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A MAS-based subjective model for indoor adaptive thermal comfort

Abstract

The achievement of high level personalized sets of comfort parameters is contemplated within the more general context of the so-called smart buildings, where people, by means of the new communication technologies, become active actors to the process of the singling out and control of the best indoor conditions. This Dynamic Intelligence approach would usefully contribute to a better energy efficient and environmental friendly management of buildings. Multi-Agent schemes are suitable tools in this aim, since they are able to manage the user-building-plant system where the adaptivity of people to the indoor conditions is suitably achieved.

In this paper a contribution to a development of the classical Fanger's model is presented, embodying user's personal preferences referring to his cognitive-emotive-relational ambit. The proposed algorithm is based on a particular Multi-Agent aimed at the assessment of subjective indoor comfort. Such subjective adaptive model is here meant as a tool for achieving an optimal control of thermal comfort conditions in buildings.

Keywords

Thermal Comfort, Subjective and Adaptive Approach, Multi-Agent Systems, Adaptive Factors

Introduction

Researchers and technicians are facing two main issues for an optimal design and management of buildings and plants (Naidu and Riege 2011; Naidu and Riege 2011), that is the improvement of the level with which energy is utilized for climatization purposes and, in the same time, the mantaining of optimal indoor conditions for occupants (La Gennusa, Nucara et al. 2007; Marino, Nucara et al. 2012). In addition, comfort and energy demand in buildings are strongly interrelated (De Wilde and Tian 2010), since the accomplishment of assigned indoor performances involves a given energy cost (Woods 1989; Seppanen and Fisk 2006; Calvino, La Gennusa et al. 2010) that must be properly taken into account. On the other hand, the suitable limitation of energy consumption in the climatization of buildings is the main concern at the European regional level (Dixon, McGowan et al. 2010), particularly in the new vision of the so called "net-zero energy" buildings (Directive 2010/31//EU; Radermacher 2011; Marino, Nucara et al. 2013).

Within this deeply modified framework, the relationship between environment and subject must assume a new approach, where the user is the central point of the technological applications (Haldia and Robinson 2011; Boerstra, Loomans et al. 2013). Clearly, the support of innovative technical tools are of paramount importance (Nassif, Kajl et al. 2005), thanks to their capabilities of managing complex sets of data that allow to shift from the old approach based on the management of the HVAC-*building* system, towards the new vision based on the control of the *people-HVAC-building* system. In this way, control conditions and environmental parameters are addressed in a more complex and comprehensive scheme (Rijal, Tuohy et al. 2008; Haldia and Robinson 2010).

Intelligent Agents can be usefully utilized in this aim, by means of the Multi-Agent System (MAS) which as it is well known, are software applications recognized as the most efficient to follow occupants preferences, including indoor thermal comfort (Yang and Wang 2013). Within this frame, adaptive comfort approaches (de Dear and Brager 2001; Nicol and Humphreys 2002; Halawa and van Hoof 2012), other than the deterministic approaches (Fanger 1967), play a significant role due to their intrinsic capability to follow the user throughout its adaptation process to the environment.

The present work tries to give a contribution to the definition of a MAS based subjective adaptive model for the indoor thermal comfort control. The model is found on a new approach that considers the occupant (with its own preferences and expectations) as a part of a context offering a global experience.

Here, the attention is only focused on a single aspect of the comfort, that is the thermo-hygrometric one, although other aspects should be considered as well.

Compared to the traditional approaches, the benefit of such an approach is in that it makes possible the design of climatization systems (and their control systems) more respondent to the users preferences, since they follow them rather than set the control parameters only once.

This new approach would be a contribution towards personalized services where the whole system “user – plant – building” is contemplated, so constituting an evident enhancement respect to the conventional vision limited to the system “building – plant”.

It is worth mentioning that this approach is more and more used also to control energy consumption for climatization and general management of buildings. For these applications it refers to the new branch called “cognition engineering” (Binh Le, Kashif et al. 2010; Masoso and Grobler 2010) based on the Bayesian theory of random modeling. Furthermore, the multi-agent approach is frequently used in the field of designing and controlling of demotic systems.

Toward a new subjective adaptive approach by means of a multi-agent system

It is well known that the human body comfort sensation depends on environmental and subjective factors (Fanger 1970; ASHRAE 2004), involving several issues like indoor microclimatic conditions, thermo-physical characteristics of the building envelope, presence in the air of physical and chemical agents, behaviours of occupants (the so-called user profile) and user related features referring to psycho-physiological-metabolic ambits. Some of these factors should be evaluated accurately, due to their high influence on the indoor thermal comfort (d'Ambrosio Alfano, Palella et al. 2011; d'Ambrosio Alfano, Dell'Isola et al. 2013).

By applying the first law of thermodynamics to the human body it is possible to assess its thermal comfort equation, that can be represented in the following form:

$$\Delta S = f\left(M, I_{cl}, p_a, t_a, v_a, \bar{t}_r, t_{sk}, E_{sw} \right) = 0 \qquad (1)$$

where S is the internal energy, M is the metabolic rate, I_{cl} the thermal resistance of clothing, p_a the partial vapor pressure, t_a the air temperature, v_a the air velocity, $\bar{t}_r$ the mean radiant temperature, t_{sk} the mean skin temperature and E_{sw} the heat lost by evaporation of sweat from the surface of the skin.

The presence of subjective variables in this equation, referring to personal preferences (thermal resistance of clothing, I_{cl}) or to physiological factors (metabolic rate, M, heat lost by evaporation of sweat from the surface of the skin, E_{sw}, mean skin temperature, t_{sk}) confirms the subjectivity of the human body comfort sensation.

As a consequence, it is likely to have different comfort evaluations although same environmental conditions, so as same users, because of possible different psycho-emotional-metabolic conditions occurring in diverse circumstances, are likely to express different comfort evaluations in different times even though the climatic conditions are still the same. Results concerning values of the comfort indexes, predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD), currently available in literature, are undoubtedly noteworthy (de Dear 1998; ISO 2005).

Other than the subjectivity related to individual choices or physiological parameters, the psychology and adaptive behaviour of human beings should be considered. Apparently, such an approach shows a great potential at the moment to realize a “user tailored” comfort model able to take account the comfort preferences of each single individual (Brager and de Dear 1998; Cigler, Prívara et al. 2012).

Generally, three different types of adaptation mechanisms of human beings to external stimuli to reach a comfort sensation can be distinguished (Folk 1981; Baker, Nikolopoulou et al. 1999), they include: physical-behavioural adaptivity (Wohlwill 1972), physiological and psychological adaptivity (Sundstrom and Sundstrom 1986; Nikolopoulou and Steemers 2003).

The deterministic PMV method proposed by Fanger has largely been criticized over the last decades (Kaplan and Kaplan 1982; McIntyre 1982; Griffiths, Huber et al. 1988; Humphreys and Fergus Nicol 2002). Basically, the criticisms were in that the method did not embrace user's psychological data (Sundstrom and Sundstrom 1986; Nikolopoulou and Steemers 2003) and data referring to the cognitive-emotive-relational sphere. The importance of including such factors in a comfort model had already been recognized by Brager and de Dear (Brager and de Dear 1998). More recently, also Humphreys and Nicol (Humphreys and Fergus Nicol 2002) underlined the inadequacy of the deterministic Fanger method in predicting comfort conditions.

To help providing a contribution to overcome the limitations of Fanger's model, in the present work a new approach for predicting comfort sensations is proposed. It constitutes an enrichment of the deterministic Fanger method in predicting comfort conditions, since it integrates Fanger's theory with an adaptive approach.

PMV is here used as a base computation scheme and the reason of this choice lies on the fact that the PMV index allows an environmental control founded on the global comfort sensation of subjects. This has also a relevant influence from the standpoint of the minimization of energy consumptions: it has been widely demonstrated (Kang et al., 2010) that an environmental control based on global comfort of occupants allows relevant energy savings. Furthermore, it is worthy to note that PMV model has been received by several international standards (ISO, 2005) and it has been also used to design a classification scheme of the comfort quality of indoor spaces (CEN, 2007), so that it would seem consequent to design the environmental control on this basis.

The proposed model tries to evolve this sensation index introducing the subjective-adaptive choices of the user in the classical computation scheme and, doing so, it tries to overcomes the criticism regarding the original Fanger's model.

It can be defined as *scenario-adaptive subjective comfort model* (Marino, Nucara et al. 2008), where "scenario" is here meant as the information, continuously collected by the different agents, which serve to define a logical representation of the context where the user operates.

Such an innovative model, aimed at maintaining users in comfort despite changes of the scenario, is intended to provide more and more personalized comfort conditions in every context. To do this, a continuous feedback from user in relation to real condition change should be introduced, so guaranteeing a real-time reactivity to allow comfort changes to be predicted.

Intelligent Agents (IA) are adaptive systems suitable to survey the user preferences and to react to the variation of the whole set of variables, adapting themselves to user choices (Shoham 1993; Bates 1994; Wooldridge and Jennings 1995). The approach proposed is based on a peculiar Intelligent Agent, that is the *Multi Agent System* (*MAS*), characterized by high level of adaptivity and by the the ability to be integrated in existing and new systems (Lesser

1995; Rosenschein and Kaelbling 1996; Jennings, Sycara et al. 1998). Four agent typologies have been selected in the present work, each attending to a particular aspect, that is: User-Building-Activity Agent (*UBA*), Scenario Management Agent (*SMA*), Environmental Agent (*EA*) and Plant Management Agent (*PMA*).

The User-Building-Activity Agent *UBA* is associated with a user *i* performing an activity *k* in a particular position *p* of the building *j*. It is a personal agent that supports user i since he has entered the network of the system by means of his own remote controller, by turning on the plant, until he has decided to disconnect and shut down the system.

The Scenario Management Agent (*SMA*) has to manage the whole set of distributed information collected from the different agents which are dynamically, autonomously, pro-actively handled in order to create the environment logical representation and the particular contextual situation where the user operates that is, the so called, scenario. Differently from *UBA*, that is a client side agent, *SMA* is a server side agent and, as a consequence, there is no limitation in handling the huge amount of data stored in global database. In other words, *UBA* handles the processes occurring in the remote controller device, while *SMA* handles what happens on the side of the hardware controller of the plant system.

The Environmental Agent (*EA*) attends to the measurement and monitoring of thermal data and environmental variables. It is a server side agent that supports the whole system with the needed information in order to compute the comfort level of the different locations. This agent retrieves the environmental information by means of a sensor modular system that acquires the values of the needed variables using specific thermal instruments and measurement devices. This monitoring is continuous and the interaction between *EA* and other agents happens in real-time.

The Plant Management Agent (*PMA*) acts as a “mediator” between *SMA* and HVAC plant. It is responsible for the reservation, allocation and de-allocation of plant resources according to *SMA* indications as well as for the determination of resources availabilities. Then, *PMA* has to choose the best strategies to be followed in order to set in the best way the HVAC plant with the aim of reaching the targets indicated by *SMA*.

Figure 1 depicts both the scheme with which users interrelates with the HVAC system by means of a remote controller and the way MAS interrelates with the existing plant through sensors conscious of the milieu.

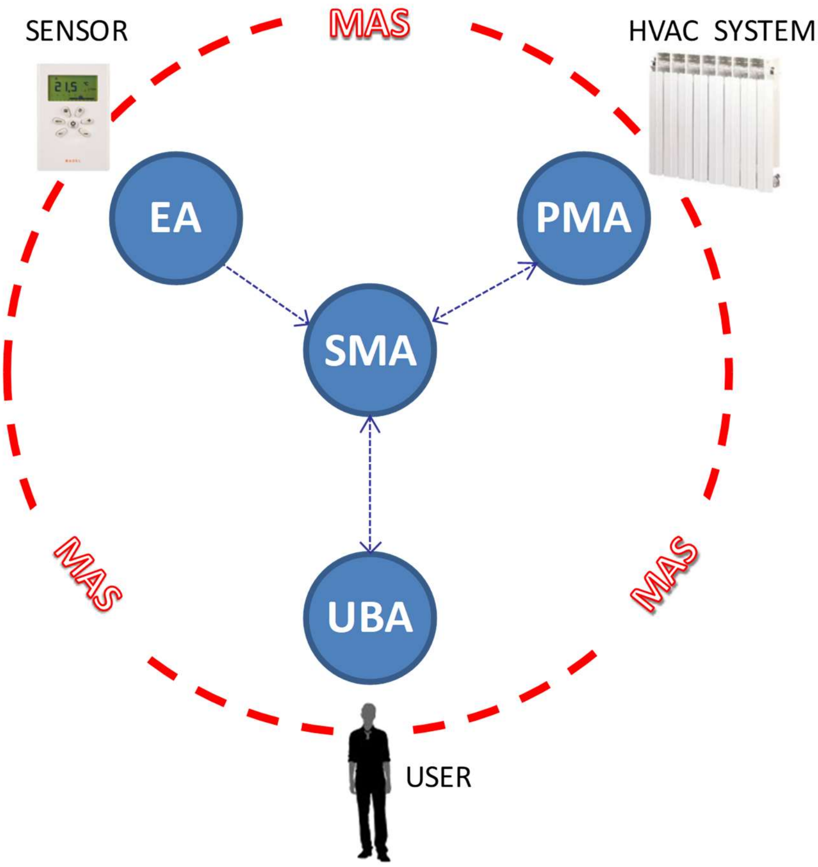

Figure 1. Relations connecting users, environmental context and pre-existing plant.

The proposed new system

The flowchart in Figure 2 and Figure 3 illustrates how the system operates, pointing out the different decisions to be made. It provides a general overview of the main features of the approach without going into a technical description of the actions taken by each agent.

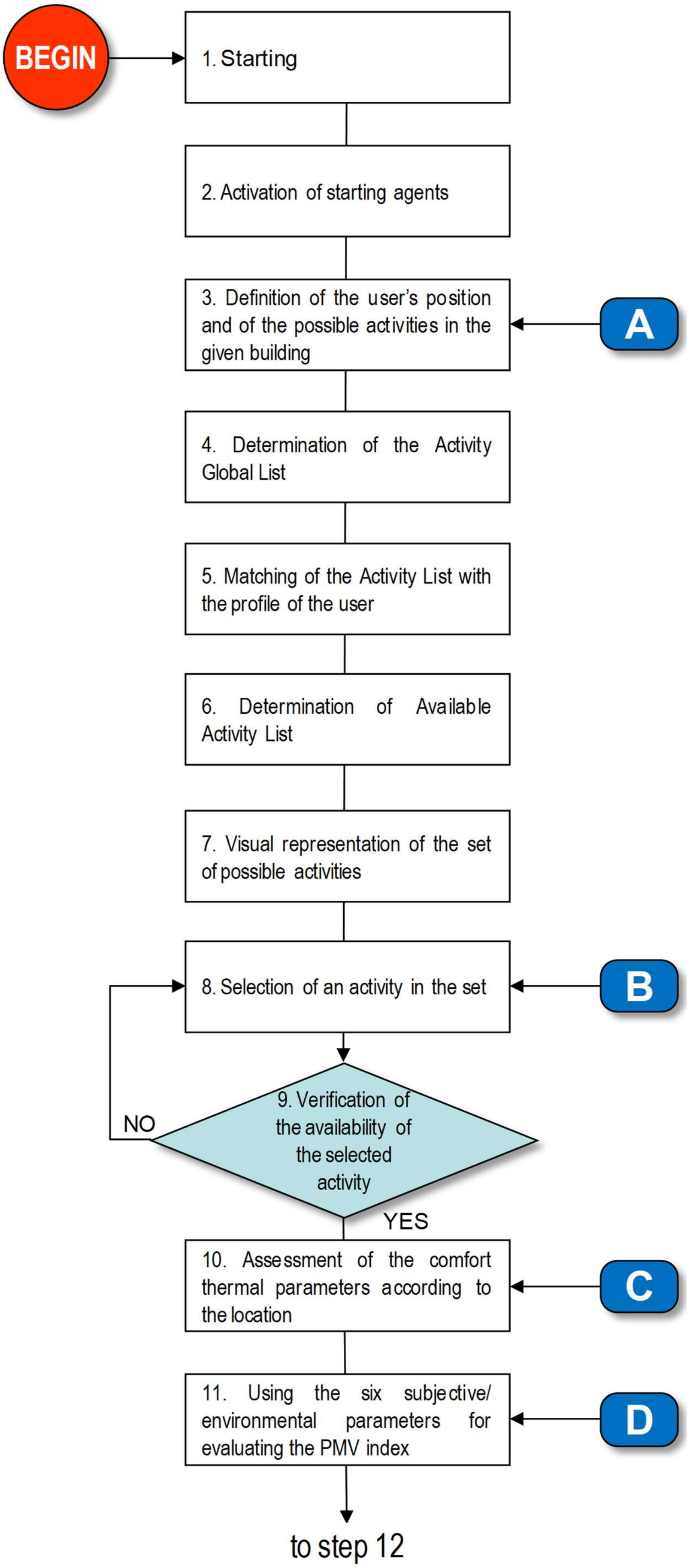

Figure 2. Flowchart of the general algorithm – Part I.

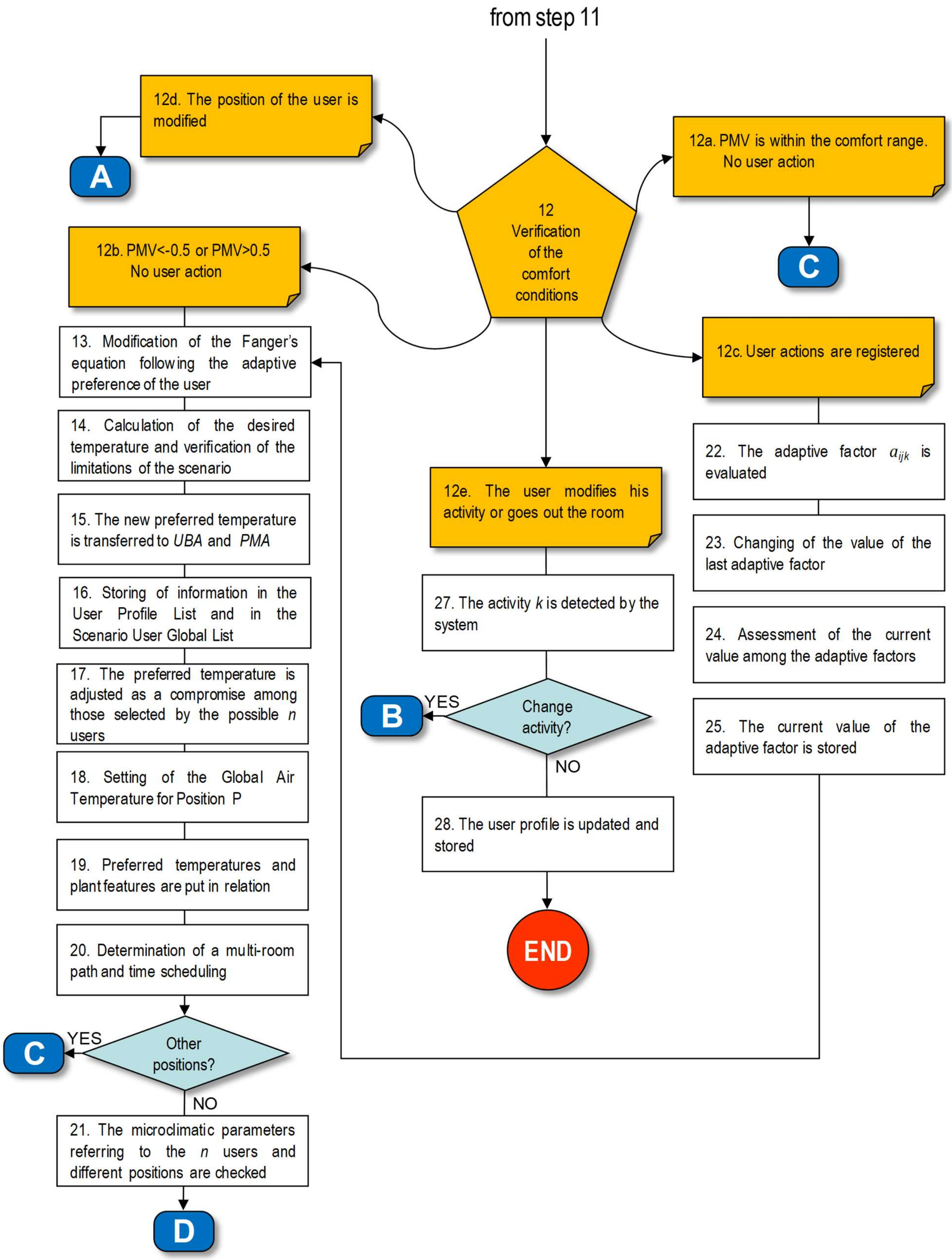

Figure 3. Flowchart of the general algorithm – Part II.

As a general description, this algorithm can be subdivided into five main phases. *Phase 1* is the starting one and it comprises steps 1 and 2. This is the point at which user enters the area under control of the system, activating the plant by means of a remote controller (it can be also activated by sensors or time scheduling strategies).

Phase 2 refers to the data collection and includes steps ranging from 3 to 10 of the algorithm. All data representing the scenario, referring to user's preferences are here retrieved. In addition, data required to quantify the heat exchange between user and indoor environment (ISO 1998; Calvino, La Gennusa et al. 2005) and data pertinent to clothing and metabolism of the subject are obtained, for example, from a database of ISO 8996 (ISO 2004) and ISO 9920 (ISO 2007) tables.

The evaluation of the desired comfort levels related to subjective adaptive PMV equation is performed in *Phase 3*, that is the crucial segment of the whole procedure, starts at step 11 and includes the steps belonging to the possible paths resulted from the choices effected at step 12. In particular the possible paths may alternatively start at step 12a, 12b, 12c or 12d (which, in turn, may lead up to beginning Phase 2 for a further loop), whereas step 12e does not belong to Phase 3 but is the beginning of *Phase 5*.

It is important to observe that the starting point of the whole procedure is here derived from the Fanger's model but after this, the employer, independently by the PMV current value, is allowed to set the preferred air temperature set-point t_{ap}, acting on the plant controller directly (step 12c) and, doing so, he makes the *SMA* know that the comfort conditions are not verified for him in that scenario and personal cognitive-emotional state. This action sets up an iterative procedure (from step 12c to14) that calculates a set of coefficients (the *adaptive coefficients*) exploited to make PMV "subjective-adapitive"and is used by the system to pro-actively define the air temperature value corresponding to a personalized comfort (from step 22 to 25 to 14).

At this point the procedure verifies the presence of possible scenario constrains (step 14); for example, there might be a well defined range of permitted values of air temperature and if this is the case then SMA sets t_{ap} with the value that represents the best trade-off between comfort and context constraints.

All the information (adaptive coefficients and preferred air temperature) resulted from the described procedure is transferred to UBA which stores it in a specific database, the User Profile List, and to PMA which stores it in the Scenario User Global List where the possible presence of different users in the same position P is also stored (steps 15 and 16).

From these databases the information will be retrived in case the user is in a known scenario, classical PMV comfort limits are not verified and no user action is detected by the system (step 12b) in order to modify the Fanger's equation following the adaptive preference of the user and asses the correct value of t_{ap} (step 12b to 14).

As far as the presence of different user is concerned, it makes a further elaboration needed (step 17): SMA manages social interaction among occupants assessing the value of t_{ap} *as* a compromise among those related to the possible n users. The compromise may consist, for example, either in the assessment of a medium value or in a more sophisticated procedure where the importance of various needs are compared and interpersonal interaction among occupant are simulated

In *Phase 4* plant (PMA) is in charge of the continuous setting of comfort conditions (step 18 to 19) and the procedure is repeated for all the points P that may characterize the user's path performing the activity k; therefore the phase 4 also includes the steps from 20 to 21.

In *Phase 5*, when the utilizer stops interacting with the system, the procedures end (step 12e to 28) and the achieved profile is definitively stored until a further access into the system takes place.

Computation of the adaptive factors

The assessment of comfort conditions by means of the PMV computation scheme, modified in order the subjective adaptive choices to be embodied, is the core of the whole process (*phase III steps 11-17 through 12b or 12c).* In fact, in this phase, PMV values for the user, corresponding to various positions, several activities and to a path through different rooms, are computed.

The preferred user outline, referring to the actual context, is defined starting from an initial conventional situation corresponding to the output of a classical application of the Fanger model. After this, the interaction of the utilizer with the context drives IA toward the constant updating of his profile: this enables a sort of continuous adaptation of comfort conditions to the user preferences. This is obtained by means of the introduction of a suitable set of factors a_i, that properly take into account the adaptive feature of these comfort conditions and affect each parameter of the original Fanger's equation. That is:

$$PMV = f\left(a_1 M, a_2\, I_{cl}, a_3\, p_a, a_4 t_a, a_5 v_a, a_6\, \bar{t_r} \right) \quad (2).$$

Obviously, in case of a poor (or absent) quantity of information concerning the adaptive behaviour of utilizers, the system trivially turns toward a classical Fanger PMV scheme (a_i=1).

The adaptive factors a_i need to be defined for suitably describing the personal choices of a given utilizer and,. on purpose, the system utilizes a training period to set a proper group of a_i factors, that constitute a comprehensive representation of the user's outline. For example, by simply referring to the indoor air temperature (that is one of the most important parameter perceived by people and affected by the people's tendency towards modifications), it can be said that a_i=1 for i≠4 and $a_4 = a$.

As that, referring to the user *i*, the building *j* and the action *k*, equation (2) becomes:

$$PMV = f\left(M,\, I_{cl}, p_a,\, a_{ijk}\, t_{ap}, v_a,\, \bar{t_r} \right) \quad (3)$$

The preferred temperature t_{ap} indicates to SMA that the user is supposed to be in comfort at that value of indoor air temperature (Point 12c, Figure 3): as a consequence of this adaptive preferences, it is considered that PMV = 0 for that specific value of temperature. Then, the modified Fanger's equation results in the following expression:

$$PMV = f\left(M,\ I_{cl}, p_a,\ a_{ijk}\, t_{ap}, v_a,\ \bar{t}_r \right) = 0 \tag{4}$$

where the only unknown parameter is the adaptive factor a_{ijk}, that is thus calculated as a function of the subjective and microclimatic parameters as:

$$a_{ijk} = g\left(M, I_{cl}, p_a, t_{ap}, v_a, \bar{t}_r \right) \tag{5}$$

that is:

$$a_{ijk} = \{PMV \cdot (0.0303 e^{-0..036M} + 0.028)^{-1} - (M - W) + 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M - W) - p_a] +$$
$$+ 0.42 \cdot [(M - W) - 58.15] + 1.7 \cdot 10^{-5} M (5867 - p_a) + 3.96 \cdot 10^{-8} f_{cl} \left[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4 \right]$$
$$+ 0.0476 M + f_{cl} h_c t_{cl} \} \cdot \frac{1}{t_{ap} (0.014 + f_{cl} h_{cl})} \tag{6}$$

This new value of the adaptive factor is assumed to be the most recent input parameter, that is $a_{ijk\_N} = a_{ijk}$ (step 23 of the algorithm), and is stored in a list named the "Outdoor Climate List", continuously revised by *SMA* each time the user *i* located in building *j* enters the system, while performing an activity *k* in a given position *p*.

The Outdoor Climate List is subdivided in four seasonal sub-sections and each of them is further subdivided according to different levels of weekly mean temperature, tipically clustered into 5°C intervals. Therefore the Scenario Management Agent *SMA*, is able to continuously store new values of the adaptive factor by properly taking into account weekly values of the mean air temperature, since adaptive criteria establish that the thermal sensations are influenced by outdoor temperatures (Nicol and Humphreys 1972; de Dear, Fountain et al. 1993; de Dear and Brager 1998; Cena and de Dear 2001): as a consequence, we are entitled to suppose that this can be a good adaptive principle to adjust adaptive PMV equation on the basis of seasonal differences, due to which there could be different thermal comfort evaluations, especially caused by subjective user expectations.

Once stored the new value of a_{ijk} (a_{ijk_N}), *SMA* must choose which value of adaptive factors stored in the "Outdoor Climate List" has to be considered as the better one ($a_{ijk\_Current}$) for utilization in the modified expression of PMV adaptive function.

Two situations might be considered, depending on the value of the number of values stoted in the list, *N*, that is *N*=1 and *N*>1.

If N=1, the user i is supposed to experience the considered scenario for the first time and he is setting a value of the indoor air temperature dissimilar from the value hypothesized by the Fanger's PMV classical scheme. In other words, in this case, despite the system is still referring to the prediction of Fanger's equation, the user indicates another preference for the air temperature. In this circumstance SMA queries the database to identify a similar scenario, for example a building w that can be considered as belonging to the same class of the actual building j where user has already experienced the same activity k. As a consequence, two different cases might occur.

In the first one user has already experienced a similar scenario and a factor $a_{iwk\_Current}$ is already present in the data base; in this case:

$$a_{ijk\_Current} = \frac{a_{ijk\_N} + a_{iwk\_Current}}{2} \tag{7}$$

In the second case a similar scenario is not present in the data base; in this case:

$$a_{ijk\_Current} = a_{ijk\_N} \tag{8}$$

If N>1 the system is able to find in the list more than one value of adaptive factors and, therefore, the current value $a_{ijk\_Current}$ can be assessed as a function of the other N values stored in the list (Figura 4).

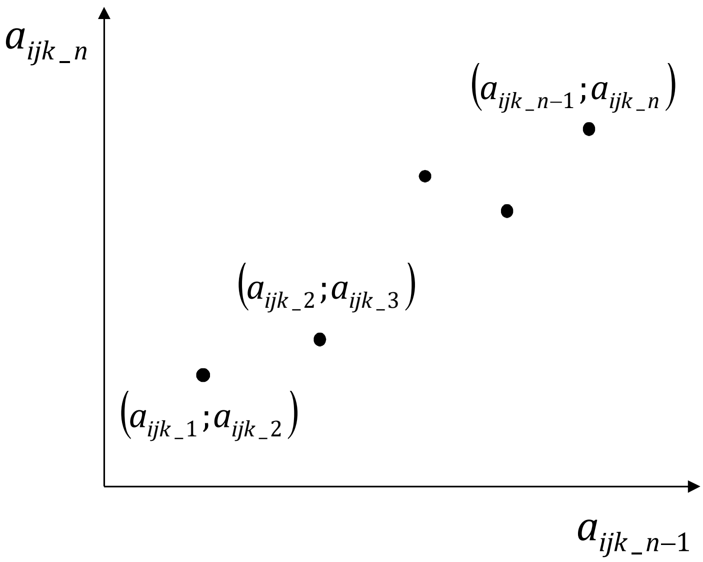

Figure 4. Graphical representation of the adaptive parameters a_{ijk}.

As a preliminary approach, with the aim of identifying the optimal value of factors reproducing the global trend of these factors, a linear regression has been utilized. This approach would be founded on the basis that the adaptive factors would result from a sort of small successive approximations. In other worlds the assumption is based on the hypothesis that the range of choices related to the user's emotional-psychological-social state is not wide and unlimited and follows a sort of fluctuation around a medium value.

As it is well known, the linear regression model can be written in vector-matrix notation as:

$$[Y] = \beta[X] + \alpha \tag{9}$$

The term α is the model's "error term" representing the unpredicted or unexplained variation in the response variable; it is conventionally called the "error" whether or not it is really a measurement error. For simple linear regression, where there is only a single explanatory variable and two parameters, the above equation turns into a formulation that explicitly shows the linear regression as a model of conditional expectation:

$$y = \beta x + \alpha \tag{10}$$

Using the least-squares method to solve the regression problem and construct the linear equation, the values of α and β can be assessed as:

$$\beta = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad \text{and} \quad \alpha = \bar{y} - \beta\bar{x} \tag{11}$$

where:

- $\bar{x}$ and $\bar{y}$ are the mean values of the examined variables;
- the conditional distribution of y given x is identical to the distribution of the error term α.

We can consider N-1 couples of data that are formulated considering the different values of a_{ijk_n} and the previous value a_{ijk_n-1} (with n varying from 2 to N) that are computed by means of Equation (6).

These couples of variables a_{n-1} and a_n are linked by a relation that we can express as:

$$a_{ijk\_n} = \alpha + \beta\, a_{ijk\_n-1} \tag{12}$$

where:

$$\beta = \frac{\sum_{n=2}^{N}(a_{ijk\_n-1} - \bar{a}_{ijk\_n-1})(a_{ijk\_n} - \bar{a}_{ijk\_n})}{\sum_{n=2}^{N}(a_{ijk\_n-1} - \bar{a}_{ijk\_n-1})^2} \tag{13}$$

and

$$\alpha = \bar{a}_{ijk\_n} - \beta\bar{a}_{ijk\_n-1} \tag{14}$$

that is:

$$\alpha = \bar{a}_{ijk\_n} - \frac{\sum_{n=2}^{N}(a_{ijk\_n-1} - \bar{a}_{ijk\_n-1})(a_{ijk\_n} - \bar{a}_{ijk\_n})}{\sum_{n=2}^{N}(a_{ijk\_n-1} - \bar{a}_{ijk\_n-1})^2}\bar{a}_{ijk\_n-1} \tag{16}$$

where $\bar{a}_{ijk\_n}$ and $\bar{a}_{ijk\_n-1}$ are the mean values (i.e. the barycentres) of n and n-1 values, respectively.

In this way, the linear form expressed by Equation (10) for current adaptive factor $a_{ijk\_Current}$ becomes:

$$a_{ijk\_Current} = \alpha + \beta\, a_{ijk\_N} \tag{17}$$

$$a_{ijk\_Current} = \overline{a}_{ijk\_n} - \beta\overline{a}_{ijk\_n-1} + \beta a_{ijk\_N} \tag{18}$$

$$a_{ijk\_Current} = \overline{a}_{ijk\_n} - \beta\left(\overline{a}_{ijk\_n-1} - \overline{a}_{ijk\_N}\right) \tag{19}$$

It is worth pointing out that in these equations each a_{ijk_n} value is determined by means of the procedure that leads to Equation 5: these values differ from the actual adaptive factor $a_{ijk\_Current}$ that is used in the modified subjective PMV equation. Eventually, substituting Equation (13) in the previous Equation (19) we have:

$$a_{ijk\_Current} = \overline{a}_{ijk\_n} - \frac{\sum_{n=2}^{N}(a_{ijk\_n-1} - \overline{a}_{ijk\_n-1})(a_{ijk\_n} - \overline{a}_{ijk\_n})}{\sum_{n=2}^{N}(a_{ijk\_n-1} - \overline{a}_{ijk\_n-1})^2}\left(\overline{a}_{ijk\_n-1} - \overline{a}_{ijk\_N}\right) \tag{20}$$

In this way we have expressed the actual adaptive factor $a_{ijk\_Current}$ as a function of the *N* previously computed adaptive values a_{ijk_n}. This is very important in order to both take into account the past history of user preferences and express the adaptive factor by means of a detailed statistical relation.

The procedure used to asses the adaptive factor $a_{ijk\_Current}$ is depicted in Figure 5.

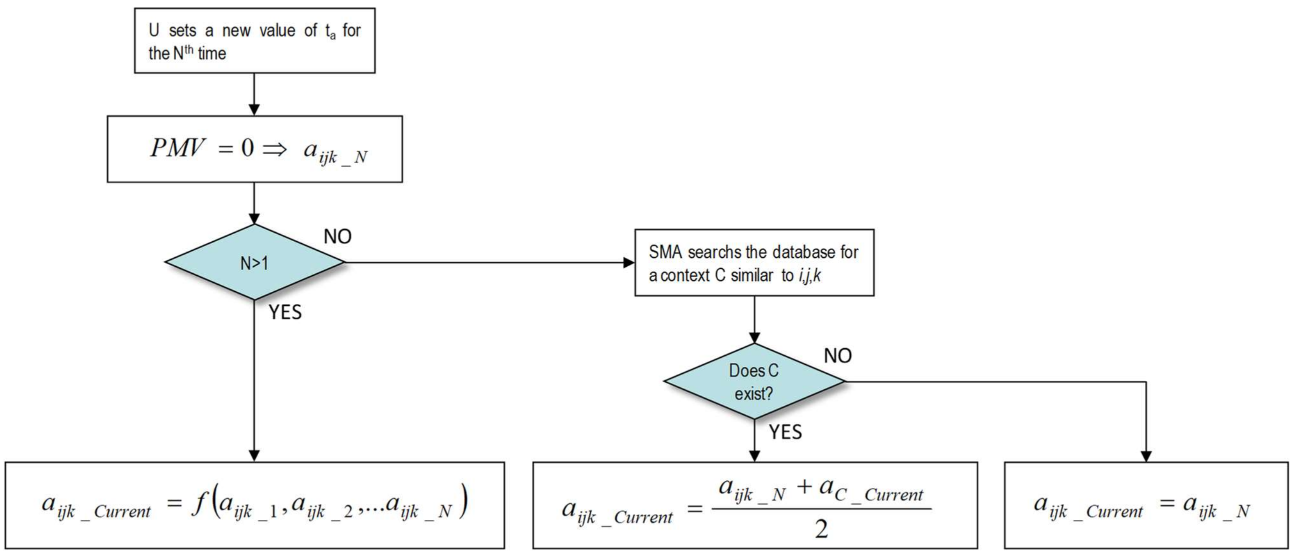

Figure 5. Flowchart of the procedure used to assess the adaptive factor $a_{ijk\_Current}$..

At this point (step 25 of the algorithm), new value of the factor will be stored in the database and sent to *UBA* to be successively retrieved to construct the modified personalized scheme of the classical PMV equation utilized by *SMA* system for comfort assessment and for deducing the new value of air temperature (t_a^*) which is intended to satisfy personalized comfort requisites (step 13 to 14).

In conclusions the system has singled out the personalized adaptive definition of PMV, suited for a specific situation of a particular user, that is:

$$PMV_{ijk} = f\left(M, I_{cl}, p_a, a_{ijk\_Current}\, t_a, v_a, \bar{t}_r \right) \quad (21)$$

That is:

$$PMV_{ijk} = (0.0303e^{-0,036M} + 0.028) \cdot \{(M - W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M - W) - p_a] +$$
$$- 0.42 \cdot [(M - W) - 58.15] - 1.7 \cdot 10^{-5} M(5867 - p_a) - 0.0014 \cdot M(34 - a_{ijk\_Current}\ t_a) - f_{cl} h_c (t_{cl} - a_{ijk\_Current}\ t_a) +$$
$$+ 3.96 \cdot 10^{-8} f_{cl} [(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] \quad (22)$$

Summing up, equation 22 represents the adaptive formulation of the PMV function, personalized for a given user *i* involved in an activity *k* within building *j*. This means that this PMV expression meets the scenario$_{ijk}$, and is handled by the system *SMA*.

It is used any time a new value of air temperature (t_a^*) satisfying personalized comfort requisities is to be assessed by imposing:

$$PMV_{ijk} = f\left(M, I_{cl}, p_a, a_{ijk\_Current}\, t_a^*, v_a, \bar{t}_r \right) = 0 \quad (23)$$

The procedure is continuosly repeated so that the system is able to pro-actively define the air temperature value corresponding to a personalized comfort.

A simple application

To better understand the core of the proposed algorithm it could be useful considering the following situation: for the first time an user enters inside an indoor environment, that may be, for example, his office; the values of parameters to be used for PMV assessment are assumed as follows: M=1.2 met; I_{cl}=1 clo; RH=50%; t_r=20°C; v_a=0,15 m/s.

In these conditions, the classical (with no adaptive coefficients) equation PMV=0 yields an air temperature value of 23.4°C.

Being the first time that the user is in that scenario, no adaptive coefficient is in the database, therefore the system assumes the value of 23.4 as preferred one, so that it is communicated to UBA and PMA by SMA. UBA stores it in the specific database, PMA reacts setting the plant for the correct functioning in order to reach the assessed set-point .

If no user action is registered the system continues monitoring the environmental and plant parameters as well as subject activity to detect any possible change.

Let we assume that the air temperature value is too hot for the subjective preferences of the user and that he reacts changing the temperature set-point to 18°C.

This change is detected by the system that will assume 18°C as a comfort value for the user and SMA will be able to assess the first value of adaptive coefficient by means of eq. (6) that will yield: a_1=1.300.

Given that N=1 and that no similar scenario is supposed to be in the database, following the procedure depicted in Figure 5, it can be written: $a_{current}$=a_1=1.300. At this point this value is to be used in eq. (23) to assess the air temperature (t_a^*) value that satisfies the personalized comfort equation (that, of course, being $a_{current}$=a_1, is 18°C).

Let we assume, now, that the selected set-point has caused environmental conditions that are judged too cold by the user and that he reacts changing the temperature set-point to 20.0°C.

This action gives start to the procedure again and a new value a_2= 1.170 is calculated. In this case N>1, hence the linear regression procedure must be applied, but it will concern one point (a_1, a_2) so that it will yield $a_{current}$= 1.170= a_2. Substituting this value in eq. (23), it will yield t_a^*=20.0°C.

In the hypothesis that the cold sensation persists causing a new change in the temperature set-point to 21.0°C, another loop of the procedure will start, assessing: a_3=1.115; $a_{current}$= 1.115; t_a^*=21.0°C.

If the set-point is changed yet another time to 22°C: a_4=1.064; $a_{current}$= 1.072; t_a^*=21.8°C. The story of the calculation is summarized in Table 1.

Table 1. Adaptive coefficients and air temperature values satisfying personalized comfort requisities

N	t_{ap}	a_n	$a_{current}$	t_a^*
1	18.0	1.3006	1.3006	18.0
2	20.0	1.1705	1.1705	20.0
3	21.0	1.1148	1.1148	21.0
4	22.0	1.0641	1.0724	21.8

Let we assume, now, that no further action is ever detected, this means that the subjective comfort is reached and that the last value of t_{ap} is the comfort one: this value will be retrieved by the system and transmitted to PMA when the user will be in that same scenario.

The system has undergone a sort of training during which it has built up an user profile (the list of adaptive coefficient and preferred air temperature values) to be utilized whenever the user is in the same scenario.

For example when he enters the room the next day t_{ap}=21.8°C will be selected by the system as set-point-temperature.

If user emotional-cognitive state makes him non-comfortable with the environmental conditions because,say, it is perceived as too hot, he will start the process again changing the set-point to a lower value, e.g. to 19°C.

Then it will yield: a_5=1.232; $a_{current}$= 1.150; t_a^* =20.4°C

The user profile, hence, is not fixed but continuously updated following the user choices and preferences.

If a second user is in the environment, the algorithm does not change, but the setting of the temperature set-point should be carried out taking his preferences into account, realizing compromise or trying to simulate the interpersonal interaction among subject.

In particular the system may decide to give priority to one user preferences (e.g. because he belongs to special need/favourite categories) or may set a medium value that could satisfy both users, or, alternatively through a terminal connected to UBA, might suggest to one user to change his clothes if this is consistent with the constrains of the scenario (user profile and allowed values of thermal resistance of clothes).

Discussion

The most important feature of the adaptive factor calculated by means of the previously described procedure is in that it is founded on actual experiences of a given user, and that its computation is requested when the user declares to prefer a value of air temperature different from the predicted one. This means that this factor is not a static parameter, but it is adaptive to the different evolutions of both user preferences and behavior, and thermal sensation related to contextual situations, so correcting the predictive reliability of the model.

Moreover this factor, showing the structure typical of a corrective coefficient, could be usefully adopted not only for the evaluation of the preferred indoor air temperature, but also for the others parameters affecting the comfort perceptions.

It is also relevant to note that this adaptive factor, being evaluated as a kind of afterwards modification, could easily embody the correction of the measurement errors affecting the detected thermal comfort variables, which are due to the general contextual situations or instrumental limits, along with all the personal features related to the specific user in that particular situation.

In other words, by means of adaptive factor the whole PMV scheme can be subsequently corrected and modified suitably: in this way the definition of the relations between subjectivity and environmental thermal parameters is integrated in this particular afterwards solution driven by the user's adaptive behavior.

Consequently, this adaptive factor can be assumed as a global factor that allows the accomplishment of the main aim of the present work, that is integrating the Fanger's theory with subjectivity and adaptivity by means of an improved PMV equation.

Indeed, this adaptive method is based on the traditional PMV equation, that is used as a kind of collaborative technique, utilized only for an initial execution, in order to avoid the long training procedures usually required by content-based techniques to define the user profile. As that, this approach interrelates past history of the user, his expectations and preferences referring to contextual data and factors, both thermal and non thermal ones.

Future development of our research has been planned in order to realize the full implementation of the model. Therefore further analyses have to be carried out in order to better understand the possible trends of the crucial parameters of the procedure, the adaptive factors, and to build up a consistent “user profile”.

To better understand the role of these factors a sample case is to be considered, with reference to the procedure reported in Figures 2 and 3.

When an user U enters the room to occupy the position P, where he can perform the activity k, the User-Building-Activity (UBA) agent and the Scenario Management Agent (SMA) are activated [steps 1→2].

By means of the interaction between the UBA and the SMA the customer related information is retrieved [steps 3→9]: the customer’s position and associated user profile are communicated to the SMA which will react selecting a list of possible activities associated to that position and compliant with the customer’s preferences stored by the UBA; by means of the UBA the customer could be required to choose the right activity and related clothing so that the correct metabolic rate and clothing thermal insulation can be retrieved from a specific database.

At this stage of the process, the SMA must be able to completely characterize the scenario, therefore data concerning plant configuration and status are requested to the Plant Management Agent (PMA). Furthermore, the SMA reacts requesting environmental data to the Environmental Agent (EA), so that the proper comfort conditions can be evaluated [steps 10→12] by means of the PMV index (Figure 6). Environmental data are retrieved by means of specific sensors connected to the EA.

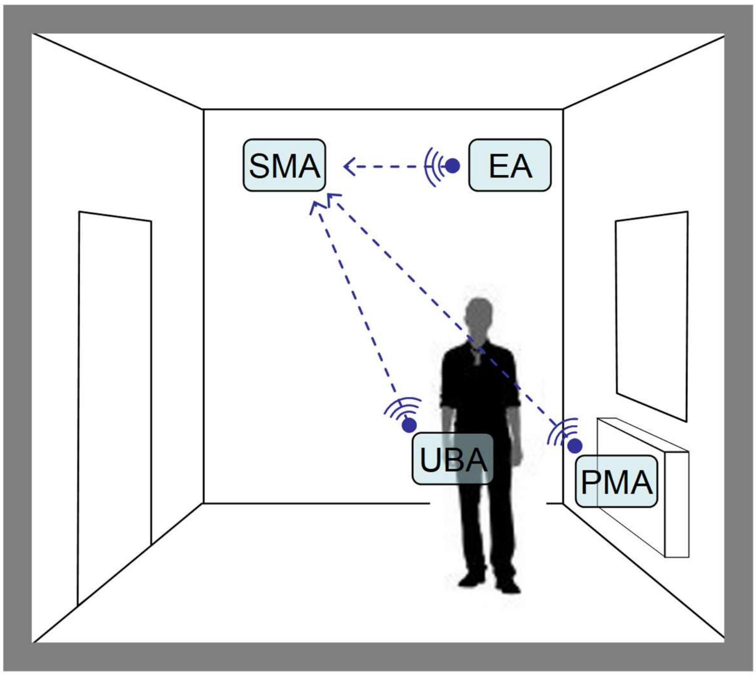

Figure 6 – Response of the system to the entry of the user into the environment.

If no action is registered and the PMV index is in the comfort range, the procedure continuously acquires the environmental data and calculates the PMV index [steps 12a→C→10→12] until a new event occurs (Figure 7).

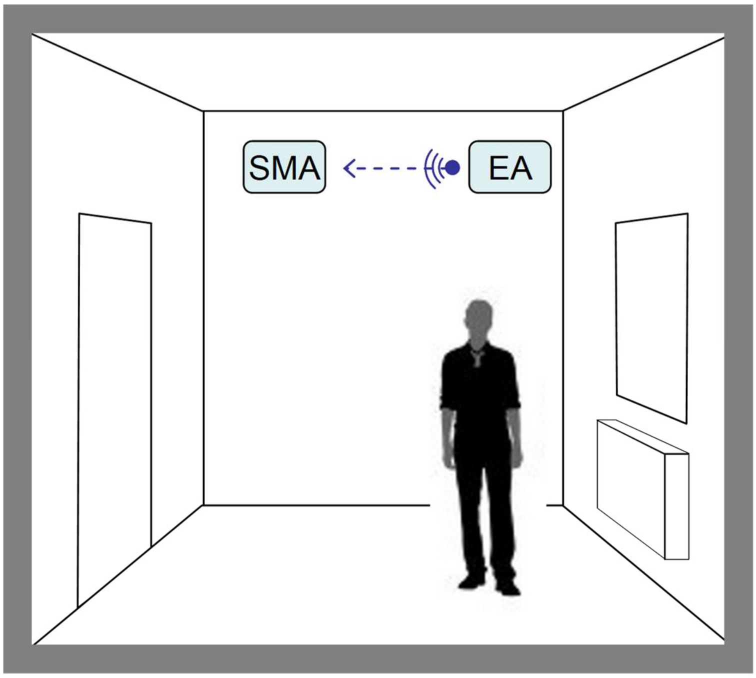

Figure 7 – Response of the system when PMV index is inside the comfort range and no action is undertaken by the user.

On the contrary if no action is registered but the PMV index is outside the comfort range (step 12b), the procedure modifies the Fanger's equation using the adaptive factors, stored as user profile data, and determines a new preferred temperature that will be communicated to the PMA which, in turn, will adjust the plant status to meet the new conditions [steps 12b→C→10→12] (Figure 8).

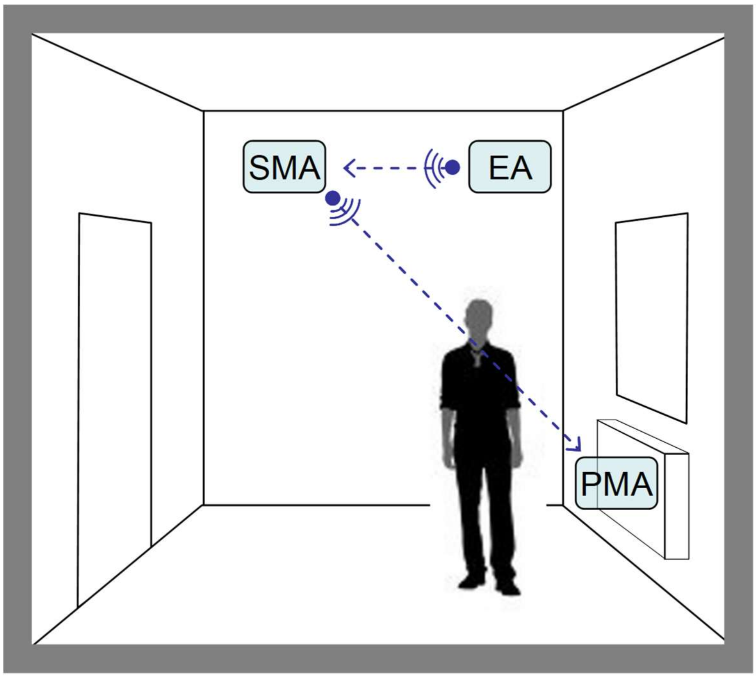

Figure 8 – Response of the system when PMV index is outside the comfort range and no action is performed by the user.

If the user is not satisfied by the current conditions, regardless of the calculated PMV value (step 12c), he will react turning up/down the room thermostat controls; this circumstance will be registered and stored by the UBA which will communicate the measure of the change to the SMA so that the new value of the adaptive factor can be evaluated by means of eq. (6). This new value will be stored and used to assess the current value of the adaptive factor, $a_{ijk\_Current}$, that, in turn, will be stored and used to calculate the new preferred temperature. This value must be communicated to the PMA which will adjust the plant status to meet the new requested conditions [steps 12c→25→13→C→10→12] (Figure 9).

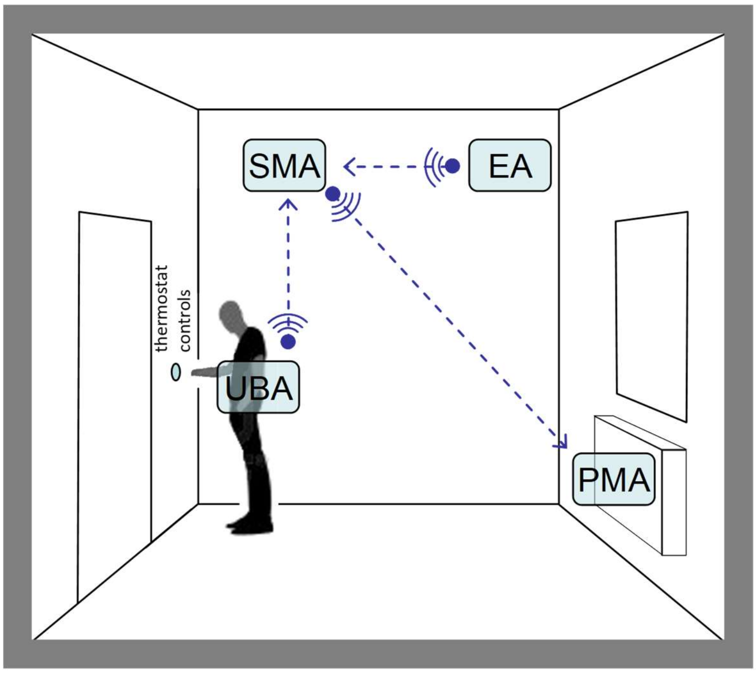

Figure 9 – Response of the system to user action.

As clarified by the example, the right development of the process depends strongly on the correct assessment of the adaptive factors; therefore, further analyses in this direction are needed and the first step of such a study should entail the costruction of a suitable user profile.

This task implies the assessment of the sensitivity of the human behaviour for control and management of the environmental parameters and could be carried out by means of either survey statistics or human behaviour simulators.

The statistic surveys may be largely suitable to determine occupant patterns describing an occupant's interaction with the controls of appliances, plants and systems. As a matter of fact, the collected data may lead to the determination of both the probability of turning up/down the heating/cooling controls and the assessment of the measure of the set-point change (Fabi et al., 2013). Both these informations may be utilized to derive a realistic user's scenario assessing the adaptive factors by means of eq. (6) and eq. (20). This procedure will be developed in the planned progress of our research.

As far as human behaviour simulators are concerned, as a rule, they are tools able to perceive changes in the environment and take actions dynamically to change the state of the objects and appliances in the building, but to be suitable for the purposes of the proposed model, they should also be able of taking into account adaptive and context items. In other words, they should represent a realistic interaction of the human being with the environment (context) and, since behaviour varies from one occupant to another, they should also be equipped with a sort of generalization method that is effective for all occupants.

The results of a preliminary analysis suggest that Brahams environment (Sierehiuis et al., 2007; Clancy et al., 1998) might be a simulation tool consistent with the above described requisities. Furthermore, it takes into account social interaction among occupants realizing compromises when different needs are brought forth by two or more different occupants, this feature might contribute to solve one of the drawbacks of the proposed model, which is structured to be focused on a single user's behaviour.

Nevertheless, at the present stage of our research, coupling the proposed model with such a human behaviour simulator is far to be solved and further analyses are needed.

Conclusions

The present work is intended as a first contribution to the embedding of the comfort needs of people in buildings in a behavioural control strategy for climatisation systems. Moreover, such strategy can refer not only to the required indoor conditions but also to the possible energy constraints imposed by the current technical standards and regulations. In this sense, it can be considered as an attempt for embodying subjective preferences into more general energy strategies. It is based on the evaluations of the occupants response to a given indoor environment. Here, the attention is exclusively paid to the thermo-hygrometric aspects of the whole people comfort, but other issues could be considered in the method. The novelty of the model consists in considering occupants (with their preferences and behaviours) as a part of a general context offering a global experience.

Such an approach, although starting from the deterministic classical theory of P.O. Fanger for the indoor comfort evaluation, mainly apply to adaptive comfort approaches, thanks to their intrinsic capability to follow the user throughout its adaptation process to the environment.

The Multi-Agent Systems are chosen here as effective tools for modelling and properly following the occupants thermal comfort needs. In fact, within the context of multi-agent systems, control systems can be designed by adopting fuzzy and neural algorithms that are able to "learn" the behaviour of a given group of users and reset the control parameters not merely on the basis of the design prescriptions but also on the ground of the real experiences of occupants. This can lead towards more personalized services, characterized by an attention to the whole "user – plant – building" system, that represents an useful improvement compared to the traditional approach of technicians essentially limited to the "building – plant" system.

The dynamic management and control of the indoor environments, by taking into account the people preferences and the general limitations imposed by the energy policies and regulations, candidate this approach as a possible tool toward the design and management of smart and sustainable buildings. Anyway, some problems are still open and need further analyses and researches.

The main issue to be deeper developed concerns the intelligent agents here singled out for the assessment of the subjective adaptive control model, that is the Multi Agent Systems. In order of getting an operative design of the proposed system, the suitable ontologies of the involved MAS must be defined properly. These, in fact, are needed to confer to the agent tools an efficient knowledge handling. From the Artificial Intelligence point of view, ontology is an engineering artefact that describes a certain reality with a specific vocabulary, using a set of assumptions regarding the intended meaning of words in this vocabulary. These Ontologies are used to express "a shared and common understanding of some domains that can be communicated between people and application systems" (Gruber 1993). In this way, the ontology-based system can be used for knowledge acquisition, conceptualization, and representation of the comfort related context, so transforming the implicit into the explicit knowledge. Actually, ontologies of MAS involved in the model have shortly been described through this work but, surely, require a more deep investigation.

After this, a field application of the method will take place and this will represent the next step of the ongoing research here presented.

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