
Mohamad Rida¹, Sabine Hoffmann¹
¹Technische Universität Kaiserslautern, Kaiserslautern, Germany

Abstract
People adapt to thermal conditions by altering their clothing, hence clothing insulation is a significant parameter for the thermal comfort calculation. Fixed clothing insulation is usually used when evaluating thermal comfort in building simulation. Therefore, this study proposes a dynamic clothing model to predict the clothing insulation of building occupants. The model considers outdoor temperature, operative temperature in addition to the sensation history, as well as the present local sensation. This model is combined with PhycSO, a thermo-physiology model fully implemented in ESP-r. This tool predicts occupant thermal comfort in a more realistic way, which increases the accuracy of prediction of building energy consumption, and consequently, it helps avoiding the design of oversized HVAC systems.

Introduction
One of the primary clothing functions is to protect the human body from cold. People dress for multiple reasons, and clothing selection may refer according to fashion, social criteria and workplace environment criteria (de Carvalho et al. 2013). Clothing can be considered as a mobile environment, which allows the human to adapt to various indoor and outdoor environmental conditions. In addition, clothing can be considered a clean and cheap source of controlling the micro-climate (Tamura et al. 2007)

The amount of clothing insulation a person wears has a big influence on the body’s heat loss. Further, clothing is one of the six main variables that affects the calculation of occupant thermal comfort (Fanger 1971). The clothing insulation value is expressed in clo unit. 1.0 clo is equivalent to 0.155 \( \text{m}^2\cdot\text{K}/\text{W} \). The widely used overall clothing insulation values of 0.5 clo for summer and 1.0 clo for winter are assumptions that mostly lead to some inaccuracy in the simulation prediction.

A number of researches have been conducted, pointing out the significance of the variability of clothing insulation for thermal comfort. Most clothing insulation models developed were based on either the current daily outdoor temperature or on the outdoor temperature of the previous day. (De Dear 1998; ASHRAE standard 55 2013; Schiavon and Lee 2013)

Morgan and de Dear (2003) observed the clothing behaviour with respect to thermal environments in a shopping mall and call centre, they found that clothing changed significantly in the shopping mall compared to the call centre where a dress code was imposed. Based on these observations they developed a linear regression equation for the average clothing value based on the daily mean outdoor temperature.

De Carli et al. (2007) used the outdoor temperature measured at 6 o’clock in the morning to predict the clothing insulation. They also found that in a mechanically conditioned buildings a change of 0.1 clo is capable of changing the comfort evaluation significantly.

Liu et al (2018), developed a dynamic clothing model called the IC-RM model (indoor clothing –running mean outdoor temperature) to predict the clothing insulation based on people’s thermal history. The developed model is based on the running mean outdoor temperature, which is calculated based on the history of the outdoor temperature. They stated that the most influential outdoor temperature on the indoor clothing insulation is the recently experienced outdoor temperature. They developed the “Trm” running mean outdoor temperature, which is an exponentially weighted temperature and is used as the outdoor temperature index. Their model is based on sensation surveys done in two different naturally ventilated buildings.

Parsons (2002) conducted an experiment over eight male and eight female seated subjects to investigate the behaviour of people to maintain thermal comfort by adjusting their clothing. He found that by adjusting clothing people can reach their own thermal comfort requirement.

De Carvalho et al. (2013) observed from their study that the clothing insulation level is affected by the recent thermal memory and weather prediction.

Schiavon and Lee (2013) tested multiple parameters and they found that the two main influential parameters that affect clothing selection are the outdoor temperature at six in the morning and the indoor operative temperature. They developed a model to predict the clothing insulation based on the two previously mentioned parameters and they integrated it in the building simulation tool Energy plus (Lee and Schiavon 2014).

From above, we conclude that using a fixed clothing in building simulation can lead to some inaccurate results. Furthermore, the clothing insulation selection also affects the building energy performance. Using a dynamic clothing model in building simulation can lead
to a better results prediction. Moreover, a dynamic clothing model has never been used with a multi-segmented thermo-physiology model where each body part requires a local insulation value.

In this approach we used PhySCo, a multi-segmented thermo-physiology model coupled with the sensation and comfort model of Zhang (2003), which we integrated in the building simulation tool ESP-r. This coupling represents the combination of building simulation - physiology model - Sensation Comfort model working together simultaneously (Boudier et al. 2016).

For the dynamic clothing model, the model developed by Schiavon et al. (2013) to predict the initial overall insulation value was selected. A correction value for the total clothing insulation was introduced. It is based on the sensation history of the previous day. The overall insulation values were categorized into four clothing ensembles of which each ensemble constitutes of 16 values associated with the corresponding human body part. The local clothing insulation values play a major role in predicting the heat transfer from the human body and consequently, the thermal comfort perception.

Finally, in each clothing category, the local clothing insulation values for the chest, back and shoulders were also dynamically altered by adding or removing a layer during the day based on the occupant’s thermal state calculated with PhySCo.

This study indicates that using a dynamic clothing insulation model was an effective method of maintaining thermal comfort in the simulation compared to the fixed clothing ensemble approach. Moreover, there is a potential for energy savings during the design stage, where the influence of clothing on thermal comfort may lead to an adaptation of cooling and heating set points or influence the sizing of the HVAC system.

**Methodology**

**PhySCo**

PhySCo is a thermo-physiology model based on the Berkeley model and the Tanabe’s 65 node model (2002). The model is constituted of 16 body parts (head, back, chest, pelvis, shoulders, arms, hands, thighs, legs and feet) where each body part has four concentric layers (bone, muscle, tissue and skin) in addition to a central blood node. The physiology model is combined with the thermal sensation and comfort model of Zhang (2003). The model predicts local sensation and local comfort based on local skin temperatures and core temperature.

The overall sensation and comfort reflect the overall thermal state of an occupant. (Boudier et al.2016, Hoffmann et al. 2016)

**ESP-r**

The building simulation tool ESP-r was selected in our study for multiple reasons as for its research orientation, the accuracy and dynamic of the model, and the availability of the source code as an open source (Clarke 2001). PhySCo is already coupled with ESP-r and the integration showed a strong usability working together. (Boudier et al. 2016, Hoffmann et al. 2016)

**Dynamic clothing model**

Schiavon and Lee (2013) developed a model to predict the clothing insulation dynamically. The model is based on 6333 selected observations taken from the ASHRAE RP-884 and RP-921 databases. They investigated multiple variables which can affect the clothing insulation selection and among those variables they found that the outdoor temperature at 6 o’clock and the indoor operative temperature were the two main variables that influence the insulation clothing prediction.

For that we have adopted the model of Schiavon to predict the daily total insulation value.

\[ DI_{cl} = 10(0.0134 - 0.0063 \times t_{ambat 6} - 0.0165 \times t_{op}) \]  

\[ DI_{cl} \] is the daily clothing insulation in clo, \( t_{amb at 6} \) is the outdoor temperature of the day at 6 am in °C, and \( t_{op} \) is the zone operative temperature in °C.

**Considering sensation history**

The daily total insulation prediction gives a good assumption for the clothing insulation value. Although it considers the operative temperature, the model does not consider the occupant thermal state accurately especially in a naturally ventilated building. Other parameters can influence the occupant thermal state, for example the activity level, air velocity and relative humidity. In buildings that allow for a wide range of indoor temperature the previous equation alone will not be sufficient. For that a clothing correction factor based on the occupant overall sensation history was introduced.

The PhySCo model predicts the overall sensation at every time step based on the physiology model prediction. The overall sensation recorded during the previous day is used to calculate the average overall sensation, and the average overall sensation of the previous day represents the sensation history.

The average overall sensation OS is calculated for the previous day based on the equation 2.

\[ OS_B = \sum_{i=1}^{n} \frac{OS_i}{n} \]  

\( OS_B \) represents the overall sensation history, and \( n \) is the number of simulation time steps during one day.

As the history of the thermal conditions can influence the future clothing decision, a model for the clothing correction factor was developed based on the sensation history, equation (3). The correction factor will be used only when overall sensation history is greater than 0.5 or less than -0.5 as any value in between is considered neutral.

Figure 1 shows how the clothing correction value changes with respect to the sensation history, based on our model.
The local clothing adaptation works as follows:

1. If the chest local sensation is less than -0.5 OR the overall sensation is less than -1.5 move to “Feels cold”.
2. If the chest local sensation is greater than 0.5 OR the overall sensation is greater than 1.5 moving clothing to “Feels warm”.
3. If the chest local sensation reaches zero the clothing insulation will be reset to “Feels neutral” until we reach a new condition.

Table 2: local clothing control

<table>
<thead>
<tr>
<th>Chest/Back local sensation</th>
<th>Overall sensation</th>
<th>Clothing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ls&lt; -0.5 OR OS&lt; -1.5</td>
<td></td>
<td>Feels cold</td>
</tr>
<tr>
<td>Ls&gt; 0.5 OR OS&gt; 1.5</td>
<td></td>
<td>Feels warm</td>
</tr>
</tbody>
</table>

Thermo-neutrality Set-point temperatures

The thermal sensation and comfort model used in our model is Zhang’s (Zhang 2013) model. The local sensation model requires the local skin temperature and the core temperature as inputs. In addition, the model is based on the thermo-neutral set point temperature, these temperatures represent the body parts skin temperatures for a specific metabolic rate and clothing in a neutral condition where the model feels neutral.
For the new clothing files new set points are calculated via an interpolation between the set points of two known clothing in order to find the unknown one based on the following equation (5).

\[
T_{\text{set},\text{new},i} = T_{\text{set},\text{sum},i} + \frac{T_{\text{set},\text{win},i}}{I_{\text{cl},\text{new},i} - I_{\text{cl},\text{win},i}} (I_{\text{cl},\text{new},i} - I_{\text{cl},\text{win},i} + T_{\text{set},\text{win},i})
\]

Where, \(T_{\text{set},\text{new},i}\) is the new neutral set point temperature, \(T_{\text{set},\text{sum},i}\) is the neutral temperature for summer cloth, \(T_{\text{set},\text{win},i}\) is the neutral temperature for the winter cloth, \(I_{\text{cl},\text{new},i}\) represents the new local insulation value and \(i\) is the body part index from 1 to 16.

**Flowchart**

The flow chart below shows the different stage process of the dynamic clothing model in the coupled Physco and ESP-r it summarizes all the steps previously explained.

**Case study and simulation results**

In the following section we test the capability of the dynamic clothing model in prediction and its effects on the occupant thermal comfort in building simulation. Three tests were conducted: one with a free float controller, the second represents a changing metabolic rate with fixed indoor temperature, and the third represents a simulation during winter season to show how dynamic clothing can lead to a lower set point heating temperature.

The results of thermal comfort and sensation are based on Zhang’s model (2003). For that in the following results graph, the overall comfort Co scale is (+4/-4), where -4 refers to very uncomfortable and +4 to very comfortable and the zero+ refers to just comfortable. The sensation scale is also (-4/+4) where -4 refers to very cold and +4 to very hot and 0 is neutral.

**Free-float controlled room**

To test the effect of variable room temperature on the dynamic clothing prediction we used a free-floating system.

For this case study, we used a small office model with a window. The office has 15m² floor area and has dimensions of 3m width x 5m depth x 2.7m height. Figure 4 shows the geometric representation of the office modelled in ESP-r. The weather file for Mannheim, Germany, was used. The construction material is shown in table 3.

<table>
<thead>
<tr>
<th>Construction</th>
<th>U-value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External walls</td>
<td>0.38</td>
</tr>
<tr>
<td>Internal walls</td>
<td>1.55</td>
</tr>
<tr>
<td>Ceiling</td>
<td>0.33</td>
</tr>
<tr>
<td>Ground</td>
<td>0.15</td>
</tr>
<tr>
<td>Window (double glazed)</td>
<td>2.24</td>
</tr>
</tbody>
</table>

**Figure 4: The office model geometry.**

The simulation ran over the three months of May, June, July. The occupant activity was considered constant and equal to 1 met.

The results in figure 5 show the predicted dynamic total clothing value in (Clo) with respect to the outdoor temperature of every simulation day at 6 am and the room temperature. As temperatures increase the predicted clothing insulation decreases. The results show...
how during the transition season from winter to summer clothing insulation decreases gradually.

To show the effect of using the dynamic clothing model, another simulation was performed with the same simulation setup but with a constant clothing insulation. For that we used the spring clothing of 0.73 Clo total insulation value.

The metabolic rate is one of the influential parameters on the human thermal comfort. In this scenario we will increase the metabolic rate to show its effect on thermal comfort and to see how the dynamic clothing model will respond. For that a schedule for the metabolic rate was set: the metabolic rate remains equal to 1.0 met during

day and increases to 1.4 met from 10:00 to 13:00 as shown in table 4. The metabolic rate 1 met represents an occupant seated quietly, reading and the 1.4 met for an office occupant represents office work while standing (ASHRAE 55 (2013)).

The same office as in the previous case was used, but without the window to neglect the effect of solar radiation from the window on the thermal manikin. Figure 7 shows the office geometry.

The model was simulated over a typical spring day. The simulation runs over one day of May using again the Mannheim weather file.

The rise in the metabolic rate has an influence on the skin temperature of all body parts. Consequently, the rise in skin temperature will give an unpleasant warm sensation which leads to a drop in the comfort level.

Simulation setup: Basic controller fixed indoor temperature of 20°C.

The human being normally reacts to this change by removing some clothing layers (reducing clothing insulation). In our simulation the dynamic clothing model selected a lower clothing insulation for the chest, back and shoulders according to “feels warm” for the higher metabolic rate period as figure 8 shows.

Figure 8 shows that the spring clothing ensemble was predicted for that day. The day started with the “feels cold” with a total insulation of 0.83 Clo to increase local sensation to a value greater than -0.5. When metabolic rate was increased, the clothing changed to “feels warm” with a total insulation of 0.63 Clo. Once metabolic rate went back to its original value, clothing changed to “feels neutral” with a total insulation of 0.73 Clo. The model kept the “feels neutral” clothing for one hour and 15 minutes before the body cools down and clothing changed back to “feels cold” for the rest of the day. Figure 8 also presents the local sensation of the back Sl_back. The results show that by reducing the clothing insulation, the body part will be cooler.
Clothing insulation prediction with respect to local and overall Sensation when an increase in metabolic rate occurs.

Figure 9 and 10 show the overall sensation So and comfort Co for this simulation case for both fixed and dynamic clothing. Figure 11 shows an example of the chest local skin temperature.

The chest skin temperature rose when metabolic rate increased. Once clothing was adjusted, the chest skin temperature decreased due to a higher heat loss to the environment.

After the metabolic rate was set back to 1.0 met, the chest skin temperature decreased again. Since clothing was on the lower level, the temperature continued dropping until another change in clothing took place. Insulation was then increased and a reduction in heat loss happened, which resulted in an increase of skin temperature. After that skin temperature continued steadily for the rest of the day.

Figure 12 shows the total sensible heat loss prediction from the human body of dynamic clothing vs. fixed clothing.

**Winter case**

In the following simulation a cold day was selected with a controlled room air temperature to 20°C. The aim of this case is to show how it is possible to predict the thermal state of an occupant wrongly by using a fixed
clothing insulation value. In addition, it shows the possibility of reducing energy.

In this case we used the same office model similar to the previous case, the weather file of Mannheim was selected again and the simulation was conducted over two days in December.

Figure 13 shows the clothing insulation prediction from the dynamic model compared to the selected fixed value. The outdoor temperature at six am for the two selected days were -0.5 and -2.4 °C consecutively. The selected fixed clothing value of 0.85 Clo corresponding to Autumn clothing for comparison with the dynamic clothing.

Results from figure 13 shows that during the simulation, the dynamic clothing selected the winter clothing for the first day with a value of 1 Clo, that was due to the low outdoor temperature. In the first couple of hours was swinging fast due to the threshold defined for altering clothing as overall sensation has influence on that. In the second day of the simulation the spring clothing “feels cold” was predicted with a value 0.83 Clo and that was due to the overall sensation history.

![Figure 13: Clothing insulation prediction vs. fixed clothing value.](image)

Figure 14 shows the overall comfort prediction and figure 15 shows the overall sensation prediction of the occupant in both cases of dynamic clothing and fixed clothing. From the results we can notice that although the occupant was comfortable in the first day, the sensation was slightly warm, and clothing moved to a lower level on the second day in order to reduce the sensation to a neutral level between 1 and -1 in the scale.

On the second day comfort was slightly lower compared to the fixed clothing due to the differences in the local sensation and comfort values affected by the different clothing layer distribution over the body.

Comparing the two days results one can conclude that it is possible to allow for a lower set point temperature and keeping clothing at the higher rate is sufficient to keep the occupant comfortable. In our case we have a room temperature set to 20°C, in the first day of the simulation with a high insulated clothing the overall sensation was slightly higher than 1 means the occupant feels slightly warm. Additionally, the second day showed that using a lower clothing insulation can keep the body in the comfort level. From what we provided we can suggest that a 1 or 2 degree reduction in the set point temperature, can keep the body comfortable adapting for higher clothing insulation which may results in saving energy.

![Figure 14: Overall comfort prediction of dynamic clothing vs. fixed clothing.](image)

![Figure 15: Overall sensation prediction of dynamic clothing vs. fixed clothing.](image)

**Conclusion**

Building occupants have a significant impact on the energy consumption in buildings, both in terms of behaviour but also physiologically. Using fixed clothing insulation in the building simulation could lead to an obvious error in prediction. For that a dynamic clothing model should be used in order to attain better and more realistic thermal comfort prediction. The more accurate thermal comfort can be predicted, the more energy savings can be achieved, and HVAC systems can be sized more appropriately.

The simulation results show that using the dynamic clothing model will give more realistic results compared to the fixed clothing approach.

We can conclude from the first case of simulation, that it is very important to have a dynamic model that changes the clothing insulation values with respect to the changes in outdoor weather. Moreover, when allowing a wide range of indoor operative temperatures as in naturally ventilated buildings, the dynamic clothing model becomes a necessity. The results show that changing the
clothing insulation value may lead to a higher predicted thermal comfort. 

In cases of HVAC design based on comfort prediction a more energy efficient system might be chosen based on the more accurate results. Clothing plays a major role on comfort and people tend to change the clothing level as a first adaptation to thermal condition changes. This could be proved in the second simulation case where an increase in the metabolic rate for a small period of time is capable to have an impact on the occupant thermal state. Consequently, the case showed how a change in clothing can bring the occupant thermal state to neutrality. Reducing clothing insulation increased the heat losses from the body and local sensation could be kept at a neutral level.

The third scenario demonstrated that a controlled room with a fixed set point temperature may drive the occupant to select lower clothing insulation even in winter season to achieve thermal comfort. From above, we can conclude that we can ensure energy savings by allowing a lower set point where occupants can keep their thermal state comfort by adding a clothing layer.

The model is a good approach for predicting thermal comfort in transient conditions. Further studies are planned for varying environmental condition scenarios, for example, when an occupant moves from outdoor to indoor and vice versa.

References


Parsons K.C. (2002), The effects of gender, acclimation state, the opportunity to adjust clothing and physical disability on requirements for thermal comfort, Energy Build. 34 (6) 593–599.


