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Developments in the Built Environment 4 (2020) 100032

Contents lists available at ScienceDirect

Developments in the Built Environment

journal homepage: www.editorialmanager.com/dibe/default.aspx

The adaptive thermal comfort review from the 1920s, the present, and the future

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ARTICLE INFO

Keywords:
Thermal comfort
PMV-PPD
Adaptive approach
Explainable AI
Action on the global climate change
Disabled and elder group of people

ABSTRACT

The typical method for comfort analysis is the Predicted Mean Vote and Predicted Percentage Dissatisfied (PMV-PPD). However, they present limitations in accommodating the comfort of a disabled and elder group of people, which are the most vulnerable to climate change and energy poverty. The adaptive method can give flexibility and personalisation needed to overcome the problem due to the variability of the people's metabolism, historical and behavioural preferences. Investments to upgrade the indoor environmental quality and building design can then be effectively used and, for the first time, it will be possible to tailor the solutions for these particular groups of people. The adaptive approach uses Artificial Intelligence (AI), where it can introduce the imperfect learning process. Overcoming this, instead of going further for the Explainable AI, the PMV–PPD approach can be used for the learning validation and verification needed for the adaptive setting point and standards.

1. Introduction

About eighty-seven per cent of the population spends their time in an artificial climate (indoor), according to the research of NHAPS (Klepeiset al., 2001). This justifies that over the past fifty years, there has been a dramatic increase in research on thermal comfort methods. Human comfort is a state of mind expressing satisfactory adaptation with the immediate environment. Human comfort can be divided into smaller aspects of comfort, such as lighting comfort, acoustics comfort, air quality, and thermal comfort. These aspects are not independent, but there are relations between these comforts which are being visualised in Building Bulletin 101 Guidelines on ventilation, thermal comfort and indoor air quality in schools (Daniels, 2018) as shown in Fig. 1. The arrows represent the relations of each aspect of comfort.

Although outdoor comfort is also studied in some of the papers from Höppe (2002), Coccolo (Coccolo et al., 2016) and Lai (Lai et al., 2019), the majority of research is focussed on indoor thermal comfort. Based on the Scopus search result, "indoor" "thermal comfort" returns 73.3% more dominant compared to "outdoor" "thermal comfort due to the nature of human living. Based on this fact, this paper will focus mainly on indoor thermal comfort.

1.1. Thermal comfort impact on humans life

The thermal comfort is one of the primary concerns in the design process of the artificial climate inside the building and has a significant impact on health and safety. Some of the research found the strong relationship between ambient temperature and the cause of specific morbidities. The lag effect of hot temperature on morbidity was shorter than the cold and will also be affected by sociodemographic and pollution factors. There are enough studies to claim that mortality can be associated with cold and heat waves (Ye et al., 2012). Heat exposure was identified to be associated with increased risk of cardiovascular, cerebrovascular and respiratory mortality. Cold-induced cardiovascular morbidity increased in youth and the elderly (Songet al., 2017).

In the past 30 years, The World Health Organization estimates that yearly over 150,000 morbidities are caused by climate change (Patz et al., 2005). Besides the human factors, the dwelling has a significant influence on the protection against heat and cold waves. Many existing dwelling stocks can not provide enough protection against the heat and cold waves (Ormandy and Ezratty, 2016). Besides health and safety risks, thermal comfort will be beneficial also for productivity. If people work in an uncomfortable environment, they will behave unsafely due to the deterioration of their physical performance and thinking ability. The

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https://doi.org/10.1016/j.dibe.2020.100032
Received 19 June 2020; Received in revised form 7 October 2020; Accepted 8 October 2020
Available online 26 October 2020
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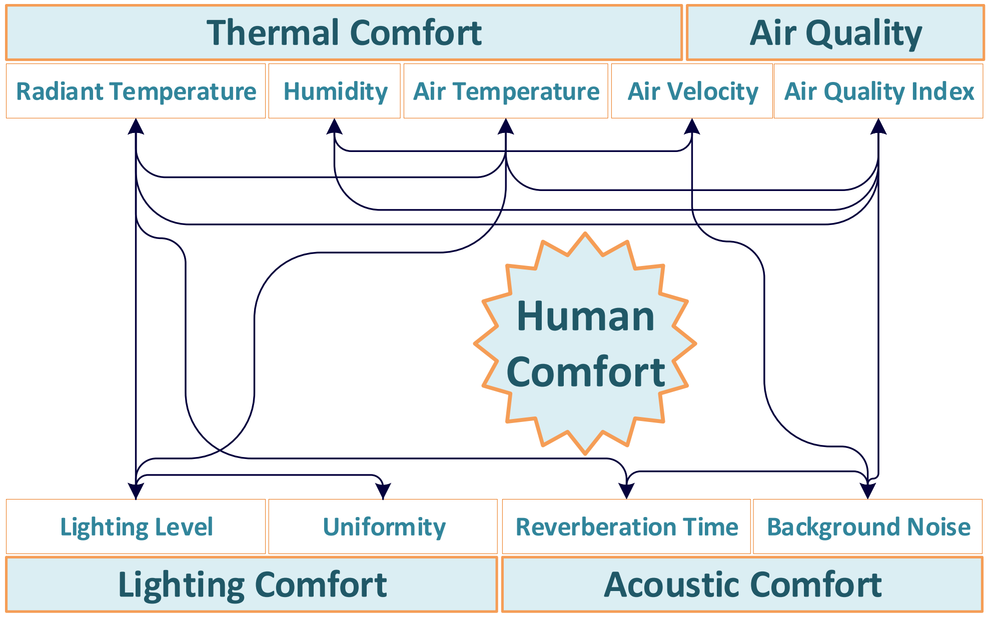


Fig. 1. Human comfort aspects and their relations.

probability of committing an error will be higher due to the lower concentration. The indirect effect of thermal comfort is to improve morale in the working environment (Executive, 2019).

1.2. Thermal comfort and climate change

The previous references show that thermal comfort has been mainly focused on health and safety concerns. Nowadays, there also a complementary shift for research focused on lowering energy consumption and climate change. TheCO_2 emission has grown 1.7% to reach 33.1 Gt and become the highest growth since 2013. This is due to the higher energy consumptions (Eurostat, 2019). The growth in the global economy and the increase of the energy demand for heating and cooling are the leading cause of this increase. Global climate change (GCC) can decrease by 2% of heating needs.

On the contrary, the need for air conditioning increased, especially in cooling during summer, due to the effects of increased humidity (Scott et al., 1994). An increase in the global mean surface air temperature would benefit some countries but will trigger higher loss to others. In the United States, the weather condition triggered about 60% in the increase of CO_2 emissions (Tol, 2002a). The UK Climate Projections 2018 (UKCP18) which gives the UK climate projection tools also predicts that the future will have warmer, wetter winters and hotter, drier summers (Jason et al., 2018). Using globally averaged values, world impact would be excess spending of 3%to compensate the GCC (Tol, 2002b). The GCC impact will be worse in the later years and will make a worse impact on the more impoverished regions (Tol, 2002a). The development of energy-efficiency scenarios should differ from one location to another due to the effectiveness of such designs will not be the same for each case (Scott et al., 1994).

HVAC (Heating Ventilation and Air Conditioning) system is employed to maintain comfort. In Europe, the primary use of energy by households is for HVAC. It can reach more than 64% of final energy consumption for the residential (Eurostat, 2019), which is very significant. The more power being produced will always contribute to the carbon footprint and will have a consequence on climate change and temperature rise. The household sector represents 27.2% of final energy consumption in Europe. Anticipating these trends, the UK will introduce a Future Homes Standard, mandating the end of fossil-fuel heating systems in all new houses from 2025 (Treasury, 2019), drive zero carbon emission and leveraging the Paris Agreement. The target is to keep the global temperature rise this century below 2 °C and even further to limit the temperature increase for 1.5 °C (U. N. F. C. o. C. Change). More energy-efficient systems are proposed without leaving the aspect of human comfort. There has been a tremendous increase in the paper published from the 1970s–2010s (Rupp et al., 2015).

This review paper presents the comparative development timelines between the human thermal physiology approach and the human behaviour approach for thermal comfort. These are not presented clearly in other papers. This paper also proposes the work in progress for improving the adaptive approach by using Artificial Intelligence (AI). The work will use the Artificial Neural Network (ANN) and employs the combination of the Predicted Mean Vote and Predicted Percentage Dissatisfied (PMV-PPD) method and behavioural aspects in the AI learning process. The aim is producing a better smart system by coping with the limitation of AI. The approach is becoming the other alternative for the Explainable AI, which is resource consuming.

2. The research progress on thermal comfort

Thermal comfort term beginning to gain attention in the early 1920s when it became possible to control the microclimate of the indoor environment directly. In the traditional approach, the use of fireplaces to control the temperature was mandatory. In the second half of the nineteenth century, it was necessary to model the building as an open system and apply the laws of thermodynamics (Fabbri, 2015). Various electronic controllers were developed, which leads to the evolution of comfort monitoring. Fanger's comfort model introduced in the 1970s, based on physically based determinism and formulate comfort equation. The quality of air movement and sophisticated models which map both physics and physiology of the human body were also developed to build coherent, global thermal perception. These developments also are driven by energy efficiency (de Dearet al., 2013). In the twentieth century, the focus goes to humans as the centre point of the design to improve the health and comfort of men and their homes (Fabbri, 2015), (de Dearet al., 2013).

The equivalent temperature of an environment corresponds to the same temperature there would be in an environment where the temperature is uniform, the air is stationary, and the moisture content corresponds to 100%. Therefore the human body cannot exchange energy with the environment. If the actual temperature of an environment is 22 °C with a relative humidity of 50% and airspeed of 0.2 m/s, it is equal to

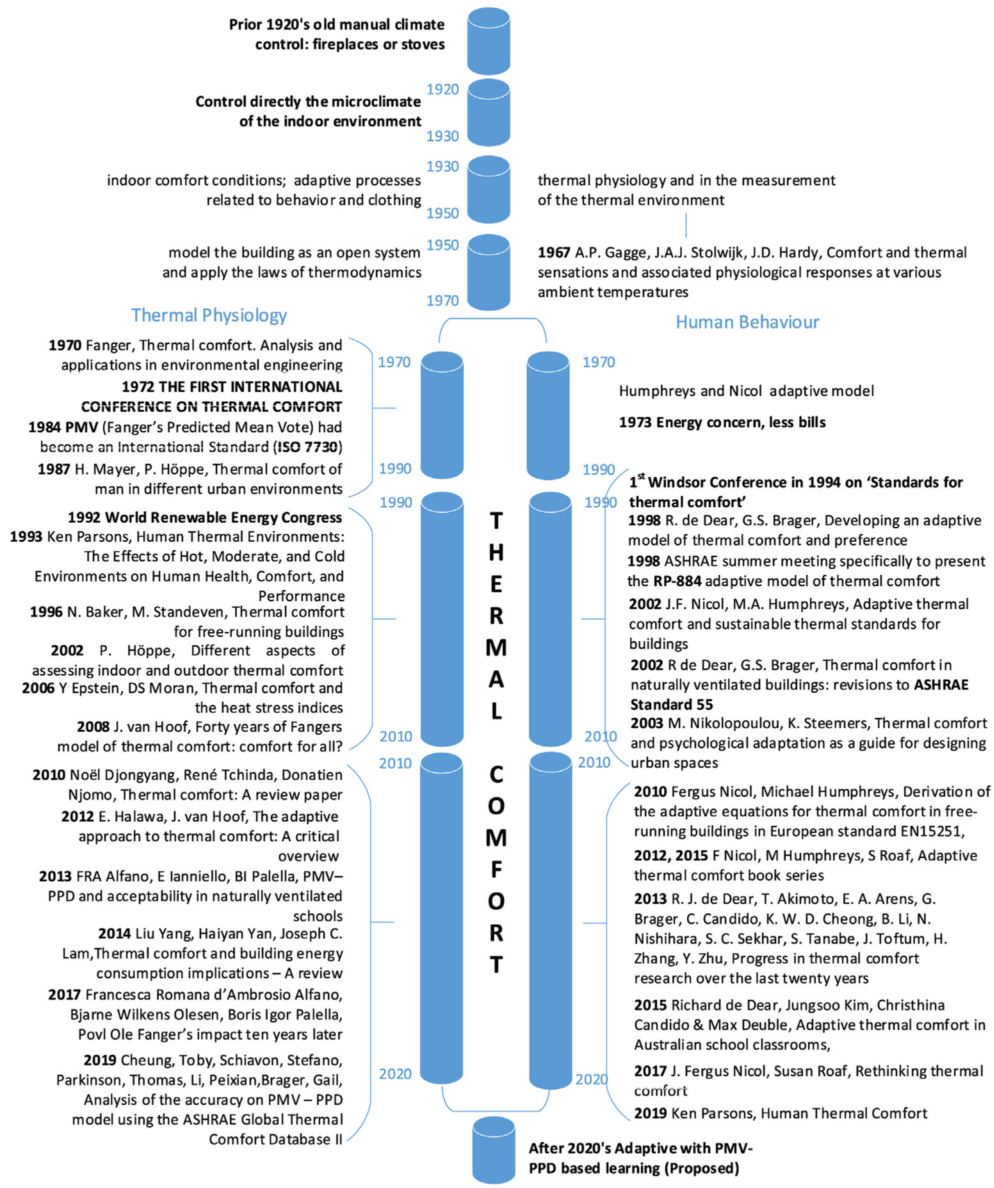


Fig. 2. Timeline diagram for the development of the methods in "Thermal Comfort" from 1920 until now.

the temperature of 19.6 °C with relative humidity 100% and no airspeed (Patz et al., 2005).

It is now becoming essential to review the progress of thermal comfort due to the growth of low-cost sensing solutions. The provision of lighting and thermal comfort has been widely increased to existing and future smart buildings to aid productivity, health, and wellbeing. Thermal cameras, for example, has the potential to be used widely in the home comfort system nowadays. It was costly that only the military, firefighters, and surveyors were able to use it due to its price (villo, 2002; Tu, 1997; BBC, 1985). Besides sensors, artificial intelligence also plays a vital role in creating smarter solutions for human comfort. The system can perform smartly to maintain comfort while still lower down the energy usage.

Fig. 2 presents the evolution in the enhancement of the thermal comfort approach. PMV-PPD is the typical method for comfort analysis. It focussed on the thermal physiology. The other method, the adaptive method, is based on human behaviour. The adaptive method can give flexibility and personalisation needed to overcome the problem due to the variability of the people's metabolism, historical and behavioural preferences.

There are three thermal adaptation types (Brager and de Dear, 1998):

- Physiological which is related to the body reaction due to the temperature change
- Psychological which is derived from the state of mind of previous experiences
- Behaviour related adaptation

Fig. 2 also highlights the two clusters of research in thermal comfort: thermal physiology and the human behavioural aspect. With this approach, many thermal comfort methods studies can be associated with these two clusters. The ASHRAE standard 55 also acknowledges both approaches. The physiological was acknowledged in ASHRAE 55 (1981), ISO 7730 (1984), and adaptive behavioural aspect in ASHRAE 55 (2004). This simplification is becoming the special attention of this review paper. With this approach, it will be easier for the researchers to classify the positioning of their work.

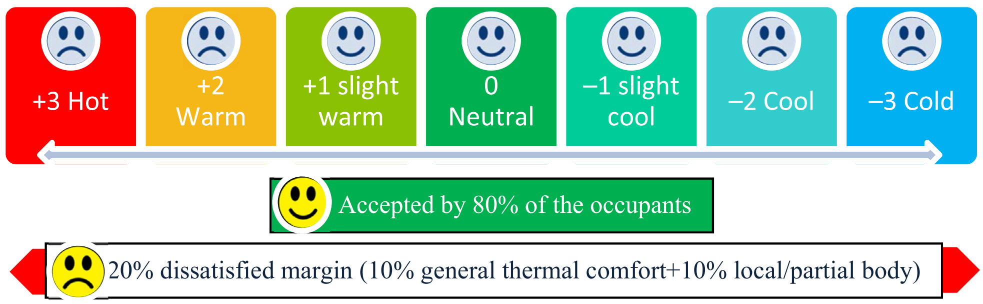


Fig. 3. Thermal comfort definition from PMV-PPD acknowledged in ASHRAE standard.

3. Fanger's equation, PMV, PPD, and adaptive approaches

3.1. Fanger's equation, PMV, and PPD

The development of a thermal model considered to be the milestone is by Fanger in 1970 (Fanger, 1970). This work becomes a standard reference work on the thermal comfort, due to the experiments and model it has presented. The experiments were conducted in a controlled room condition. The formulated model makes it possible to calculate the effect of variables to gain comfort. This model stated that no significant difference generated by sex, age, body build, menstrual cycle, ethnic differences, food, circadian rhythm, crowding, and colour. This model is known as the Predicted Mean Vote (PMV)/Predicted Percentage of Dissatisfied (PPD). This model has also become the basis of the ISO 7730–2005 (Höppe, 2002). The mean radiant temperature and radiation data can be calculated for human comfort.

Fanger's equation shows the relation of the parameters that can have effects on human comfort. This equation also being acknowledged by ASHRAE, comprises the PMV-PPD model into the ASHRAE-55 Standard (Enescu, 2017). This standard mentions about the parameters which can have effects on human comfort. Six parameters are mandatory for thermal comfort.

Two parameters are related to the occupants, which are:

- metabolic rate
- clothing insulation

Four others are related to the surrounding environment, which are:

- air temperature
- radiant temperature
- airspeed
- humidity

The met unit represents the individual metabolic rate. Writing for example, equal to 1.0 met unit or 60 W/m^2 or 18 Btu/h.ft^2. The activities within 0.1 met units can be grouped into one entity. The limitation for this for the occupants, whose time-averaged metabolic rate is more than 2.0 met. The basic equation for thermal balance can be calculated using the formula presented in equation (1) (Fanger, 1970).

$$M-W = C + R + E + (Cres + Eres) + S \quad (1)$$

Where: M: the metabolic rate.

W: mechanical work is done
C: convective heat loss from the clothed body
R: radiative heat loss from the clothed body
E: evaporative heat loss from the clothed body
Cres: convective heat loss from respiration
Eres: evaporative heat loss from respiration
S: the rate at which heat is stored in the body tissues

There is an empirical table that lists common activities, and their met units (ASHRAE, 2017). Clothing insulation also presented in the form of a table which is consists of the clothing items and its clothing insulation values in clo units. The limit of occupants grouping is when the clothing difference is more than 0.15 clo. However, to use the table values, there are some limitations for the clothes with high impermeable to sweat, value more than 1.5 clo, and if the occupants are in contact with bedding. The seven levels of people's thermal sensation can be seen in Fig. 3.

In the cold environment, the additional 0.1 clo or 0.1 met will have an impact on saving the energy because it can lower the operating temperature at approximately 0.8 °C or 0.5 °C. On the contrary, with a decrease of 0.1 clo or 0.1 met corresponds approximately to a 0.8 °C or 0.5 °C increase in operative temperature (Enescu, 2017). Achieving comfort can be done by maintaining a humidity ratio below or the same as 0.012. The lower level is not specified, but if the humidity is very low, it can cause skin drying, irritation of mucous membranes, dryness of the eyes, and static electricity generation. The high airspeed can extend the thermal comfort range. This approach can be used if the occupants' condition is slightly warm. When the sunray falls on the occupant, the mean radiant temperature should be considered with regards to the type of window gazing, the shade and the body which is exposed to sunray.

Regarding the procedure for measurement, the sample location should be selected where the occupants are spending their time. The measurement has to include the centre of the room and the 1 m inward from the centre of each of the room's walls. The measurement height shall be 0.1, 0.6, and 1.1 m above the floor for seated occupants and 0.1, 1.1, and 1.7 m for the standing occupants.

Since Fanger's trial was done in the chamber, it was unable to capture the difference between sex, age and special populations like disabilities, elderly people, babies, and children, the sick, pregnant women and people from different cultures. In reality, sometimes noted that males and females have different thermal comfort responses and related to the clothes that they wear. Some work is carried out to improve the PMV regarding these matters (Parsons, 2003) or focus on the particular aspects of the comfort factors like the inversely determined metabolic rate (Zhang et al., 2020/02). Some of the works also lead to the adaptive approach, which will be clarified in the next subsection.

3.2. The adaptive approach

The other method, which is the adaptive method, was introduced by Nicol and Humphreys (Rupp et al., 2015), (Enescu, 2017). The adaptive model is formulated on the nature of humans who can adapt. Beside acknowledge the PMV-PPD method, ASHRAE-55 Standard also acknowledges the adaptive method (ASHRAE, 2017). This model defines the comfort zone, which also related to thermal experiences changes in clothing and activities, unlike Fanger's model. In this model, gender, age, physical disabilities will affect thermal comfort. There are three thermal adaptation types. They are physiological, which is related to the body reaction due to the temperature change, psychological which is derived from the state of mind of previous experiences and behaviour related adaptation (Brager and de Dear, 1998). This model can become the

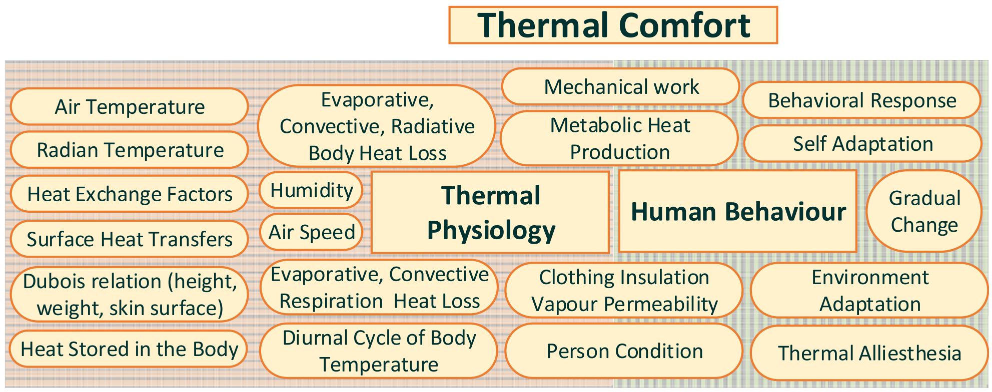


Fig. 4. The thermal comfort parameters.

solution if the PMV cannot easily be obtained due to the properties that PMV is not individual, not adaptable and no input modification. This model is based on the work being done by Macpherson, which considers the heat balance of the body. This balance is affected by the personal parameters representing characteristics of the occupants and ambient parameters. The personal parameters can include the clothing insulation, metabolic heat rate or activity level. The temperature, air velocity, and relative humidity can become the ambient parameters considered for comfort (Enescu, 2017). Based on this model, the ambient parameters can be controlled by opening windows or fans (Rupp et al., 2015). Besides the fan, which can be used to give, influence to the ambient condition, there is some equipment, for example misting fan, heater (centralised or personal heating) and air conditioning. The parameter which affects the thermal experiences can be in the form of gender (Song et al., 2016) and age, for example, the elder or disable user group, which needs a higher temperature setting (Salata et al., 2018). In this case, a particular group of people has to be considered in the design of the human comfort system.

Regarding the adaptive behaviours for assessing energy-efficient building indoor cooling and lighting environment towards buildings sustainability, many techniques are available. However, these tools have not yet measure energy efficiency index by involving user satisfaction from adaptive behaviours dependently, which can determine the actual energy consumption versus the planned energy consumption of the building. Sensor technology development is crucial. A list of adaptive behaviours already identified from users regarding energy-efficient systems for an indoor environment is provided below (Keyvanfaret al., 2014):

a) Self-adaptation category: drinking cold beverages, less-sweating lifestyle, restraining physical activity level, changing or adjusting clothes from warm to cool, decreasing the level of body skin moisture.
b) Adaptation to the environment category: taking a break and moving to a cooler location, changing position and direction, adjusting furniture/finishing material, opening or closing doors using a feedback system, opening or closing operable windows (with/without feedback system), using the portable fan, using had fan, adjusting room's thermostat, adjusting air-condition operative hours.

All of these are adaptive behaviours or actions to control the environment and combine it with physiological reactions. Time is essential for these behavioural interactions and the periods can be grouped into four distinct period's groups as follows:

1) Immediate, for example, the use of coat in anticipation of a thermal change
2) Within-day, for example, the clothing changes to cope with changing environments within a particular day.
3) Day-to-day, for example, the learning process from one day to the next to cope with changing conditions such as the weather.
4) Longer-term, for example, the clothing adaptation with the seasonal changes and activities learned over a more extended period.

The value will change with climate, place and time dynamically and interactively (Fergus Nicol and Roaf, 2012).

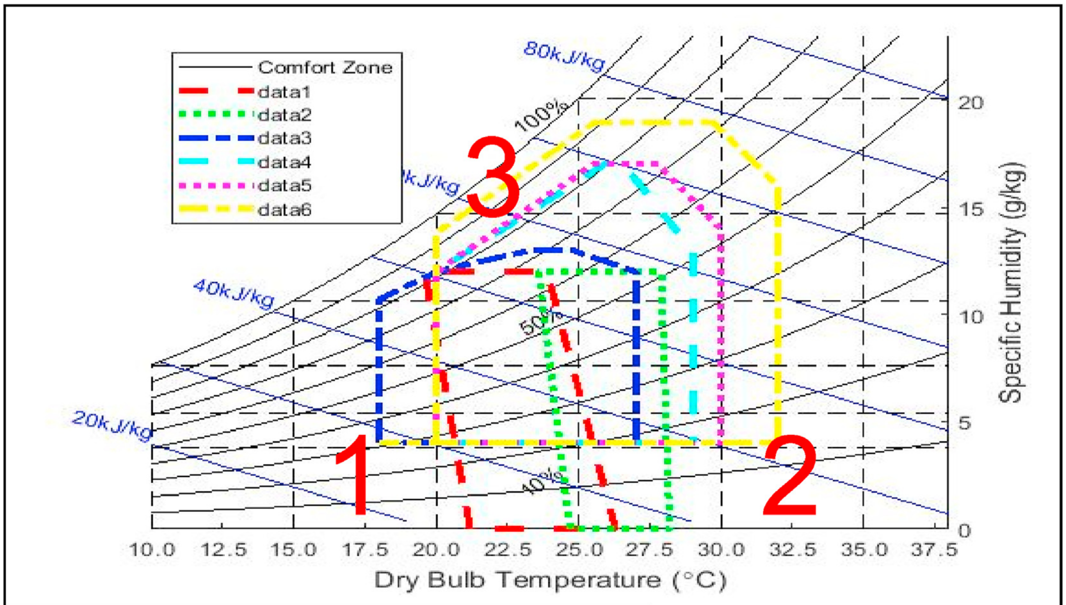
The following Fig. 4 presents the parameters taking into consideration for the Thermal Physiology methods (PMV-PPD) (left-hand side, horizontal stripes) and the Human Behaviour adaptive methods (right-hand side, vertical stripes area).

Parameters listed in the left-hand side are considered unimportant by the adaptive approach since people will always behave to make themselves comfortable as far as it is possible (Fergus Nicol and Roaf, 2015). This work also addresses that comfortable temperature are changeable rather than fixed. Discomfort also can be caused by excessive constraints on these choices and adjustment process, rather than merely the surrounding temperature. Comfort can be reached if there are sufficient opportunities for people to adapt. Only with the adaptive approach, all parts of the whole system become part of the comfort solution (Fergus Nicol and Roaf, 2015).

Many adaptive thermal comfort models using the black box approach without integrating it to the thermal physiology models. This makes the model incompatible one another (Luo, 2019). The quantitative characteristics of building occupants thermal adaptation has been studied and found that full thermal adaptation requires a more extended period. It is difficult for people from the warm thermal conditions to adapt to cold indoor conditions in a short period.

People can still be in comfort if the change in skin temperature happens gradually. The skin temperature will be non-uniform. The cold is comforting for overheated bodies but unpleasant for already cold bodies. The hot sensation is pleasant if we are cold, but give discomfort if we are already hot. The sensation effect will depend on time, clothing and the temperature of the surroundings. The adaptive action is to drink much water to maintain thermal balance in hot, dry weather. A sudden change in weather conditions will require people to act accordingly and avoid the danger of heatstroke (Fergus Nicol and Roaf, 2012).

Regarding the adaptive behaviour effect on assessing energy-efficient building indoor environment, quantitative indicators or methods and works should support the verbal qualitative analysis where they are determined. Instead of static set points for standard thermal comfort setting value, the study to use adaptive comfort values have been carried out (Sánchez-García et al., 2020). The model is being validated and fed with temperatures in 2050 and 2080. Another approach for the model is based on the exergy comfort temperature calculation (Buyak et al., 2017). Both of the models present the acceptability and the possibility to decrease the energy demand for thermal comfort. However, the human adaptability to the temperatures in 2050 and 2080 is not predicted in this work.



Prescriptive:
data1: the PMV-PPD comfort zone for 1.0<met<1.3 and 1.0 Clo, ASHRAE Standard 55
data2: the PMV-PPD comfort zone for 1.0<met<1.3 and 0.5 Clo, ASHRAE Standard 55
data3: Givoni comfort zone for still air condition for winter
data4: Givoni comfort zone for still air condition for summer
data5: Givoni comfort zone for winter with assumed air speed about 2 m/s.
data6: Givoni comfort zone for summer with assumed air speed about 2 m/s.

Goal based method:
1 The potential adaptive comfort zone by thicker clothing, prominent activity, etc.
2 The potential adaptive comfort zone by light clothing, less sweating activity, drink cold beverages, etc.
3 The potential adaptive comfort zone by moving to less humid room, installing dehumidifier,

Fig. 5. Psychometrics chart showing the comfort zone (PMV-PPD (R. American Society of HeatingI. Air Conditioning Engineers, 2017) and Givoni (Givoni, 1992)) and potential adaptive comfort zone.

Another work also focuses on exergy analysis of human with their environment (Shukuya, 2019a). The relation between building physics with human biology is referred to as bio-climatology (Shukuya, 2019b). It will be possible to use the exergetic comfort model for assisting the quantitative analysis of the physiological part of the adaptive comfort model. However, this approach and the PMV model still cannot fully explain the observed sensation votes, especially in the cases of higher outdoor temperature (Schweiker and Shukuya, 2012). The following works which implement the model also acknowledge the effect of variations caused by weight, stature, age or gender differences (Guo et al., 2019). These individual differences are also acknowledged to have significant influence by the research conducted temperate climate zone (Turhan and Gokcen Akkurt, 2019).

Further conducted study also acknowledged that decreasing ambient temperature would increase exergy consumption within the human body. The comfortable air temperature will remain the same, and the reference environment can be chosen equal to the ambient temperature (Deshko et al., 2020). The analysis of adaptive comfort and the changes in human exergy consumption will have an impact on building energy performance and saving whilst considering the comfortable indoor temperature.

Parameters listed in Fig. 4 shows that the adaptive approach is a goal-based method, and the PMV-PPD is prescriptive. The comfort zone for the PMV-PPD and potential adaptive comfort zone can be seen in Fig. 5.

The difference in the methods will give different impacts on comfort temperature values. PMV-PPD approach will give more exact definitions of comfortable temperature (ASHRAE, 2017), while adaptive methods will not give exact boundaries on the comfortable temperature. This potential zone can be elaborated to minimise energy use.

3.3. *The adaptive approach focused on disabled, temporarily ill and elderly groups*

The group of people who are the most vulnerable to climate change and energy poverty is the disabled and elderly people group (Wolbring, 2009), (Radford). Nowadays, the elder people group is reaching 8.5 per cent of people worldwide (617 million) and continues to grow in the number and percentage. It is predicted to reach about 17% of the world's population by 2050, which is about 1.6 billion (Wan He and Kowal, 2016). The number of disabled people is also significant. Based on the WHO and World Bank report, there are about 15% or more than 1 billion of the world's population lives with some form of disability. To be more specific, 2–4% of them living in significant difficulties in functioning (Bank, 2011).

PMV-PPD method is the comprehensive analytical methods which have limitations if the clothing/insulation exceeds 1.5 clo; having high impermeable to moisture transport; in contact with bedding (sleeping) (ASHRAE, 2017) or having difficulties in dealing with a specific group of people like young, elder, disabled or temporary ill people group.

The disabled, temporarily ill and elderly groups are known to have different standards of thermal comfort (HAGHIGHATMEGRI et al., 2000), (Haghighat). These previous studies also show that:

- the mean body temperature and the mean weighted skin temperature of the elder group are lower than the young

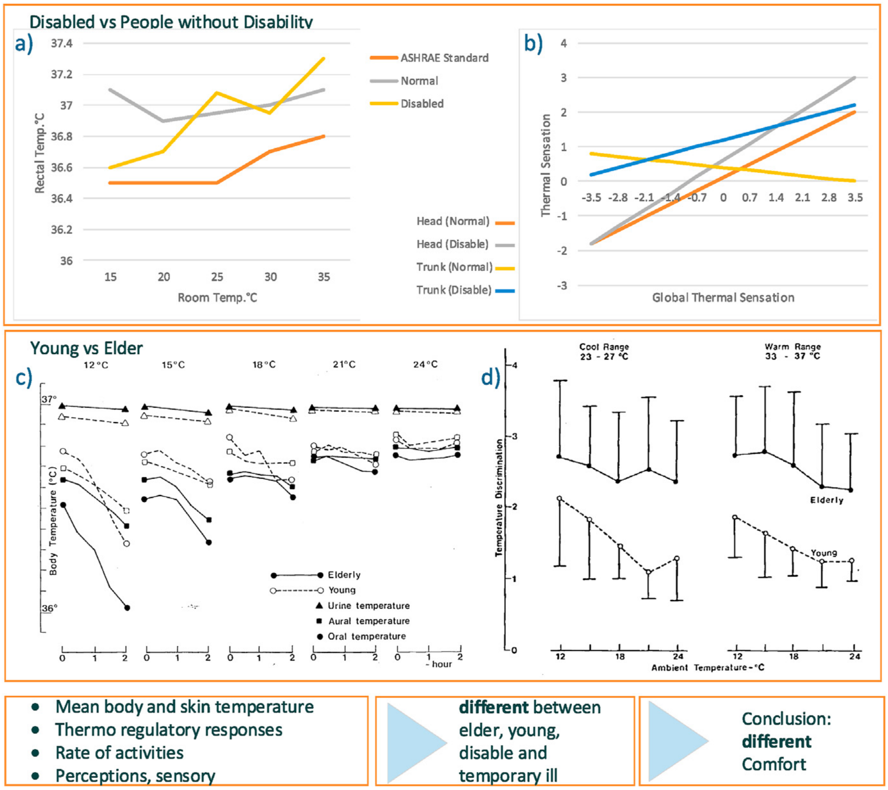


Fig. 6. Illustration for showing the difference of comfort temperature from previous research (Yung et al., 2019), (Basu and Samet, 2002).

- the elder group preferences will be different from the standard because of the relatively low level of activity
- the elder group is in the risk of cold because of inadequate thermo-regulatory responses and blunted perception of temperature changes
- the clothing level has no influence on the elderly's satisfaction (open space) and more on their activity level (Yung et al., 2019)
- the body temperature is not related to the heart rate, but the activity level (Basu and Samet, 2002)
- the correct comfort setting can also be considered to be uncomfortable because of the perception.
- thermal alliesthesia which is an alliesthesia of the thermic perception related to thermoregulation will give complex parameterisations in defining thermal comfort (de Dear, 2011), (Parkinson and de Dear, 2014), (Parkinson et al., 2015)

The illustration in Fig. 6 shows the difference between the temperature needs for disabled, temporarily ill, and elderly groups compared to people without the disability group mentioned in the previous research (Yung et al., 2019), (Basu and Samet, 2002).

Fig. 6a) shows that there is a gap between the behaviours of disabled people in comparison to people without disability. Besides this, the figure emphasis that the gap seems more significant for room temperatures below 23 °C and above 30 °C, which are more frequent temperature domains due do climate change (cold and heat waves tend to happen often). This highlights the importance of this study.

Fig. 6a) also shows that there is a gap between human temperature and the prediction from ASHRAE. This means that the PMV-PPD comfort zone is far away from this research result. However, Fig. 6a) results may not have enough data to develop a more detailed analysis and generalise the result for all disabled people group.

Fig. 6b) shows a further comparison of the thermal sensation between the disabled and people without disability. For the head thermal sensation, the disabled feel that the thermal sensation is higher than people without the disability. The very different result happened in the trunk thermal sensation. Not just the gap, the tendency of the disabled people is flipped compared to the people without disability. Again, Fig. 6b) is based on a limited amount of data and cannot be generalised for all disabled people groups.

Align with the result in Fig. 6a and b; Fig. 6. c shows that the young people group also has a different average temperature compared to the elder people group. This difference gap is not proportional so that the approach of thermal setting or regulation cannot be set based on the percentage of the correction based on the standard thermal settings. This again emphasises the importance of this study. The thermal setting cannot be generalised and become more personal. This thermal sensation also being validated by the trial shown in Fig. 6d). The temperature discrimination between the young and elder people group is not proportional, and there are significant gaps between the two people groups.

The work which acknowledges similar result from the disabled people group is also being stated in (Brager and de Dear, 1998), (Parsons, 2020) and for elder people (Maeda et al., 2005). In the case of the elder people, thermoregulatory responses to both cold and hot temperatures were delayed. This is caused by the degradation of vascular regulation ability and thermogenesis due to the ageing process. The seasonal change and seasonal characteristics are also significant in the thermal sensation of the elder people group (Salata et al., 2018), (Mishra and Ramgopal, 2013).

Defining the correct setting of thermal will be difficult because of individual variability in temperature (Collins and Hoinville, 1980). ASHRAE releases an Open Database of Global Thermal Comfort Database II (The Comfort Database) to simplify the implementation of the thermal comfort approach. The database maps the cooling strategy, building type, meteorological context, indoor climatic physical parameter ranges, along with various human factors. The human factors consider characteristics such as sex, age, clothing insulation, and metabolic rate and the availability of indoor environmental controls, such as operable windows, doors, thermostats, blinds, heaters, and fans (Executive, 2019). This database is not targeted for the disabled, temporarily ill and elderly

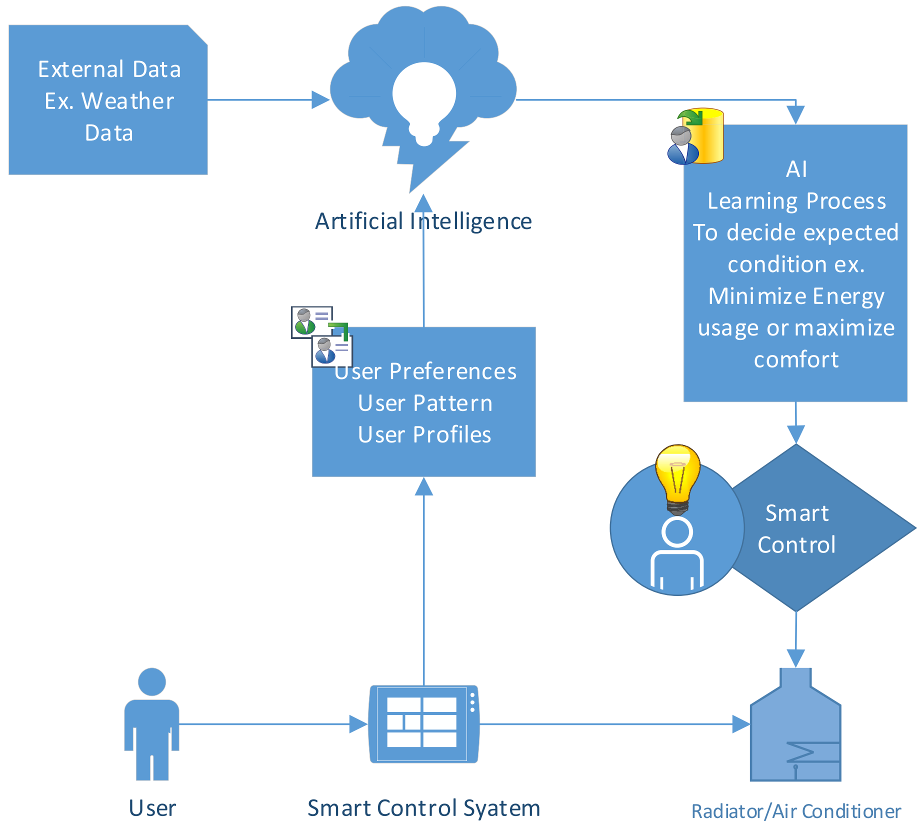


Fig. 7. Simplified AI system for thermal comfort.

groups.

This complex and personalised parameterisation will be ideal to be solved with an adaptive approach. Personalised parameter settings can also be supported by intelligent technology for minimising frequent user manipulation, which can generate uncomfortable activities and will provide optimum thermal comfort for everyone, without significantly increasing energy use (v HoofHensen, 2006).

4. Adaptive approach improvement by the use of AI

The previous studies emphasise the need to improve the thermal comfort methods, namely for particular groups of people. Those methods have a focus on the way to achieve comfort, to maintain health and safety within the energy efficiency corridor. Besides the variety of human physiology, there is also the human behaviour factor, which can be different from one to another. The researcher also uses some methods in order to make the system able to cope with such variability and able to adapt to get the optimal performances. These methods are giving the capability for the system to act like uninterrupted human control, and being called as having artificial intelligence (AI) (Moon et al., 2011). Supported by AI features, the control system can gain a better solution and can cope with people's preferences. The setting adjustment can be made based on the setting for the specific use of the system as training data. The simplified system for thermal comfort can be seen in Fig. 7. There are currently two most common methods in AI for thermal comfort. The first method is Fuzzy Logic or fuzzy in short, and the second method is an Artificial Neural Network (ANN).

4.1. Fuzzy Logic

This method can interpret the verbal human perception or preferences such as 'warm' or 'cool' which are not easily interpreted by the control system. The fuzzy methods are being used in the control system to give more human comfort while trying to minimise energy use. This approach is used to get a better result compared to the Proportional Integral Differential (PID) control. Some of the previous work results are implemented in the form of simulation, which is MATLAB based (Lachiver, 1998), (Calvino et al., 2010), (Nowak and Urbaniak, 2011), (Rawi and Al-Anbuky, 2011), (Moon et al., 2011) and (Zhang et al., 2014). These methods have also implemented in the form of the prototype for controlling the air conditioning operations (Yonghong Huang, 2006), (Ciabattoni et al., 2015) or heater (Walek et al., 2014). The comfort parameter is based on the PMV model. The fuzzy method is also used in the research of material/fabric (Huang et al., 2008) and comfort in the automotive industry (Farzaneh and Tootoonchi, 2008), (Beinarts, 2013). This system will also have the drawback if the data are widely varied so that the fuzzy membership function cannot be clearly defined. Some methods like genetic algorithm (Shaikh et al., 2014) or ANN are being used to compensate for the drawback of fuzzy methods (Duan and Li, 2010). This ANN and fuzzy hybrid method are becoming the most popular methods (Enescu, 2017).

4.2. Artificial Neural Network

In ANN, deep learning or shallow learning, the intelligence of the system is gained from the human sensory analogy. This method can work as a black box by giving a set of learning processes, especially with supervised or directed learning. The learning process is essential for this method. The same system can perform differently when trained with a different set of training data. This method is preferable by the system developer to build the thermal comfort system where not all of the connections between all of the thermal comfort factors are well known and well defined. The ANN/deep learning research has been widely used and give significant results in thermal comfort. Some of the previous work is implemented in the form of model and simulation (Liu et al., 2009), (Yalong et al., 2011), (Moon et al., 2011), (Rodríguez-Alabarce

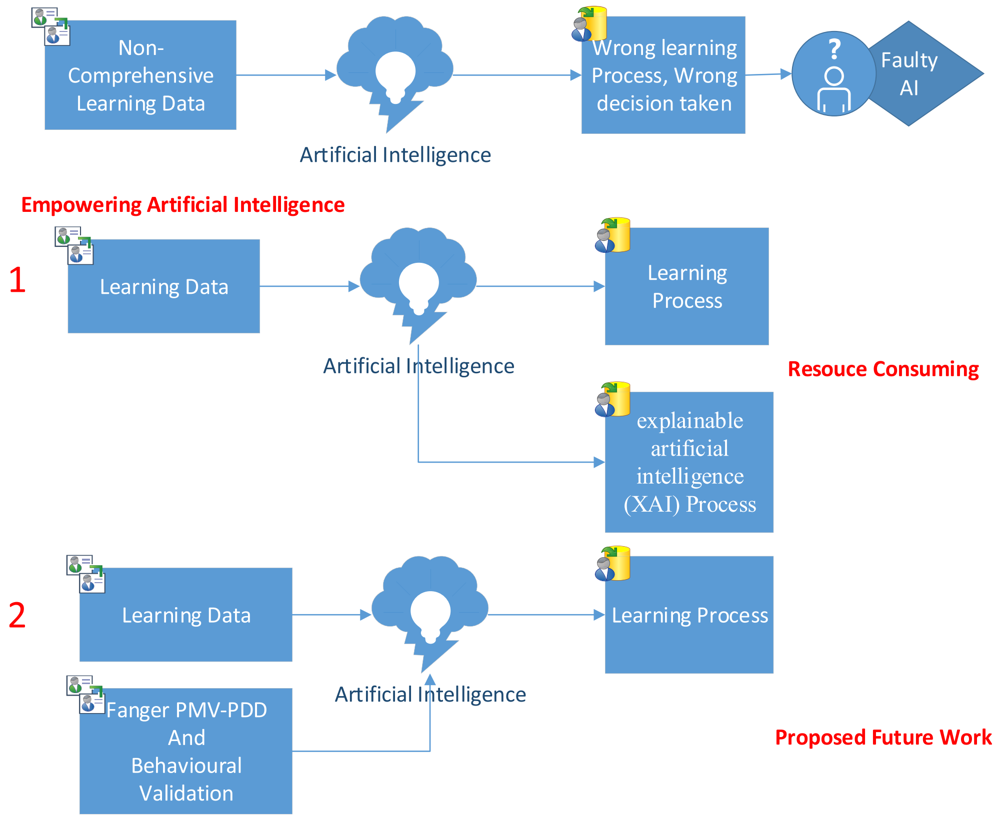


Fig. 8. Proposed Solutions for Empowering AI using Fanger PMV-PPD and Behavioural Validation.

et al., 2016), (Moon and Jung, 2016), (Zhang et al., 2018), and (Escandón et al., 2019). Some of these models are developed to be implemented in tropical region (Bingxin et al., 2011), (Zeng et al., 2011), (Songuppakarn et al., 2014), (Chaudhuri et al., 2017) or to overcome the extreme condition (Liu et al., 2009), (Yalong et al., 2011). The result from the system prototype also presented in (Kojima, 2010), (Kojima, 2011), and (Zhai et al., 2017) which implement the ANN to overcome individual preferences. This method also being used for the research in fabric/materials (Baozhu and Shan, 2010), (Baozhu, 2011) and also in lighting comfort (Kandasamy et al., 2018).

The ANN methods being used is a typical feedforward neural network architecture for example backpropagation (BP) (Liu et al., 2009), (Kojima, 2010), (Kojima, 2011), (Bingxin et al., 2011), (Zeng et al., 2011), (Moon et al., 2011), (Songuppakarn et al., 2014), (Moon and Jung, 2016), (Chaudhuri et al., 2017), (Zhai et al., 2017), and (Escandón et al., 2019). BP is the most common because of the simplicity of the model. There are other types of ANN methods such as Multilayer Feed Forward (Duan and Li, 2010), Radial Basis Function (Yalong et al., 2011), Nonlinear Autoregressive Model (Songuppakarn et al., 2014), C-Mantec (Rodríguez-Alabarce et al., 2016) and Deep Neural Network (Zhang et al., 2018). The ANN has also come in hybrid with another model such as with Fuzzy (Nowak and Urbaniak, 2011), (Enescu, 2017) and with genetic algorithm (Bingxin et al., 2011). ANN approach also has a better performance in thermal comfort applications rather than the Fuzzy approach (Moon et al., 2011).

Although this system is very powerful in processing the unclearly defined relations, it has a negative impact due to the learning process. If the training process is not done with proper data, or the data is not defined correctly with all of the cases available, the system can perform falsely. In the system for recognising male or female, for example, if all data provided for women are always in the kitchen and men are always in the office, the system can interpret wrongly. If the new case appears that the man is inside the kitchen, it can be interpreted as a woman. That is why it can also be said that one pixel can make the wrong interpretation (Su et al., 2019). The classification can be easily altered by adding relatively small perturbations to the input vector and can become the source of an attack by only altered one pixel. This matter is one aspect that can be associated with producing natural stupidity in AI.

4.3. Quality assurance for ANN tailored for thermal comfort

Thermal comfort is crucial to support the health and safety of all people groups. The young generation and mostly the elderly are susceptible to sickness because of the heat- or cold-related causes (Ye et al., 2012). The wrong thermal arrangement can be fatal for some groups of people, especially on the GCC when there can be sudden cold or hot waves. ANN can give the personalisation setting, but the result should be controlled and validated.

The system, which is targeted for precision and fault-tolerant, and wants to use ANN methods now use the novel approach called explainable artificial intelligence (XAI). The process can backtrack the learning process, whether it has the wrong interpretation (Samek WMüller, 2018), (Joel Vaughan, 2018). This process of tracking will require the use of excessive resources. The devices used in the thermal comfort subsystems will have difficulties to implement this method due to the limited processing power and memory. Strengthening the learning process for the neural network while still maintain the processing power and memory usage will be the challenging part. This is the work in progress for using the combination between the human physiology method and human behaviour methods (Fanger PMV-PPD model along with the human behaviour AI system) to achieve a faster and more reliable solution for thermal comfort. Instead of backtracking the whole learning process. The PMV-PPD model can be used to check the training parameters and processes. If it deviates over certain levels from the standard or the comfort guidelines, the PMV-PPD equation can then be referred for the validation of the learning process, which will involve the user or the user stored parameters. The learning process will then be updated with the most recent data before the controlling result being sends to the controller for thermal correction actions. This will make the outliers can be validated and accommodated, increase security protection, to lead to a more comfortable user, and gain more thrust. This approach has the potential to perform better compared with the XAI approach. In the future, it will introduce a safer environment and a lower probability of error triggered by the limitations of AI and probably AI hacking. The diagram of the approach is presented in Fig. 8.

5. Conclusion and future work

Many researchers are still conducting research to produce a better solution for thermal comfort. It is now inseparable between the necessities to get better settings achieving health, wellbeing and the ability to minimise energy use. The approach of Fanger's equation (the physiological aspect of the human) will give comprehensive analytical methods but have limitations in accommodating the disabled and elder group of people. The elder people group is predicted to reach about 17%, and the disabled people group is about 15% of the world population.

The adaptive approach is used to achieve a solution for those groups of people. The adaptive approach will give the PMV and PPD flexibility and personalisation needed to overcome the problem due to the variability of the people's metabolism, historical and behavioural preferences. The adaptive method acknowledges the different needs of thermal comfort between different people group, young, elder, disable and temporary ill. The adaptive method has the potential to alter the comfort zone to minimise energy use. The adaptive approach uses Artificial Intelligence (AI), where it can introduce the imperfect learning process.

Instead of going further for the Explainable AI to validate the learning process, which is resource consuming, the PMV–PPD validation approach is proposed for the learning validation. Fanger's equation and the PMV-PPD will give base setting, calculation and learning verification needed for the adaptive method to perform better. The thermal comfort system design will become more robust because they use the proper calculation standard, yet flexible enough to cope with the psychological aspect of human beings when using the combination of these approaches. Our future work will focus on creating the model, the prototype and test this approach so that the performance of this system can be compared with the existing system.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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