Influences of indoor clothing adaptations on energy consumptions in rural houses

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# Abstract

Occupant behaviours significantly influence building energy consumption. As one of human beings' most efficient and common thermal adaptation behaviours to achieve thermal comfort, the clothing adjustment of building occupants may have pronounced energy-saving potentials. This paper quantitatively studied the influence of clothing adaptation of Chinese rural residents on the heating and cooling energy consumptions in rural houses. The "Ladybug Tools" in Grasshopper was adopted to simulate the diurnal performance of a typical rural household with dynamically adaptable and constant clothing insulations in winter and summer. Grasshopper components were developed to implement the prediction of dynamic clothing adaptation of building occupants using the "Python Component". Results indicated that the impacts of clothing adaptation on the indoor comfort temperature were significant in winter while negligible in summer. The energy-saving potential of the clothing adaptation was obvious in both seasons. Clothing adaptation of rural residents reduced heating loads by 35.6% (PMV=0) and 63.1% (PMV=-0.85) in winter and cooling loads by 20.2% (PMV=0) and 34.4% (PMV=0.85) in summer. The decreases in energy consumption in rural houses, with the influence of clothing adaptation of rural residents, were more pronounced in winter than in summer, and became more prominent with lower thermal comfort requirements.

# Highlights

* New method to evaluate clothing adaptation impacts on heating/cooling loads
* Clothing adaptation significantly reduces heating and cooling loads
* Energy saving was more significant in winter
* Energy saving was more significant with lower thermal comfort requirement

# Introduction

In 2021 the operation of buildings accounted for 30% of global final energy consumption and 27% of total energy sector emissions (8% being direct emissions in buildings and 19% indirect emissions from the production of electricity and heat used in buildings) (IEA, 2022). The majority of building energy consumption is used for conditioning our living and working environment and providing comfortable indoor thermal conditions. Air-conditioning system alone makes up more than 50% of the global total building energy consumption (Wu et al., 2018).

The setpoint temperature influences the energy consumption of air-conditioning system to various extent. Parry et al. studied the energy consumption of an office building in Zürich and found that the increase between 2$℃$ and 4$℃$ in the cooling setpoint temperature reduced the annual energy consumption by 1/3 (Parry et al., 2007). Another study by Wang et al. presented that a 4$℃$ decrease in heating setpoint temperature resulted in a 43.3% reduction in heating energy consumption in residential buildings in China (Wang et al., 2018). To align with the Net Zero Scenario, carbon emissions from buildings operations need to more than halve by 2030, requiring significant efforts to reduce energy demand through clean and efficient technologies in all end uses, including leveraging the potential of behavioural change (such as changing thermostat set points)(IEA, 2022). Occupant behaviour is identified as one of the most significant factors influencing building energy performance and greatly affects building energy consumption (Chen et al., 2021).

Clothing adaptation is one of the most efficient thermal adaptation behaviours for occupants to achieve thermal comfort (Zhao et al., 2022). People can efficiently adapt themselves to various thermal conditions and achieve thermal comfort by increasing and reducing their clothing (Xu et al., 2020). Indoor clothing insulation was found strongly associated and can be predicted by using the outdoor climate (Nicol et al., 1999, Liu et al., 2018). Quantitative relationships have been established between indoor clothing insulation and outdoor temperatures, including the daily outdoor temperature (Haldi and Robinson, 2011, Shao and Jin, 2020), running mean outdoor temperature (Nicol and Raja, 1996, Liu et al., 2018), temperature at 06:00 a.m. (De Carli et al., 2007) and daily outdoor temperature in the previous day (de Carvalho et al., 2013). The indoor clothing insulation changes in response to the outdoor temperature.

According to heat balance thermal comfort models (such as the PMV model), increasing clothing insulation results in decreases in comfort temperatures, and reducing clothing insulation results in increases in comfort temperatures. Humphreys concluded that one-half of the seasonal changes in the comfort temperature could be attributed to clothing adaptation (Humphreys, 1994). Indraganti and Boussaa proposed that the indoor neutral temperature decrease by 0.7$℃$ for every 0.1clo increase in clothing insulation, according to the ﬁeld surveys conducted in nine air-conditioned oﬃce buildings in Qatar during the ﬁve summer months (Indraganti and Boussaa, 2017). Another study by Liu et al. indicated that a 0.1clo increase in clothing insulation resulted in 0.4$℃$ and 0.7$℃$ decreases in winter and summer neutral temperatures (Liu et al., 2013).

The dynamic adjustment of indoor clothing insulation results in dynamic setpoint temperatures. Higher setpoint temperatures can be adopted in summer, and lower setpoint temperatures can be adopted in winter, if flexible clothing adjustments can be applied by the occupant. The dynamic setpoint temperature responds to clothing adaptation and outdoor climate fluctuations and has pronounced energy saving potentials (Newsham, 1997). Deng et al. (Xu et al., 2020) studied the energy-saving potential of clothing adaptation in an office building in China; Dynamic setpoint temperatures based on dynamic clothing insulations were applied; Results revealed that 65.5% of energy consumption could be saved compared with the traditional fixed setpoint temperature.

Indoor clothing behaviours of rural residents were found to have distinct characteristics from that of urban residents (Zhang et al., 2019, Shao and Jin, 2020). Studies on clothing insulations of rural and urban residents in Harbin (Cao et al., 2016, Wang et al., 2015), Beijing (Cao et al., 2016, Fan et al., 2017), Yinchuan (Zhu and Liu, 2010, Yan et al., 2016), Nanyang (Yan et al., 2018, Li et al., 2008) and Xi'an (Yang, 2010, Yoshino et al., 2004) presented obvious discrepancies in clothing insulations between rural and urban residents. Rural residents had significantly higher winter mean clothing insulations and upper limits than urban residents. Consequently, the findings in the energy-saving potential of clothing adaptations in urban contexts may not apply in rural contexts in China. Clothing adaptation of rural residents may have higher energy-saving potentials, especially in heating seasons, considering their distinctively higher winter clothing insulations. The extent to which rural residents' clothing adaptation affects building energy consumption is largely unclear.

This paper aims to study the influence of clothing adaptation of rural residents on the heating and cooling energy consumption in typical rural residences.

# Method

Firstly, a clothing insulation model for rural residents proposed in the author's previous study was adopted to predict the diurnal variation of indoor clothing insulation. This was then used to calculate the diurnal variation of the indoor comfort temperature based on the PMV model. Following these, building energy simulations were conducted by using the "Ladybug Tools" in Grasshopper. Two new GH (GH=Grasshopper) components were developed to implement the above predictions and were connected to the simulation. Finally, the cooling and heating energy consumptions in a typical rural house under different clothing conditions (constant and dynamic) and different comfort requirements (PMV=0 and PMV=$\pm 0.85$) were revealed and compared.

## Prediction of indoor clothing insulation

A clothing insulation model was proposed in the author's previous research to predict diurnal mean indoor clothing insulations of rural residents in winter and summer(Zhao et al., 2022). A five-parameter logistic mathematical model was used to fit the quantitative relationship between clothing insulation and 7-days running outdoor temperature, as shown in **Equation 1**. More details concerning selections of mathematical model and temperature indices could be found in the journal paper. The equation applies in a $T\_{rm,7}$ range between -4$℃$ and 5$℃$ for winter indoor clothing insulation prediction, and in a $T\_{rm,7}$ range between 24$℃$ and 31$℃$ for summer indoor clothing insulation prediction.

$I\_{cl}= 0.381+\frac{2.044-0.381}{(1+ e^{(0.158∙T\_{rm,7}-3.168)})^{2.977}}$ ($R^{2}=0.982$) **(1)**

## Calculation of indoor comfort temperature

PMV model was established by Fanger to assess the comfort level of indoor thermal environment(Fanger, 1970). The thermal environment is considered thermally neutral if PMV equals zero and is considered comfortable for 80% of occupants if PMV is between -0.85 and 0.85. PMV is a function of indoor air temperature ($T\_{a}$), mean radiant temperature ($T\_{r}$), relative humidity (*RH*), air velocity ($V\_{a}$), activity level (*Met*) and clothing insulation ($I\_{cl}$), as shown in **Equation 2**.

$PMV=f(T\_{a}, T\_{r}, RH, V\_{a}, Met, I\_{cl})$ **(2)**

Neutral thermal environment has no obvious cold or hot radiant, which causes discomfort, and has gentle breeze velocity and medium humidity (Xu et al., 2020). Therefore, the mean radiant temperature and the indoor air temperature approximate each other and are equal to the comfort temperature in a neutral thermal environment. With this assumption, **Equation 3** could be derived from **Equation 2**. The comfort temperature ($T\_{comf}$) will be a function of relative humidity (*RH*), air velocity ($V\_{a}$), activity level (*Met*) and clothing insulation ($I\_{cl}$) and PMV.

$T\_{comf}=T\_{a}=T\_{r}=f( RH, V\_{a}, Met, I\_{cl},PMV=0)$ **(3)**

When the relative humidity, air velocity and activity level are set with constant values in rational ranges, the comfortable temperature ($T\_{comf}$) will be a function of clothing insulation ($I\_{cl})$ and PMV, **Equation 4**.

$T\_{comf}=f(I\_{cl},PMV)$ **(4)**

The ISO 7730 PMV model applies in an indoor air temperature range between 10.0$℃$ and 30.0$℃$, and a mean radiant temperature between 10.0$℃$ and 40.0$℃$. Consequently, **Equation 3** only returns comfort temperatures between 10.0$℃$ and 30.0$℃$. When the input $I\_{cl}$ and PMV result in comfort temperatures beyond the range, the boundary values are used. For example, when the in input $I\_{cl}$ and PMV result in comfort temperatures lower than 10.0$℃$, the comfort temperatures are set at 10.0$℃$.

## Simulation software

The building simulation tools “Ladybug Tools” in “Grasshopper” are selected in this study. Honeybee provides building energy modelling features on the foundation of the validated energy simulation engine "EnergyPlus". Simulation results of “Ladybug Tools” have been evaluated as sufficient accuracy. The plugin has been employed for building energy modelling in many previous studies and showed great reliability (Konis et al., 2016, Ganji et al., 2019).

Grasshopper also provides a Python component that allows users to develop their own components. The developed components allow users to customize dynamic inputs and outputs for for building energy simulation.

In this research, two components were developed with the programming language "Python". The "Clothing Prediction (CP)" component implemented the function of **Equation 1**. The CP component takes weather data as input and computes clothing insulation (output). The "Find Comfort Temperature (FCT)" component implemented the function of **Equation 4**. The FCT component takes season, clothing insulation and aim PMV as inputs, and computes the comfort temperature. The Python Package ("pythermalcomfort") developed by the Lawrence Berkeley National Laboratory for the thermal comfort research was adopted to develop the FCT component (Tartarini and Schiavon, 2020).

## The rural house

A single-story detached rural house was modelled for the energy simulation. This is one of the most representative type of rural houses in the research district. A photo of the modelled rural house and the plan were presented in Figure 1.

|  |
| --- |
|  **(a)** |
|   **(b)** |

Figure 1: A typical single-story detached rural house.

## Model settings

Thermal property and structure of building envelops referred to the U-value limits and samples in the Chinese standard GB/T 50824 2013 (MOHURD, 2012).

Table 1: U-values of building envelops.

|  |  |  |
| --- | --- | --- |
| Envelop | U-value | U-value limit in standard |
| Exterior wall | 0.52 | 0.65 |
| Interior wall | 1.95 | \ |
| Roof and ceiling | 0.30 | 0.50 |
| Ground floor | 0.34 | \ |
| *Unit: W/(m2·K)* |

Infiltration rate was set with 0.5ach. Natural ventilation was turn off when outdoor temperature is beyond indoor comfort temperature (either lower than indoor comfort temperature in winter or higher than indoor comfort temperature in summer).

Lighting, cooking and the use of home appliances emit heat into ambient environment which may interfere with the calculation of heating and cooling loads. Moreover, there was no literature on the typical type, model, timetable and loads of home appliances in rural households. It would be another huge project to solve these uncertainties. Consequently, lighting and home appliance loads were set at zero.

The model accommodated two occupants. However, there were neither reliable occupancy timetable nor related studies for the residents in the researched area. This research assumed the occupants to stay at home all day long during the simulation period.

The HVAC system was set to the "Ideal Air Loads" provided by the software. More specific explanations of the system can be found in the "Engineering reference" of EnergyPlus (EnergyPlus, 2022).

## Simulation period

The typical meteorological years' weather data of Kaifeng was used for simulation and was downloaded online (Lawrie and Drury, 2019); The weather files have been peer-reviewed by interested parties.

The summer simulation starts from 17th June to 26th August. The winter simulation starts from 6st December to 14th February of the following year. Outdoor temperatures over the simulation periods are within the application range of the indoor clothing adaptation model.

## Simulation scenarios

Four simulation scenarios were proposed for winter and summer simulations, respectively. The four scenarios and their parameter settings are listed in **Table 2**.

PMV values of 0 and ±0.85 were adopted to calculate the temperature for the neutral and 80% comfort thermal environment respectively in the two seasons.

A medium relative humidity level of 60% was set for all simulation scenarios in both summer and winter. The air velocities were set at 0.02m/s and 0.2m/s for winter and summer respectively, which were the averages of the measured air velocities in the previous research (Zhao et al., 2022). Activity levels of 1.2*met* and 1.0*met* were set for summer and winter, respectively.

In the winter simulations, Scenario\_C0 and Scenario\_C1 adopted the constant clothing insulation of 1.0 *clo* over the simulation period. It is the highest the value of the clothing insulation model in ASHRAE 55 (ASHRAE, 2020).In the summer simulations, Scenario\_C0 and Scenario\_C1 adopted the constant clothing insulation value of 0.46 clo over the summer simulation period. Scenario\_D0 and Scenario\_D1 for both seasons adopted the dynamic clothing insulation predicted by using **Equation 1**.

**Table 2:** Scenario settings of winter and summer simulations.

|  |  |  |  |
| --- | --- | --- | --- |
|  | Winter simulation scenarios |  | Summer simulation scenarios |
| Scenario\_C0 | Scenario\_D0 | Scenario\_C1 | Scenario\_D1 |  | Scenario\_C0 | Scenario\_D0 | Scenario\_C1 | Scenario\_D1 |
| Relative humidity | 60% | 60% | 60% | 60% |  | 60% | 60% | 60% | 60% |
| Air velocity | 0.02 *m/s* | 0.02 *m/s* | 0.02 *m/s* | 0.02 *m/s* |  | 0.2 *m/s* | 0.2 *m/s* | 0.2 *m/s* | 0.2 *m/s* |
| Activity level | 1.2 *met* | 1.2 *met* | 1.2 *met* | 1.2 *met* |  | 1.0 *met* | 1.0 *met* | 1.0 *met* | 1.0 *met* |
| pmv | 0 | 0 | - 0.85 | - 0.85 |  | 0 | 0 | + 0.85 | + 0.85 |
| Clothing insulation | 1.0 *clo* | Dynamic | 1.0 *clo* | Dynamic |  | 0.46 *clo* | Dynamic | 0.46 *clo* | Dynamic |
| Comfort temperature | HST\_C0 | HST\_D0 | HST\_C1 | HST\_D1 |  | CST\_D0 | CST\_D0 | CST\_C1 | CST\_D1 |

# Results and Discussion

## Diurnal indoor clothing insulations

The predicted diurnal indoor clothing insulations over the winter and summer simulation period were presented in Figure 2. In winter, the dynamic clothing insulation ranged from 1.72 *clo* to 1.93 *clo*, with a mean value of 1.82 *clo* which was averagely 0.82 clo higher than the winter constant clothing insulation of 1.0 *clo*. In summer, the daily clothing insulation ranged between 0.39 *clo* and 0.45 *clo*, with a mean value of 0.41 *clo* which was *0.05 clo* lower than the summer constant clothing insulation.

## Diurnal indoor comfort temperatures

Indoor comfort temperature during the winter simulation were calculated and presented in Figure 3 (a). When PMV =0, indoor comfort temperatures remained at 21.2$℃$ over the simulation period in Scenario\_C0. In contrast, indoor comfort temperatures fluctuated between 15.6$℃$ and 16.8$℃$ with an average value of 16.2$℃$ in Scenario\_D0. When PMV=-0.85, indoor comfort temperature remained at 17.4$℃$ over the simulation period in Scenario\_C1. In Scenario\_D1, the indoor comfort temperature varied between 10.0$℃$ and 11.5$℃$ with an average value of 10.7$℃$.

Figure 3 (b) presented the indoor comfort temperature during the summer simulations. When PMV=0, the indoor comfort temperature remained at 26.7$℃$ over the simulation period in Scenario\_C0. In contrast, indoor comfort temperatures fluctuated between 26.8$℃$ and 27.1$℃$ with an average value of 27.0$℃$. When PMV=0.85, the indoor comfort temperature remained at 28.8$℃$ over the simulation period in Scenario\_C1. In Scenario\_D1, indoor comfort temperatures fluctuated between 28.8$℃$ and 29.1$℃$ with an average value of 29.0$℃$.

Dynamic indoor clothing adaptation of rural residents averagely reduced the indoor comfort temperature in rural houses by 5.0$℃$ and 6.7$℃$ respectively under PMV requirements of 0 and -0.85 in winter. In contrast, in summer, the indoor comfort temperature was only reduced by 0.3$℃$ and 0.2$℃$ respectively under PMV requirements of 0 and 0.85. The influence of dynamic indoor clothing adaptation of rural residents on indoor comfort temperature was more obvious in winter than in summer.

|  |
| --- |
|  |
| (a) |
|  |
| (b) |

Figure 2: Diurnal indoor clothing insulation during the winter(a) and summer(b) simulations.

|  |
| --- |
|  |
| (a) |
|  |
| (b) |

Figure 3: Indoor comfort temperatures in winter (a) and summer (b) simulations.

## Diurnal heating/cooling energy loads

Figure 4 presents the diurnal heating/cooling energy loads in different simulation scenarios. The reduced heating/cooling energy loads due to the dynamic indoor clothing adaptation were marked by gray blocks.

In Figure 4 (a), PMV=0, the peak heating energy loads were 41.1*kWh* in Scenario\_C0, and was reduced to 28.0*kWh* due to the dynamic indoor clothing adaptation adaptation. The diurnal heating loads were averagely reduced by 11.9 *kWh*.

In Figure 4 (b), PMV=-0.85, the peak heating energy loads were 31.7*kWh* in Scenario\_C0, and was reduced to 14.2*kWh* due to the dynamic indoor clothing adaptation adaptation. The diurnal heating loads were averagely reduced by 15.9 *kWh*.

The CV(RMSE) values showed a more significant reduction in the diurnal heating loads in the winter simulation where PMV=-0.85.

|  |
| --- |
|  |
| (a) |
|  |
| (b) |
|  |
| (c) |
|  |
| (d) |

Figure 4:Diurnal heating/cooling energy loads over winter (a)PMV=0 and (b)PMV=-0.85 and summer (c)PMV=0 (d)PMV=0.85 simulations.

In Figure 4 (c), PMV=0, the peak cooling energy loads were 47.8*kWh* in Scenario\_C0, and was reduced to 44.4*kWh* due to the dynamic indoor clothing adaptation adaptation. Moreover, the diurnal cooling loads were averagely reduced by 2.5*kWh*.

In Figure 4 (b), PMV=0.85, the peak heating energy loads were 19.6*kWh* in Scenario\_C0, and was reduced to 16.3*kWh* due to the dynamic indoor clothing adaptation adaptation. Moreover, the diurnal heating loads were averagely reduced by 0.6*kWh*.

The CV(RMSE) values (24.4% for PMV=0, 65.0% for PMV=0.85) showed a more significant reduction in the diurnal heating loads in the winter simulation where PMV=0.85.

Moreover, In the summer simulations, when $PMV=0$, there were 9 and 12 days on which there were no cooling energy consumptions in Scenario\_C0 and Scenario\_D0, respectively. The number of "no cooling days" was increased by three days due to the clothing adaptation. When $PMV=0.85$, the number of "no cooling days" increased from 28 in Scenario\_C1 to 33 in Scenario\_D1. The number of "no cooling days" was increased by five days due to the clothing adaptation.

## The total loads

In winter, the total heating load in Scenario\_C0 was the highest (2442.1*kWh*). This was followed by Scenario\_C1 (1788.3*kWh*), Scenario\_D0 (1573.5*kWh*) and Scenario\_D1 (659.2*kWh*) in sequence. The total heating load was reduced by 868.6*kWh* due to the clothing adaptation in winter when $PMV=0$. The saving rate was 35.6%. When $PMV=-0.85$, the reduced total heating loads increased to 1129.0*kWh*, and the saving rate increased to 63.1%.

In summer, the total cooling loads in Scenario\_C0 was the highest (858.41*kWh*). This was followed by Scenario\_D0 (684.6*kWh*) and Scenario\_C1 (108.2*kWh*). Scenario\_D1 had a total cooling loads of only 71.0*kWh* over the whole summer simulation. The total cooling load was reduced by 173.8*kWh* due to the clothing adaptation in summer when $pmv=0$. The saving rate was 20.2%. When $PMV=0.85$, the reduced cooling load decreased to 37.2*kWh*, while the saving rate increased to 34.4%.

Table 3:The total heating/cooling loads and saving ratios.

|  |  |  |
| --- | --- | --- |
| Winter |  | Summer |
| **PMV = 0** |  | **PMV = 0** |
|  | Scenario\_C0 | Scenario\_D0 | Energy saving | Saving rate |  |  | Scenario\_C0 | Scenario\_D0 | Energy saving | Saving rate |
| Total | 2442.1 | 1573.5 | 868.6 | 35.6% |  | Total | 858.4 | 684.6 | 173.8 | 20.2% |
| **PMV = - 0.85** |  | **PMV = 0.85** |
|  | Scenario\_C1 | Scenario\_D1 | Energy saving | Saving rate |  |  | Scenario\_C1 | Scenario\_D1 | Energy saving | Saving rate |
| Total | 1788.3 | 659.2 | 1129.0 | 63.1% |  | Total | 108.2 | 71.0 | 37.2 | 34.4% |
| *Unit: kWh.* |

# Conclusion

This paper investigated the impact of dynamic indoor clothing adaptation of rural residents on heating and cooling loads in typical rural houses. Building energy simulations were carried out to quantify the changes in indoor comfort temperatures, heating and cooling loads under the influence of indoor clothing adaptation.

The influence of indoor clothing adaptations on indoor comfort temperatures differed between winter and summer. With the influence of indoor clothing adaptation, the indoor comfort temperature averagely decreased by 5.0$℃$ ($PMV=0$) and 6.7$℃$ ($PMV=-0.85$) in winter, and averagely increased by 0.3$℃$ ($PMV=0$) and 0.2$℃$ ($PMV=0.85$) in summer.

The influence of indoor clothing adaptations of rural residents on heating and cooling loads was significant in both winter and summer. The total heating load was reduced by 35.6% ($PMV=0$) and 63.1% ($PMV=-0.85$) in winter simulations, and the total cooling load was reduced by 20.2% ($PMV=0$) and 34.4% ($PMV=0.85$) in summer simulations. The energy-saving potential of indoor clothing adaptations was more obvious in winter than in summer, and lower thermal comfort requirement ($PMV=\pm 0.85$) amplifies the energy saving effects.

The findings of this research underline the significance of occupant behaviour in building energy use. Considering the prominent energy saving potential of indoor clothing adaptation, it is mandatory for the indoor clothing adaptation and other occupant behaviours being taken into account in the future design and operation of rural houses and HVAC systems.

It is notable that the simulation results may not accurately mirror the energy saving effects of indoor clothing adaptations in a real world, as the simulation modelled ideal conditions with assumptions in parameter settings. Further study are needed for detailed information on rural houses and households, for example the occupancy, loads and schedule of lighting and appliances, to improve the accuracy of the simulations.

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