

Aim of the current study was to analyze the extent to which simplifications in a calculation model for summer comfort are justified against less accurate results, and to examine the applicability of a simplified model in EDP. This was investigated through a detailed parametric study in the simplified model and in TRNSYS. The emphasis of this research is on EDP. In these phases it is particularly important that architects are able to quickly assess the summer performance of their design and to distinguish problem zones without the need for accurate temperature predictions. This would enable them to early explore conceptual and architectural solutions. As such, absolute accuracy is of minor importance.

The results of this study stress the importance of considering multiple zones in a dwelling versus a single zone model. With regard to EDP the data further suggest that it is acceptable to consider these zones individually from each other. The results also imply that indirect solar gains may be ignored in EDP. However, these results apply in particular to well insulated constructions (the research only considered opaque U-values up to 0.4W/m²K) and to the moderate Belgian climate. The mean U-value also appeared to be acceptable for an early indication of summer comfort.

Overall, the results support the application of the simplified model in EDP, with respect to the particular objectives of these phases as stated earlier. Although the simplified model appeared to overestimate the temperature, it nevertheless is able to provide a decisive answer regarding design problem zones. Similar trends are predicted as TRNSYS, but with a small safety margin. Therefore, the communication of the results should require special attention. Further, largest deviations with TRNSYS occurred at high WFRs. This was related to the injection of solar gains directly into the air temperature, which seems to be one of the largest simplifications of the model. A review of models reported in literature (see also section 1), points out that the model described in (Nielsen, 2005) also seems to require limited data-input, but this model distinguishes between indoor air temperature, surface temperature and temperature in the construction. Also, solar gains are first partly absorbed in the internal surfaces before submitted to the air temperature. Consequently, this two-node model is more detailed and could possibly provide a better answer. However, this model was only subjected to a few tests. Therefore the applicability of this model clearly deserves further investigation, which will be the subject of future research.

Finally, it could be argued that considering the various simplifications one by one does not provide a comprehensive understanding of the applicability of the simplified model. Therefore, some case studies of real houses were performed to compare the simplified model with TRNSYS. Some of these results are reported in Weytjens and Verbeeck (2011). These case studies corroborate the former results.

Acknowledgement

Research funded by a Ph.D. grant of the Agency for Innovation by Science and Technology (IWT).
References

EPB Besluit Bijlage I (2005), Bepalingsmethode van het peil van primair energieverbruik van woongebouwen.


Appendix 1. List of symbols

- $\Phi_s$: solar gains (in W)
- $\Phi_i$: internal heat gains (in W)
- $\Phi_h$: heating or cooling demand
- $\Phi_T$: transmission heat losses (in W)
- $\Phi_V$: ventilation heat losses (in W)
- $\frac{dU}{dt}$: thermal capacitance
- $\rho$: density (kg/m³)
- $c$: heat capacity (J/kgK)
- $d$: thickness (m)
- $A$: surface area (m²)
- $\theta$: temperature (°C)
- $\theta_i$: indoor temperature (°C)
- $\Delta t$: time step (s)