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Resource Allocation in Smart Homes Based on Banker's Algorithm

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***Abstract*—This paper proposes a method for improved energy management in smart homes by means of resource allocation. For this purpose, a Banker's algorithm based strategy has been developed. It is used to control the system and decide which of the given processes should be provided with resources at the time. Constraints such as due time of a process, limit of electrical energy consumption and use of preferable resources are taken into account. The smart home environment is developed and simulated in Matlab. The proposed strategy and also the standard strategy of the typical household are implemented and compared based on the criterion of economic costs. We show that potential implementation of the proposed strategy would improve energy management by proper choice and timing of resource usage in smart homes.**

I. Introduction

Use of sustainable, renewable energy sources and economic efficiency of resource management are receiving more interest and becoming increasingly significant. With fast development of ICT, the solutions of the home automation related challenges are becoming implementable and, therefore, feasible in practice. Though smart grids and smart homes are a hot topic in science and engineering, there are still challenges to be solved. One of them is energy consumption and energy cost minimization in a smart home.

In this paper, we propose an algorithm for creating a more economically efficient smart home. We aim at modeling a smart home that is able to independently decide, based on predefined criteria, which process (for instance, a washing machine or a dishwasher) should be provided with necessary resources (e.g. electricity, hot water). Criteria include completion of the process before the predefined due time, keeping the amount of allocated electricity below a certain threshold, and preferred use of sustainable energy resources such as solar energy. The criteria are easily extended, so additional constraints on the currently allocated amount of any other resource could be put to any of them.

In the considered problem, the uncertainty of the system poses the major challenge. It originates from the fact that it is unknown which of the processes would request to be completed. Also, the availability of each resource is not constant because, for example, there can occur an electricity curtailment. The possibility of resource shortage, e.g. electricity curtailment, or unknown number and start times of processes make the system uncertain. Furthermore, human users present disturbance to the system by means of unpredictable use of the resources.

Similar problem has already been considered, but the applied methods were different. For instance, Conte et al. in [1] based a solution to resource allocation problem on multi agent system theory. Ha et al. [2] made a step forward in dynamic optimization for demand-side load management. Negenborn et al. [3] applied an MPC algorithm for minimizing costs to a household energy consumption. The latter two take into account only electrical energy consumption, while our model takes into account water as well and is easily extendable to more resources such as gas.

Herein we propose resource allocation in smart home by employing modified Banker's algorithm [4], and giving priority to using economically and ecologically more acceptable resources.

The Banker's algorithm is known to be applied for deadlock avoidance, but to best of our knowledge, it has never before been adjusted for use in an uncertain environment. We compare this future concept to the current practice and show the gained benefits.

The rest of the paper is structured as follows. Section II introduces basic terms and definitions and explains the considered problem and set-up. Section III elaborates on the method applied and discusses the reasons for modifying the original Banker's algorithm. In Section IV we present the results and after that we conclude in Section V.

II. Definitions

A. Smart home

In our setup, a smart home is a system that controls processes by means of providing them with resources they request to complete tasks given by a user. To be completed, every process requires a certain amount of resources. The developed algorithm decides on the schedule of assigning each process by requested resources. For illustration of a smart home setup, the considered processes and resources and their interconnection are depicted in Figure 1. The user is marked in red, as he/she is not controllable by the system and introduces uncertainty by his/her actions. Note here that in the setup, the considered system is equipped with its own photovoltaic system. Thus, the resource management puts an emphasis on the use of sustainable and economic resources.

B. Set of resources

The set of resources consists of four elements: low-cost electricity, expensive electricity, solar energy (coming from

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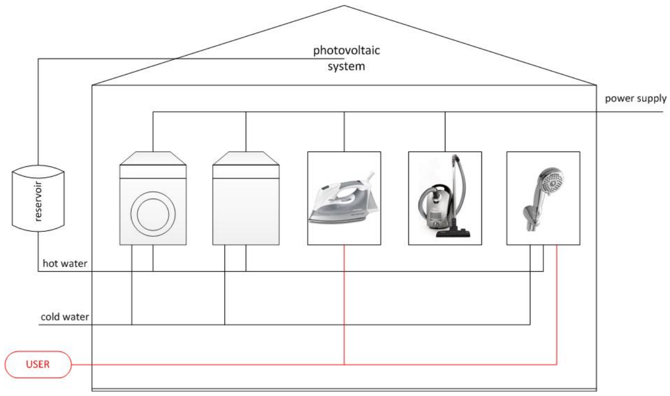


Fig. 1. The smart home.

photovoltaic system) and cold water.

Electricity. Electricity is split into two different resources: low cost, and expensive electricity, because of daily changes of electricity prices in certain countries [5]. Electrical energy is cheaper by night because of the smaller demand at that time of a day. In the setup, the expensive tariff is chosen to last from 8 a.m. till 10 p.m., while the low-cost lasts from 10 p.m. till 8 a.m.

There are two parameters that describe the resources of electricity: the maximal reserved power, and the limit power. The maximal reserved (allocated) power is the maximal amount of electric power that can be provided to a household. The limit power is defined by a user and it is the amount of electricity defined as the maximal power that can be drawn from the grid. That amount should never be reached in the normal working conditions. For example, if the maximal reserved power is 6kW and the limit power is defined as 3kW, the smart home will try to work at every time instant with only 3kW. Default limit power will be exceeded only if not using it would threaten the performances of the processes (short duty time). As user's actions cannot be interfered by a designed algorithm, this occurs in the case when the user initiates too many processes with too strict deadlines for the execution. In that particular case, crossing the limit power is inevitable. However, it is not possible to withdraw more power than the maximal reserved power. Such a description of the resource has been chosen for the sake of simplicity, so that the system is not too complex and still able to simulate a very primitive and limited demand response. In the future work, it is straightforward to extend this description to simulate a behavior of a price elastic smart home.

Cold water. The resource of cold water comes from the water supply line.

Hot water. Solar energy is used only to heat the water that is necessary for some processes. It is possible to lower the use of electricity and reduce total costs by using the hot water instead of cold one. Considered smart house is equipped by photovoltaic system to heat the cold water tanks. In this setup, the water tanks are designed as separated tanks to ease the calculation of the amount of heated water.

Furthermore, as the tanks are considered to be already filled by water, they are autonomous and independent of the current situation in the water supply line, i.e. on the cold water. That means that the situation when hot water is available and there is no cold water is possible.

The resource of hot water could be described by two parameters: its current amount and temperature. For the sake of simplicity of computation, it is assumed that the temperature of the hot water is always 60 [°C]. The amount of heated water is calculated from the available solar energy, bearing in mind the installed power of photovoltaic systems. Furthermore, it is assumed that the water is heated from initial temperature of 15 [°C]. From these assumptions and from the expressions for calculating the amount of heat

$$Q = mc_v\Delta T = 1 * 4200 * 45 = 189000 \text{ [J]}$$

and power, it follows that for heating one liter of water in a period of $\Delta t = 15$ minutes it is required approximately $P_{15} = 0.21$ [kW] of solar energy:

$$P_{15} = \frac{Q}{\Delta t} = \frac{189000}{15} = 0.21 \text{ [kW]}$$

Hot water obtained by heating is a specific resource. If it is not used when it is available, it "goes away" because the water cools down. It is possible to include the effect of cooling by reducing the available amount of hot water because of the assumption that a temperature of water is constant. The greater the amount of hot water is, the greater is the area of the tank where the hot water is located, and, therefore, the loss of hot water per unit of time is greater. Due to the above described phenomena, a relative factor, δ, which represents the percentage of the remaining amount of hot water after one hour is introduced. Therefore, during the solar radiation the hot water emerges and disappears at the same time, even if it is not used by processes. The above explained phenomena is mathematically represented as

$$\frac{\mathrm{d}(v(t))}{\mathrm{d}t} = \frac{P_s}{Q_1} - v(t)\frac{1-\delta}{60}, \tag{1}$$

where $v(t)$ is the amount of hot water in continuous time domain, P_s is the power of photovoltaic system, and $Q_1 = mc_w\Delta T$ is the total amount of thermal energy transferred to the cold reservoir. Here, the effect of decreasing the amount of hot water due to cooling is taken into account in calculations of the total amount of available hot water. Discretisation of the given equation in a time interval of 15 minutes gets to:

$$w(i) = w(i-1) + \frac{s(i-1)}{P_{15}} - \left(w(i-1) + 0.5\frac{s(i-1)}{P_{15}}\right)\frac{1-\delta}{4} \tag{2}$$

where index $i-1$ marks the beginning of the interval, index i denotes the end of the interval, $s(i-1)$ is the energy of the photovoltaic system in the considered time interval, $w(t)$ is the total amount of spent hot water and $w(i)$ is the total amount of spent hot water during the time interval denoted by index i.

To compute the amount of hot water in the interval according to (2), one should know the amount of the hot water at the beginning of the simulation. This parameter could be interpreted as the unused amount of hot water that was accumulated, for example, during the previous day. For the sake of simplicity, here it is assumed that the hot water temperature remains constant while the amount of available hot water is reduced, even though in reality the cooling of the hot water gradually reduces the temperature. At the end of the simulation, the total consumption of hot water is converted from the total amount of used hot water into equivalent electrical energy that should be used for heating in order to calculate the optimization criterion. Calculation is done according to the following expression:

$$W = \sum_i w(i) P_{15} \Delta t, \tag{3}$$

where W is a total electricity that would be required to heat the total amount of hot water consumed.

C. Set of processes

Set of processes consists of five elements: ironing, showering, washing the dishes (dishwasher), doing the laundry (washing machine), and vacuum cleaning (done by a robot). This set could be separated into two parts: first group consists of processes that require user's involvement, e.g. ironing or showering, while the second group consists of processes that, once they have been started, are able to get completed without human presence, e.g. dishwashing, washing machine, robot vacuum cleaner. First group of processes is included to increase the generality and to simulate user's interference which can be seen as a disturbance of the smart home system and developed algorithm. When assigning, each process is given following values:

- start time - the time instance at which a process has been started
- due time - by that time instance a process has to be done, at any cost

In case of processes of the first group such as ironing, the due time should be interpreted as end time of the process. This time is uncertain.

Each process has a predefined sequence of execution, i.e., each process consists of certain number of subprocesses. Every subprocess has the duration of the discretization step. In our setup, each process can be suspended after performing any of subprocess and be resumed later, when the conditions to proceed are reestablished. In this sense, every process is a series of smaller processes consolidated together in particular order. For example, after a washing machine is started, it can finish with the first cycle, pre-washing, and after that stop because of electricity curtailment. The process will be temporarily suspended, and when the power becomes available again, it will continue.

D. Banker's Algorithm

Banker's Algorithm [4] is used for allocating resources and avoiding deadlocks. Although the algorithm itself is intuitively clear and easy to implement, its application is limited because of certain assumptions of the algorithm. These assumptions are listed below:

- The number of processes must be predefined and constant.
- The number of resources must be predefined and constant.
- All processes announce in advance how much of every resource each of them needs.
- After completing, each process returns all the allocated resources, so they can be reused by assigning to some other process(es).
- Each process is completed in a finite time.

In the considered setup, not all of the listed assumptions are fulfilled. For instance, it is impossible to predict in advance which of the processes will be assigned on a considered day. During the execution of one process, another process could ask to be started, which is contradictory to the assumptions of the algorithm. Furthermore, the available amount of each resource is not known in advance, as it is impossible to accurately predict the output power of the photovoltaic system or possible power curtailments. Also, requirements of each process could vary as the process might use low-cost instead of expensive electricity, and hot instead of cold water. Lastly, in the considered model some resources cannot be returned to the system, e.g., if the washing machine consumes 10 liter of hot water, it cannot give back that amount of water to the system to reuse it.

In addition, to obtain better energy management, the considered system should satisfy several additional constraints:

- the use of sustainable energy resources such as hot water and low-cost electricity
- completion of given tasks before the deadline (respecting the due times),
- keeping the power below a specified threshold (the limit power).

III. Modifications of Banker's algorithm

From everything written above, it follows that the original Banker's algorithm is not applicable to the described set-up as it is. To meet all performance requirements, the method has been modified.

A. Discretization of the processes

Assumptions on constant number of resources and processes are satisfied by introducing discretization and dividing each process into several subprocesses of which each lasts one period of discretization, Δt. In addition, it is assumed that within one period of discretization, the amount of resources is constant. This does not introduce conservatism in the system, as Δt can be chosen to be sufficiently small. The smaller Δt is, the more complex the system is, as the number of subprocesses increases. On the other hand, the smaller Δt is, the faster the communication with the user is.

B. Priorities of the processes

Priorities of the processes are introduced to distinguish between the two groups of processes as defined above. Higher importance is given to the processes of the first group, i.e. processes activated by user. The processes of the first group have the highest priority, and they are superior to processes managed by the modified Banker's algorithm, i.e., the processes belonging to the second group. Each process is assigned the default priority - the first group has priority 2, and the second group has priority 0. The higher the priority of the process, the more urgent the start of its execution is. The priority of the process that belongs to the first group (managed by user) is constant. In case there are not enough resources to immediately perform this type of process, a request for its performance is going to be neglected. If a user wanted to iron and currently there is no electricity, he or she will go to deal with some other work, and not constantly check whether the electricity has come. At the time when electricity is available again user may even no longer be in the house. In contrast, the priority of the processes managed by the modified Banker's algorithm changes during the simulation. It changes according to the following expression depending on the given deadline and depending on how many subprocesses of given process are still to be executed:

$$p = \frac{N_p}{N_{\Delta t}} \tag{4}$$

where p is the priority of the process, N_p is a number of remaining subprocesses (subprocesses to be executed), and $N_{\Delta t}$ is a number of remaining steps of discretization, i.e. number of discretization intervals between the observed moment and the deadline of the process.

If the priority of the process managed by Banker's algorithm grows to 1, the process has to be started at this particular time instance. If the value of the priority exceeds 1, the process will not be completed in time. In case there is not enough resources to perform the process of the second group (process managed by Banker's algorithm), it will be postponed until the conditions for its execution are met.

C. Modifying the requirements of the processes (priorities of the resources)

By default, in the beginning all defined processes demand low-cost electricity and hot water rather than expensive electricity and cold water. It can happen that during the execution of a certain process, these requirements should be changed into e.g., requirement for cold water and the equivalent of low-cost (or expensive) electricity which would heat the cold water to the required temperature of the hot water. The resource demand of each process has to be adjusted in every Δt, depending on the priority of the process, and availability of the resources. Because in the original Banker's algorithm the needs for all necessary resources per process are stored in the matrix *NEED*, this corresponds to changing the matrix of needs, *NEED*.

To (re)allocate resources to processes, certain auxiliary variables should be introduced:

- expectation of the sun - due time until it makes sense to wait for the sun to warm water,
- weather forecast
- low-cost electricity expectance time - a time instance when the tariff of electricity changes from expensive to low-cost (set to a constant),
- status - a vector of integers, which holds information about the status of each process (this vector is variable in time, i.e. its value changes in every step of the discretization). As explained above, if the value of vector element set to 0, the process is not executed at a considered time instance, if it is 1, the process is about to be included in that particular moment, if the value is 2, the first subprocess is completed and the performance of the following subprocess is prompted, etc.
- permission - a boolean vector. The value 1 shows that the process got the permission to start and that it has been assigned the necessary resources, a value 0 shows that process is refused and it must wait for the next time instance to re-requested resources.

D. Creating the matrix of needs for resources

The needs for resources of all currently activated processes are stored in matrix *NEED*. It changes depending on the currently available resources, the priority of each process and the management strategy. By management strategy, we mean two possible approaches: *(i)* standard strategy, conventional household, and *(ii)* "green strategy". The first one executes the processes as soon as they are given, no matter of the costs. There is no waiting for the green energy resources such as warmed water, and there are no attempts to reduce the final costs.

The values of matrix *NEED* are changed if the chosen management strategy is standard strategy approach simulation. They are changed in a way that for each process which should be executed in a considered time instance, its needs for hot water are converted into the need for cold water and equivalent electricity for heating cold water to desired temperature if there is not enough hot water for the performance of the process. After possible conversion of requests for hot water, if the process has such a priority that it must be executed in this step and has a need for low-cost electricity which is not available at the moment, but there is expensive electricity, once again the change of the values in the matrix *NEED* will be done. The processes that are executed first are the processes whose priority is higher or equal to 1. If there is yet not enough of hot water to perform processes of priority lower than 1 in this step, it will be checked whether it is sensible to wait for the sun to heat the water in the tank. Here the weather forecast plays a role. Finally, it is checked whether it makes sense to wait for low-cost electricity. If given due time for process is prior to low-cost electricity expectance time, needs for low-cost electricity are changed into needs for expensive electricity. Note that in case one would like to consider a more advanced demand response with prices for energy changing in real-time, a price prediction algorithm should be implemented.

E. Creating the vector of available resources

The available resources are stored in vector *AVAILABLE*. Its size corresponds to the number of resources. It contains current amount of available resources. To create it, firstly, the total request for electricity of all processes whose priorities are higher or equal to 1 is calculated. Then it is compared to the limit power and the maximum amount of electricity. If the need for electricity is greater than the limit power, the amount of electricity in the vector *AVAILABLE* increases exactly to the needs of electricity at the considered time instance to execute all processes with priorities higher or equal 1 (but not other processes!). If the need for electricity is greater than the maximum amount of electricity, the amount of electricity in the vector *AVAILABLE* increases exactly to the maximum amount of power.

After all the matrices have been calculated, the resources are assigned to processes. Note here that in the classical Banker's algorithm, there is a check whether assigning the resources to the processes leads the system to an unsafe state, i.e. to the possible deadlock. In this, modified, version of Banker's algorithm, this check is omitted. The reason is that the smart house cannot reach deadlock in the classical sense. However, it may happen that some started processes will not be executed or will be delayed because of the inability to satisfy all the preset requirements (infeasibility of the problem).

IV. Results

Here we present the obtained results. The default availability of resources is assumed to be as indicated in Figure 2. The

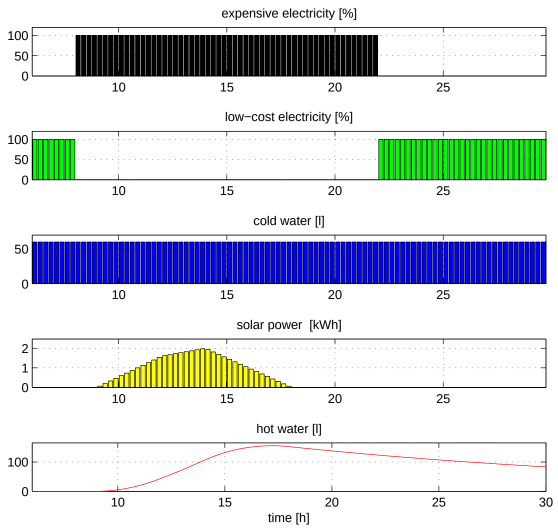


Fig. 2. Available resources.

base case of 9 processes has been simulated. The schedule of these processes is given in the Table I[1]. Note once again that this schedule is not known to the system in advance, it is used as a real-time input. Simulated time is 24 hours, starting at 6am and finishing at 6am on the following day. The base case was created so that it represents a typical behavior of a four member family in the framework of our set-up.

We compared the standard strategy and the proposed algorithm by simulating two different scenarios of the proposed modified Banker's algorithm, with and without given due times

[1]Note: * The due time is 6.00 of the following day.

-	Proces	Start time	Due time (for *(iii)*)
1.	taking a shower	6.30	-
2.	dishwasher	7.30	17.30
3.	washing machine	8.30	23.15
4.	ironing	9.15	-
5.	vacuum cleaning	12.00	20.00
6.	taking a shower	15.00	-
7.	dishwasher	19.00	6.00*
8.	taking a shower	21.00	-
9.	taking a shower	21.30	-

TABLE I
A BASE CASE LIST OF PROCESSES.

of the processes. These scenarios have been simulated for three cases that vary depending on the availability of the resources: *a)* sunny day, with default availability of reserves (see Figure 2); *b)* a rainy day, no solar power, i.e. no hot water; *c)* shortage of electricity (10.30 am-12.00 pm and again 9.30 pm-11.00 pm). Note that in case *b)*, the system acts as if it was not be equipped by a PV system. The different scenarios and cases are listed in Table II. Here, the acronym "MBA" stands for "modified Banker's algorithm".

Simulation number	Scenario	Availability of resources
*(i)*a	standard strategy	default
*(i)*b	standard strategy	no solar power
*(i)*c	standard strategy	shortage of electricity
*(ii)*a	MBA, no due time	default
*(ii)*b	MBA, no due time	no solar power
*(ii)*c	MBA, no due time	shortage of electricity
*(iii)*a	MBA, due time	default
*(iii)*b	MBA, due time	no solar power
*(iii)*c	MBA, due time	shortage of electricity

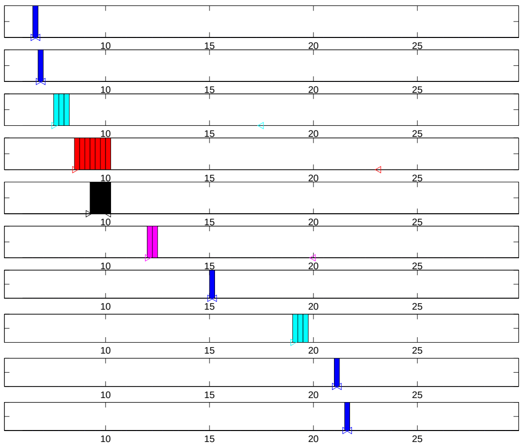
TABLE II
A LIST OF SIMULATIONS.

The comparison of cases *(a)* and *(b)* is to be interpreted as a comparison of a house with and without a PV system. We include this to validate the system. According to the literature, see [6] or [7], by installing the PV system, compared to the conventional buildings, it is possible to save energy in the amount of 25% up to almost 70%. We have chosen to be at the conservative edge of that interval, see savings columns in Table III.

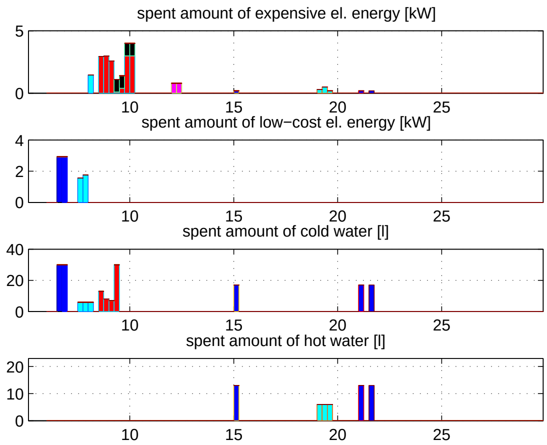
Figure 3 and Figure 4 compare the outcome of a current system (Figure 3) versus the outcome of the proposed smart home (Figure 4). For the sake of brevity, the results of other simulations are not given in figures in this paper, but they can be seen in [8].

Furthermore, Figure 4 shows that, unlike in the standard Banker's algorithm, in our case temporary interruptions in execution of a process are allowed, see e.g. the washing machine cycle colored in red, or the dishwasher cycle colored in cyan in Figure 4.

As expected, the results show that it would be possible to increase the user benefit by better choice and timing of the processes, no matter if a house is equipped by a PV system or not. The comparison of costs for all the simulated cases is given in Table III.

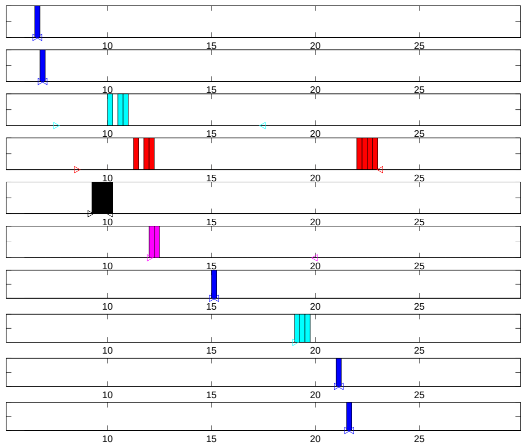


(a) Simulated processes execution for the simulation *(i)*a

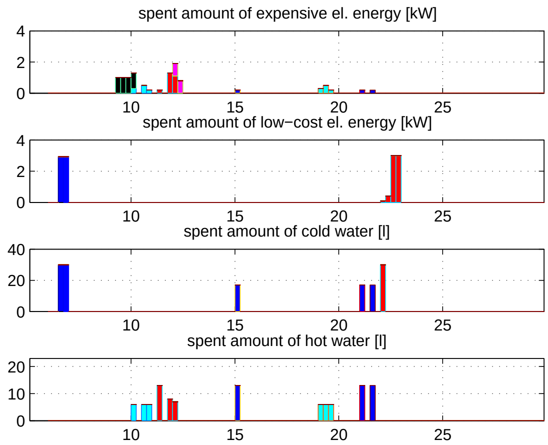


(b) Amounts of spent resources for the simulation *(i)*a

Fig. 3. The base case scenario, simulation *(i)*a. The simulation represents the current practice. *Legend: blue color represents showering, cyan dishwasher, black ironing, red washing machine and magenta vacuum cleaner.*



(a) Simulated processes execution for the simulation *(iii)*a



(b) Amounts of spent resources for the simulation *(iii)*a

Fig. 4. The base case scenario, simulation *(iii)*a. The simulation represents the proposed resource management approach. *Legend: blue color represents showering, cyan dishwasher, black ironing, red washing machine and magenta vacuum cleaner.*

The second column in Table III, ”Total cost” is presented in equivalent kWh of expensive electricity. The expensive electricity is chosen to be twice expensive as low-cost electricity. To incorporate the benefits of using hot water, the amount of used hot water is recalculated into the amount of the expensive electricity that would have to be used to heat the water, as explained in subsection II-B. Also, it is assigned a weight factor, as it is assumed that using the hot water heated by PV system is roughly three times cheaper than using electricity for power supply.

The third column in Table III, ”Savings with respect to the simulation *(ii)*a”, represents the reduction in energy consumption and is calculated as $\frac{c_{ref}-c_{case}}{c_{ref}} \cdot 100$, where c_{ref} are the total costs in the reference case, i.e. simulation *(ii)*a, and c_{case} are the total costs in the observed case, i.e. all the other simulations. Note that in simulation *(iii)*c, the process under number 3, the washing machine, was not finished on time due to shortage of electricity.

The last column in Table III, ”Savings with respect to the case *(a)*”, is very similar to the third column, but in order to divide the benefits of using PV system from applying the proposed algorithm, we calculated the benefits for each scenario in relation to its nominal case, i.e. the case when all the resources are fully available. This column demonstrates how much energy it would be possible to gain in case there is a PV system installed over the conventional house.

Finally, we increased the number of processes three times, while the amount of available resources remained the same level as in the previous examples. The system proved to be capable of handling such a challenge, see Figure 5.

V. Conclusions

The algorithm for resource management in a smart home based on Banker’s algorithm and the simulation set-up to test it have been successfully developed. The original Banker’s

Simulation number	Total cost [kWh]	Savings [%] wrt *(ii)*a	Savings [%] wrt *(a)* per scenario
*(i)*a	7.96	20.8	ref. case (-)
*(i)*b	5.67	43.59	28.77
*(i)*c	5.87	41.6	26.25
*(ii)*a	10.05	ref. case (-)	ref. case (-)
*(ii)*b	7.38	26.57	26.57
*(ii)*c	8.73	13.13	13.13
*(iii)*a	7.96	20.8	ref. case (-)
*(iii)*b	5.67	43.59	28.77
*(iii)*c	5.87	41.6	26.25

TABLE III

A COMPARISON OF CURRENT AND PROPOSED OPERATION OF A SMART HOME.

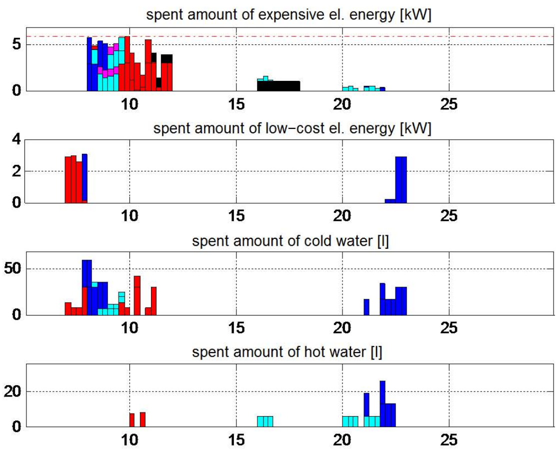


Fig. 5. Increased number of processes, same amount of resources.

algorithm has been adapted so that it can be applied to the considered system. The major improvement is that now, unlike in the conventional Banker's algorithm, the processes can now be interrupted. We showed how the proposed algorithm could be implemented and what the gains are over the current practice. This approach could be further improved by introducing more prediction. For instance, learning about users' habits and sensing which user is in the house could reduce uncertainty. By reducing the discretization step, the algorithm would receive faster response to user's commands and system changes and become more robust.

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