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Multi-Agent Systems as Effective Tools for the User-Based Thermal Comfort: an Introduction

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Abstract: Through the paper the characterization of a comfort model, enriching that proposed by Fanger with an adaptive approach, is carried out using a *Multi Agent System* (MAS). This is a well suited coordinated set of Intelligent Agents, that are software applications interacting in order to follow user in his own needs and preferences in relation to indoor comfort, adapting to the changes of context variables. As a matter of fact, MAS are systems aware of the scenery where users live, following them in their own needs and preferences and adapting to their expectations. Indeed, 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 using profile and to the biological-metabolic-psychological characteristics of the users. Within this frame, as a consequence, it is very useful to formalize new models, both subjective and adaptive to the environmental scenery, where users are represented as an integral part of the global experience context, in a particular holistic vision of the problem, strongly addressed towards the personalization of the service, with regards to the novel tern user-plant-building system. In this aim, *Intelligent Agents* can be considered as the best solution to be adopted, allowing characterization of a control model for an Advanced Smart Conditioning System, that would realize integration of Fanger's theory with an adaptive approach, also proposed by other authors (Brager and de Dear, Nicols, etc.), in particular by means of a *Multi Agent System* (MAS).

Key words: Indoor thermal comfort · Holistic comfort · User behaviour · Adaptative subjective approach · lntelligent agents

INTRODUCTION

Scientific community pay a big attention to the realization and preservation of indoor life conditions as comfortable as possible.

Indeed, nowadays, users enjoy the most 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 quality of life.

Within this frame, indoor comfort is a complex argument that represents the heart of a large number of researches aimed at improving both the qualitative and operative standards related to it.

The main challenges to face up are both the control of the building energy consumptions and the obtainment of more and 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.

As a consequence, actual research and also technology is 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. They are in fact very significant in order to evaluate subjective comfort conditions and make the support of novel techniques to be a topical argument in research 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

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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 telecommunications (*ICT - Information and Communication Technology*) and automatics, can hold a leading role in order to realize quality levels higher than the actual ones as concerns the design and fruition of the buildings.

These disciplines may be very useful in order to both improve performances and reduce costs; they also result essential for data collection and huge information exchange, considering the great amount of information, both physical and contextual-subjective ones, that is handled in environmental analysis.

Within this frame *home automation* (or *domotics*) is born, allowing an advanced management of the control of environmental conditions.

Thanks to this new engineering branch, residential buildings are going to enjoy more and more benefits from the increasing automatization and optimization of operations involving electrical and electronic devices, household appliances and air conditioning systems, communication, control and security systems.

As a consequence, houses will become suitably designed and technologically equipped environments (the so called *intelligent houses*), inside the which activities (such as light switching, appliances activation e control, climatization management, door and window opening, etc.) will become more easy, safety will be increased (anti-intrusion control, escape of gas, fires, floods, etc.) and remote connection with assistance services (tele-aid, tele-assistance, tele-monitoring, etc.) will be allowed.

Moreover, buildings provided with a simple, reliable, flexible and cheap automation system, can also reach much higher comfort conditions compared to the traditional environments.

On the matter, for example, AICARR (the Italian Association of Air Conditioning Heating and Refrigerating) itself suggests "domotics and adaptive model as the true revolution in matter of building intelligent management. Formed by a mix of technologies including ICT and in particular internet protocols, domotics allows in real time remote building management, also allowing anticipating building needs in terms of energetic and climatic exigencies and anything else is at the basis of occupants' comfort and safety" [2].

As a consequence, it results very important to make stronger relations between technical physics and information and communication technologies, in order to reinforce the actual trend that allows to deal environmental conditions with more advanced control instruments.

In this direction is oriented the research proposed in the present paper that, in order to carry out environments more and more careful of user comfort exigencies, is addressed towards adaptivity in the managing of the complex user-building-plant system, proposing a new system based on Intelligent Agents.

In particular the use of a Multi-Agent System (MAS), allowing integration of Fanger's theories with adaptive approach, seems to represent the most appropriate solution in order to evaluate highly subjective and scenario adaptive comfort states looking out to the global multidimensional complex vision of human nature.

USER GLOBAL COMFORT: THE "HOLISTIC" VISION

Medical science consider comfort as a global state outcoming from the interaction of different ambits, that is an holistic concept [3], defined in relation to psychological, emotional, relational and biological aspects and strictly linked also to physical sides [4-8]. This is the so called "holistic" concept of comfort.

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.

Starting from these considerations, a complete definition can be found in Kolcaba [9]: "*holistic comfort is the immediate state to which one tends in order to reach respectively the states of relief, ease and transcendence met in four contexts of experience (physical, psycho-spiritual, socio-cultural and environmental)*".

In particular *relief* consists in having a discomfort mitigated or alleviated; *ease* is a general comfort or satisfaction state with respect to the above four contexts of experience, whereas *transcendence* is the ability to "rise above" discomforts when they cannot be eradicated or avoided: consequently it represent a particular skill or motivating and supporting psychological state necessary in contexts where it is impossible to reach one of the previous comfort states [4, 8].

Related to these three states, the four cited contexts of human experience can be described as follows:

- *Physical*, concerning all the body sensations;
- *Environmental*, concerning the external environment in which human experience is carried out (including thermo-hygrometry, visual, acoustic, landscape aspects, etc…) [10];
- *Socio-cultural*, concerning all the social and relational aspects;
- *Psycho-spiritual*, related to people's inner world and its linked aspects (such as self-esteem, personal motivations, etc.).

Obviously one may separately deal with physical, psycho-spiritual, socio-cultural or environmental comfort in relation to the particular context of human experience which attention is paid to.

Each comfort state is fundamental in order to reach a global comfort: holistic comfort, in fact, even if not resulting from a simple sum of the different comfort aspects, nevertheless represent a global sensation not obtainable without reaching comfort in the different ambits.

As a consequence, we have [3]:

- A psychological or physical discomfort related to a particular ambit of experience remarkably changes the perception of environmental comfort (e.g. a very anxious user could experience very much heat than another that is emotionally stable) and makes holistic comfort to be impossible;
- Any intervention aimed at increasing comfort in a particular ambit considerably influence the perceived global sensation.

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.

This approach does not consists in a methodological limitation, but only represents an operative simplification: similar considerations could in fact be effected with regard to other aspects contributing to holistic comfort perception.

THERMAL COMFORT: FROM FANGER MODEL TO AN ADAPTIVE SUBJECTIVE ONE

As far as thermal comfort is concerned, we can refer to ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) definition [11]: "*mind condition of satisfaction in relation to the surrounding microclimate, that is an individual condition for which the person does not want to feel either colder nor hotter*".

Starting from this definition we can immediately point out the big importance of a subjective opinion given by the occupants about the environment they are in.

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

- Microclimatic conditions;
- Building structural and thermo-physical features;
- Physical and chemical agents;
- User activities;
- User work and life habits;
- User psycho-physiological-metabolic characteristics.

Indeed, the well known Fanger equation of human body balance [12]:

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

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

Such a large judgement relativity implies that rooms with same climatic conditions may produce very different evaluations about comfort, in relation to both the different users and the context where they are expressed. In addition, evaluation can also be different for a same user, owing to his different psycho-emotional-metabolic conditions in spite of the same thermal ones.

This evidence confirms the greater and greater importance that must be given to the subjectivity role, that is fundamental along with the referred context for thermal comfort evaluation.

Consequently main goal of a correct design of the building-plant system is always keeping user in comfort conditions although context variables change, warranting a real-time reactivity of the system and reducing the Percentage of Dissatisfied present in the experience scenery.

In order to reach such an objective, innovative tools of artificial intelligence and ICT, as intelligent agents, prove to be particularly effective, allowing to create a system that is reactive to both characterization and change of experience context.

Indeed, such a control system in indoor environments allows to continuously implement a trading-off between available resources and the desiderated purpose, considered as comfort tailored to each user's needs in relation to the specific related context.

Finally, last but not least, we have to consider that this sort of applications and methodologies allow the community to have significant benefits in terms of energetic and economic saving.

A NEW "ADAPTIVE SUBJECTIVE" APPROACH: FROM FANGER TO AN HYBRID SMART APPROACH

Due to the difficulty of this topic and the different interrelated implications, in our opinion an adaptive approach represents the most effective way to be followed in order to evaluate and obtain comfort conditions, trying to keep them in spite of changes of context variables [13].

In particular, different kinds of adaptivity can be considered [14-17]:

- *Physical-behavioural adaptivity*, involving all the changes a person makes, in order to adjust oneself to the environment, or alter the environment to his needs. We can, therefore, identify two different kinds of adaptation: reactive and interactive ones. In reactive adaptation, the only changes occurring are personal (such as altering one's clothing levels, posture and position, or even metabolic heat with the consumption of hot or cool drinks); in interactive adaptation, on the contrary, people make changes in the environment in order to improve their comfort conditions (such as opening a window, turning a thermostat, opening a parasol, etc.) [18];
- *Physiological adaptivity*, implying changes in the physiological responses resulting from repeated exposure to a stimulus, leading to a gradual decreased strain from such exposure. Such a mechanism is defined physiological acclimatization and becomes crucial in extreme environments, but is not of central importance in the context of the present research;
- *Psychological adaptivity*, involving all the cultural and cognitive variables, describing the way the different expectation of the user and his habits influence the climatic perception. Indeed, different people perceive the environment in a different way and human response to a physical stimulus is not in direct relationship to its magnitude, but depends on the information that people have for a particular situation [14, 19].

These three kinds of adaptivity remarkably influence the user's comfort perception [20]: in this sense, the literature results related to PMV and PPD values are very significant [17, 21].

Different authors show in fact as the Predicted Percentage of Dissatisfied (PPD) obtained from the theoretical computation of Fanger PMV, which is based on a deterministic approach, is very different from the *Actual Percentage of Dissatisfied* (APD), that represents the real number of dissatisfied users in real everyday environmental conditions. These results are obtained even when the comparison is done in the same climatic chambers (let us remember that the parameters of Fanger's PMV are measured in climatic chambers where it is possible to set them only for the time necessary to reach thermal equilibrium). An example of this discrepancy is reported in Figure 1.

The explanation to this phenomenon must be ascribed to user subjectivity and, as a consequence, to his physical, physiological and psychological adaptivity to environmental stimuli [17, 20, 22].

Consequently this result makes more and more important evaluating the influence of non thermal factors [14] present in everyday life, with regards to the novel tern *user-plant-building system*.

Brager and de Dear [14], different years ago, already gave a large importance to all those factors omitted in Fanger energetic balance model: these were personal factors (sex, age, culture, economical state, …), contextual ones (activity, emotional state, building using profile, contingent situation, …), interaction with environment (illuminating and acoustic aspects, thermal and air quality issues, …) and cognitive-psychological (attitudes, preferences, expectations, …).

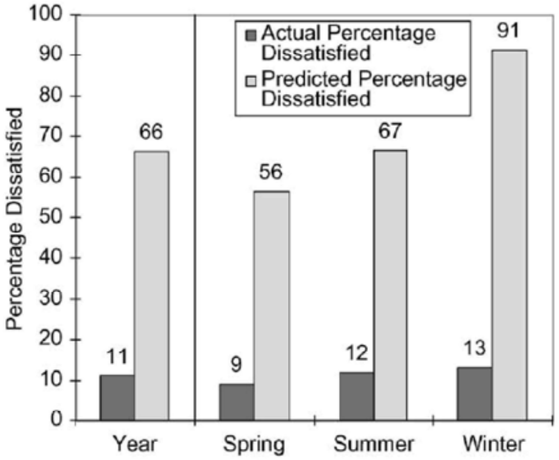

Fig. 1: Discrepancy between PPD and APD [22]

Lately, also Humphreys and Nicol have confirmed the inadequacy of the deterministic method for PMV in order to predict comfort conditions in relation to people groups living in real buildings 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 methodology: consequently in the scientific community there is now general awareness about the fact that the perception of a same environmental stimulus is different from a user to another and, in different conditions, for the same user.

This makes it necessary to take into great account also the global psychological data of user (habits, emotive state, adaptivity skill, motivations for staying in a particular environment, etc.) [17] and all the information related to the cognitive-emotive-relational sphere.

As a consequence, also the simplest considerations about comfort must be strictly linked to global evaluations about the subject, considered as integral part of the whole observation system: a correct analysis has therefore to take into account both his past climatic history and his expectations in relation to the environment where he is and the context he is living [14].

According to these theories, it follows that the deterministic principle present in Fanger's energetic balance model, based on the relation:

Physical data → physiological reaction → comfort shows to be insufficient.

Indeed, it would be better to consider the improved relation:

Physical data → stimulus + related contextual information → comfort perception

where big importance is given to the perceived information in relation to contextual issues and subjective preferences and sensations [31-33].

It should anyway be remembered that also the same Fanger formulation on PMV asked users to express their own personal vote about comfort by administering questionnaires, stating in this way that is the user to declare his own comfort state. Starting from this consideration, it is consequent the advisability of introducing a continuous feedback from user in relation to real conditions change, in order to evaluate in real time the influence of both thermal parameters and "non thermal factors" on subjective assessment and allowing comfort changes to be predicted.

The first objection that could arise about this could concern the way to follow in order to continuously administer concise tests that take into account the whole set of contextual variables related to holistic comfort, being they very numerous and of very different nature.

The resolution of this issue can be implicit in the same concept of adaptivity: user always tries to keep himself in comfort and, as a consequence, each his action directed towards the surrounding environment (building, system, clothes) implicitly represents an evaluation about comfort conditions.

Therefore, if an user acts on system (e.g. modifying temperature or opening windows), it is consequential that he is in a discomfort state, so that his actions aim at making better comfort conditions [18].

As a consequence, a system able to both register all these actions and deduce the exact interpretation and interrelation with the collected contextual data is also able to follow the global subjective comfort experience of an user: after a training phase, in fact, such a system could also be able to react to the variation of the whole set of variables, adapting to user choices and preferences.

Hence, in order to obtain a global approach, Fanger relation could be enriched by introducing a subjective model for comfort state perception, the schema of which is showed in Figure 2.

This new model could be defined as scenario-adaptive subjective comfort model [31-33].

Scenario is the whole set of information, continuously evolving and reacting to the various circumstances, that contribute to define the logical representation of what the world around a user is. Consequently it is constituted by all the whole set of parameters (both thermal and non thermal factors) and data exchanged among physical environment, system and building, filtered by the subjective user perception that determines his own evaluation about comfort state.

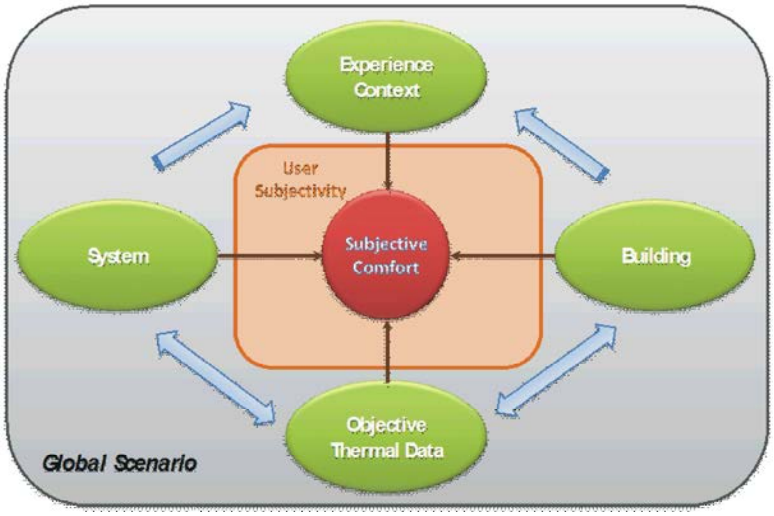

Fig. 2: Scenario-adaptive subjective model for comfort perception [31-33]

In particular the variables involved are related to user and his psychological characteristics, to the plant and building along with their using profile, to microclimatic conditions and the specific contextual situation, that are controlled in real time.

The scenario evolves in time through different states: it is therefore necessary to perfectly handle information in real time in order to update the description of reality; nevertheless, the real time observation of such a complex situation and the prediction of its evolution represent a very difficult task [31-33].

ADAPTIVE SUBJECTIVE COMFORT USING INTELLIGENT AGENTS

The proposed system aims at reaching the best trade-off between user needs and data and resources management: therefore, it has to warrant comfort conditions with the lowest energetic and economic consumptions.

Due to the large number of different situations that have to be represented, during the analysis it is necessary to take into account a huge number of information, continuously evolving and interacting in the different situations and contributing in defining the world around user.

Interaction is anyway strictly linked not only to user preferences, but also to the limits owing to the context (e.g. with a system that is only capable of ventilation it is not possible to reach the same goals that an HVAC system could): as a consequence, it is necessary to create a system that is aware of context [31-35]. Such a system should be able to react to the different situations according to both the specific application, activity, available resources and context.

One of the unavoidable consequence, caused by our approach, is the interrelation among different users: it refers to the optimization of the comfort level in situations in which the presence of different users in the same environment would probably arise concurring objectives. Due to the high subjectivity of comfort perception, in fact, the same thermal characteristics considered as comfort conditions by some people could be considered as a discomfort state by others.

The high complexity of the system makes a traditional, deterministic approach unsuitable to face the problem: it is consequently advisable to use the main techniques of computer science and information theory, in particular those of artificial intelligence and, among them, those indicated as user modelling [36], on the basis of which it is possible to build a rich and detailed user profile, continuously updated in real time.

As a consequence, in order to implement a system able to face up such a complex problem, it is necessary the synergy among technical physics, computer science, telecommunication technology and automation: in particular, computer science gives us all the necessary instruments in order to process the data that are collected and interchanged by means of telecommunication systems, making easier handling such a huge set of information. Moreover, as the described system cannot be realized using a single software, but different integrated systems and technologies are necessary, the use of a certain number of smaller and autonomous systems proves to be more efficient and able to provide better global management. In this aim the intelligent agents, innovative tools of artificial intelligence and ICT, have shown particular effectiveness in the creation of systems able to react to the changes of experience context.

Starting from these exigencies, the approach here selected for the aim is based on Intelligent Agents that, as a matter of fact, are able to manage "information at any time, at any place, at any form" [37]. Among them a Multi Agent System (MAS, that will be described in a next paragraph), owing to its intrinsic peculiarity, represents the most effective system in order to reach a real prediction and scenario adaptivity.

Then, the intrinsic features of MAS warrant a high versatility to our approach, making possible the integration of our system in both new buildings and pre-existing ones.

In particular our work proposes the development of a modular system that is able to collect the desired information by means of micro-ambient sensors. Along with them, it is also possible to modularly use other kinds of sensors in order to collect also the user metabolic data, or other indicators that are useful in defining user activity, clothes, profile or whatever is necessary in describing experience context and so on.

According to the desired complexity level, a single module (e.g. simple thermal data collected by means of a HVAC unit) or more complex systems, with different modules, can be used (i.e. it could be useful to collect different kinds of data of a patient, as the metabolic-physiological ones, in a specific context like a ward).

All the collected information have to be stored and used in order to follow the specific user in his own comfort experience, along with all his preferences. This lets system trace iso-PMV curves that are totally personalized and subjective.

As a consequence, on the whole the new system proposed shows particularly important features, such as:

- *High subjectivity*, being the user followed in all his own preferences in force of the definition of a detailed user profile;
- *High adaptivity*, since system reacts to the typology of scenario user is involved in, adapting its action in relation to his preferences;
- *High prediction and proaction*, being the system able to analyze the user global experience and to predict his reaction on the basis of his past history, acting in his favour (pro-activity) [38];
- *High capability of integration* with pre-existing technology in order to improve it and make it user-centred;
- *Use generality*, being applicable in environments very different for user profile, resources availability (such as the plant characteristics) and intervention emergency level (for instance discomfort in an operating theatre).

In addition, our model presents the following advantages:

- High comfort improvement;
- Integrated and holistic approach;
- Possibility to reduce energetic consumption, also thanks to the interrelation between external (and related tracking) and plant set-point temperature;
- Possibility of use both in new and in pre-existing buildings, with marked improvements of comfort levels even in these latter through relatively cheap interventions.

FROM FANGER TO ADAPTIVE SUBJECTIVE MODEL: DEFINITION OF COMFORT USER PROFILE

In the literature concerning Artificial Intelligence, Jennings and Wooldridge [38] define Intelligent Agents as "a software (or sometimes hardware) system showing the following properties:

Autonomy: Agents operate without man direct intervention and present a certain level of awareness and control on their actions and their internal state;

Social Ability: Agents interact with other agents (and eventually also with human beings) by means of a proprietary language;

Reactivity: Agents are aware of the environment in which they operate and immediately react to its changes;

Proactivity: Agents not only react to the environment changes, but are also able, on their own initiative, to assume behaviours oriented to precise objectives."

Their high "intelligence" contributes to their flexibility and versatility in the actions carried out and, then, to their adaptivity [39].

Another important characteristic of AI, with regard to comfort analysis, is their characterization by means of typically human mental elements, such as knowledge, beliefs, intents, expectations and duties, that describe psychological-adaptive-cognitive aspects of human beings [40]: on the basis of this, some researchers have even defined Intelligent Agents as "emotional agents" [41, 42], in order to underline their ability in managing and represent human mental states.

Being adaptivity, meant as the ability to follow a user in all his actions, behaviours, preferences and decisions, contained in the same definition of Intelligent Agent, their use for the implementation of a subjective adaptive comfort system results extremely appropriate.

Particularly they allow the definition of a user profile rich in information, continuously updated in real time according to the User Modelling techniques [36], that can be classified into two big categories:

- *Collaborative Techniques*, based on the insertion of users in a belonging group (people with the same sex, age, social class, etc.), according to the principle that people belonging to the same group behave in the same way and show a similar profile.
- *Content-Based Techniques*, that refer to every single user without considering his belonging to a group and presuppose that if the user himself assumes a particular behaviour under determined context circumstances, such behaviour will recur under analogous circumstances.

The collaborative techniques present a more immediate use, but do not consider the existence of differences in the behaviour of a user in relation to the characteristics of his belonging group.

On the contrary, content-based techniques, strongly based on the user real knowledge, are strictly linked to his past behaviour and are very precise when pointing out a real profile, even if only at the end of a long training phase.

Solving orthogonal problems, both categories show to be effective in order to tackle comfort description; anyway an hybrid approach using both categories reveals itself as the most appropriate for the definition and the updating of the user profile, as several lines of information theory for User Modelling techniques state [34, 35, 43, 44].

In order to exploit the best features of each technique and to avoid their limitations, in accordance with different computer science authors [34, 35, 43-47], in our system we will adopt an hybrid strategy that makes use of both of them.

The use of this hybrid strategy, for the implementation of the proposed comfort model, particularly provides the characterization of user profiles considering two phases:

1. A new user is provided with a starting user profile, determined by means of a collaborative technique, assigned on the basis of PMV Fanger model [12] and by means of the data collected by de Dear and Brager in the ASHRAE adaptive comfort database [1, 13, 48]: in this way the user is inserted in a starting belonging group. On the basis of the data at disposal, the system creates the logical representation of the contextual reality where user is involved and, as a consequence, it is at once able to determine if the user is in a comfort or discomfort state without long training phases;
2. The starting user profile is improved by means of content-based techniques: for each access into the system, the user profile is updated through relevant information. This implies that a more and more detailed background is continuously built: therefore, following each action-reaction couple of choices, 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 this way, our system enriches Fanger model with other considerations related to adaptivity and subjectivity. Indeed, a new user is firstly provided with a starting default profile obtained from Fanger rules, that is continuously updated as user interact with the system. Working in this way, our approach realizes a strict correspondence of user, his past history, his expectations and preferences to reference contextual data and factors, both thermal and non thermal ones.

The comfort conditions that are traced are expression of a global, holistic state of comfort: in the future, we can also suppose to store user profiles in a SIM Card in order to obtain HVAC intelligent systems.

We can also assume to share different profiles by means of Internet services, in order to create a global comfort system that is aware of context and users everywhere: for example, user that subscribes the service is provided with a personalized comfort service everywhere and every time (e.g., at the hotel, at home, at office, etc.) by means of the system that retrieves his own comfort information from web by means of internet connection.

Then, it is possible to foresee a realization of the system with particular features: data are collected by means of thermal and metabolic-contextual sensors and are exchanged by means of wireless technology and internet services, making it possible to realize an adaptive system that follows user everywhere and every time.

For example, supposing the diffusion of a common technology standard definition, a user that travels and spends a night in hotel can enjoy a personalized comfort service in his own room retrieved from his profile by system: in this way, no time is necessary to set up system for that specific context and user may find a room with thermal condition as comfortable as possible.

MULTI-AGENT SYSTEMS IN COMFORT TREATMENT

In order to realize the system here described, it is not possible to use a single application software, but it is necessary different systems and technologies to be integrated. As a consequence, the collaboration of several different applications and the employment of different protocols allowing this integration are necessary.

In fact, according to all the previously pointed out issues, the presence of intricate interactions among users, information flows, thermal data, non thermal factors and building features, makes the use of a single, centralized and very complex system, taking the control of the whole situation, not advisable.

On the contrary, it results more efficient to use a certain number of smaller and autonomous systems that are able to provide a better global management: they are the intelligent agents, that allow a more detailed and easier control of the global situation and different systems and technologies to be integrated.

Different typologies of agents are defined in this aim (collaborative, interface, mobile, information-Internet, reactive, hybrid and smart agents), that can be used in dependence of their respective characteristics.

In particular Artificial Intelligence define systems composed by different agents, among which *DPS* (*Distributed Problem Solving*) and *MAS* (*Multi-Agent Systems*) can be distinguished: for the aims of our study these latter will be used [49]. DPS obtain the solution of a problem by means of a number of modules (nodes) that cooperate, dividing and distributing the knowledge of the problem and the evolution of its solutions.

Differently from DPS, MAS carry out an interaction among different autonomous systems (i.e. an "agency" [50]), that act independently to solve problems (that can be common, interrelated or completely independent) which cannot be solved by a single agent: in this way, a MAS is collectively capable of reaching goals that are difficult to be achieved by an individual agent or monolithic system [49].

Indeed, a Multi-Agent System can be also defined as a loosely coupled network of problem solvers that work together to solve problems that are beyond the individual capabilities of each of them: the different problems can be common, interrelated or independent ones and the topical characteristic of a MAS is the social ability that realize a representation of human beings with their own behaviours, mental states and notions.

The choice of the system to be used has fallen on the MAS due to their particular characteristics [51]:

- Decentralization of data;
- Lack of a single global control system in advantage to the autonomy of each single agent;
- Incomplete viewpoint of the world for each agent;
- Asynchronous and synchronous computation.

In particular MAS are very useful to solve complex and distributed problems such as the one under examination, thanks to their intrinsic efficiency, robustness, ability of integration of various systems and flexibility.

In addition it benefits from the advantages offered by the distributed approach with respect to the centralized one, presenting:

- *High reliability* (high tolerance to faults);
- *High Modularity and Scalability:* Agents can be created and eliminated without invalidating the global system functioning and can considerably increase the computation capacity of the system;
- *High Adaptivity:* Agents can reconfigurate their functions in order to satisfy the varying needs of the system;
- *Easy Clash Overcoming:* Agents can reason and fulfil parallel tasks in an asynchronous way, making quicker and flexible the process execution;
- ***High Dynamicity:*** Agents can collaborate to create dynamic groups aimed at the solution of specific problems, allocating, distributing and releasing resources;
- ***High Mobility:*** Agents can move through all the system, fulfilling specific tasks, drawing or delivering the right resources and the necessary know-how for the realization of specific processes.

Nevertheless, the high complexity of the system obviously requires a massive formalization work aimed at representing the whole reality to which one refers.

According to the exigencies of interaction and knowledge management, besides a standard language, the necessity for a powerful knowledge conceptualization arises. The huge heterogeneity of agent typologies and the various application fields imply the need for an efficient knowledge handling that is achieved by means of the so called ontology. Ontology is discussed from philosophical and Artificial Intelligence perspectives.

From a philosophical point of view, ontology is the science of being. It studies categories of a particular system that reflects a specific view of the world.

From an Artificial Intelligence point of view, ontology is an engineering artefact that describes a particular reality with a specific vocabulary, using a set of assumptions regarding the intended meaning of words in this vocabulary.

In this perspective, ontology can be defined as a "shared and common understanding of some domain (a sort of representation of knowledge) that can be communicated among people, agents and application systems" [52].

As a consequence, one of the main problems is to realize suitable ontologies that can realize the best representation of such a complex model, in which both the thermo-physical data, the non thermal factors and all the contextual information concurring to define the scenery under examination can be correctly expressed.

TECHNICAL DATA ABOUT MULTI AGENT SYSTEM

Using the main theories about MAS, our system will be realized by means of a BDI Model (*Belief Desire Intention Model*).

This is a model suitable to characterize Intelligent Agents using typically human mental notions and states [53].

Moreover, advanced communication among agents (and also among users and agents) will be based on speech acts theory [54, 55], allowing interaction among agents and among users and agents.

The used language will be *XML* (*eXtensible Markup Language*), that allows communication among agents through *ACML* (*Agent Communication Markup Language*) [56], a special language obtained through the combination of *XML* and *KQML* (*Knowledge Query and Manipulation Language*), a choice that allows integration of agents with a large variety of technologies in a very easy way.

In order to realize the proposed system, through the work four agent typologies have been characterised:

- User-Building-Activity Agent (UBA).
- Scenario Management Agent (SMA).
- Plant Management Agent (PMA).
- Environmental Agent (EA).

Each agent attends to a particular aspect: The global functioning is the total result given by the integration of the different elements of the system.

In particular SMA has been exploited in order to manage the environmental (provided by EA) and profile information, 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. All the collected information is stored and used in order to follow the user in his own comfort experience, along with all his preferences.

The different agents are 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.

The interaction between the system and the user is designed in the aim of warranting adherence to different standards and interoperability: indeed, a relevant aspect of the system is its possibility of being used as an interface with pre-existing technology.

In order to warrant this, user interacts with the new central unit of our system and this last one (provided with a programmable remote controlling system capable of reproducing the infrared signal of the pre-existing device and a sensor system to be aware of the context) interacts with the older plant. The schema of this interaction is shown in Figure 3.

Fig. 3: Interaction style between user and subjective-adaptive scenario aware system

Further advantage of the system is its versatile use of user profiles defined in force of information collected (generally through thermal and metabolic-contextual sensors and wireless technology), 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 FUNCTIONING

In a global general vision, without entering in a deeper detail in order to warrant the easiest comprehension of the system behaviour, we can distinguish five different macro-blocks, representing different phases of the whole adaptive process. In Figure 4 the representation of the different phases is reported along with the interrelation described by the global arrows of the dataflow.

It is worth pointing out that the different phases are not apart processes, but contain different interrelated processes and decision mechanisms giving rise to a very complex algorithm and an intricate information flow (Figure 5). In the figure, according to the main trends of artificial intelligences literature, the different agents are expressed by means of cartoon-style icons.

Fig. 4: Different phases of the global algorithm

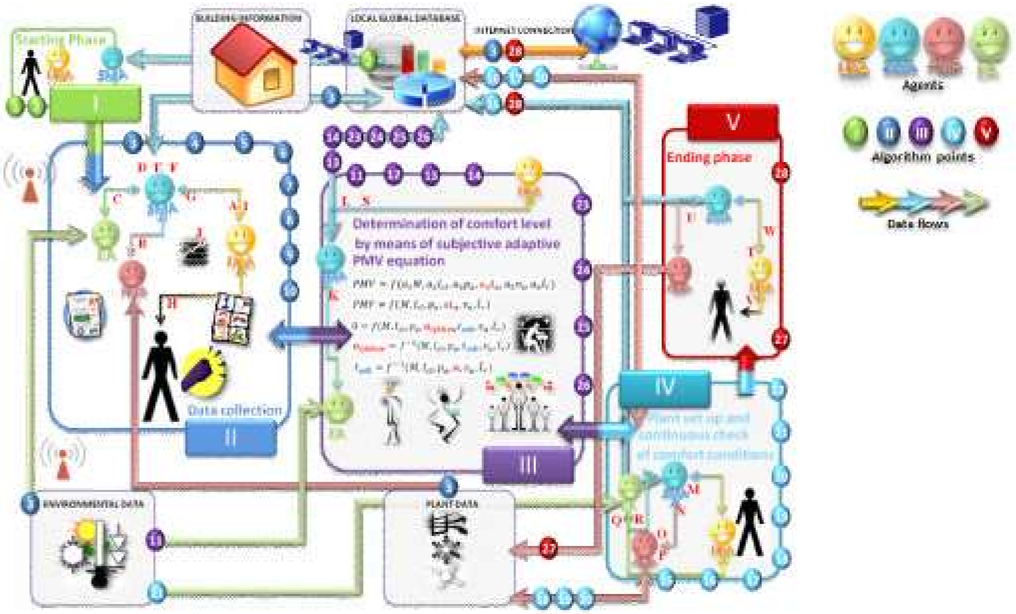

Fig. 5: Data flowchart referring to the different phases of the global algorithm

In the following five points an overall analysis of the different phases, giving a schematic description of the system functioning, is reported.

Point I: Starting phase.

In this phase user enters in the area controlled by the system. The first step is the activation of the plant by means of either the suitable remote controller or other suitable devices, such as sensors or time scheduling strategies. Two agents are also activated: UBA, the personal agent and SMA, the agent following user in all the scenarios he is involved (step 1 and 2 of the global algorithm).

Point II: Data Collection.

In this phase the location of the user in the area of interest (i.e. a specific room in a building) is firstly retrieved. Then, the different agents interact in order to retrieve all the data useful to create a representation of scenario, containing both thermal data and non thermal factors related to user's comfort preferences: particularly environmental data are provided by EA whereas the plant and resource information are attended by PMA.

Afterwards, UBA allows user to choose his activity and, finally, information related to clothing and specific metabolism issues is retrieved either from an opportune modular sensor system or from the global database storing data taken from ISO 9920 and ISO 8996 tables.

At this point SMA becomes able to use all the information provided in order to create a logical representation of 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 throughout his whole experience (this phase is realized through the steps 3 to 10 of the global algorithm).

Point III: Determination of comfort level by means of subjective adaptive PMV equation.

This phase is the core of the whole process and also the most delicate one in order to pro-actively determine comfort conditions following user in his own preferences and activities. 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, the following procedure is adopted.

A new user is firstly provided with a starting default one, obtained using Fanger model, on the basis of which the system creates the logical representation of the contextual reality; as a consequence, the system is at once able to determine the user comfort state.

Subsequently, as user interacts with the system, his starting profile is continuously updated by Intelligent Agents that, following every access to the system, tailor it to the specific user.

On purpose an opportune PMV equation based on Fanger theories and opportunely modified through introduction of adaptive factors a_i is used:

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

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 during their interaction with the plant), the previous relation can be simplified as follows:

$$PMV = f\left(M, I_{cl}, p_a, at_a, v_a, t_r\right) \quad (3)$$

As a consequence, when the user sets the desired temperature t_{adi} 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:

$$0 = f\left(M, I_{cl}, p_a, at_a, v_a, t_r\right) \quad (4)$$

that leads to

$$a = f^{-1}\left(M, I_{cl}, p_a, t_a, v_a, t_r\right) \quad (5)$$

Of course, after air temperature changes other parameters will change as well. It is worth pointing out that 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.

The procedure that leads to the computation of the best adaptive factors is expressed in the global algorithm from point 23 to point 26.

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.

The description of this process is provided on points 13 and 14.

Point IV: Plant set up and continuous check of comfort conditions.

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 (i.e. without user intervention).

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: this represents a trade-off problem, where system has to choose the best solution satisfying 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 our work and as a consequence, we do not deal with it in detail.

This phase is described in the global algorithm from point 15 to point 22.

Point V: Ending phase.

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.

GENERAL CONSIDERATIONS AND DEVELOPMENTS ON THE MODEL

From the above it follows that the use of the described technologies allow to build up a system that represents a new model realizing an advanced, holistic view of comfort, keeping in high consideration the user needs and preferences in any moment and in any environment.

Synthetically, the main features characterizing our system will be:

- *High Subjectivity:* It handles quite a rich and detailed user-profile definition to record all relevant information about the user comfort characteristics and behaviour in particular contexts;
- *High adaptivity* with regard to user-plant-building system coordinates and ability to dynamically react to their variations, in relation to both the context and to resources availability;
- *High dynamicity and flexibility*, since it is provided with suitable mechanisms for reacting to the variations of the needs of either the same user or different ones;
- *Very highly general*, since it is capable of operating on a large variety of application contexts. It can be used in environments that are very different for using profile, resources availability (e.g. system typology) and emergency degree (i.e. discomfort in surgical operation);
- *High capability of integration* with pre-existing technology: indeed, the system characteristics allow existing technology to be integrated in order to make it better and user centred;
- *High predictivity and proactivity* [38] because it is able to analyze the global experience situation and to predict the user's reactions on the basis of his past history, anticipating his actions and consequently acting in his favour.

Then, in accordance with the theories of Brager and de Dear [14] our model presents the following advantages:

- High improvement of comfort level, due to the strict interrelation existing between contextual variables and use preferences. This makes possible personalized iso-PMV for each user to be traced;
- Integrated and holistic approach, that takes into account the multidimensional human nature;

- Possibility of reducing energy consumption, thanks to the interrelation between the external temperature and the related tracking of the set point temperature of the system. This is also in relation to the subjective preferences of the user and to all the information of his own profile, that make possible the predictive and pro-active actions of the system;
- Using capability in both new buildings and in pre-existing ones. In the latter case, our system could noticeably improve comfort conditions with relatively cheap interventions.

It should obviously be sufficiently underlined that the proposed model, although representing an highly innovative system in comfort service handling, has necessarily to face up many challenges before being able to be introduced in system production: as above cited, at the time one of the main issues to be faced in its formalization is represented by the concurrent goals existing when many users are present in a same environment at the same time.

Nevertheless in future developments the model candidates itself to be inserted in the new branches of comfort theories that take into high account the characteristics of both context and building using profile, correlating them to the subjective preferences of users.

CONCLUSIONS

In the last years, in the literature the discrepancies existing between comfort data collected in climate chambers and comfort conditions in everyday life context, mainly ascribable to the so-said non thermal factors and to user subjectivity, have been more and more evidenced.

In the management and control of confined environments the importance of subjectivity and of reference context in comfort evaluations is in fact coming out with increasing urgency, making extremely necessary the support of more complex techniques in the information management.

As a matter of fact, in current research the new idea concerning the necessity of changing the approach from the classical viewpoint that analyzes the couple plant-building system to a more complex one that takes into account the tern user-plant-building system is arising.

Therefore, it is extremely urgent to consider comfort from a multidimensional, holistic point of view, in which environmental comfort and in particular thermal-hygrometric one, represents an indispensable component in order to reach a global comfort state.

Within this frame, an adaptive comfort approach shows 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.

As a consequence, the complexity of the problem noticeably rises, making strongly urgent the support of new technology and more complex techniques for the handling of huge information flows.

In this aim, through the paper a new model of scenario-adaptive subjective comfort (scenario is the logical representation of the global context where user comfort experience happens), suitable for indoor environments and based on Intelligent Agents, is proposed.

In particular a Multi-Agent system 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 tern user-building-plant: MAS constitute, in fact, powerful and flexible instruments perfectly suitable for the aim, constituting an ideal basis for data interchange and interaction, guaranteeing the maximum operative efficiency.

Starting from Fanger theories about energetic balance and integrating them with the main studies about adaptive comfort, by means of a Multi Agent System it is possible to realize a system aware of the scenario where user live and able to adapt to the context as variables changes, allowing to maintain conditions of subjective comfort, tailored to user specific requirements.

APPENDIX

Through the paper, due to its intrinsic multidisciplinarity, several acronyms have been utilized, mainly referring to Artificial Intelligence techniques. For the reader's convenience in the following a list of these acronyms is provided, along with a short description of their meaning.

- AI: Artificial Intelligence
- ICT: Information and Communication Technologies
- DAI: Distributed Artificial Intelligence. It is defined as the research about systems composed of multiple agents.
- DPS: Distributed Problem Solving. It considers how a particular problem can be solved by a number of modules (nodes) which cooperate in dividing and sharing knowledge about the problem and its evolving solutions.

- MAS: Multi Agent System. System composed of several agents, collectively capable of reaching goals that are difficult to be achieved by an individual agent.
- BDI: Belief, Desire and Intentions. Formalism used to represent the knowledge in systems based on Intelligent Agents. They are concepts strictly linked to mental human notions in order to represent the human behaviour and to create a representation of goal-oriented actions typical of human beings. On the bases of these concepts the architecture of a Multi Agent System is realized.
- XLM: Extensible Markup Language. It is a general-purpose markup language, whose primary purpose is to facilitate the sharing of data across different information systems, particularly via Internet.
- ACML: Agent Communication Markup Language. It is an XML-based Agent Communication Language, obtained by combining XML and KQML. It is the XML encoding of FIPA (Foundation for Intelligent Physical Agents Specifications) Agent Communication Language (ACL). The choice of this language makes very simple to integrate agents with a large variety of technologies.
- KQML: Knowledge Query and Manipulation Language. It is one of the best known example of interaction language based on speech act theory.

Speech Acts Theory: It enables agents using FIPA ACL to be sure that other agents will understand the meaning of utterances in the same way as the speaker.

User Modelling: The whole set of techniques utilized in order to create a very detailed user profile that enables agents to interacts with users and predict their actions in a pro-active way.

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