FROM TECHNICAL TO USAGE ENERGY EFFICIENCY IN BUILDINGS: APPLICATION TO A HEATED ROOM

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ABSTRACT

In the context of more and more efficient building research, as passive house or Energy plus building, the occupants have become a central actor of building system. In order to integrate them in the design phase of a building, it is proposed to complete the classical definition of "energy efficiency" with the concept of "usage energy efficiency". This concept integrates the notion of satisfaction and energy consumption which are summarized in a compromise decision plane. The research work is ilustrated thanks to a real platform, where the proposed tool has been applied to a heating system. It appears that this tool, used as a decision support in the design phase, could both improve the integration of user in building system and reduce energy consumption.

INTRODUCTION

In the context of efficient buildings, such as passive house or energy plus buildings, the occupants have become central actors of the building system (Madhavi et al, 2009). Indeed, inhabitants have a great impact regarding thermal internal gains but also as occupants using appliances and having expectations in terms of comfort and services (Ha et al, 2006). The human interaction with building system has been modelized under different aspects such as room occupation (Hoes, 2006), thermal reaction with the heating system (Haldi et al, 2010) or light switching (Lindelöf et al, 2006) but such models describe more the usage behaviour than the real efficiency of usage.

Since the 1970's and moreover this last decade, the buildings follow new trends in terms of functionalities as energy efficiency expectations (with passive homes) or health and media expectations (with smart homes (Chan et al, 2008) and intelligent building (Wong et al, 2005)). Nevertheless, those last services (media, leisure and health services) are provided by electrical appliances and consume more energy due to the higher level of service expectations. So, there will be some compromise to find between the different expectations and the electric energy consumption in order to reach the energy efficiency of a building.

To reach this goal, such questions have to be taken into account from the design phase of energy systems

Impact of inhabitants on the energy consumption: the experience of MIB platform

It appears in the litterature that the energetic impact of user behaviour is very important due to the nature of usages and social profiles of users. According to the profiles of home ownerships for example, an English report concluded that energy waste reduction could vary from 10% to more than 40% due to sociological parameters as gender, culture or age of inhabitants (Mansouri, 1996). Another case in tertiary building shows that between the expected energy consumption of an energy plus office building during the design phase and the real consumption after one year of operation, the electrical part of energy consumption was underestimated by 50% compared to real use because the real needs of users were not investigated and deeply modelized (Lenoir, 2010).

The MIB (Monitoring and Intelligent Building) platform, which is used as an illustration, is a part of a renovated building. This platform is entirely equipped with temperature, air flow and electric energy consumption sensors and with a BMS (Building Management System) which records data. The purpose of this platform is to study the user behaviours in a building focusing on the impact on the energy (thermal and electric energy) consumption of the building.

From the experience of one year operation of the MIB platform, the annual energy balance is a 153 kWh/m².y instead of 50 kWh/m².y as designed in the HEQ (High Environmental Quality) process of the building (NF, 2005). A sociological interview has been elaborated and applied on the users of the MIB platform in order to investigate the user satisfaction in different aspects of the comfort (thermal, air quality and visual comfort) and to know their reactions during uncomfortable situations. It appears some significant feedback as the thermal uncomfort during summer and hot days (75% of the user disagree with the efficiency of freecooling system) or the inacceptability of automatic switching lights even if those energy system were designed as efficient systems: a double flow ventilation system for the heating and cooling of the platform, and a dimming regulation for the artificial lightning. This feedback also provided the reactions of the users to some discomfort situations (for example 30% of the MIB platform users leave the room for air conditioned room

during hot summer) which will impact the total energy efficiency. From this experience, it can be noticed that, despite the installation of efficient technologies, the use of such building system make the building over consuming because the expectations of use have not been taken into account in the design phase of the building.

From a more general point of view, it suggests that the energy efficiency concept should be revisited in order to integrate also the occupant behaviours and comfort expectations.

First, a new concept of usage energy efficiency, which integrates the usage in the classical "technical" energy efficiency, is proposed. Then, a decision support tool, which makes it possible to compare different scenario of use and equipment configurations according to a compromise cost/satisfaction, is presented. It is applied and validate on a simulated heated room. The proposed approach and tool could be integrated upstream or directly in energetic simulation tools such as Energy Plus (Crawley et al, 2001), TRNSys (Beckman et al, 1994) or Comfie (Peuportier, 1990) during the design phase of the building system in order to integrate the usage energy efficiency on the modelized system.

A NEW CONCEPT: USAGE ENERGY EFFICIENCY

Limits of actual energy efficiency concept

In litterature and in current language, the energy efficiency concept of a system or an appliance is most of the time considered from a physical point of view and does not refer to the usage. According to Patterson (Patterson, 1996), two particular concepts in energy efficiency terminology can be distinguished: thermodynamical and physico thermodynamical energy efficiency.

The thermodynamical energy efficiency is an adimensional number representing the ratio between the output and the input of a same measurable quantity (most of the time the power, especially for electric system such as motors). This definition of efficiency is the most commonly used in engineering sciences.

The physico thermodynamical energy efficiency is a dimensional number representing the ratio between the end use quantity (as defined by Lovins (Lovins, 2004)) and the input quantity. Those quantities have not to be in the same physical units. In Energy building domain, this definition is used to evaluate the energy efficiency of a building (kWh/m².y) or the energy efficiency of appliances through energy labels (for example for dishwasher, it may represents the energy consumed (input) to wash 12 dishes (output): see (EUC, 1992)).

Those two aspects of energy efficiency have a technico-focused point of view because only physical quantities from the technology is included and it misses a relation with the usage: how does the user react to the service provided? What does the user want in terms of services and comfort? How users interpret the physical phenomena provided by such appliance? (the term phenomena used as defined by Kant (Kant, 1781).

Analysis of the link between users and the equipment of a building

In order to (re)place the user in the centre of attentions, an analysis of the link between the user and the building system and its equipments is needed (see figure 1).

Users have initially desires and needs (Maslow, 1943) (Epicure, 270BC) and then, they express their will through actions on the building system. Those actions can be direct or indirect action on the equipment. For example, if the need is to have a cooler temperature, either the user can play on the cooling temperature set point or can open a window or even set up a personal cooling system. If he is hungry, he can open the door of the fridge to get cold food, etc…

According to the actions of the user on the equipment, the artificial system (the corresponding appliances or components of the building system) will then integrate
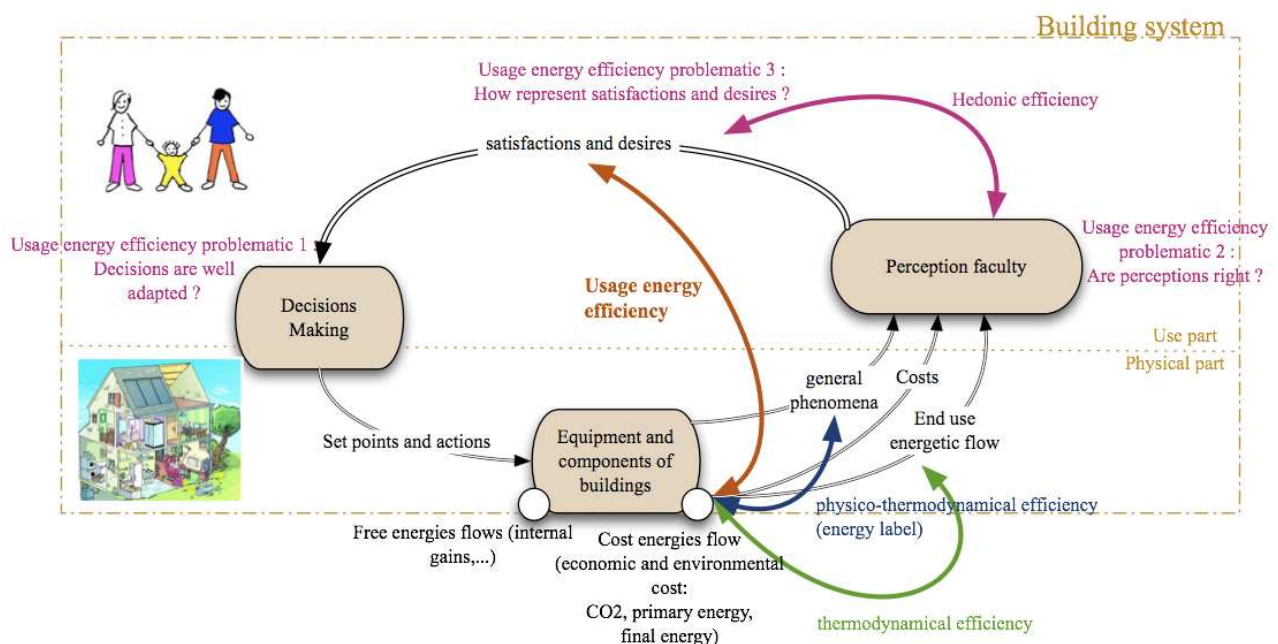

Figure 1: Representation of the usage in a building system

it as a set point of its process. This appliance will convert energy to phenomena corresponding to the service provided by the appliance according to the set point/action required by user and the intrinsic operating mode of the system. This conversion corresponds to the end use service as defined by Lovins (Lovins, 2004). From the provided service, the user perceive a resulting feeling and make a judgement, corresponding to the satisfaction in terms of cognitive process. The satisfaction is defined according to the relation between the initial will and the final perception of the service

Definition of the Usage energy efficiency concept

From this representation of the usage, a definition of "usage energy efficiency" concept, which integrates the usage dimension, is proposed. The usage energy efficiency is defined as a multi objective relation between the satisfaction of user about one service and the energy consumption of the service.

The objective is to maximize the ratio:

$$\frac{Services\_Satisfaction}{Energy\_Consumption}$$

This concept includes 3 issues related to the use and the user integration:

- The first issue (problematic 1 in figure 1) deals with the real use and the effectiveness. Indeed, the following questions have to be considered: Does decisions and actions from user really correspond to their desires and needs? Are other actions/decisions available to offer the same satisfaction/service at the end (less energetic consumer preferably)? This issue is related to the effective use, and can be investigated by studying the relation between the action done and the related cognitive will.

- The second issue (Problematic 2 in figure 1) is related to the perception of a service by users and to the acceptability of users faced to certain level of service/comfort. Are these users having different level of expectation and what is the impact on the service and energy consumption of this expectation? Could other services provide the same perceived comfort (and consuming less energy)? This issue concerns the study of the relation between the service and the perception (and then the satisfaction). Those two approaches question about the relation between user and equipment and systems.

- The third issue (problematic 3 in figure 1) questions about the expression of user satisfaction and desire which are cognitive concepts. Linking it to the two other issues yields the modelling of human appreciation/will in order to characterise the use.

QUANTIFICATION OF THE CONCEPT AS A COMPROMIZE BETWEEN COST AND SATISFACTION

The relation between satisfaction and consumed energy determined in the usage energy efficiency concept can be seen as a compromise between the cost of a service (link to the energy consumption) and the satisfaction provided by such a service to the user (ratio $\lambda_{compromise}$ of equation 1). Such a compromise can be defined as a point in a compromise diagram with Cost and Satisfaction as Cartesian coordinates (see figure 2).

$$\lambda_{compromise} = \frac{Satisfaction}{Cost} \quad \text{Equation 1}$$

The couple (cost value, satisfaction value) of each point of the diagram corresponds to the mean values of the cost function and the satisfaction function associated to the equipment/system service

The "cost function" of the diagram refers usually to the financial costs related to energy costs of the service but that concept could be expanding to a more general consideration like mental costs or environment impacts.

Evaluation of satisfaction functions

Different kinds of satisfaction functions can be built according to the usage issues (figure 1):

-a satisfaction function evaluates the quality of the usage regarding issue 1 in order to distinguish good use from bad use (energy waste for example)

- a satisfaction function of the comfort regarding issue 2 represents the satisfaction of users according to the perceived service or phenomena.

- a global satisfaction function, which can be a combination of the two previous functions is related to issue 3.

Those satisfaction functions would be defined as continuous function between 0 and 1 where 0=Unacceptable and 1=Totally satisfied

Usage energy efficiency diagram (or compromise diagram) description

Because the objective of the usage energy efficiency is to maximize this compromise ratio ($\lambda_{compromise}$) , it can be obtained either by minimizing the denominator (the cost) or bt maximizing the numerator (the satisfaction) of equation 1. For each system, it exists, in the compromise diagram, a Pareto front which is defined by an set of $\lambda_{compromise}$ for which a parameter (cost or satisfaction) change cannot improve one criteria without degrading the other (see dot line in figure 2). The best point of this compromise diagram is located in (0,1) where satisfaction is maximum and energy consumption is equal to zero.

In figure 2, the satisfaction corresponding to the thermal comfort (based on the level of temperature) is applied to 3 trivial heating systems which will be detailed later. The reading of the compromise diagram tells whether the anticipative system (triangle plot in figure 2) has a better usage energy efficiency than the system with regulation (square point) and even more than without regulation (round point). It means that the anticipative system provides the best comfort (better temperature perception in this case) and, at the same
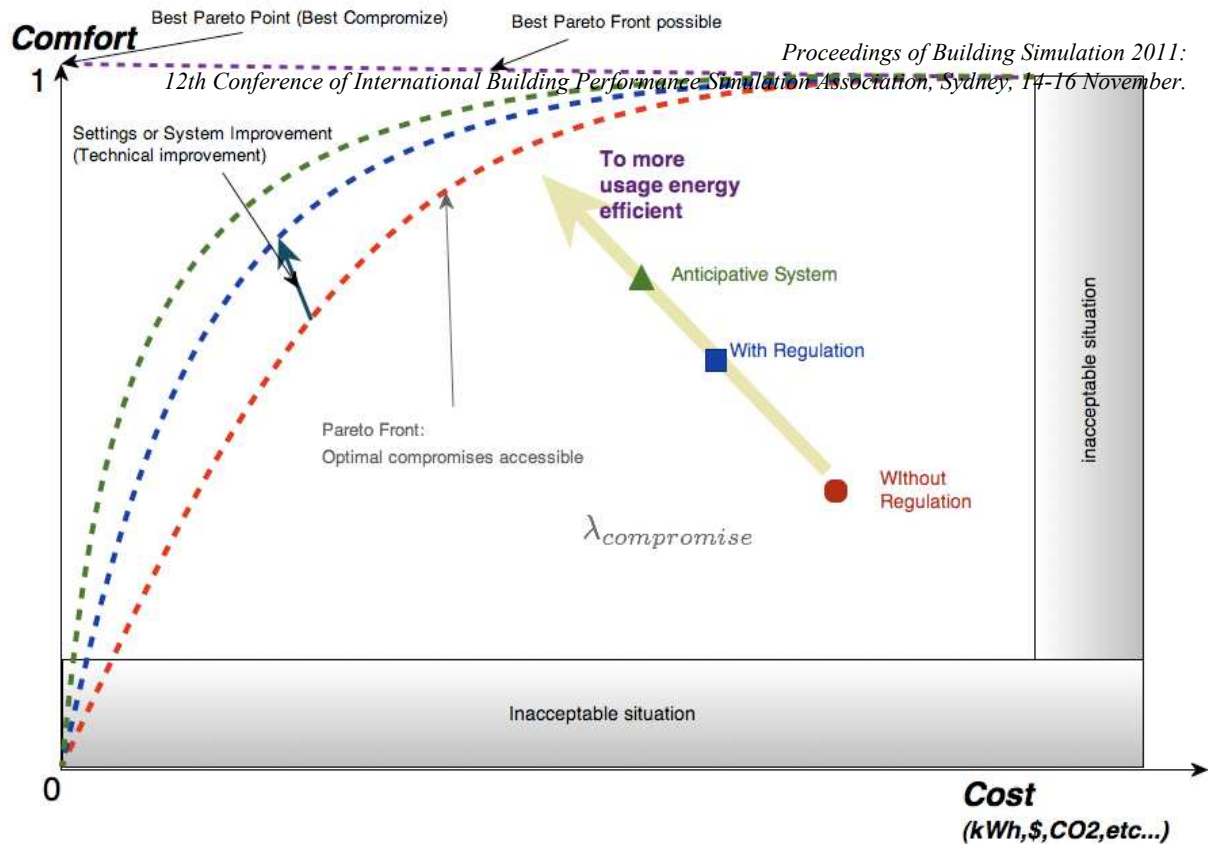
Figure 2: Example of compromise diagram for satisfaction function of thermal comfort

time, consumes the least energy. This performance is due to a better integration of the use in the heating system.

UTILISATION OF THE USAGE ENERGY EFFICIENCY DIAGRAM: APPLICATION TO A SIMULATED HEATED ROOM

To illustrate and validate the usage energy efficiency diagram (see figure 2), a heating system, where the cost is the energy consumption, and the comfort the satisfaction of users according to the ambient temperature, has been chosen.

The purpose of this application is to compare different heating system controls, regarding one scenario of occupation and to evaluate at each time the usage energy efficiency. The objective is to find the best configuration accessible in terms of energy savings and satisfaction of users, which would be, for the designer, the configuration to choose.

Case of Study: the computer classroom of MIB platform

The application example is the computer classroom's heating system of the MIB platform. It focuses on one particular week: from Monday 29th November to Friday 3rd December 2010.

The studied heating system is a real case. It contains a double flow mechanical ventilation, which has been modelled in different simulation tools (Hoang, 2011) but, in this example, it is considered that the double flow ventilation is just involved in the heating system but not in the ventilation system.

As the Computer classroom is part of the MIB platform, the insulation is quite good (*Uwall*=3.19 W/m².K, *Ufloor*=0.14W/m².K, *Uroof*=4.92 W/m².K) and have a low thermal inertia (about 3 hours) for a floor area of 110m².

Thermal models

The pertinence of the usage energy efficiency diagram is now studied, particularly during the design phase of the computer classroom. As previously presented, 3 control systems of the heated room have been studied:

- The first system control (without regulation control in table 1) corresponds to a basic heating system, like heaters without any thermal regulation system. This configuration provides a constant thermal power of 3kW during the opening time of the building: from 8am to 8pm.
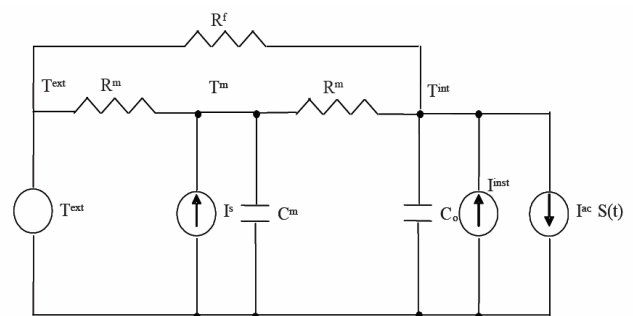

Figure 3: Electric equivalent thermal model of a heated room

$$\begin{cases} \dfrac{dT_m}{dt} = \dfrac{I_s}{C_m} + \dfrac{T_{int}}{R_m C_m} + \dfrac{T_{ext}}{R_m C_m} - \dfrac{2T_m}{R_m C_m} \\[2ex] \dfrac{dT_{int}}{dt} = \dfrac{I_{inst}}{C_o} - \dfrac{I_{ac}S(t)}{C_o} + \dfrac{T_{ext}}{R_f C_o} + \dfrac{T_m}{R_m C_o} - \dfrac{T_{int}}{C_o}\left(\dfrac{1}{R_m} + \dfrac{1}{R_f}\right) \end{cases}$$

T_{int} = ambient temperature (°K)

T_{ext} = external temperature (°K)

I_{inst} = Internal gains Power (W)

I_{ac} = Heating System Power Flow (W)

I_s = Solar radiation (W)   *Equation 2*

R_m = thermal resistance of walls (°K/W)

R_f = thermal resistance of windows and air infiltration (°K/W)

C_o = air thermal capacity inside the room (J/°K)

C_m = material thermal capacity of the walls, windows (J/°K)

The ambient temperature evolution is calculated thanks to a simplified thermal model based on a electric equivalent model (Madsen et al, 1995; Coley et al, 2002) (see figure 3). It is defined by the equation system: equation 2. It can be noticed that the case does not take much into account the use of the room from a thermal point of view.

The second and third heating control systems are implemented in an energy simulation software model (COMFIE Pleaïdes; Peuportier et al, 1990) where the computer classroom and the whole MIB platform has been modelled. This model is based on the architectural materials and weather data available during the design phase of the platform, corresponding to the available data for a design office for example

 - The second thermal control system has a regulation system depending from the ambient temperature in order to regulate the thermal power according to the ambient temperature. This configuration corresponds to a thermostat technology that is the most common regulation in actual heating system. This configuration (regulation control is given by table 1) is defined as fixed set point of 19°C during opening time (8am-8pm) and a 16°C set point during closing time. In term of usage integration, this

solution takes into account the number of persons.

- The third configuration can be assimilated to an anticipative system. Indeed, assume that the heating temperature set point has been set to 19°C according to the planned occupancy of the room. During occupancy periods, the system regulates the ambient temperature, which takes into account the internal gains (anticipative control mentioned in table 1). In case of absence, ambient temperature is lowered.

Those 3 configurations lead to a more and more complex integration of the users.

Model of the "scenario of use"

This scenario (presence scenario in table 1) supposes that the effective period when people are in the room is known. It corresponds to a standard number of people (25 in our case) during the occupancy schedule of the room. This scenario corresponds, in operation phase, to a building system equipped with a presence or moving sensor. Because only the presence is detected, a standard number of people during those periods is assumed.

Satisfaction models

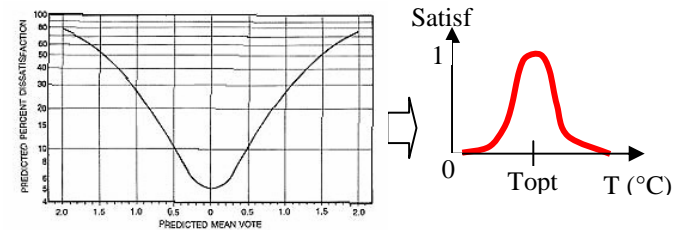Firstly, satisfaction perceived by users is considered:

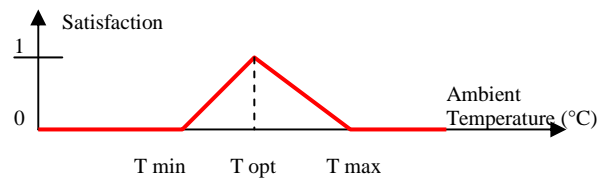*Figure 4: Thermal satisfaction function from PMV-PPD model*

Figure 5: Thermal satisfaction model

Table 1: Scenarios of heating control system and use of IT classroom during the week 48
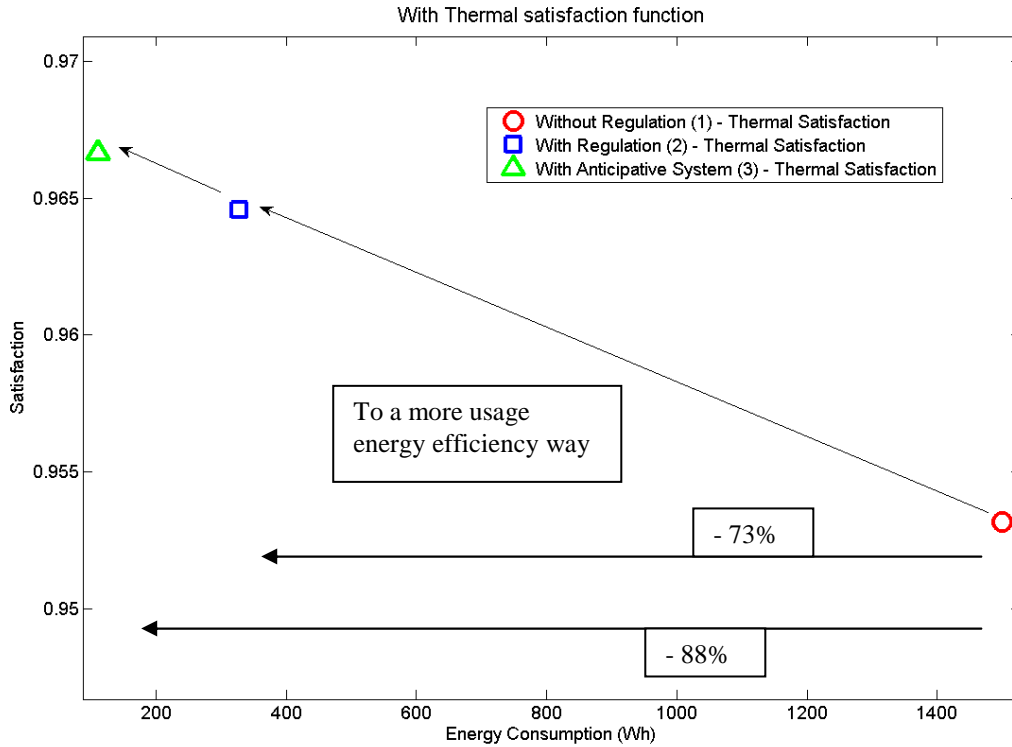
With Thermal satisfaction function

Figure 6: Compromise diagram with satisfaction function of the thermal

here, it corresponds to the thermal comfort defined according to the ambient temperature. The thermal satisfaction model is defined from PMV-PPD model (ISO, 2005; ASHRAE, 2004), which described dissatisfaction (figure 4). The relation between temperatures and percentage of satisfaction can then be linearized as shown in figure 5.

During the user presence period, the satisfaction level reach its maximum for a optimal temperature (*Topt*) and acceptability limits are given by *Tmin* and *Tmax*. Satisfaction is not defined when inhabitants are not there.

Plotting the usage on the compromise diagram

Each point corresponding to the scenario describe in table 1 is defined by a couple (X,Y) coming from the equations 3 (corresponding to the mean values over the considered week) and can be plotted in the compromise diagram (see figure 6)

$$X_i = \frac{1}{T}\int_1^T E_{(i,j)}(t)dt \qquad \textit{Equation 3}$$

$$Y_j = \frac{1}{T}\int_1^T S_{(i,j)}(t)dt$$

$i = 1..n$: indices of heating system control scenario (Table 1)

$j = 1..n$: indices of scenario of use (Table 1)

$E_{(i,j)}(t)$: Energy consumption of the scenario (i,j) at time t

$S_{(i,j)}(t) = S_{thermal} * S_{energy}$: Satisfaction of the scenario (i,j) at time t

T : Time period of study (T=5 days*24h=120)

DISCUSSION ON THE INTEREST OF THE COMPROMISE DIAGRAM

In this first test, with only the thermal satisfaction function, the different points (1), (2) and (3), corresponding to the scenarios of table 1, are well located in the compromise diagram (figure 6) according to trivial expectations. Indeed, with no regulation, consumption is high and the thermal satisfaction is degraded due to the absence of consideration of internal gains, which increases the ambient temperature and degrades the thermal satisfaction or thermal comfort which is the same here (see round point in figure 6). By improving the system with regulation, the energy consumption as well as the thermal satisfaction (square points of scenario 2 in figure 6) can be improved. It yields a more usage energy efficient solution with the anticipative system (triangle points of figure 6). Actually, this last heating control system fits more precisely with the reality and regulate according to the real usage by taking into account the real occupancy of the room. This evolution shows that by integrating more and more the user and its behaviour in the control (and more generally in the design), the usage energy efficiency can be improved: it improves the satisfaction and reduces at the same time the costs (up to 88%).

This diagram can be used in the design phase of a building in order to compare different solutions/ settings. In this case, this diagram favours the choice of the anticipative control system compared to the others. Such tool can also be used in the operation phase of the building in order to validate if the settings are fine.
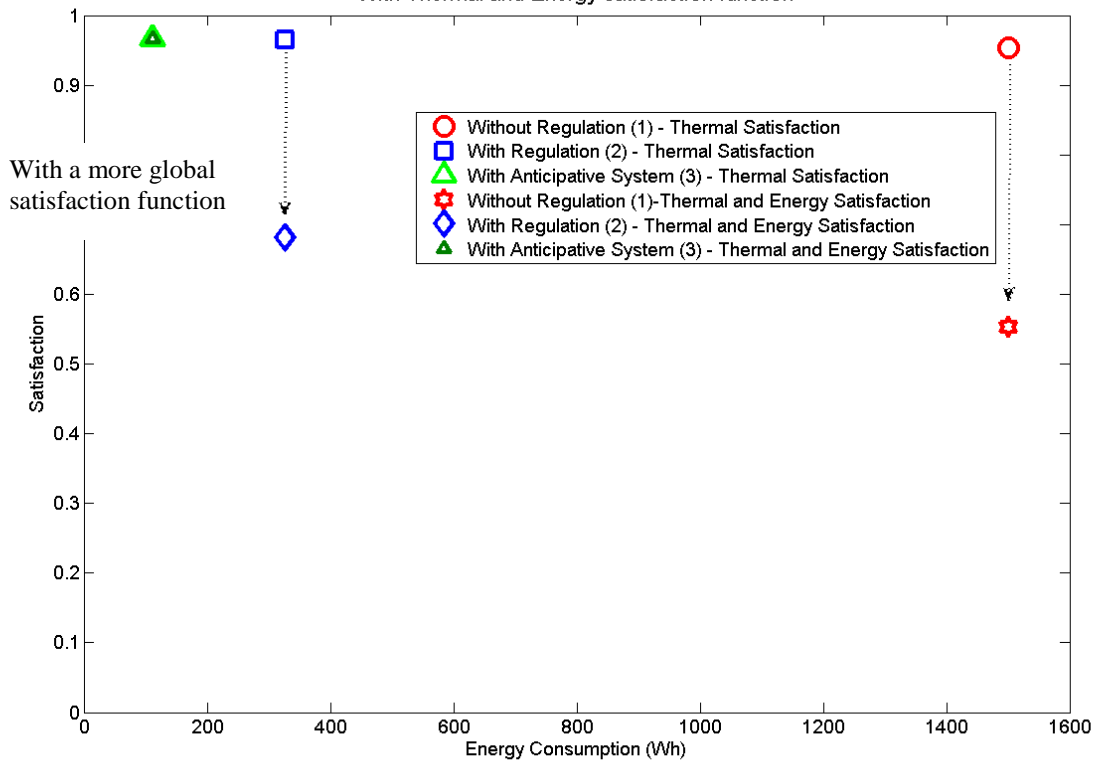
Figure 7: Compromise diagram with comfort thermal and energy satisfaction

Introducing functions related to quality of usage

The previous result was only based on the thermal comfort that leads to a first choice between the control solutions.

Regarding the satisfaction, it can be noticed that the levels of satisfaction are quite closed (between 0.955 and 0.967) because the ambient temperature do not vary a lot from one option to another. Other functions of satisfaction corresponding to the "quality of usage" (issue 1 of figure 1) can be introduced. These functions can model the building operator expectations and can point out the technical solutions where there is waste of energy. Such a function depends also on the theoretical occupancy of the room, called building occupancy, which corresponds to an assumed occupancy. If the room is not occupied and the heating system is on, there is a waste of energy and the global satisfaction should be reduced. The energy function (S_{energy}) is defined as:

if User occupancy =1 and Building Occupancy=1

$S_{energy} = 1$

if User occupancy =0 and Building Occupancy=0 and Thermal Power=0

$S_{energy} = 1$

if (User occupancy =0 and Building Occupancy=1 and Thermal Power>0)
or (Building Occupancy=0 and Thermal Power>0)

$S_{energy} = 0$

Result with the global function of satisfaction

Regarding the issues of usage efficiency (figure 1), the global satisfaction between expectations of user (corresponding to the actions, the use of users) and the perceived comfort of the service can be described

as a combination of the satisfaction function of use and the satisfaction function of comfort. It is proposed to link them with a conjunctive relation (multiplication of the functions). Thanks to the global satisfaction function, the result of usage energy efficiency is more discriminant in this compromise diagram (figure 7).

The no controlled system (1) and the controlled system (2) see their satisfaction degraded because their configurations (table 1) are based on the theoretical occupation but not on the actual one: the energy satisfaction is thus 0. Thanks to a better integration of use, the anticipative system (point 3) remains to a high usage energy efficiency value.

In conclusion, we can manage to have some decision about the choice on control system and this diagram help to integrate the use and evaluate the consequence of each scenario on the compromise cost/comfort. This tool allows quantifying the energy saving (over than 88% of energy consumption reduction) and satisfaction improvement (increasing from to 0.6 to 0.96) resulting to a more usage energy efficiency effort.

CONCLUSION AND PERSPECTIVES

This paper proposes a new concept of usage energy efficiency to better take into account the user impact in energy efficiency. It is an addition to the technical point of view of energy efficiency.

A new decision support tool has been presented as a compromise diagram between energy cost and satisfaction. It makes it possible to compare different sets of system control strategies and scenarios. It provides a heuristic to question designers about usage energy efficient of new configurations. The issue is

no longer to reach the best energy savings with an assumed theoretical behaviour of the occupants but to question about the occupant expectations and the adequation with the proposed solutions, especially for the design of control systems. It points out that the global satisfaction function of the system building depends on the usage and on the perception of a service which can be combine either in a conjunctive way or a disjunctive way in order to reveal the final compromise the users will have to do between usage and energy savings. Let's recall that without considering satisfaction, in terms of control, the optimal solution for energy saving is to switch off all the energy consuming appliances.

Finally, the concept and the compromise diagram contribute to the socio technical approach of the building systems in which more and more studies are related.

In the present paper, the compromise diagram has been applied on a simple heated room but in a building system many others services exist like washing of the clothes, cooking of the lunch, etc. Other satisfaction functions have then to be defined but how to do it generally to get reference satisfaction functions?

The concept of usage energy efficiency is necessary to properly formalize energy management problems: the question is no longer to only reduce energy consumption but to provide the maximum levels of satisfaction to the occupants for the minimum energy costs in energy managment system (Ha, 2006). Therefore, a question arises: how to combine service related satisfactions in order to get a global satisfaction function representative of the occupant welfare?

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