AN ALGORITHM FOR THE ASSESSMENT OF SUBJECTIVE ADAPTIVE THERMAL COMFORT CONDITIONS BASED ON MULTI-AGENT SYSTEMS

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ABSTRACT
Thermal comfort conditions in the built environment are strictly related not only to the thermal and geometric building features and to air-conditioning systems, but also to the building destination, to its using profile and to the biological-metabolic-psychological characteristics of users.
As a consequence, there is a strong claim for new models, both subjective and adaptive to the environment, in a particular holistic vision of the problem, with regards to the novel tern user-plant-building system.
In such a frame, through the paper the caracterization of an algorithm aimed at subjective adaptive thermal comfort evaluations, enriching the one proposed by Fanger with an adaptive approach, is carried out using a Multi Agent System (MAS), based on Intelligent Agents, able to follow user’s needs and preferences in different contexts and expectations.

INTRODUCTION
Both scientific community and people in everyday life nowadays pay a big attention to the realization and preservation of indoor life conditions as comfortable as possible.
Indeed, nowadays, users enjoy the greatest part of advanced services in indoor environment and express clear demands for bigger and bigger personalization and reliability, showing high performance levels, in order to reach global improvements in the quality of life.
At the moment, the main challenges to face up are both the control of building energy consumption and the obtainment of more advanced and personalized services, in order to reach comfort conditions by means of a trading-off among employed resources, costs and effectiveness of energy performance.
Consequently, actually both research and technology are mainly addressed towards a scenery where the user is the centre of every application, in the so called user centred application vision.
Within this vision, subjectivity and reference context assume a role of increasing importance, being very significant in order to evaluate subjective comfort conditions; moreover, the support of novel techniques shows to be a topical argument for data management and service provisioning.
In particular, it seems to be more and more necessary to change the focus of the approach from a classical vision that analyzes the pair plant-building system, to a novel tern user-plant-building system, offering a more complex vision of comfort and context issues: of course, this implies more complex problems to be faced up.
According to these theories, in the literature the most suitable approach appears to be an adaptive one [1], in order to realize a system able to evaluate comfort conditions and react to context variables changes to preserve
user comfort.

In this aim, computer science along with the whole improvements of ICT (Information and Communication Technology) and automatics can hold a leading role in order to realize higher quality levels as concerns the design and fruition of buildings.

In addition, these disciplines may be very useful in order to both improve performances and reduce costs; finally, they also result essential for data collection and huge information exchange, allowing anticipating building needs in terms of energetic and climatic exigencies and anything else is at the basis of occupants’ comfort [2].

Within this frame, in order to carry out environments more and more careful of user comfort exigencies, the research proposed in the present paper is addressed towards adaptivity in the managing of the complex user-building-plant system, allowing development of Fanger’s theories with adaptive approach. A new system based on Intelligent Agents, based on a Multi-Agent System (MAS), is proposed in this aim.

**THERMAL COMFORT FROM AN HOLISTIC POINT OF VIEW: FROM FANGER MODEL TO A NEW SUBJECTIVE ADAPTIVE APPROACH**

Medical science consider comfort as a global state coming out from the interaction of different ambits [3], that is an holistic concept [4,5], defined in relation to physical, biological, psychological, emotional and relational aspects [6-10].

Reaching an holistic comfort, user is allowed to enjoy a big efficiency in the different activities and a general satisfaction in relation to the global context and, consequently, to the different spheres of the multidimensional human nature. Anyway, holistic comfort represent a global sensation not obtainable without reaching comfort in different ambits.

Human behaviour is naturally aimed at reaching holistic comfort, which is a highly dynamic state, subject to frequent changes caused by the context user is involved in: this implies user adaptivity to the experience context, with consequent actions aimed at reaching and keeping comfort conditions.

Nevertheless, it is undoubtedly very difficult to reach holistic comfort, as well as it is very difficult to formalize such a state: as a consequence in the present work we will limit our attention to environmental comfort and, in particular, to the thermal-hygrometric one [11], anyway analysing it from an holistic point of view.

Human body comfort sensation is due to both environmental and subjective factors [12], the most relevant of which are:

a) microclimatic conditions;

b) building envelope and thermo-physical features;

c) physical and chemical agents;

d) user activities, work and life habits;

e) user psycho-physiological-metabolic characteristics.

Indeed, the well known Fanger equation of human body thermal balance [13]:

\[
f(M, I_{cl}, t_a, p_a, v_a, t_r, t_{sk}, E_{sw}) = 0
\]

confirms this subjectivity, being based on both objective environmental variables (temperature \(t_a\), air speed \(v_a\) and humidity, expressed in terms of vapour pressure \(p_a\), and mean radiant temperature \(t_r\)) and subjective ones, related to individual choices (clothing thermal resistance \(I_{cl}\)) or physiological parameters (metabolic rate \(M\), power lost for skin evaporation \(E_{sw}\), skin temperature \(t_{sk}\)).

Such a large judgement relativity implies that environments with same climatic conditions may produce different comfort evaluations, in relation to different users and contexts they are expressed in. In addition, evaluations can also be different for same users in different times, owing to different psycho-emotional-
metabolic conditions in spite of same thermal ones. On the matter literature results related to PMV and PPD values are very significant [14, 15].

Due to the difficulty of the topic, at the moment an adaptive approach represents the most effective way to be followed in order to obtain comfort conditions in spite of changes in the context variables [16].

Different kinds of adaptivity remarkably influence the user’s comfort perception [17-18]:

- physical-behavioural adaptivity, involving changes aimed to adjust user to the environment (like altering one’s clothing, posture and position, or metabolic heat by assumption of hot or cool drinks) or the environment to user’s needs (i.e. opening a window, turning a thermostat, opening a parasol, etc.) [19];
- physiological adaptivity, implying changes in the physiological responses resulting from repeated exposure to a stimulus, that leads to a gradual decreased strain from exposure (acclimatization);
- psychological adaptivity, involving all the cultural and cognitive variables, describing the influence of different expectation and habits on users’ climatic perception [20-21].

Brager and de Dear [16], several years ago, already gave large importance to all the factors omitted in Fanger energy balance model, like personal ones (sex, age, culture, economic state), contextual ones (emotional state, building using profile, contingent situation), environmental (illumination and acoustics, air quality issues) and cognitive-psychological (attitudes, preferences, expectations).

Lately, also Humphreys and Nicol confirmed the inadequacy of the deterministic PMV method in order to predict comfort conditions in relation to people groups in everyday life conditions [22].

On the whole, criticisms reported in the literature by different authors [23-30] evidence the necessity of an evolution of Fanger method, taking into account user’s psychological data [20-21] and information related to his cognitive-emotive-relational sphere.

Hence, in order to obtain a global approach, through the paper an enrichment of Fanger model is proposed by introducing a new model for comfort state perception, defined as scenario-adaptive subjective comfort model [31-33] (Figure 1), where scenario is intended as the whole set of information, continuously evolving and reacting to the varying context, that contribute to represent the environment surrounding the user, filtered by his subjective perception.

One of the unavoidable consequences of the approach is represented, anyway, by the concurring objectives the might arise in presence of different users, as thermal conditions considered as comfortable by some users could be considered as a discomfort by others.

![Figure 1. Scenario-adaptive subjective model for comfort perception.](image-url)
ADAPTIVE SUBJECTIVE COMFORT USING INTELLIGENT AGENTS: THE PROPOSED MULTIAGENT SYSTEM

From the above it follows that main goal of such an innovative model is keeping users in comfort although context variables change, warranting a real-time reactivity: consequently the used model should carry on a continuous trading-off between available resources and expectancies, providing comfort conditions tailored to each user in every context.

If it is possible to configure a system able to both register users’ actions and deduce their exact interpretation and interrelation with the contextual data, after a training phase, the system could also adapt to follow user choices and preferences.

This sort of applications and methodologies allows significant benefits in terms of **Percentage of Dissatisfied**, energetic and economic saving.

It follows that a traditional, deterministic approach shows unsuitable to face the problem, being impossible to describe such a complex model simply using predictive mathematical models. On the contrary, a synergy among different sciences (computer science, telecommunication technology and automation) is necessary; better, different integrated systems and technologies should be used.

At the moment, particularly advisable is the use of artificial intelligence techniques and ICT, and, among them, **user modelling** [34], showing particularly effective in building detailed user profiles, updated in real time.

In this field **Intelligent Agents (IA)**, adaptive systems able to follow a user in all his actions, behaviours, preferences and decisions, show to be the most effective system reactive to context changes [35-38].

An important characteristic of *IA*, with regard to comfort analysis, is their characterization by means of typically human mental elements, such as knowledge, beliefs, contents, expectations and duties, that describe psychological-adaptive-cognitive aspects of human beings [39]: on the basis of this, some researchers have even defined Intelligent Agents as **emotional agents** [40], in order to underline their ability in managing and represent human mental states.

In order to satisfy the above-described exigencies, particularly small and autonomous systems represent the most efficient system providing global management.

In the following, the selected approach is based on particular types of Intelligent Agents, known as **Multi Agent Systems (MAS)**, able to warrant high adaptivity and integrations of existing and new systems [41-43]. Through the work four agent typologies have been characterised, each attending to a particular aspect:

1. **Scenario Management Agent (SMA)**
2. **Plant Management Agent (PMA)**
3. **Environmental Agent (EA)**
4. **User-Building-Activity Agent (UBA)**

In particular SMA has been exploited in order to manage the environmental and profile information provided by EA, in order to properly handle the scenario and react to it, whereas PMA has been assigned to handle the whole plant, along with the resource distribution and availability for the area of interest.

Indeed, most information is exchanged among SMA, PMA and EA and only the data elaboration output is sent to UBA, thus consistently reducing network load.

The different agents work continuously interacting as a self-organizing application software operating in the global architecture of the system, even if each of them is independent in order to achieve the different attended goals [44-45].

They dynamically and continuously exchange information and negotiate with each other in order to get the best conditions for user comfort.

Information is collected through a modular system, consisting of micro-ambient sensors (generally thermal sensors) and wireless technology; along with them, other sensors are used, collecting user metabolic data or selected indicators of user activity, clothes, and so on, in order to predict user reaction and act in his favour (pro-
activity) [46].

All the collected information is stored and used in order to follow the user in his own comfort experience. Fully personalized and subjective iso-PMV curves can also be traced.

In order to well understand the whole process, the way of working of the agents can be compared with the way some internet search engines, e.g., Google, work, that is searching for the best possible answers to the questions or tasks they were given by the users: in such a way the agents try to give the most suitable answer for user needs.

The interaction between the system and the user is designed warranting an interface with pre-existing technology: in general user interacts with the central unit of the system by means of a programmable remote controlling system, able to reproduce the infrared signal of the pre-existing device and the MAS interacts with the older plant through a sensor system aware of the context (Figure 2).

Further advantage of the system is its versatile use of user profiles defined in force of information collected, that can either be shared by internet services or stored in a SIM Card, in order to obtain HVAC intelligent systems, providing user personalized comfort services anywhere and anytime (e.g., in hotels, at office, etc.).

GENERAL DESCRIPTION OF THE PROPOSED SYSTEM

In a global vision, five different macro-blocks representing different phases of the whole adaptive process can be distinguished (Figure 3). In the figure the different phases are reported along with the interrelations, described by the arrows of the data flows, and they do not represent apart processes, but contain interrelated processes and decision mechanisms giving rise to a very complex algorithm and an intricate information flow (Figure 4).

In Figure 5 the detailed global behavior of the algorithm, is reported in 28 points, along with the data flowcharts and agent interactions.

The flowchart representation is useful also in order to understand the global robustness of the whole system. In the figures, according to the main trends of artificial intelligences literature, the agents are expressed by means of cartoon-style icons.
As above said, the system is thought to enrich Fanger’s model with considerations related to adaptivity [47] and subjectivity; in order to do so, the proposed model provides the characterization of user profiles obtained starting from Fanger rules, subsequently updated as user interact with the system.

Following each action-reaction couple of choices, the system is able to update a much detailed and subjective profile, tailored to each single user, in order to represent his own way of comfort perception: in such a way, a strict correspondence among user, his past history, his expectations and preferences and contextual factors is realized.

Indeed, in such a system, it is important to reduce the user interventions in order to create a system able to be transparent to his normal life habits; consequently, the required interventions of the UBA agent in the global functioning are very few: UBA interacts only in the first steps of the algorithm in order to set the desired starting parameters, when user wants to change something about his comfort state, and at the end of monitoring, when user shuts down the system.
In the following, an overall analysis of the different phases of the algorithm reported in Figure 3 will be presented, giving a schematic description of the system functioning [47].

- **Phase I: Starting phase** *(steps 1 and 2 of the global algorithm).*
  User enters in the area controlled by the system. The plant is activated by either a remote controller or other suitable devices (sensors or time scheduling strategies). The personal agent UBA and the agent following user through the scenarios, SMA, are activated;

- **Phase II: Data Collection** *(steps 3 to 10 of the global algorithm).*
  In this phase the location of the user in the area of interest is firstly retrieved. Then, the agents interact in order to retrieve all the data useful to represent the scenario, both thermal and non-thermal factors related to user’s comfort preferences (environmental data provided by EA and the plant and resource information attended by PMA).
  Afterwards, UBA allows user to choose his activity and, finally, information related to clothing and specific metabolism issues are retrieved either from an opportune modular sensor system or from the global database storing data taken from ISO 8996 and ISO 9920 tables [48,49], along with the useful information of ISO 7726 [50].
  At this point SMA becomes able to use the information provided in order to create a logical representation of the comfort scenario in relation to PMV considerations.
  A particular multi-room path is also determined, along with a secondary activity time scheduling, in order to pro-actively set the plant to follow user’s comfort preferences.

- **Phase III: Determination of comfort level using subjective adaptive PMV equation** *(steps 13-14 and 23-26)*
This phase is the core of the whole process. The system is ready to compute PMV values for all the positions interested in a multi room path related to user activity.

In order to define the desired user profile, a new user is firstly provided with a starting default one, obtained from Fanger model, on the basis of which the system creates the logical representation of the context, determining the user comfort state.

Subsequently, as user interacts with the system, his starting profile is continuously updated by IA, thus tailoring comfort to that specific user. On purpose an opportune PMV equation based on Fanger theories and modified through introduction of adaptive factors is used:

\[
PMV = f(a_1M, a_2l_{cl}, a_3p_a, a_4t_a, a_5v_a, a_6\bar{t}_r)
\] (2).

If available information about users is not enough, the system uses the un-modified Fanger PMV model \((a_i = 1)\), otherwise the above factors have to be set in order to represent the subjective preferences of the considered user.

In this aim the system retrieves all the necessary data obtaining, after a training phase, the definition of an opportune series of \(a_i\) and a detailed characterization of the user profile. In particular, when considering only the adaptive factor related to air temperature (the most sensitive parameter modified by users), the relation can be simplified as follows:

\[
PMV = f(M, l_{cl}, p_a, a, t_a, v_a, \bar{t}_r)
\] (3).

As a consequence, when the user sets the desired temperature \(t_{ad}\) the system, and in particular SMA, understands that he would be in comfort at that specified temperature: the adaptive principle entitles to consider PMV = 0 and the related adaptive factor can be computed by means of the following equation:

\[
0 = f(M, l_{cl}, p_a, a_{t_{ad}}, v_a, \bar{t}_r)
\] (4)

that leads to

\[
a = f^{-1}(M, l_{cl}, p_a, t_{ad}, v_a, \bar{t}_r)
\] (5).

Of course, after air temperature changes other parameters will change as well. The system warrants a continuous adaptivity to user and scenario by means of an unceasing and real-time determination and update of the transfer function of the model.

Once known the adaptive factors, the system is able to pro-actively determine the desired air temperature to be reached in order to realize personalized comfort in the different rooms of the activity path. The computed values have to be stored and communicated by SMA to PMA in order to realize the right plant settings.

- **Phase IV: Plant set up and continuous check of comfort conditions (steps 15 to 22).**

The results of the previous phase are sent by SMA to PMA. Now, PMA is able to set the plant according to the personalized user preferences.

The scenario evolution is followed warranting a real-time reaction to the variations of the scenario variables and of comfort level in a proactive way.

When necessary, PMA has to take into account also the simultaneous presence of different users in the same environment, taking the best decision in modifying environmental parameters in order to satisfy all the users. According to the system design complexity and to the different level of awareness the system has, PMA could also be able to decide different policies and strategies in order to reach the goals to be attained, aiming at reaching the best comfort level with the minimum power consumption. This energy saving goal is not anyway the main argument of the study and as a consequence, we do not deal with it in detail.

- **Phase V: Ending phase (steps 27-28).**

User stops exploiting the system. User profile, that has been continuously updated during the whole process, is now definitively stored until the next access into the system. This profile is also shared between the local database (provided also with a SIM Card) and the remote one by means of opportune connection.

DETAILED DESCRIPTION OF THE GLOBAL ALGORITHM

In Figure 6 the global behaviour of the system is described in details by means of a data flowchart, where the high level algorithm is represented along with the different decisions, but neglecting the deeper technical details related to the behavior of each agent.

Each point of the global procedure, is identified in Figure 5 by the related number whereas each information flow is represented by a red letter, also present in the data flowchart.
Figure 6. Global behaviour of the system: flowchart of high level algorithm
1. **Starting phase.**

A user $U_i$ enters in an area of the building $B_j$ controlled by the system. He is not doing any specific activity and can be mobile, through the different rooms, or staying in a room. He starts interacting with the system, by means of a specific device (e.g. a remote controller), in a particular **Position**, defined by a specific location of the area of interest.

2. **Activation of starting agents $UBA_{ij}^{Starting}$ and $SMA_{ij}^{Starting}$.**

When $U_i$ accesses the system, a corresponding $UBA_{ij}^{Starting}$ is activated (in the starting phase the agents, being not referred to any particular activity, are called $UBA_{ij}^{Starting}$ and $SMA_{ij}^{Starting}$), which sends to the corresponding $SMA_{ij}^{Starting}$ the identifiers of $U_i$ (letter A in Figure 5). $SMA_{ij}^{Starting}$ retrieves the $U_i$ profile from a global database containing all the information about users.

3. **Retrieval of micro-climatic data, plant information and achievable activities for Position $P$.**

$UBA_{ij}^{Starting}$ sends to $SMA_{ij}^{Starting}$ the **User Position** (A). $SMA_{ij}^{Starting}$ determines the location area where $U_i$’s **Position** $P$ lies and extracts the building identifiers of $B_j$ from a global database, along with the building using profile.

By matching the user position with the building identifier and using profile, $SMA_{ij}^{Starting}$ retrieves all the practicable activities in that specific location (e.g. sleeping in bedrooms, physical exercise in gyms, and so on) and in the adjacent rooms. Each activity is defined by means of a specific profile in the database, along with all the information retrievable in ISO 8996 tables [48].

Then $SMA_{ij}^{Starting}$ sends to $PMA$ (B) a request for receiving the whole resource set available therein (e.g. information about specific plant and its power, along with the instruments present in that location), together with the status of the plant resources, in terms of current power consumption, maximum power, plant capability of affecting environmental parameters and so on.

At the same time, $SMA_{ij}^{Starting}$ asks $EA$ (C) to retrieve, through specific sensors, the micro-climatic information related to PMV index (air temperature, air velocity, mean radiant temperature and relative humidity). At this point the two personal variables (clothing insulation and activity level) are still missing (they could be available if a sensor retrieving user’s vital parameters were used, e.g. in hospital applications).

$SMA_{ij}^{Starting}$ is now able to start to characterize the scenario in the specific location. Finally, $SMA_{ij}^{Starting}$ adds the user $U_i$ to the person list present in **Position** $P$ (D).

4. **Determination of the Activity Global list.**

After creating a list of activities practicable at **Position** $P$, (E) $SMA_{ij}^{Starting}$ schematizes such activities in an **Activity Global List** (F), specifying, for each of them, the required resources, the suitable clothes and the related rooms. Some of the activities will be marked as **Not Available**, meaning that $U_i$ should change room in order to satisfy activity requirements (e.g. he desires to have a shower but he currently is in the bedroom).

5. **Determination of Available Activity List.**

Matching resources and requirements $SMA_{ij}^{Starting}$ defines the **Available Activity List** in **Position** $P$.

6. **Forwarding of Available Activity List sorted according to user preferences.**
SMAijStarting compares the Available Activities List with the characteristics of \( U_i \) stored in his profile determining, among the activities preferred by \( U_i \) those available in the current scenario, also according to the non thermal information concerning him.

The Available Activity List is sent to UBAijStarting (G).

7. **Representation of activities by means of a graphical interface.**

UBAijStarting shows to \( U_i \) the whole set of Available Activities sorted according to both his profile preferences and the building using profile for the different rooms.

At the end of the list, UBAijStarting inserts all the activities of the Global List, that are:

- activities marked as Not Available in the current location, but available in other rooms or positions;
- activities impossible to achieve, owing to the building profile definition and the system features (e.g. swimming in a hotel without swimming pool).

8. **Choice of the activity \( Act_k \) to be performed.**

By means of a graphical interface of the remote controller, \( U_i \) can choose the activity along with the corresponding clothes (H).

If the user chooses an activity \( Act_k \), the algorithm goes to next point 9.

If no new choice is done, the system verifies two possibilities:

8a. the current position is inserted in a multi-room path (defined in the next points) associated to activity \( Act_k \) already chosen: as a consequence, SMAijk continues to follow the user performing his previous activity in the new position reached;

8b. the current position is not inserted in a multi-room path of activities: on the basis of the user’s history, SMAijk proactively sets a standard activity \( Act_k \) and standardized the clothing referred to the building profile and the room specifications.

9. **Verification of activity availability:**

9a. Activity is available (yes). It goes to point 10.

9b. Activity is not available (no). If the selected activity is not available, a graphical landmark points out that it is not achievable and UBAijStarting shows the user a suitable message. The algorithm returns to point 8.

Along with the activity, \( U_i \) also chooses the clothing he wears and those related to the multi-room path, in a sort of activity scheduling. The system is also able to take decisions about clothing in a proactive way, related to the user preferences and according to ISO 9920 [49].

10. **Determination of a multi-room path and time scheduling in relation to the chosen activity.**

When \( U_i \) chooses an available activity \( Act_k \), the system understands which locations are involved (multi-room path) and proactively set the thermal parameters in order to warrant the best comfort level. This feature is particularly important in relation to energy savings.

Indeed, for a same activity different spaces are interested, in a sort of time scheduling (i.e., for a user doing gymnastics, the gym room is interested, where the activity is done, but also the bathroom, immediately after the activity, and the changing room, before and after shower). On this evidence it is possible to realize the zoning by activity level, according to an automatic time
scheduling on the basis of the user preferences: in such a way the system can proactively set the
plant in order to achieve comfort conditions in different rooms at predicted timetables.
In order to do this, \( UBA_{ijk} \) sends to \( SMA_{ijk} \) (the name of the agents has been changed into \( UBA_{ijk} \) and \( SMA_{ijk} \) as the user \( U_i \), situated in the Position \( P \) of the building \( B_i \) has chosen an activity \( Act_k \)) the identifier of the activity chosen and \( SMA_{ijk} \) finds out the other possible rooms or positions that will be involved in \( Act_k \). As a consequence, \( SMA_{ijk} \) retrieves a set of \( m \) positions representing the multi-room path in different time cells and sends it to \( UBA_{ijk} \).

11. Computation of the PMV index for each location of the multi-room path.

\( SMA_{ijk} \) asks to \( EA \) the micro-climatic data for the other \( m-1 \) future positions related to the chosen activity that \( EA \) has retrieved by the sensors located in the different rooms; on the other hand, \( U_i \) has already selected the subjective variables (his activity along with the opportune clothes).

For each position, the system now knows the values of the six variables necessary in order to compute the PMV index; then \( SMA_{ijk} \) can foresee the next, most probable activity in relation to \( Act_k \) (i.e. shower is the most likely activity after gym).

In absence of a suitable sensor capable to measure the actual activity level (e.g. on the basis of heartbeats), its value is taken from both the tables collected in ISO 8996 [48] and the database of thermal comfort studies collected during Brager and De Dear studies for an ASHRAE research project (RP-884) [51].

The same consideration is valid for clothing insulation supported by ISO 9920 [49].

For each location stored in the multi-room path, \( SMA_{ijk} \) is then able to compute a subjective PMV value (called X) by means of a personalized mathematical relation associated to the specific scenario.

Each scenario has a range of acceptability for PMV values, defined by means of two parameters, \( S \) (starting) and \( E \) (ending): \( S < X < E \). Without other specifications \( S = -0.5 \) and \( E = 0.5 \) will be assumed, but the range can also be set in accordance with the user’s preferences, the activity profile or the general scenario (for example, the different category ranges proposed in ISO 7730 [15] in relation to global comfort).

<table>
<thead>
<tr>
<th>Category</th>
<th>PMV</th>
<th>PPD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-0.2 +0.2</td>
<td>&lt; 6</td>
</tr>
<tr>
<td>B</td>
<td>-0.5 +0.5</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>C</td>
<td>-0.7 +0.7</td>
<td>&lt; 15</td>
</tr>
</tbody>
</table>

12. Check of comfort level by means of PMV relation.

For each location, five cases might occur in relation to the computed \( PMV = X \):

12a. \( S < X < E \) (i.e. \(-0.5 < X < 0.5\)) and no action is performed by the user in order to change the environmental parameters.

Algorithm returns to point 11. The user is supposed to be in comfort conditions according to the adaptive principle and \( SMA_{ijk} \) communicates it to \( UBA_{ijk} \). The
system follows the variation of the scenario variables in order to maintain the comfort level.

12b.  \( X < S \) or \( X > E \) and no action is performed by the user in order to change the environmental parameters.

The system proactively creates comfort conditions, finding the value of thermal parameters that guarantee a PMV value as near to zero as possible in relation to the scenario constraints. The system jumps to point 13.

12c. The user sets another desired air temperature \( t_{\text{adi}} \) (even if \( S < X < E \)).

This means that the user is in discomfort according to the adaptive principle, even if the system has set the best temperature in order to warrant the foreseen subjective comfort condition according to Fanger’s theory. PMV equation must be modified to be adaptive for the user. The algorithm goes to point 22.

12d. The user changes his position and goes to another room.

The system reacts to the movement retrieving the new position and the new necessary information, jumping again to point 3.

12e. The user changes his activity or turns off the system.

Algorithm jumps to point 27.

13. Pro-active computation of the desired air temperature \( t_{\text{adi}} \) warranting personalized comfort conditions for the user \( U_i \).

Using the personalized PMV equation, the system finds the values of the different parameters that allow comfort conditions. The PMV Fanger’s equation is modified according to user’s knowledge and reference context, by introducing multiplicative factors \( a_i \):

\[
PMV = f(a_1 M, a_2 l_{cl}, a_3 p_o, a_4 t_a, a_5 v_o, a_6 T_r) \quad (6).
\]

When Fanger’s model is suitable, all \( a_i \) are equals to one:

\[
a_i = 1 \quad \forall i: 1 \leq i \leq n
\]

otherwise the system has to set them according to user’s preferences.

In adaptive theories, air temperature \( t_a \) is considered as the most sensitive parameter, most frequently modified by people by easily setting it in the thermostat of the HVAC system. In order to obtain operative simplifications, only this parameter has been adopted as an adaptive variable proactively set in order to reach comfort. The previous relation is simplified in:

\[
PMV = f(M, l_{cl}, p_o, t_a, v_o, T_r) \quad (7)
\]

Different \( a \) values can be associated to a same user in relation to different scenarios.

Consequently:

13a. \( a = 1 \). Either it is the first time that the user is involved in a specific scenario or Fanger’s PMV equation is valid.

The system has got no information about the particular situation. Fanger’s PMV equation could be used without any adaptive modification (\( a = 1 \)).

User’s thermal clothing insulation and his activity level are retrieved by means of ISO 8996 and ISO 9920 [48, 49], by user’s indications or even modular instrumentations. The
The following procedure is used: $SMA_{ijk}$ finds, in correspondence to the values of the measured variables provided by $EA$, the value of the temperature $t_{adi}$ that makes PMV closest to zero, i.e. the PMV with the minimum absolute value (with $-0.5 < PMV < 0.5$);

For $U_i$ the desired air temperature $t_{adi}$ can be set:

$$t_{adi} = t_a$$

13b. $a \neq 1$. This means that the system already knows the user and consequently is able to know personalized PMV conditions for the specific user. The system uses PMV equation modified with adaptive considerations in order to find the air temperature value to be set to warrant comfort conditions. Therefore, $SMA_{ijk}$ uses equation (7) with the adaptive value of $a$ already determined for the specific scenario (in point 23) according to the following procedure:

i. $SMA_{ijk}$ sets the desired PMV $X_d$ value equal to 0 ($X_d = 0$), that can be achieved at the unknown desired air temperature $t_{adi}$.

ii. The previous personalized PMV equation becomes:

$$0 = f(M, l_{ct}, p_a, \alpha_{t_{adi}}, v_a, \bar{T}_r)$$

in which the unique unknown variable is the desired air temperature $t_{adi}$.

14. Verification of the respect of eventual scenario constraints.

Two cases can occur:

14a. The desired temperature $t_{adi}$ does not respect the constraints of the scenario (for example, there is a well defined range of permitted values and $t_{adi}$ is not therein): then $SMA_{ijk}$ sets $t_{adi}$ with the value that represents the best trade-off between comfort and context constraints, i.e. the value, in the permitted range, nearest to the previously computed $t_{adi}$. More specifically, $SMA_{ijk}$ finds out air temperature value $t_{ac}$ in relation to constraints and sets $t_{adi} = t_{ac}$.

14b. The desired temperature $t_{adi}$ respects the constraints of the scenario: the system goes to the next instruction.

15. Communication of the desired air temperature providing comfort conditions according to personalized PMV. $SMA_{ijk}$ communicates to $UBA_{ijk}$ and to $PMA (M)$ the desired air temperature value for that user in that particular scenario and stores the information in the database containing the global history of all the users, along with the profiles of the different situations, continuously updated during the system functioning.

16. $UBA_{ijk}$ stores this information in the user profile whilst $PMA$ stores it in the Scenario User Global List, where the presence of different users in the same position $P Position_p$ is stored.

17. $PMA$ has to set the Global Air Temperature for Position $T_{gP}$, useful in order to manage more than one user. Two cases might occur:

17a. In the Scenario User Global List there is only one user $U_i$ associated to $Position_p$. This means that there is only the user $U_i$ located in Position $p$. As a consequence, $PMA$ sets

$$T_{gP} = t_{adi}$$
17b. In the Scenario User Global List there are n users associated to Position \( p \) at the same time. As a consequence, PMA could set

\[ T_{gP} = \frac{\sum_{i=1}^{n} t_{adi}}{n} \]

for the simplified model considering only the air temperature parameter.

This is only a simplified choice, but other values could be adopted, based on different criteria (e.g. minimization of PPD). Indeed, when the whole set of variables (only the modifiable ones) is considered, the representation of the preferences in a multi-dimensional space can be used.

18. **PMA sets up the thermostat to** \( T_{gP} \) **for Position** \( p \) **and sends this information to SMA (N).**

19. **All the instructions from the points 12 to 18 are executed also for all the m predicted positions involved in activity** \( Act_k \) **(the multi-room path).**

As a consequence, the Global Air Temperature \( T_{gP} \) is found for each \( P \), with \( 1 \leq P \leq m \), along with the related time scheduling of the plant functioning. These temperatures are stored and sent by PMA to SMA\(_{ijk}\) (O).

20. **Proactive choice of the best strategy in order to reach the goals.**

In order to reach the desired air temperatures for each position with respect to the time scheduling, PMA analyzes the plant details relating it to the building features and to the environmental data and determines the best choices to be taken (P).

21. **EA monitoring of environmental values at the different positions in the multi-room path.**

EA sends air temperature values to both UBA\(_{ijk}\) and SMA\(_{ijk}\) (Q); on the other hand, SMA\(_{ijk}\) is informed about all the environmental data referring to the different positions related to the global scenario and to user activity (R).

22. **The system jumps again to point 11 of the algorithm.**

23. **Computation of the adaptive factor** \( a_{ijk\text{New}} \).

It is possible to arrive to this point only from the 12c point of this algorithm. SMA\(_{ijk}\) has to find the adaptive factor in relation to the user contextual situation. The user \( U_i \) has set his desired air temperature \( t_{adi} \) and the adaptive principle entitles the system to deduce that such value is the best one in order to warrant comfort conditions in the specific situation.

Although Fanger PMV could assume other values for the situation, a personalized contextual PMV equation, equal to 0 when measured air temperature is equal to \( t_{adi} \), has to be found. Equation (7) is used, where now the suitable value \( a_{ijk} \neq 1 \) for the adaptive parameter \( a \) has to be found. Considering the user in comfort in that specific situation:

\[ 0 = f(M, l_{cl}, p_w, a_{ijk\text{New}} t_{adi}, v_w, \bar{v}_r) \]

where the only unknown parameter is \( a_{ijk\text{New}} \) that can be found by SMA\(_{ijk}\) as:

\[ a_{ijk\text{New}} = f^{-1}(M, l_{cl}, p_w, t_{adi}, v_w, \bar{v}_r) \]

24. **Treatment of the adaptive factor** \( a_{ijk\text{New}} \).
The value is now stored as the last input \( a_{ijkN} = a_{ijkNew} \) (\( N \) stands for the number of \( a \) values already found and stored) in a list of array that \( SMA_{ijk} \) updates for each access of user \( U_i \) performing activity \( Act_k \) in \( Position_j \) situated in building \( B_j \).

According to the adaptive principle the perceived thermal sensation is also influenced by outdoor climate and mean monthly outdoor temperature [1, 22, 28, 29, 52, 53, 54]. Consequently the list, called Outdoor Climate List, is subdivided into four sections, each related to a different season, further subdivided according to different values of outdoor monthly average temperature, at 5°C intervals. In order to warrant the adaptive principle, each adjacent couple of intervals has 1°C of overlapping slot. Also adjacent seasons have a week overlapping slot. Consequently, when a measured monthly temperature falls within the overlapping slot, the computed values of \( a_{ijkNew} \) are stored in both adjacent intervals. An example can be found in Table 2.

<table>
<thead>
<tr>
<th>Season</th>
<th>Monthly Mean Outdoor Temperature Intervals</th>
<th>Adaptive Factor ( a_{ijk} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autumn</td>
<td>0 – 5°C</td>
<td>( a_{ijk} ) … ( a_{ijk} )</td>
</tr>
<tr>
<td>Winter</td>
<td>-5 – 0°C</td>
<td>( a_{ijk} ) … ( a_{ijk} )</td>
</tr>
<tr>
<td>Spring</td>
<td>5 – 10°C</td>
<td>( a_{ijk} ) … ( a_{ijk} )</td>
</tr>
<tr>
<td>Summer</td>
<td>15 – 20°C</td>
<td>( a_{ijk} ) … ( a_{ijk} )</td>
</tr>
</tbody>
</table>

On the basis of both system date and monthly mean temperature, \( SMA_{ijk} \) stores the new computed value \( a_{ijkNew} \) in the right section of the list.

25. Choice of the most suitable adaptive factor \( a_{ijk} \) that becomes \( a_{ijkCurrent} \). \( SMA_{ijk} \) has to choose the better value (\( a_{ijkCurrent} \)) to be used in the personalized PMV adaptive function.

The new value inserted is \( a_{ijk,N} = a_{ijkNew} \), whilst the current value is \( a_{ijkCurrent} \). Different cases might occur:

25a. \( N = 1 \). It is the first time that the user \( U_i \) is involved in the scenario and that he has set a temperature different from that predicted by Fanger’s PMV. This means that currently \( a_{ijkCurrent} = 1 \), i.e. the system is still using Fanger’s equation, but the temperature value is not a suitable value for the user’s preferences. Then \( SMA_{ijk} \) looks through the database in order to find a similar scenario, i.e. another building \( B_n \) of the same class or typology of building \( B_j \) where the user has already performed the activity \( Act_k \). Two different cases might occur:
i. The user has already been involved in another similar scenario and there is a well known value of $a_{ijkCurrent}$:

\[
a_{ijkCurrent} = \frac{a_{ijkN} + a_{ijkCurrent}}{2}
\]

ii. There is no other similar scenario and then:

\[
a_{ijkCurrent} = a_{ijkN}
\]

25b. $1 < N \leq 5$. The system has already found different values of $a$ for that specific scenario. This also means that the adaptive factors $a$ previously found are not satisfying enough in order to predict the user’s actual thermal sensation. In order to find the best value for the current adaptive factor $a$, the following mean value can be used:

\[
a_{ijkCurrent} = \frac{\sum_{n=1}^{N} a_{ijkN}}{N}
\]

25c. $N > 5$. The system has already found more than 5 different values for the adaptive factor $a$. These values can be represented in a diagram where each value of $a_{ijkCurrent}$ is expressed in function of the last $a_{ijkNew}$. The best value approximating the global trend of the adaptive factor can be expressed by means of a regression (e.g. a linear regression), where each point is expressed by coordinates as follows $(a_{ijkN-1}, a_{ijkN})$.

26. Storing the chosen $a_{ijkCurrent}$ and determination of the personalized PMV equation. SMA$_{ijk}$ stores the previously found value in the database and sends it also to UBA$_{ijk}$ (S). In such a way the system has found the personalized PMV formulation in that specific situation for that particular user, that is the adaptive PMV function personalized for the user $U_i$ performing activity $Act_k$ in building $B_j$, (i.e. Scenario$_{ijk}$, handled by SMA$_{ijk}$):

\[
PMV_{ijk} = f(M, I_{cl}, p_a, a_{ijkCurrent}, v_a, \tilde{T})
\]

The system jumps to the point 13 of the algorithm.

This adaptive factor represents a sort of feedback parameter based on the real considerations expressed by the user, computed every time he sets a temperature different from the predicted one.

Being a multiplicative factor, it can be considered in a particular black-box vision, not only in relation to temperature, but also to all the other parameters involved in comfort considerations: indeed, it is computed in a sort of afterwards integration and, as a consequence, it includes also the correction of all the measurement errors related to physical variables, to the general contextual situations, along with all the personal issues. This means that there is an afterwards global correction of the whole PMV function that avoids a definition of the strict mathematical relation between subjectivity and thermal sensation.

27. User stops interacting with the system for the activity $Act_k$.

Two cases might occur:

27a. The user $U_i$ decides to change his activity, choosing another one by means of his remote controller. UBA$_{ijk}$ communicates it to SMA$_{ijk}$ (T) that asks to PMA to release the previously occupied resources (U). The whole process starts again from point 8.
27b. User Ui decides to stop monitoring and shuts down the system (V). Algorithm jumps to point 28.

28. Ending phase: the user profile is updated and stored. When the user decides to shut down the system, his profile is updated and stored in both the SIM Card and the global database. \(UBA_{Ending}\) sends a suitable command and the updated profile to \(SMA_{Ending}\) (W). \(SMA_{Ending}\) stops to support him and updates the \(U_i\) profile in the server database with the new information stored during the last interactions. PMA detracts the user from the location where he was inserted and considers him as inactive until his next access.

CONCLUSIONS

Recently, a new and more complex approach which includes also the user in the plant-building system has been gaining foot in current research regarding comfort conditions evaluations in confined environments. In fact, people behaviour and reference context have turned out increasingly as important factors to be taken into account in subjective comfort conditions evaluations.

Within this frame, an adaptive comfort approach seems to be the most appropriate in order to take into account the complex reality of experience and obtain a real prediction contextualized to the real environment where users live, so allowing to maintain conditions of subjective comfort, tailored to user specific requirements.

It is long time since the adaptive comfort has considered as a valid approach in order to establish the acceptability of environments where people live and work. In fact, by means of such approach it is likely to take into account properly the effect of user subjective behaviour; the subjectivity, therefore, is not exclusively confined to standard and immutable parameters (metabolic rate, clothing index).

A typical application of adaptive techniques is represented by either plane or bus seats where passengers can adjust the air conditioning system based on their own needs and adapt their physical behaviour to the environment.

Nevertheless, it seems remarkable to notice that the adaptive comfort analysis belongs to a broader and more complex context since both it has to consider several agents which contribute to render an environment acceptable and it has to be based on Fuzzy or neural approaches.

In this paper, based on such considerations, an enrichment of Fanger model being capable to take into account user’s psychological data and information related to his cognitive-emotive-relational sphere, is proposed. In detail, the structure of an algorithm for adaptive subjective comfort evaluations which is based on Multi-Agent system (a particular types of Intelligent Agents) is presented. A Multi-Agent system, in fact, seems to be the most suitable solution for the purpose, useful to implement a system predictive and adaptive to the context, that takes into account the novel term user-building-plant.

REFERENCES


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