Agent-Based Modelling of Occupants’ Clothing and Activity Behaviour and Their Impact on Thermal Comfort in Buildings

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Abstract. This paper proposes a new agent-based approach to model the clothing and activity behaviour of occupants in buildings. An autonomous agent is created to interact with the surrounding thermal environment and make decisions based on its comfort level. The agent-based behaviour model was implemented by MATLAB and was linked with building energy simulation program EnergyPlus via Building Controls Virtual Test Bed (BCVTB) and MLE+. A simulation experiment was conducted to see how an agent adapts to the dynamic thermal changes in different seasons and how it affects the annual thermal comfort. Obvious variation in the predicted annual discomfort time can be observed when using the agent-based method compared with a traditional commonly used method with static parameters. The paper concludes with a discussion of the model's current limitations and possibilities for future development.

1. Introduction

Energy modelling is commonly used during the design phase to estimate future building energy performance and indoor comfort levels. Predictions obtained from common energy estimation software typically deviate from actual energy consumption and comfort levels. This discrepancy can be partially attributed to the misrepresentation of the role that building occupants play in the energy calculation equation. Although occupants might have different and varying comfort-related behaviours over time, current energy estimation tools assume they are constant. For example, clothing adjustment is a very important comfort adjustment available to occupants in office buildings, and has a substantial impact on thermal comfort[1]. A person can also adjust his or her activity level, such as from sitting to walking, to control the body heat generation and resist the outside temperature changes. Furthermore, both clothing and metabolic activity are two of the six variables that affect the calculation of the Predicted Mean Vote (PMV) and are inputs for thermal comfort calculations. However, in energy models, clothing insulation is often assumed to be 0.5/1.0 clo, and metabolic rate is usually assumed 1.2 met (seated) if other information is not available. These simplifications may lead to inaccuracy in the calculation of thermal comfort.

Agent-based modelling (ABM) is a social science method to simulate human behaviour that allows for the observation of aggregate behaviours emerging from the interactions of large numbers of autonomous actors. An agent can be defined as a system that acts and thinks like a human, which operates under autonomous control, perceives its environment, adapts to changes, and is capable of taking on specific goals[2]. This modelling method provides us with an opportunity to mimic the real-world occupants that can put on or take...
off clothes, or adjust activities according to its comfort level in the built environment. Therefore, this study aims to develop a clothing and activity behaviour simulation engine based on the agent-based technique, while further bridging the gaps between the simulated and actual thermal comfort results.

2. Methodology

2.1. Human behaviour model

The Theory of Planned Behaviour (TPB) developed by Ajzen [3] was adopted in this paper. The theory states that attitude toward behaviour, perceived behaviour control and subjective norms shape an individual behaviour together. TPB is an improvement of the Theory of Reasoned Action (TRA) [4]. Both theories hold that “human social behaviour follows reasonably and often spontaneously from the information or beliefs people possess about the behaviour under consideration”. TPB model focuses on the “belief” concept, which can be categorized as follows:

- **Behaviour belief**: an individual’s observable response in a given situation with respect to a given target. As in this case, a person believes that if he or she wears more clothes or increases activity, one will get warmer. Here, the behaviour belief is that to put on more clothes or increase activity intensity is equated with getting warmer.

- **Control belief**: an individual’s perceived ease or difficulty of performing the particular behaviour. For clothing and activity behaviour, the control belief is the person’s easiness of wearing or undressing clothes and changing activity status.

- **Normative belief**: an individual’s perception about the particular behaviour, which is influenced by the judgment of significant others. For example, a person might think that it is he or she who should not wear too little, or do heavy load exercise in the office, so as not to affect other people in the office.

The behavioural intention for the Theory of Planned Behaviour can be expressed as a simple mathematical function (Eq. (1)):

\[
BI = w_A A + w_{SN} SN + w_{PBC} PBC
\]  

(1)

*BI*: Behaviour intention, *A*: Attitudes toward behaviour, namely behaviour belief, *SN*: Subjective norm, namely normative belief, *PBC*: Perceived behaviour control, *w*: empirically derived weight/coefficients.

Once the behaviour intention is determined, the occupant needs to decide the behaviour for the next step. Here the well-known “sense-think-act” loop is adopted to describe the decision-making process: firstly, an agent perceives something (sense), then it processes what it perceives (thinks), and lastly it executes an action (act).

In this case, an agent firstly *senses* its surroundings, which are defined by the clothing and activity values entered by the user and the thermal conditions of the space. The external EnergyPlus simulator provides the environmental thermal parameters to the agent. In order to summarize the holistic effect of environmental factors (including air temperature, humidity, and wind speed) on the human body, the Predicted Mean Vote (PMV) index of Fanger’s model[5] is adopted to calculate the indoor thermal comfort level, which is further identified as the behaviour trigger.

An agent *thinks* itself by following 2 steps. Firstly, the Behaviour Intention (*BI*) is calculated to determine the cost of each behaviour. Secondly, based on the thermal comfort level and costs of behaviours, an agent decides on a set of behaviours to execute. The decision indicates 3 characteristics of the next action: the type of behaviour, the number of behaviour and the incremental changes of the behaviour. The decision process is closely related to an agent’s current comfort level and behaviour intention. To be more detailed, if an agent is very uncomfortable (the absolute value of PMV is large), the agent can consider both clothing and activity behaviour to mitigate the discomfort, and the increment can be large. Conversely, the smaller the absolute value of PMV is, the more likely it is to perform only one action with less increment change. On the other hand, the cost determines the likelihood that a type of behaviour will be executed. The larger the cost value of the behaviour is, the more likely it will be executed.
A simple MATLAB code using \texttt{rand()} function is used to achieve the above logic:

If \( \text{rand()} < \text{abs(currentPMV)/3} \), the number of behaviours equals 2 and the increment equals 0.2.

If \( \text{rand()} > \text{abs(currentPMV)/3} \), the number of behaviours equals 1 and the increment equals 0.1. The execution probability is then determined by the cost of each behaviour: if \( \text{rand()} < \text{(costClo/sum(costs))} \), the clothing behaviour will be executed. Otherwise, the activity behaviour will be executed.

An agent \textit{acts} itself by communicating with an external simulator EnergyPlus to calculate the behaviour impact on thermal comfort.

2.2. Agent learning

The Planned Behaviour model provides a possibility to fulfill agent learning through the behaviour belief parameter. The effectiveness of a behaviour on thermal comfort is reflected and memorized in the behaviour belief, which is updated every time step. If a behaviour has a positive effect on the agent's comfort by comparing time \( t \) and \( t-1 \), the agent will increase its behaviour belief at time \( t \) to help making decisions at time \( t+1 \). Otherwise, the agent will decrease its behaviour belief. Therefore, the agent can keep learning the effectiveness of a behaviour and better make decisions based on its experience. A MATLAB code is used to update the behaviour belief as follows (simplified):

\[
\text{If currentPMV} > 0: \\
\text{changePMV} = \text{currentPMV} - \text{oldPMV}, \text{BehavBelief} = \text{BehavBelief} - (\text{changePMV} \times \text{rand()} / 6) \\
\text{Else: changePMV} = \text{currentPMV} - \text{oldPMV}, \text{BehavBelief} = \text{BehavBelief} + (\text{changePMV} \times \text{rand()} / 6)
\]

The larger the change in PMV is, the more effective the behaviour is, and thus the larger the change in behaviour belief is.

2.3. Simulation coupling

Once the behaviour model is established, an external simulator is needed to calculate the environmental parameters. Here the environmental parameter refers to the PMV value that an agent perceives. In every time step, the PMV data caused by building design and agent properties are passed to the agent-based model (ABM), and then the behaviour model processes the PMV data and executes an action, forwarding the agent properties to the external simulator to get a new PMV value for the next step. Therefore, the interaction between human and the built environment is finally achieved through such iteration.

This paper uses EnergyPlus as the external simulator to implement the environmental calculation, and MATLAB to fulfil the agent-based model. The coupling procedure is achieved through MLE+\cite{6} and Building Controls Virtual Test Bed (BCVTB) architecture\cite{7}. A “\textit{variables.cfg}” document is written to exchange data, including PMV value, clothing, metabolic rate, occupancy status and date/time.

3. Demonstrative example

3.1. Scenario settings

The environment chosen is a typical office room in a lab at Tianjin University (Tianjin, China). The room has a width of 10 m and depth of 8 m with a 30% window to wall ratio. It is equipped with a hot water radiator heating system in winter, while using natural ventilation to cool itself in summer. The heating set point is 22 °C. The total simulation time is 1 year (8760 h) with a simulation time step of 1 hour. The climate is classified as a hot humid continental climate (Dfa) in summer and a cold semi-arid climate (BSk) in winter based on the Köppen climate classification \cite{8}.

There are a few observations to be addressed here:
A person cannot wear very little in public places, and does not wear too much as the outdoors to avoid affecting work efficiency. Also, staffs usually don’t do very intense exercise in the office. Therefore, meaningful boundaries need to be set for clothing and metabolic rate. With reference to the ASHRAE Fundamentals Handbook, the minimum value for clothing is set to be 0.4 (shorts and T-shirts), and the maximum value is 1.2 (business suits). The minimum metabolic heat generation is set to be 1.0 (reading, seated), and the maximum is 2.1 (lifting/packing).

People change clothes with the seasons all year round, so different seasons should have different upper and lower clothing limits. In summer (June, July, August), clothing is set to be bounded between 0.4 and 0.6, while it is set to be bounded between 0.9 and 1.1 in winter (December, January, February) clothing. During transition seasons (March –May, September –November), clothing is set to be bounded between [0.6, 0.9].

Since the month information is not the standard output variable of EnergyPlus, we used the Energy Management System (EMS), a high-level control method to access the month information during simulation. An EnergyPlus Runtime Language (Erl) script is written to get the month data at the simulation time \( t \) to determine the clothing boundary.

In addition, people usually wear more clothes when they go to work to cope with the more varied outdoor weather. Therefore, it is possible for people to change their clothes during the day.

People don't change clothes and activities frequently, especially when they feel comfortable, so it is set that if the PMV is within the recommended limits (-0.5<PMV<+0.5) \(^1\), the clothing and activity will not change. Besides, as metabolic rates increase above 1.0 met, the evaporation of sweat becomes an increasingly important factor for thermal comfort. The PMV does not fully account for this factor, and this method should not be applied to situations where the time-averaged metabolic rate is above 2.0 met.

Initial values are shown in Table 1. The initial behaviour belief, control belief and normative belief are all set to 0.5 for both clothing and activity. Control belief and normative belief are kept constant during simulation in this paper. The weight coefficients for all beliefs are assumed to be equal.

### Table 1: Initial variable values of ABM

| Variables         | Clothing (clo) | Activity (met) | Behaviour belief (\( A \)) | Control belief (\( PBC \)) | Normative belief (\( SN \)) | Weight coefficients (\( w \)) |
|-------------------|----------------|----------------|----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Initial value     | Summer: 0.5    |                | 1.2                        | 0.5                         | 0.5                         | 1                           |
|                   | Winter: 1.0    |                | 0.5                        | 0.5                         | 0.5                         | 1                           |
|                   | Spring & autumn: 0.8 |                | 0.5                        | 0.5                         | 0.5                         | 1                           |

3.2. Results and discussion

#### 3.2.1. Behaviour portrayal.

The weekly variation of clothing and activity behaviour in terms of the indoor comfort is shown in Figure 1 to Figure 3. In winter (Figure 1), both clothing and activity vary between days. Moreover, the clothing behaviour mainly occurs in the morning and remains constant during the rest of the day. This is because that the PMV value is the lowest at the beginning of a day—if PMV < -0.5, the agent will put on more clothes. With the full opening of the heating system and the warming of the outdoor climate during the day, the PMV increases to the comfort level and there is no need to wear more clothes.

During transition seasons, there are more changes in the clothing and activity behaviour. As shown in Figure 2, each day has a different curve. Taking the first day as an example (April 1), the clothing remains at 0.8 clo during the morning until 14:00, and then dropped to 0.6 clo at 16:00 in the afternoon because of the rising PMV. Similarly, the metabolic rate decreases from 1.2 met to 1.1 met at 14:00 when PMV increases beyond the comfort zone. At 18:00, the metabolic rate again decreases to 1.0.

This action together with the undressing behaviour makes the PMV drop to 0.457 at 18:00, which is within the comfort limits (PMV<0.5).

In summer (Figure 3), due to the hot climate and lacking of cooling system, PMV values are out of the comfort zone at the beginning of a day, which leads to the decrease of both clothing and metabolic rate at the beginning. Afterwards, PMV keeps rising and remains at a very high level (>2.5), which is out of the comfort
range, and the clothing and activity remain at a lower level since then.

**Figure 1:** Weekly variation of PMV, clothing and activity level in winter (January 7 to January 13)

**Figure 2:** Weekly variation of PMV, clothing and activity level in spring (April 1 to April 7)

**Figure 3:** Weekly variation of PMV, clothing and activity level in summer (June 17 to June 23).

Figure 4 presents the annual clothing behaviour variation of the agent. It can be seen that the clothing value decreases regularly from winter to summer. During winter the clothing values are bounded between [0.9, 1.1] clo. Then in the early spring, the clothing values tend towards the upper limit of the transition season (0.9 clo), since the climate is still cold at this time. While approaching summer, the clothing value gets closer to the lower limit (0.6 clo), because the weather is getting hotter in this period. During summer, the clothing values are mostly between 0.4 and 0.5 clo due to the hot weather and high PMVs (Figure 6). Autumn exhibits a similar trend as spring - the closer to the summer it is, the higher the clothing value is, and the closer to the winter it is, the lower the clothing value is.
The annual activity behaviours are shown in Figure 5. It is observed that the agent’s activity level in winter is relatively higher in order to keep the body warm, concentrated between [1.2, 1.3] met. While in summer, the activity level decreases to [1.0, 1.2] met to minimize the body heat production, since the PMV values are very high during summer (Figure 6).
It can be seen that the established agent-based model effectively depicts people’s clothing and activity behaviour. Agent behaviours change logically with the variations of thermal environment, and the simulation results are consistent with our daily observations. Furthermore, Figure 7 and Figure 8 present the behaviour beliefs for clothing and activity in an entire year. Both behaviour beliefs fluctuate significantly throughout the year. Sometimes the agent has higher belief on clothing, and sometimes the “belief” on activity is higher. However, both beliefs are relatively higher in the winter and yet much lower in the summer probably due to the constant high PMV values in summer. In summer days, no matter how the clothing and activity are adjusted, PMV values are stubbornly high (because of the hot climate and lacking of cooling system), causing the agent to lose confidence in these two behaviours. By the time that the hot climate is not so overwhelming in autumn and the effect of clothing and activity starts to manifest itself, both beliefs begin to rise again.

3.2.2. Impact on thermal comfort. Here we compared the comfort results of ABM method with those of the traditional fixed method (Table 2). Adopting summer clothes (0.5 clo) and fixed activity level (1.2 met) in energy simulation leads to a result of 2695.00 uncomfortable hours, while adopting winter clothes (1.0 clo, 1.2 met)
met) results in 2140.00 hours of discomfort. The model using mixed clothes (0.5 clo in summer and 1.0 clo in winter) and fixed activity level has a discomfort time of 1843.00 hours. Lastly, the ABM method results in the shortest discomfort time of 1803.00 hours. Apparently, since the agent can change clothes and the activity level according to the overheated or too cold environment in the agent-based model, its uncomfortable time is the shortest.

| Scenario | Time not thermally comfortable in a year in terms of ASHRAE 55-2004 |
|----------|---------------------------------------------------------------|
| Fixed method: summer clothes (0.5 clo) activity level (1.2 met) | 2695.00 |
| Fixed method: winter clothes (1.0 clo) activity level (1.2 met) | 2140.00 |
| Fixed method: summer or winter clothes (0.5 or 1.0 clo) activity level (1.2 met) | 1843.00 |
| ABM method | 1803.00 |

4. Conclusion

This paper presents an agent-based method to simulate the occupant’s clothing and activity behaviour for thermal comfort in buildings. It can be seen that the agent-based model effectively describes the clothing and activity behaviour of people in response to changes of indoor thermal environment. The ABM allows for intelligent, autonomous agents to adapt to the given environment and make reasonable clothing and activity behaviour decisions based on their comfort level. The energy simulation result using ABM method is quite different from that using the traditional fixed-parameter calculation method, leading to the lowest discomfort hours.

The ABM method to depict occupant’s clothing and activity behaviour is still at its early stages and there are many aspects to be improved. Firstly, field study on occupant’s behaviour in real situations is needed to validate and improve the ABM method. In addition, this paper does not explore the parameters of control belief and normative belief of the TPB model, which will have a potential effect on the behaviour, such as the difficulty of changing clothes or performing an activity, or other colleagues’ attitude towards the agent.

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