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IMPROVING BUILDING ENERGY EFFICIENCY USING DISTRIBUTED ARTIFICIAL INTELLIGENCE

Abstract: *Saving energy in buildings without losing the comfort of the occupants is contradictory request. It has been shown that the use of smart thermostats to HVAC systems reduce energy consumption as much as thirty percent. Depending on the number of different, pre-defined temperature levels, energy savings might be even greater. The method for determining the coefficient of utilization which is based on a normal time temperature distribution is proposed.*

Key words: Building energy efficiency, TRIZ matrix, Intelligent agents, Coefficient of utilization.

INTRODUCTION AND PRELIMINARIES

The coefficient of performance of a thermodynamic system, COP, is the ratio of the heating or cooling provided over the electrical energy consumed, and is the inverse of thermal efficiency for power cycles, η,

$$\frac{1}{\eta} = COP = \frac{Q}{W} \tag{1}$$

where Q is the heat supplied to, or removed from the reservoir and W is the work done by the system.

A power cycle is the process in which the system performs work on its surrounding, thereby the system acts as a heat engine. Vice versa, all the processes can be reversed, in which case system becomes a refrigeration engine. Obviously, a cycle remains the same, except that the directions of heat transfer and work interactions are reversed. Both are known as Carnot's cycles. Let Q_h and Q_c denote the heats of high-temperature and low-temperature reservoir, respectively. Then, according to the first law of thermodynamics, in a reversible system, $W = Q_h - Q_c$.

Therefore,

$$COP_h = \frac{Q_h}{W} = \frac{Q_h}{Q_h - Q_c}, \quad COP_c = \frac{Q_c}{W} = \frac{Q_c}{Q_h - Q_c}, \tag{2}$$

holds true.

It can be shown that for a system that works with the theoretical maximum of efficiency (Carnot's efficiency) the following relation is valid

$$\frac{Q_h}{T_h} = \frac{Q_c}{T_c}, \tag{3}$$

where T_h and T_c stands for absolute temperatures of hot and cold reservoirs respectively. The expressions for coefficient of performance of a thermodynamic system can be rewritten in the following forms

$$COP_c = \frac{T_c}{T_h - T_c}, \qquad COP_h = \frac{T_h}{T_h - T_c}. \tag{4}$$

The COP of thermodynamic system can be improved by reducing the difference $T_h - T_c$. For a heating system, there are just two possibilities to achieve that. The first one is to reduce the output temperature, T_h, but this solution leads to undesired effects such as subjective thermal discomfort. The second one would be increase of the input temperature, T_c, which require additional inputs and investments. For the air conditioning system, both temperatures have to be close which is neither possible nor desirable in any case. Therefore, contradictory requests appear in both, heating or cooling modes.

The energy efficiency ratio, EER, is usually connected to cooling devices and this is the ratio of amount of heat (output energy) to electric energy (input energy).

$$EER = \frac{E_o}{E_i} = \frac{output\ energy}{input\ energy} \left[\frac{\text{BTU}}{\text{Wh}}\right] \tag{5}$$

The ratio is expressed with diverse units but they are still in use. The output energy have to be taken in British thermal unit, BTU, ($1\text{BTU} = 1055\,\text{J}$) and so,

$$1\,\text{w} = 3.412\ \text{BTU/h} \quad \Rightarrow \quad 1\,EER = 3.412\ COP. \tag{6}$$

It is more convenient to relate the efficiency of air-conditioners to seasonal energy efficiency ratio, $SEER$, which was introduced by Air-Conditioning, Heating and Refrigeration Institute, AHRI. However, the SEER is a representative measurement of how the system behaves over a season where the outdoor temperature varies.

TECHNICAL PROBLEM ANALYSIS

The contribution of non-industrial buildings to the total energy consumption is between 20 and 40 percent and tends to increase, [8]. On the other hand, it is well known that conventional energy efficiency technologies, such as thermal insulation and electrohromic windows (smart glass), can be applied to decrease energy use up to 30 percent on average. Conserving energy saves valuable resources and protects the environment by reducing greenhouse gas emissions. As much as half of the energy used in building goes to heating, ventilating and air conditioning, HVAC. Therefore, a HVAC system has huge impact on energy consumption and comfort. The second largest consumer of energy is the electric light.

This study deals with the elimination of the contra-dictions that appear in efforts to save energy (and total cost) without making comfort misbalance.

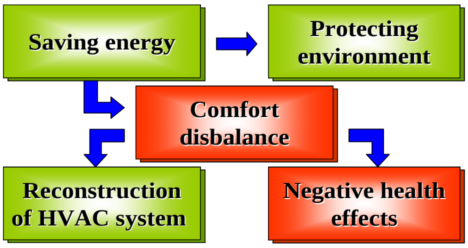

Figure 1. *Saving energy without loss of comfort?*

The main goal is saving energy that immediately leads to environmental protection through long-term vision such as achieving zero environmental footprints on the global plan. However, saving energy counteracts comfort due to frequent changes in temperature, which consequently produces negative health effects, Fig. 1. The leading question is how to reconcile two opposing uncompromising requests. In other words: how to reconstruct HVAC system that saves energy without worsening of comfort.

Overcoming technical contradictions

The Theory of Inventive Problem Solving, TIPS, (Russian: ТРИЗ - Теория Решения Изобретательских Задач) is founded on transposition of numerous known solutions from other fields to the field of interest which is not even related to the origin of a problem that has to be solved. In order to obtain an inventive solution, the TRIZ matrix is loaded with knowledge base that is packed in basic technical principles [3]. The analysis of the contradiction is the first step in solving a problem. The second step is search for one or more of the offered principles, which will overcome the contradiction and need for a compromise or trade-off between the opposite requests.

Technical contradictions

TRIZ matrix contains 39 functions, but only a few are involved in the field of interest, Tab.1. Some of these functions are desired to be improved, and some will be automatically degraded as a result.

In TRIZ terminology these functions are improving and worsening features.

TRIZ Principles for overcoming technical contra-dictions are obtained at the intersection of rows (Improving feature) and columns (Worsening feature), Tab 2. All technical principles arising from this shift are not applicable in case of reconstruction of HVAC system.

Table 1. *Selected TRIZ functions*

Order	Description
17	Temperature
22	Loss of energy
25	Loss of time
33	Ease of operation
35	Adaptability or versatility
36	Device complexity
38	Extent of automation

Table 2. *TRIZ Contradiction Matrix*

	f	Worsening feature			
		25	33	36	38
Improving feature	17	18, 21 **28**, **35**			02, 16 **19**, 26
	22	**07**, **10** 19, 32	01, 32 **35**	**07**, **23**	
	35	**28**, **35**	01, **15** 16, 34	**15**, **28** 29, 37	27, 34 **35**

Table 3. *Adopted TRIZ Principles*

Order	Description
07	Nested doll
10	Preliminary action
15	Dynamics
19	Periodic action
23	Feedback
28	Mechanic substitution
35	Parameter change

An idea for resolving contradictions:

Installation of a thermostat

↓

Reflex agent

↓

Learning agent

In terms of saving energy, adopted TRIZ principles, (Tab. 3), could be described as follows.

Nested doll means insertion one control unit into another, e.g. multipurpose detectors.

Preliminary action means to perform action before it is needed, e.g. preheating.

Dynamics means an optimal operating condition in real time, e.g. not continuos heating/cooling regime i.e. change between the different energy levels.

Periodic action means the same as the previous one, e.g. only periodic action can keep up constant temperature.

Feedback means improving an action, e.g. sensing room temperature in real time.

Mechanic substitution means substitution of mecha-nical devices with less inertial ones, e.g. microprcesor based thermostats.

Parameter change means improving the degree of flexibility, e.g. default temperature value should be variable.

On the basis of the adopted principles for resolving technical contradictions the conclusion is that there is only one way to save energy - Install a smart thermostat, i.e. learning agent.

According to the Environmental Protection Agency, EPA, a smart thermostat can save energy costs up to thirty percent. However, this statement is not documented.

IMPROVING ENERGY EFFICIENCY

A thermostat is a contol element in HVAC systems which sense a temperature of an enviroment so that a temperature is maintained near setpoint. The sensor technology still changes, from 1883 when the first electric room thermostat was invented until today, but the principle of operation is always the same - two output states: on/off. However, the classic thermostat, which works as reflex automat, is an intelligent agent, IA. In artificial intelligence, AI, intelligent agent is an autonomous system that performs action without immediate presence of humans. IA is capable to carry out tasks on behalf of users, Fig. 2.

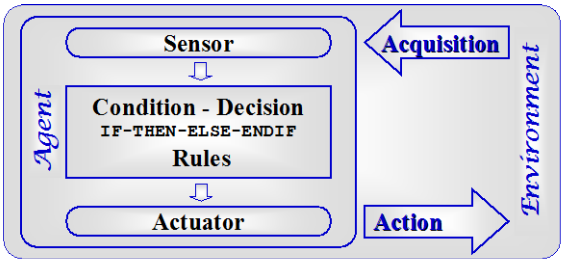

Figure 2.*Tthermostat - Simple reflex agent*

There is a similarity between the computer program and IA. Namely, IA can be described as an abstract functional system. One of the basic problems in the field of designing agent-oriented system is finding an appropriate programming language platform. Various agent-oriented programming languages have been proposed, but no language has become mainstream yet.

Hence, for regular thermostat FORTRAN code will be as follows.

```
LOGICAL FUNCTION action(setpoint,temp)
  IF(temp < setpoint)THEN
    action=.true.
  ELSE
    action=.false.
  END IF
END FUNCTION
```

Figure 3. *Simple reflex agent - Program*

This program is a function that provides transition from acquisition to specific action. In this simple case the setpoint value is unique and specified for heating mode. The same function can be applied for cooling mode when comparison sign "less than" should be replaced with "greater than". This value has to be compared with perceived (indoor) temperature. The function arguments **`setpoint`** and **`temp`** are parameter and independent variable respectively. In this case the action is also simple – activate and deactivate heating or cooling device.

If we define IA as a persistent software entity designed for specific purpose then the term "persistent" will distinguish agents from subroutines. The term "specific" distinguishes agents from variety of multi-functional applications. In essence, IA can be presented by following relationship

```
IA = architecture + program
```

The architecture is some kind of hardware platform such as a simple thermostat or even a computer. The task of AI is to create the program for IA.

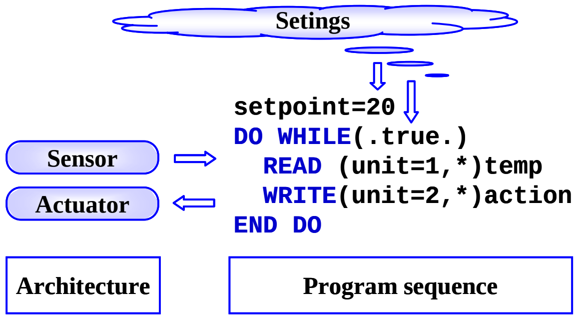

Figure 4. Agent in the environment

Everything that would be necessary to do is calling the proposed function in an infinite time loop, Fig. 4. In real circumstances, it's not an infinite loop. On the very beginning the man turns on a thermostat and adjust the temperature. In the further course of time the thermostat becomes autonomous. Until disconnection, the thermostat **`READ`**s the temperature of the environment, (**`unit=1`**) calls the function, and if the condition is met, **`WRITE`**s to a particular device (**`unit=2`**).

Definitely, IA continuously perform three function and those make main difference between IA and a program:

- percepts parmeters in the environment,
- cogitates to interpret perceptions,
- acts autonomously to achieve the goal.

State of the art solution

Basically, each thermostat tends to control and monitor the temperature of the surrounding in order to achieve efficient utilization of energy. To accomplish higher level of energy efficiency and energy optimisation, IA has to be much more than regular thermostat. Furthermore, the perceived intelligence and capability can vary and consequently, since the year 2003, IA are grouped into five categories - Simple reflex agents, Model-based reflex agents, Goal-based agents, Utility-based agents and Learning agents, [6] Concurrently, regular thermostats evolve in two categories.

The first category includes programmable thermostats which control heating and cooling devices to adjust the temperature in accordance with pre-defined values.

One of contemporary solutions is based on even eight temperature setpoint values that define so called energy levels.

- Energy level *Comfort* is activated if the room is occupied.
- Energy level *Pre-comfort* is activated for unused room which can be occupied again shortly.
- Energy level *Economy* is activated for unused room that will only be occupied again in a few hours.
- Energy level *Protection* is activated in cases of long absence and serves to protect building equipment from damage caused by frost or overheating.

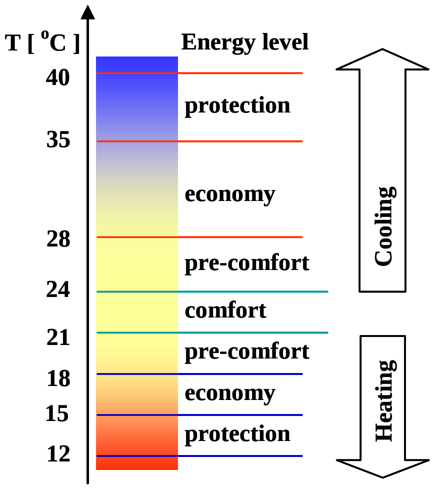

Figure 5. *Pre-defined energy levels*

The second category comprises smart thermostats which have the same characteristics as previous ones. In addition, the smart thermostats learn about the behavior of the user and reprograms itself according to their habits. Moreover, smart thermostat fine tunes its performance according to ambient temperature, humidity, presence and motion of occupants, etc. Also, smart thermostats use solutions from computer technology and enable control of cooling and heating devices from remote locations. In fact, smart thermostat is a learning agent the concept of which is one of the successful examples of the concept of clean technology. Clean technology assists in building a cleaner environment and contributes in resolving major environmental issues like global warming.

Necessity of distributed intelligence

Different purposes of rooms and different habits of occupants demands different energy levels and scenarios for temperature regimes. An IA should be installed in every single room. In this case a new problem appears: non-harmonized energy levels and temperature setpoint values in adjacent rooms. There is a necessity that agents communicate and work in synchronism. In addition, there are many other reasons for introduction of distributed intelligence, DAI, or multiagents system, MAS [2]. Actually, DAI is a predecessor of the MAS which is the system that is composed of coordinated agents including including relationships that exist between them.

Furthermore, the second largest consumer of energy in buildings after HVAC system, is a system of electric lightening. Now, the problem of energy saving and compliance of two subsystems is even more complicated. One IA for one room can be constructed for both subsystems, but IA of this kind is a bottleneck for reliability, maintainability, speed etc. Such an IA would be omnipotent and omniscient, but specialized knowledge is not often available from a single agent. Also, program for single purpose IA is simpler than for multi purpose one. Here, IA can be designed as fine-grained autonomous components of MAS that act in parallel [9]. In the the real time one IA has to know what the other IAs are doing. For example, a presence of occupants that is detected by one IA is the information that has to be forwarded to another IA and it is valid for the both systems (i.e. HVAC and subsystem of electrical lightening). So, MAS can be defined as a network of agents which are loosely coupled.

A special comunication protocol and language is needed for this purpose. The Foundation for Intelligent Physical Agents, FIPA, is a body that works on developing and setting standards for computer software for heterogeneous and interacting agents and agent-based systems. Nowadays, two most popular languages are: Knowledge query and manipulation language, KQML, and FIPA's Agent communication language, ACL, although no language is adopted as the leading one, as it is mentioned above. If agents can share knowledge using any agreed language, then the energy saving is expected to occur on all temporal and spatial levels.

In order to ensure proper cooperation of agents in the system they must operate on the following common principles:

- the single IA is at least partially independent,
- no IA has a full global view of the system,
- there is no IA that controls others.

EXAMPLE AND CONCLUSION

The amount of output energy used during one cooling or heating season is usually calculated as

$$E_o = a \cdot b \cdot c \cdot d \,, \qquad (7)$$

where:

a is a power of HVAC unit in BTU per hour, usually 60000 BTU/h is taken into account as an average value for residential buildings,

b is dimensionless coefficient of utilization, usually the unit runs at two thirds of its capacity,

c is average run time of HVAC unit per day, usually the unit runs on average eight hours a day during a season. At the end of the season, the unit may run only four hours a day, but at the peak of the season, it is running over 14 hours a day,

d is a number of days in season, typically the season lasts 180 days.

In such a manner,

$$E_o = 60000 \cdot \frac{2}{3} \cdot 8 \cdot 180 = 57.6 \cdot 10^6 \text{ BTU} . \quad (8)$$

In order to calculate the total required electrical energy (input energy) $SEER$ has to be known. The $SEER$ tests are done in a laboratory, under conditions that cannot be duplicated on already installed system. In 1992 the minimum $SEER = 10$ was established for units manufactured in the United States. New residential central air conditioner standards went into effect in 2006. Air conditioners manufactured after that year must achieve a $SEER$ of 13 or higher.

$$E_i = \frac{E_o}{SEER} = 4.43 \text{MWh} . \quad (9)$$

The calculation like this only gives a very vague and inaccurate idea of what exactly the amount of required electrical energy will be.

Most phenomena in the environment are subject to a normal distribution. Temperature distribution (daily, weekly, monthly) is also subject to the same law. The task of MAS is regulation of temperature that satisfies learned habits of occupants and their needs and save energy at the same time. That can be only possible by avoiding too big temperature difference and by using predefined energy levels. Namely, in a short period, a average person can feel change in temperature of about a 1.5 degree. Respecting these principles, the energy consumption is becoming closer to the normal distribution.

Introducing the coefficient of utilization

The calculation based on (7) involves empirical data, such as coefficient of utilization and average daily run time of a HVAC system. Bearing in mind the idea of a normal distribution of temperature, the calculation should include the coefficient of utilization which is based on a bell curve, $f(t,\sigma)$.

$$f(t,\sigma) = \frac{1}{\sigma\sqrt{\pi}} e^{-\left(\frac{t}{\sigma}\right)^2}$$

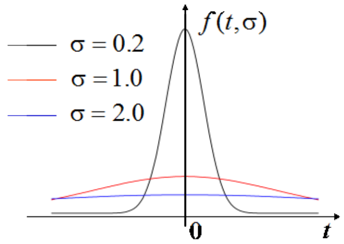

Figure 6. *Bell curve* $f(t,\sigma)$

This function is an approximation of Dirac's delta function, $\delta(t)$, where σ is stretched factor. The Dirac's delta function is the limit of sequence of zero-centered normal distributions,

$$\delta(t) = \lim_{\sigma \to 0} f(t,\sigma) . \quad (10)$$

and the less value of the stretched factor, the better approximation is. Conversely, the HVAC system should be almost equally loaded over time which means that the value of stretched factor should be greater than one.

Coefficient of utilization can be defined now as an integral over run time of HVAC,

$$F(T) = \int_{-T}^{T} f(t,\sigma) \mathrm{d}t = \frac{2}{\sigma\sqrt{\pi}} \int_{0}^{T} e^{-\left(\frac{t}{\sigma}\right)^2} \mathrm{d}t . \quad (11)$$

The integral above has a value of one for the upper bound tends to infinity, [1],

$$\lim_{T \to \infty} F(T) = 1 . \quad (12)$$

The efficiency of HVAC systems changes with operating conditions. In real conditions, the value close to one is reached in a finite time. Actual value of the integral, i.e. coefficient of utilization, depends on the exploitation time of the system, T. Because of the obviousness, the discretized graph of (10) is shown below, Fig. 7.

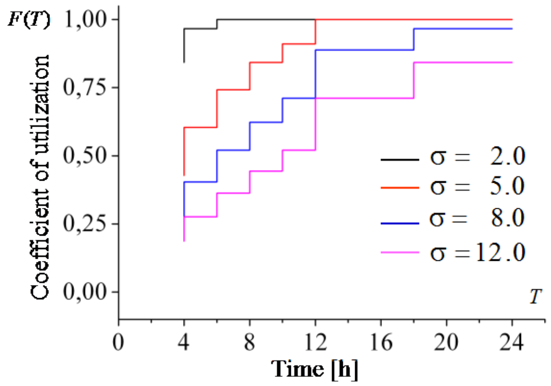

Figure 7. $F(T)$ - *Vertical step discretization*

The equation (7) should be rearranged so that a fixed value of b should be replaced by a functional coefficient, $F(T)$.

$$b \sim F(T) \quad \Rightarrow \quad E_o = a \cdot F(T) \cdot c \cdot d \quad (13)$$

In the worst case, the system is active 24 hours, and for sufficiently smooth curve, i.e. small changes in temperature, coefficient of utilization does not exceed two-thirds. Energy saving of around thirty percent was previously mentioned.

Some gaps in the implementation of DAI are still present:

- the choice of the communication language or protocol,
- the ensuring coherence of IA,
- the synthesis of results of IA group.

APPENDIX

For practical calculation of the coefficient of utilization, the integrand has to be developed in Taylor's series and then integrated. This gives,

$$F(T)=\frac{2}{\sqrt{\pi}}\sum_{n=1}^{\infty}\frac{(-1)^{n}t^{2n-1}}{(2n-1)(n-1)!}\left(\frac{T}{\sigma}\right)^{2n-1}. \qquad (14)$$

Because of the factorial function obtained series rapidly converges and for satisfactory accuracy only few first terms have to be taken into account.

LIST OF ABBREVIATIONS

ACL	Agent Communication Language
AHRI	Air Conditioning, Heating and Refrigeration Institute
AI	Artificial Intelligence
BTU	British Thermal Unit
COP	Coefficient Of Performance of a thermodynamic system
DAI	Distributed Artificial Intelligence
EER	Energy Efficiency Ratio
EPA	Environmental Protection Agency (USA)
FIPA	Foundation for Intelligent Physical Agents
HVAC	Heating, Ventilating and Air Conditioning
IA	Intelligent Agent
KQML	Knowledge Query and Manipulation Language
MAS	Multi Agent System
SEER	Seasonal Energy Efficiency Ratio
ТРИЗ	Теория Решения Изобретательских Задач

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BIOGRAPHY

Milica D. Radić was born in Niš, Serbia, in 1978. She graduated Architecture from the University of Niš, Faculty of Civil Engineering and Architecture. She is currently working toward the Ph.D. degree at the Faculty of Mechanical engineering in Nis, University of Nis. Her main areas of research include artificial intelligence, energy efficiency etc.

POBOLJŠANJE ENERGETSKE EFIKASNOSTI ZGRADA PRIMENOM DISTRIBUIRANE VEŠTAČKE INTELIGENCIJE

Milica D. Radić, Dejan M. Petković

Apstrakt: *Ušteda energije u zgradama bez gubitka komfora korisnika je kontradiktoran zahtev. Pokazano je da upotreba pametnih termostata u sistemu KGH smanjuje potrošnju energije i do 30 procenata. U zavisnosti od broja različitih, predefinisanih temperaturnih nivoa, ušteda energije može biti i veća. Predložen je metod za određivanje koeficijenta iskorišćenja koji bazira na normalnoj vremenskoj raspodeli temperature.*

Ključne reči: *energetska efikasnost zgrada, TRIZ matrica, Inteligentni agenti, koeficijent iskorišćenja.*