An Anticipation Mechanism for Power Management in a Smart Home using Multi-Agent Systems

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Abstract—**This paper presents the principles of a Home Automation System dedicated to power management that adapts power consumption to available power ressources according to inhabitant comfort and cost criteria. The system relies on a multi-agent paradigm. Each agent supports a service achieved by several devices, it cooperates and coordinates its action with others in order to find an acceptable near-optimal solution. The control algorithm is decomposed into two complementary mechanisms: a reactive mechanism, which protects from constraint violations, and an anticipation mechanism, which computes a plan for global consumption according to predicted productions and consumptions and to inhabitant criteria. The paper shows how to compute a global consumption plan relying on Tabu Search's algorithm and how to reduce the problem complexity by dividing the whole problem into independent sub-problems.**

Index Terms—**Home Automation System, Multi-Agent Systems, Automatic Control, Power Management.**

I. INTRODUCTION

The world human population increases today more than 80 millions of individuals per year, therefore, the energy needs increase more and more. A building is both a place of power consumption and potentially a place of decentralized power production using resources like wind, solar, geothermal, etc. The resort to renewable power resources comes up in homes knowing that they represent 47% of the global power consumption [2]. Therefore, the design of a control system which allows the exploitation of different energy resources, while managing globally the power needs and the production capacity of a home, is an upcoming issue.

The role of a Home Automation System dedicated to power management is to adapt the power consumption to the available power resources, and vice versa, taking into account inhabitant comfort criteria. It has to reach a compromise between the priorities of the inhabitant in terms of comfort and in terms of cost while satisfying technological constraints of devices.

Algorithms based on Multi-Agent Systems (MAS) are nowadays used in several areas such as Computer Science or Automatic Control. The first MAS approaches for energy distribution have been presented in [5] and [4].

The design of solutions based on Multi-Agent Systems, which are well suited to solve spatially distributed and open problems, facilitates the design of an intelligent **M**ulti-**A**gent **H**ome **A**utomation **S**ystem (*MAHAS*). This paper presents the architecture of a MAHAS and shows why a MAS are particularly well suited for this class of problems.

This paper presents a MAHAS. It focuses on the solving strategy and, in particular, on the way of reducing problem complexity. The paper is organized as follows: section II describes, from a general view point, the MAHAS and its two main mechanisms: the reactive and the anticipation mechanisms. Section III presents the agent modelling for the anticipative mechanism. Section IV deals with the solving strategy. Section VI concludes the paper.

II. MULTI-AGENT HOME AUTOMATION SYSTEM

A MAHAS consists of agents, each agent supports one type of service (heating, cooking, etc) achieved by one or several devices. The main features of the MAHAS are the following:

- Distributed: the energy resources and devices are independent and spatially distributed.
- Flexible: some devices can accumulate energy (different kinds of heating services) or satisfy with a timed delay the demands of inhabitants (washing service, etc).
- Open: the number of connected resources and devices may vary with time without having to completely redefine the control mechanism.
- Extendable: agents dedicated to new kinds of services may appear.

In MAS, the notion of control involves operations such as coordination and negotiation among agents, elimination of agents and addition of new agents when needed. Depending on weather forecasts, power resource information and inhabitant habits:

- an agent, dedicated to a power source, is assumed to be capable of calculating the future available power production.
- an agent, dedicated to a load, is assumed to be capable of calculating the prediction of power consumption: to

determine what are the future power needs taking into account the usual behaviour of inhabitants.

In MAHAS, an additional agent is responsible for broadcasting the computed predicted plans to the other agents.

The structure of the MAHAS is decomposed into two main mechanisms: the reactive mechanism and the anticipation mechanism.

A. Reactive mechanism

The reactive mechanism is a short time adjustment mechanism which is triggered when the level of satisfaction of an agent falls below weak values (10% for example). This mechanism, which relies on the negotiation protocol [1], reacts quickly to avoid violations of energy constraints and to guarantee a good level of inhabitant satisfaction. Therefore, the reactive mechanism adjusts, at a short sample, the set points coming from the predicted plan, the device's current state (device satisfaction value) and the constraints and inhabitant criteria. The predicted set points can be directly transmitted to the device or modified in case of emergency.

B. Anticipative mechanism

The reactive mechanism is sufficient to avoid constraint violations but a MAHAS can be improved in order to avoid frequent emergency situations. This improvement is obtained due to the anticipation mechanism. The objective of this mechanism is to compute plans for production and consumption of services in a house. The anticipation mechanism benefits from, on the one hand, some devices are capable of accumulating energy, and on the other hand, some services have a variable date for their execution: some services can be either delayed or advanced. From these preliminary observations, it is possible to imagine that if the device consumption can be anticipated, there is a way to organize it better.

It works on a time window, which corresponds to a sampling period called the anticipative period. This period is greater than the one used by the reactive mechanism. Because of the large sampling period, it considers average values of energy. This is an advantage when considering prediction because it is difficult to make precise predictions. A large sampling period is also important to keep the reactive mechanism transparent. The predicted set points can be directly transmitted to devices or adjusted by the reactive mechanism in case of constraint violation.

A third mechanism may exist: the local control mechanism i.e. the controllers endowed into devices by manufacturers. Its time response is very fast. This mechanism receives set points from the agents. In addition, some information on its current state (power needs) are sent back to the agents so that they can be taken into account in the future plans.

Because the reactive mechanism has been presented in detail in [1], this paper focuses on the anticipative mechanism.

III. MAHAS MODELLING

One of the objectives of the MAHAS is to fulfil inhabitant comfort, a notion which can be linked directly to the concept of satisfaction function [7]. Satisfaction functions have been defined for power resources as well as for devices. A satisfaction function is expressed by a function defined from the domain of characteristic variables to the interval $[0, 1]$. In MAHAS, satisfaction characterizes the inhabitant's feeling about a service where zero means "unacceptable" and 1 means "fully satisfied". For example, satisfaction function for a thermal air environment is based on room temperature values (figure 1). For instance, figure 1 can be represented by the set $\{(TMIN(heating), 0), (TPRE(heating), 1), (TMAX(heating), 0)\}$, it is implicitly assumed that before the first abscisse and after the last one, the satisfaction is null.

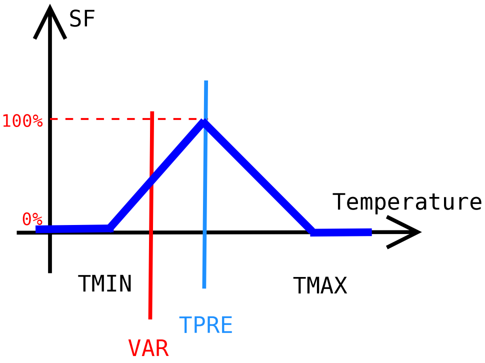

Fig. 1. *Thermal air environment satisfaction function.*

A satisfaction function can be modelled by a set of characteristic points. For instance, figure 1 can be represented by the set $\{(TMIN(heating), 0), (TPRE(heating), 1), (TMAX(heating), 0)\}$, it is implicitly assumed that before the first abscisse and after the last one, the satisfaction is null.

The satisfaction function of a power resource agent is also expressed by a function where the level of satisfaction is defined by the energy supplier.

A Home Automation System aims at reaching a compromise between the inhabitant requests in terms of comfort and cost while satisfying technological constraints of devices. A MAHAS takes into account the price variation because the energy providers could charge inhabitants for the actual energy production cost in real time. Therefore, a MAHAS aims at minimizing the cost while maximizing the users comfort.

To optimize the criteria, the agents (figure 2) must communicate and cooperate in exchanging messages based on a common knowledge model. As mentioned in section II, a MAHAS is "open" and "extendable" and because there are many kinds of services in a home, which provide predictions based on specific physical constraints, some knowledge are not shareable. It is indeed very difficult to formalize in a UML class diagram the structure of a general model, which can be composed of differential equations, recurrent equations, state machine, rules or a mix of all. It is all the more difficult that the system is extendable, it is not possible to circumscribe all the possible kinds of models. Just like for humans, some knowledge cannot be formalized in a general way. MAHAS is particularly suited because agents endowed into devices may embed their own knowledge and exchange messages based

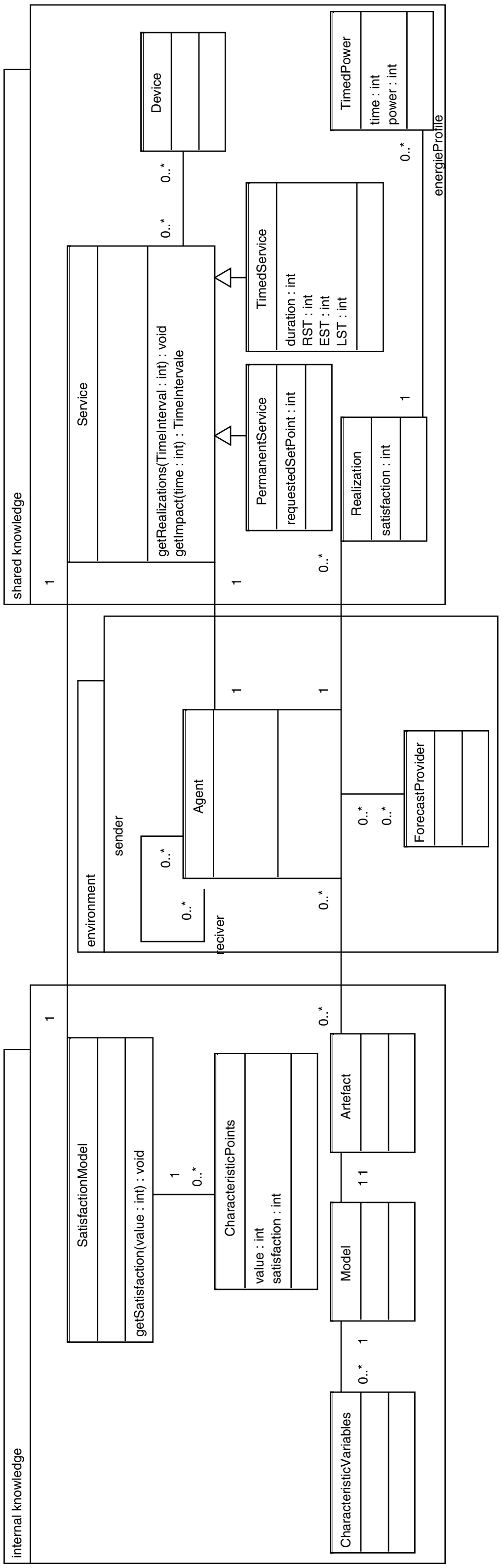

Fig. 2. *MAHAS UML model.*

only on shareable knowledge which can be analysed by all the agents (for example: a power profile of a service represents a series of consumed or supplied powers corresponding to consecutive sampling periods). These shared data have to be formalized in a standardized form. In figure 2, an agent has its internal knowledge that gathers all the data that cannot be formalized in a general manner. Each agent embeds non-shareable piece of knowledge, build up its own representation of its environment, including other agents and interacts with other agents with a protocol [1] that deals with shareable knowledge (for example: the agent dedicated to a heating service relies on the room's model (artefact) in which it is).

A. *Agent modelling*

In the MAHAS, an agent supports a service $SRV_i \in \mathcal{SRVS}$ where $\mathcal{SRVS}$ is the set of all services. A service SRV_i may be either a timed service, denoted SRV_i^T, or a permanent service, denoted SRV_i^P, achieved by one or several devices, knowing that a device may also achieve many services (figure 3).

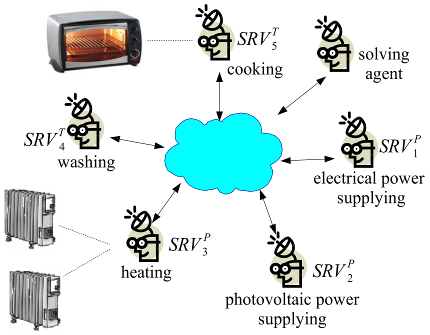

Fig. 3. *Example of agents in MAHAS.*

1) Modelling of a timed service agent : A timed service corresponds to power profiles during a given period; the flexibility of the service comes from the possibility that it may shifted. The internal knowledge of a timed service agent is modeled by:

- a characteristic variable which corresponds to the starting time of the service.
- a behavioral model that defines the possible power profiles once the service has been started.
- a satisfaction function defined from the set of possible starting time to the set of possible satisfaction values. The parameters of the satisfaction function may be gathered in a set of characteristic points: $\{(EST(SRV_i), 0), (RST(SRV_i), 1), (LST(SRV_i), 0)\}$ that represent respectively the earliest (unacceptable satisfaction), requested (fully satisfied) and latest starting times for the timed service.

A realization for a timed service agent represents the shared knowledge about a timed service. It is composed of:

- a power profile:$\Pi = [POW(SRV_i)_0, \ldots, POW(SRV_i)_n]$ where

$POW(SRV_i)_j \neq 0$ represents the average power consumption/production (negative/positive) of the service during the k^{th} sampling period. The duration of a service is determined by the length of the power profile $length(\Pi)$.

- a satisfaction value which depends on the starting time of the service.

A realization corresponds to an instantiated power profile denoted: $REAZ(SRV_i^T) = (k, \Pi, \sigma)$, where k is the selected starting sampling period, Π is the power profile and σ is the satisfaction value modelling the inhabitant's feeling about this realization.

2) Modelling of a permanent service agent: A permanent service corresponds to power profiles covering a given period. The flexibility of the service comes from the possibility of adjusting energy allocation from time to time. The internal knowledge of a permanent service agent is modeled by:

- a behavioral model linking the power profile to effect an inhabitant environment.
- a satisfaction function defined from a set of variables computed by the behavioral model to the set of possible satisfaction values. The parameters of the satisfaction function may be gathered in a set of characteristic points. Considering a basic HVAC(Heating, Ventilation and Air Conditioning) system, among these characteristic points, there is the inhabitant requested temperature and the inhabitant unacceptable temperatures.

A realization for a permanent service agent represents the shared knowledge of a timed service. It is composed of:

- a power profile: $\Pi = [\ldots, POW(SRV_i)_k, \ldots]$ where $POW(SRV_i)_k$ represents the average power consumption/production during the k^{th} period.
- a satisfaction value. Even if a realization covers several periods, there is only one value that models the inhabitant resulting satisfaction for the whole considered period: it is usually equal to the minimum of the satisfaction values computed for each period.

A realization corresponds to an instantiated power profile denoted: $REAZ(SRV_i^P) = (k, \Pi, \sigma)$, where Π is a power profile from the sampling period $[k, k + length(\Pi)]$ and σ is a satisfaction value modelling the inhabitant's feeling about this realization.

Let's define the notion of impact of a service for a given sampling period k. It corresponds to the set of realizations for a service SRV_i, which is affected by a change of power affectation at the given time k. For a permanent service, the impact coresponds to $[k-p, k+p]$ where $p \times \Delta$ corresponds to the time response of the related devices. For a timed service, it coresponds to the set of realizations defined at k.

Even if the methods for solving the optimization problem may provide good solutions, they still require long computation times and considerable working memory because the complexity is NP-Hard [6]. A relevant optimization strategy (section IV), exploiting the nature of the Home Automation System problem, is a promising avenue for performance improvement.

IV. OPTIMIZATION STRATEGY

An intelligent power management problem in buildings can be divided into sub-problems involving different agents because, generally, inhabitants do not use their devices most of the time. The basic principle is to divide the whole problem into independent sub-problems (figure 4) then to solve each sub-problem independently in order to find a solution for the whole problem. The advantage of this method is to reduce the complexity of the whole problem which depends on the number of periods for each sub-problem and on the number of devices. When the whole problem is divided into sub-problems, each sub-problem does not involve all of the services (for example: some inhabitants vacuum clean in the morning and not in the evening). Because the number of considered periods in a sub-problem is lower than the number of periods of the whole problem [3], the complexity of solving the sub-problems is less than the complexity of solving the whole problem at once.

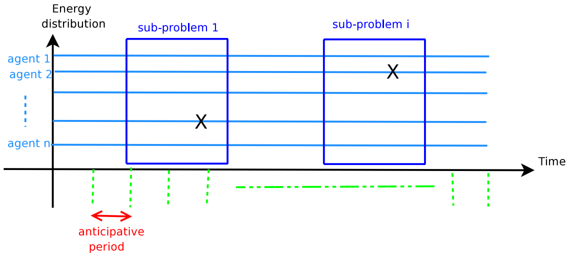

Fig. 4. *Whole problem energy distribution.*

The principle of the division of the problem into sub-problems is described in the following procedure:

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• procedure solving of the whole problem
•   distribute the energy over all periods for all the services according to the inhabitant's satisfaction;
•   if insufficient energy for some periods then
•     detect sub-problems;
•     determine the time interval for each sub-problem;
•     solve each sub-problem separately;
•     merge the sub-problems solutions to obtain a global plan;
•   else a solution according to the inhabitant's satisfaction is selected;
•   end if;
• end procedure;
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This procedure is described in the next sub-sections.

A. Energy distribution

The search for the global solution starts by distributing the available energy over all the periods for all the services according to the inhabitant's fully satisfaction where agents provide realizations with a satisfaction value equal to 1 and where agents, dedicated to a power resource, provide one realization that is the best prediction over all periods. When agents has several realizations with a satisfaction equal to 1, the solving agent verifies if the agent realizations are acceptable or not according to the available energy. At the end of the energy distribution, if there is enough energy for all devices, the search for a solution is stopped and a solution according to the inhabitant's fully satisfaction is obtained. But if there is not enough energy for all devices, sub-problems will be detected (sub-section IV-B) and then will be solved (sub-section IV-C).

B. Determination of the sub-problem interval

When the service agents suppling power have not enough power for all devices, the solving agent sends the periods for which there is not enough energy to all permanent and timed service agents. To obtain independent sub-problems, it is necessary to determine the service influences over theses periods. The principle of the sub-problem interval determination is described as follows:

First, compute the earliest and the latest starting time for the timed services:

- each realization of a timed service agent is characterized by a starting time, an ending time (equal to the starting time plus the length of the power profile).
- each timed service agent sends their intervals to the solving agent.

Each permanent service agent sends its impact to the solving agent.

The solving agent creates several intervals (sub-problem intervals) depending on the number of periods where there is not enough energy.

- The solving agent verifies the intersection between the sub-problem intervals and the earliest and the latest time of the timed services; it chooses the minimum value between the earliest time and the inferior bound of the interval and the maximum value between the latest time and the superior bound of the interval.
- The solving agent adds the impact of the permanent agent to the sub-problem intervals; the fact of adding the impact of permanent service agents increases the interval of the sub-problem but it guarantees that there is no influence on the previous or next periods.
- The solving agent merges two sub-problem intervals if there is an intersection between these two sub-problem intervals.

Then the solving agent sends the sub-problems intervals to all agents.

C. Resolution of a sub-problem

The solving agent computes a predicted plan for each sub-problem using the Tabu Search (TS) algorithm [8]. The basic principles of TS for the MAHAS problem are the following: the search for a solution starts from the initial solution found at the energy distribution step. At each iteration, the solving agent decreases the satisfaction interval (for example 5% for each time) and sends it with the best realizations (according to a combination of cost and comfort criteria) at the previous iteration to the agents; agents computes the neighborhood of the realization sent by the solving agent by generating a given number of realizations corresponding to the satisfaction interval. When the solving agent receives the agent realizations, it chooses the realizations that violate the constraints the less as possible. The search is stopped when the collected realizations do not violate the global power constraints and when the global satisfaction has converged. Because the number of realizations corresponding to a satisfaction interval is very high, an agent generates randomly theses realizations corresponding to the satisfaction in performing elementary step from the realization selected by the solving agent at the previous iteration knowing that an agent realization will not be generated and sent twice to the solving agent.

V. APPLICATION EXAMPLE

An illustrative example of a system composed of six devices and a power resource limited to $4kW$, for a sampling period of 30 minutes, is presented is this section.
The first device *washer* will be used twice:
The first timed service on the washer SRV_1=$washing_1$ is characterized by:
$RST(washing_1)$=09h00, $EST(washing_1)$=08h30, $LST(washing_1)$=10h00, $POW(washing_1)$=2.2kW over three sampling periods
The second timed service on the washer SRV_2=$washing_2$ is characterized by:
$RST(washing_2)$=19h00, $EST(washing_2)$=18h30, $LST(washing_2)$=20h00, $POW(washing_2)$=2.2kW
over three sampling periods.

The second device DEV_2=$dishWasher$ will be used twice as well:
The first timed service on the dishWasher $SRV_3 = dishWashing_1$ is characterized by:
$RST(dishWashing_1)$=9h00, $EST(dishWashing_1)$=9h00,
$LST(dishWashing_1)$=10h30,
$POW(dishWashing_1)$=2.4kW over four sampling periods.
The second timed service on the $DEV_2 = dishWasher$ $SRV_4 = dishWashing_2$ is characterized by:
$RST(dishWashing_2)$=19h00,
$EST(dishWashing_2)$=19h00,
$LST(dishWashing_2)$=20h30,
$POW(dishWashing_2)$=2.4kW over four sampling periods.

The third device $DEV_3 = oven$ will be used once, the timed service on the oven $SRV_5 = cooking$ is characterized by:
$RST(cooking)$=11h00, $EST(cooking)$=9h00, $LST(cooking)$=12h00, $POW(cooking)$=1.5kW over one sampling period.

The fourth device $DEV_3 = vacuumcleaner$ will be used once, the timed service on the vacuum cleaner $SRV_6 = vacuuming$is characterized by:
$RST(vacuuming)$=21h00, $EST(vacuuming)$=19h00,

$LST(vacuuming)$=22h00, $POW(vacuuming)$=1.5kW over one sampling period.

The fifth device is a heater in the living room ($DEV_5 = heater_1$), the permanent service on the heater $SRV_7 = heating_1$ is characterized by:
$TMIN(heating_1)$=19, $TPRE(heating_1)$=19, $TMAX(heating_1)$=19, $POW(heating_1)_{max} = 1.5kW$
the thermal dynamic model of temperature change [9] in the living room is:

$$TEMP(heating_1)_{k+1} = e^{(-1800)} TEMP(heating_1)_k + 40(1 - e^{-1800}) POW(heating_1)_k + (1 - e^{-1800}) \times 10 \quad .$$

The sixth device is another heater ($DEV_6 = heater_2$) in the bedroom, the permanent service on the heater $SRV_8 = heating_2$is characterized by:
$TMIN(heating_2)$=18, $TPRE(heating_2)$=19, $TMAX(heating_2) = 20$, $POW(heating_2)_{max}$=1.5kW
the thermal dynamic model of temperature change in the bedroom is similar to the living room's thermal dynamic model.

The solving agent starts the search by initializing the heating service to their inhabitant preferred temperature and the timed services to their requested starting time. After the energy distribution for all services over all periods, the solving agent states that the power consumption exceeds the available power twice; the first time is during the 9^{th} and 10^{th} periods, the second one is during the 18^{th} and 19^{th} periods. Instead of solving the complete problem (eight services) over 48 sampling periods, it is better to split the initial problem into easier sub-problems to be solved by the solving agent. Therefore, if the algorithm of sub-problem area determination (IV-B) is applied, two independent sub-problems are obtained. The first sub-problem involves $SRV_1, SRV_3, SRV_5, SRV_7\, and\, SRV_8$ and the second sub-problem involves $SRV_2, SRV_4, SRV_6, SRV_7, SRV_8$. Each sub-problem deals with five services over four hours and thirty minutes which reduces the complexity of the whole problem.

The results of Tabu Search's algorithm is drawn in figure (5) showing a solution for the first sub-problem where the power consumption does not exceed the available power during the sub-problem$_1$ area. Without MAHAS, services would have been performed according to the inhabitant's requests and the available power would have been exceeded. Due to negotiations and coordinations, MAHAS has converged to a feasible solution which is acceptable for inhabitants. Figure 5 only points out results obtained for sub-problem 1 but the second sub-problem can be solved in the same way and merged in order to get a global acceptable solution in a very short time (less than 1 second).

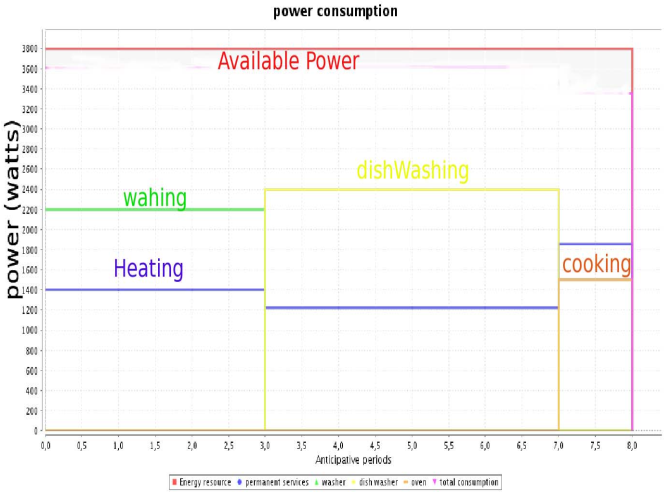

Fig. 5. *Sub-problem 1 solution.*

VI. CONCLUSION

This paper has presented the principles of a MAHAS which allows the agents to cooperate and coordinate their actions in order to find an acceptable near-optimal solution for power management. A cooperation mechanism that reduces the problem complexity has been detailed. It has also been shown why autonomous and cooperative agent are particularly well suited for spatially distributed, flexible, open and extendable context such as power management in buildings, in pointing out that there is non shareable knowledge. This feature is a clear improvement over the capabilities provided by current Automatic Controlled Systems. A simulator has been designed and results let imagine a new way for producing and consuming power. The next step is the implementation in a real building.

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