Petri Net Modelling of Smart Home Appliances

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***Abstract*—In this work, some smart appliances (i.e., smart refrigerator and smart washing machine) and the corresponding smart home model are introduced to show the importance of smartness to improve user comfort and energy efficiency in homes. Detailed Petri net models of the considered appliances are also given in order to enable a good general view of their operation and integration with the smart home. Moreover, for monitoring and controlling the smart appliances and their integrations to smart home system, a program is prepared by using both Keysight VEE 9.3 and Matlab software.**

Keywords—Petri Net; smart appliances; smart home; refrigerator; washing machine; modeling, simulation

I. INTRODUCTION

In recent years, electricity and water consumption has increased due to the increase of the world population, hence the natural resources have been depleted rapidly. Residential consumption constitutes remarkable part of the total electricity and water consumption. With the increasing technology, user expectation has increased so much so that home appliances detect user requests and provide the most suitable working conditions for spending efficient time and efforts in the use of home appliances. It is also desired to control home appliances remotely from outside of the home. Smart home appliances and smart home are the most important solutions for this request.

Smart Home (SH) is defined as a residential equipped with smart electrical appliances, sensors, communication units and controllers. A SH means a safer, comfortable and energy efficient living environment. Various hardware and software algorithms integrated to the structure of the system can be used to take precautions against unfavorable situations such as theft, fire etc. Environmental factors such as temperature, light and humidity inside the house can be kept under control to provide a high level of comfort for the user. Distributed power units containing renewable energy sources can be added to SH system [1,2]. One of the most important applications of SH is Energy Management Systems (EMS) which monitor and manage electric generation and consumption in the home to reduce energy use and electricity cost. Home energy consumption depends on user habits and requirements. For example, home users run electrical appliances in their homes according to their own preferences. Electrical appliances operating independent from each other cause instantaneous high electricity demand at the certain times of the day. This situation takes place in the literature as a problem that needs to be solved as it can cause high cost breakdown in the city network. SH systems integrated with EMS and connected with city grid provides promising offers for the solution of this problem. According to all these, SH systems contribute directly to residents and indirectly to electricity generation and distribution companies through efficient use of electricity. Consequently, home appliance manufacturers and researchers have been proposing contributions for SH systems. On the manufacturer side, Samsung announced its SH solution *Smartthings* [3], which is a kind of home monitoring kit. Samsung has also developed some smart appliances that are monitored and controlled by smart-phones. *Home Connect* was launched by Bosch&Siemens group [4]. This application enables users to control all of their connected Siemens home appliances via a smartphone or tablet from wherever they are.

SmartThingQ [5] was developed by LG to monitor and control LG smart appliances remotely. In the literature, researchers have focused on improvement of SH systems and especially on its EMS applications. For example, in [6] which is one of the studies aiming to decrease the total electricity cost in homes, a method that learns the changes in energy pricing and creates a corresponding time schedule was given, while in [7] a genetic algorithm based electricity usage scheduling method is proposed for reducing electricity charge of smart buildings equipped with smart devices. Real time price-based scheduling approaches using appliances' time of use probabilities [8] and different demand response programs [9] by considering user comfort also exist in the literature. Besides, some studies aim to increase user comfort level as well as reducing the costs. A smart building EMS based on price variations and external conditions as well as comfort requirements, is presented in [10]. Apart from these studies [11] proposes physical based load models for electric loads and presents an approach to solve the peak shaving problem that leverage the real-time scheduling discipline to coordinate the activation and deactivation of these loads. Resource priorities are considered in [12]. In that paper, a real time EMS is presented for reducing electricity cost via resource prioritization and simultaneous interference with smart appliances without exploiting their beneficial potential.

In the design of a SH, modeling is a crucial issue since it directly effects the facilities of analysis and implementation. Additionally, it is very important to provide a suitable model that endorses the verification of smart appliance dynamics. An appliance based home energy management system is proposed in [13] by using the characteristics of smart home appliances.

In this work, we focus on the detailed operating principles of smart home appliances. These appliances are very critical part of smart home concept to increase user comfort and reduce

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the electricity and water consumption bills. Two of the most used home appliances (i.e, Smart refrigerator (sREF) and smart washing machine (sWM)) are modelled by Petri Nets to show their working principles and their interactions with the smart home system. Before installing the real appliances and smart home system, proposed models allow designers to understand whether smart home appliances work well. Besides, these models are easily expandable for new features and new sensors, which are adapted to these appliances. Consequently, models of smart appliances are useful tools to develop and improve smart appliances and smart home systems.

In Section II, the general information about Petri Nets is given. Working principles of sREF and sWM are explained and compared with the corresponding conventional appliances in Section III. Petri net models of sREF and sWM are also presented in this section. In section IV, the simulation program prepared by using both Keysight VEE 9.3 [14-15] and Matlab software for monitoring and controlling sREF and sWM is explained. And finally, the conclusion of this work is given.

II. Petri Nets

A Petri Net (PN) is a graphical and mathematical modelling tool for modelling and analyzing discrete event systems [16-17]. A PN is denoted by a five-tuple $G\ (P, T, N, O, m_0)$, where $P := \{p_1, p_2, \ldots, p_{|P|}\}$ is the set of places, represented by circles, $T := \{t_1, t_2, \ldots, t_{|T|}\}$ is the set of transitions, represented by bars, $(P \cap T = \emptyset$ and $P \cup T \neq \emptyset)$, $N : P \times T \rightarrow \mathcal{N}$ is the input matrix that specifies the arcs directed from places to transitions, $O : P \times T \rightarrow \mathcal{N}$ is the output matrix that specifies the arcs directed from transitions to places and m_0 is the initial marking. Here, $\mathcal{N}$ is the set of nonnegative integer number. In a PN model places represent possible states of the system while transitions are events or actions which cause the change of state. Distribution of tokens (black dots) over the places corresponds to a state of the modelled system and called marking vector M: $P \rightarrow \mathcal{N}$ for which $M(p_i)$ indicates the number of tokens, represented by black dots, assigned by marking M to place p_i . Initial marking vector of a PN model is represented by m_0. Change of marking vector is denoted by a movement of *token(s)* from place(s) to place(s); and is caused by the *firing* of a transition. A transition $t_j \in T$ is enabled if and only if $M(p_i) \geq N\ (p_i, t_j)$ for all $p_i \in P$. Here, $N\ (p_i, t_j)$ corresponds, the element of the input matrix, corresponding to $p_i \in P$ and $t_j \in T$.

Example 1: For PN model given in Fig. 2, set of places, set of transitions and initial marking vector are denoted by $P = \{p_1, p_2, p_3, p_4, p_5, p_6\}$, $T = \{t_1, t_2, t_3, t_4\}$ and $m_0 = [1\ 1\ 0\ 0\ 0]^T$, respectively. Input and output matrices of this PN are given as follows:

$$N = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad O = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

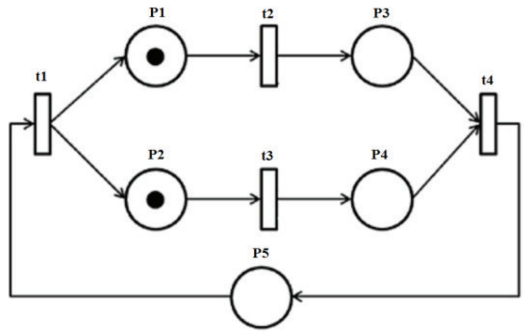

Fig. 1. PetriNet example.

III. Smart Home

A. General View

The considered SH scheme in this work (see Fig.2) is connected to city grid and consists of smart electrical appliances, sensors, power units, communication network and a Main Controller (MC) [12-13]. In this SH, smart appliances have their local controller; MC monitors sensors and smart appliances and interferes with the appliances according to an EMS or user requests as much as it is permitted and also acknowledges the new status to appliances.

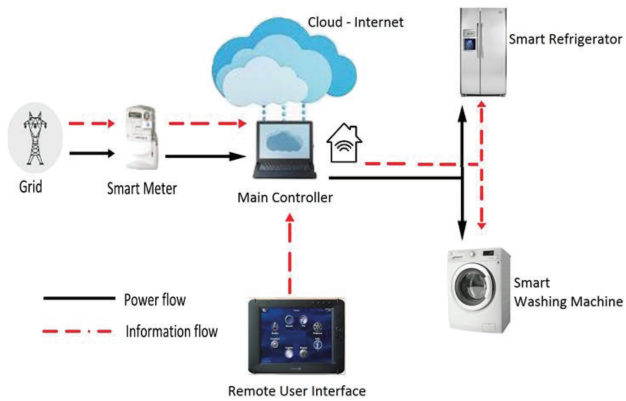

Fig. 2. SmartHome Scheme.

B. Smart Appliances

In the considered smart home appliances, three working modes and various program modes are assigned to each smart appliance a ∈ L, where L represents the set of smart electrical appliances (shortly, appliances) in SH. In order to improve user comfort and use the energy more efficiently, each program mode offers different functionality and features, such as operation times, energy consumptions and more. These program modes are allocated by manufacturers to fulfill these functions and features. The sets of working modes and program modes are represented by M_w = {on, off, standby} and $M_p = \{1, 2, 3, 4, \ldots, |M_p|\}$, respectively. The status of an appliance a ∈ L operating in a program mode i ∈ M_p at time slot t ∈ T is represented by the status vector which is defined as $X_a(t) = [X_{aw}(t)|X_{ap}(t)] \in \{0, 1\}1\times(|M_w|+|M_p|)$. Here, $X_{aw}(t) \in \{0, 1\} 1\times|M_w|$ is the working mode vector at the present time in which [1 0 0], [0 1 0], [0 0 1] representing on, off, standby working modes respectively. Similarly, $X_{ap}(t) \in \{0, 1\}1\times|M_p|$ is the program mode vector at time t in which ith element of the vector, i.e., $X_{ap}(t,i)$, is 1 others are zero when the ith program mode is active. For example, the status vector of an appliance which is operating, that is, its working mode is on, in program mode 2 through four program modes at time slot t is $X_a(t) = [1\ 0\ 0|0\ 1\ 0\ 0]$ where $X_{aw}(t) = [1\ 0\ 0]$ and $X_{ap}(t) = [0\ 1\ 0\ 0]$.

All smart appliances are able to connect to any SH by using different communication tools and protocols. In SH, MC is in communication with smart appliances and interferes with their status (working mode or program mode) if it is required. Fig. 3 illustrates an example of communication structure between MC and a smart appliance. Here, MC gathers the status information from the appliance and interferes with the program mode via switching it from program mode 1 to program mode 2.

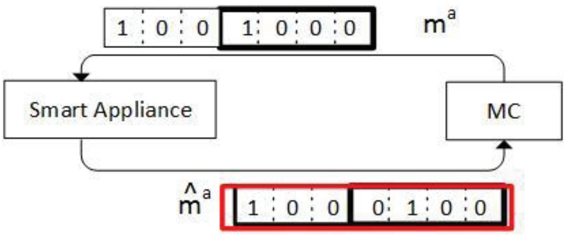

Fig. 3. Communication structure between MC and a smart appliance.

B1.Smart Refrigerator

Conventional refrigerators use conventional compressors with single-speed AC induction motors. Compressors with high cooling capacities are preferred in these cabinets in order to achieve similar cooling performance at different ambient temperatures. Such compressors require short ON / OFF cycles at lower ambient temperatures. If AC induction motors consume more power at start-up, this causes high energy consumption. In the new generation refrigerators (smart refrigerators-sREF), variable speed compressors are preferred, the temperature sensors in use and the microprocessor control card are used to calculate the in-cabinet cooling requirement and precise cooling performance is achieved by adjusting the compressor speed according to this requirement. When temperature inside refrigerator rises, due to door opening, cooling is automatically increased by increasing the compressor speed. As soon as the cooling is sufficient, the compressor speed is reduced, the minimum cooling capacity required for the cabinet is reduced and unnecessary power consumption is avoided. During the defrost which has the highest power consumption in the refrigerator, while the compressor operation is stopped, the defrost heater is activated to dissolve the accumulated ice on the evaporator. When the temperature sensed by the defrost sensor placed on the evaporator rises above the set temperature to terminate the defrost, the defrost operation is stopped. After the defrost, the compressor is operated at the maximum speed so that the temperature inside the cabinet rising during the defrost is reduced as soon as the set value is reached. In this way, the temperature inside the cabinet reaches to the set values in a shorter time. The typical time interval for defrosts is between 10 and 12 hours.

In this study, the program modes of sREF are determined according to the compressor speed, which is directly proportional to power consumption, and they are called *high speed mode*, *moderate speed mode*, *low speed mode* and *defrost mode*. In Fig.4, power consumption levels in different program modes are given. These power consumptions are measured at a real refrigerator by using Yokogawa WT210.

As the compressor speed decreases, power consumption decreases and the operating time of the compressor increases. Power consumption of a conventional refrigerator under the same conditions is similar to the power consumption of *high-speed mode* of new generation refrigerator. When compared to the conventional appliances, up to 40% improvement in daily energy consumption can be achieved by sREF.

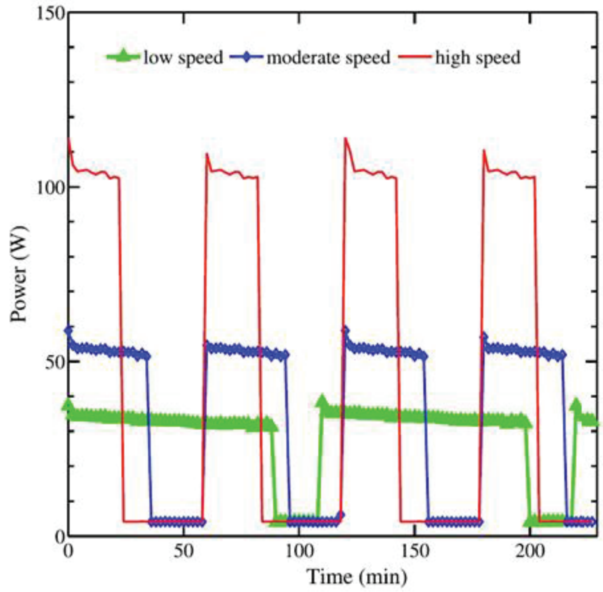

Fig. 4. Power consumptions of sREF at different program modes.

PN model of the sREF and the peripheral devices are given in Fig.5. In this PN model, user remote controller (sensor 1) is modelled by $P_{sensor1} = \{P_{s1\_1} , P_{s1\_2} \}$ and $T_{sensor1} = \{t_3 , t_4 \}$, where places P_{s1_1} /P_{s1_2} correspond to user request existence/absence. The status of this component is represented by the marking vector as $M_{sensor1} = [P_{s1\_1}\, P_{s1\_2}]^T$.

Defrost control sensor (*s*ensor 2) is modelled by $P_{sensor2} = \{P_{s2\_1}, P_{s2\_2}\}$ and $T_{sensor2} = \{t_{14}, t_{15}\}$, where places P_{s2_1} /P_{s2_2} correspond to defrost need /no-needed situation. The status of this sensor is represented by the marking vector as $M_{sensor2} = [P_{s2\_1}\ P_{s2\_2}]^T$. PN model of sREF consists of $P_{ref} = \{P_1, P_2, ...,P_7\}$ and $T_{ref} = \{t_1, t_2 ,t_5 ..., t_{11}\}$. Places $P_1/P_2/P_3$ correspond to *on/standby/off* working modes, while places $P_4/P_5/P_6/P_7$ correspond to *low-speed/moderate-speed/high-speed/defrost* modes of sREF. Mathematical model of the entire frame in Fig.5 is denoted by $P = P_{ref} \cup P_{sensor1} \cup P_{sensor2}$ and $T = T_{ref} \cup$

$T_{\text{sensor1}} \cup T_{\text{sensor2}}$. The status of the entire model is represented by the marking vector $M = [M_{\text{ref}} \ldots M_{\text{sensor1}} \ldots M_{\text{sensor2}}]^T$.

Present state of the sREF in Fig.5 is $M_{\text{sREF}} = [1\ 0\ 0\ |\ 0\ 1\ 0\ 0]^T$. In Table I, places and transitions of petri net model of sREF are given. This PN model evaluates in accordance with sREF. For example; if the user loads products when sREF is working at *low speed mode*, it switches to *moderate speed mode* for quick cooling by firing transition t_6. If defrost sensor detects the defrost need when sREF is in *low-speed/moderate speed/ high-speed* mode, s-REF switches to *defrost mode* by firing transition $t_{10}/t_{12}/t_{13}$. In this petri model, the red lines and circles show the relationship between refrigerator and main controller of smart home. If EMS system requests demand reduction when sREF is in *moderate-speed/high-speed/defrost* mode, MC interferes with the program mode of sREF and it switches to *low-speed* mode by firing transition t_mc1/t_mc2/t_mc3.

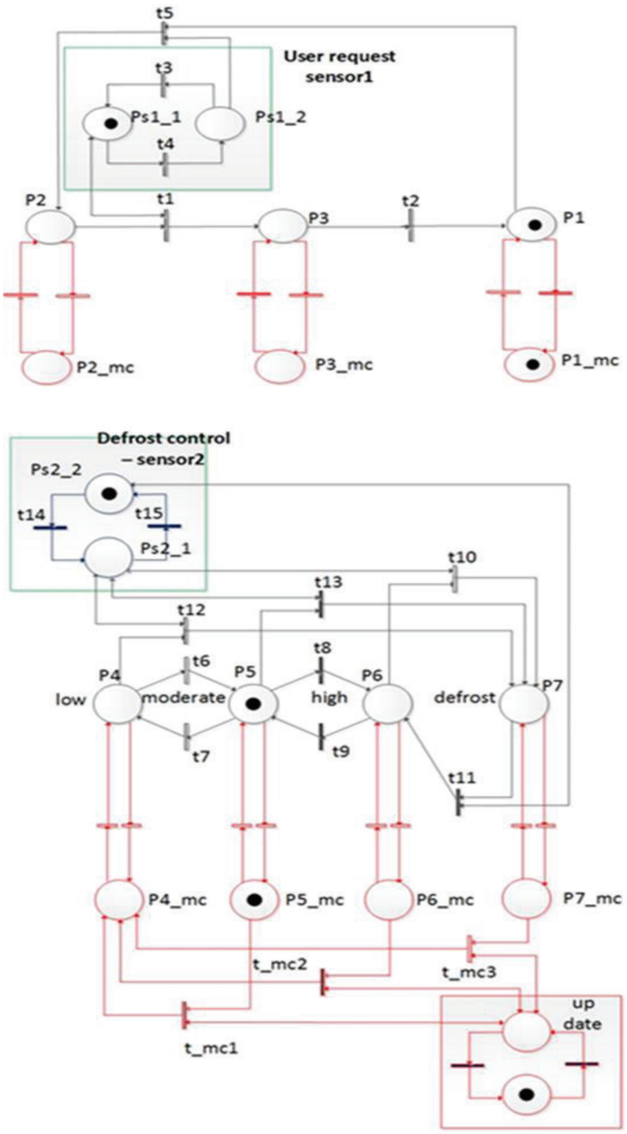

Fig. 5. Petri Net model of smart refrigerator.

TABLE I. Places and Transitions of s-REF Petri Net Model

Places		***Transitions***	
P_1	working status-ON	t_1	Change the working status from OFF to STDBY
P_2	working status-OFF	t_2	Change the working status from STDBY to ON
P_3	working status-STDBY	t_3	User request is received
P_4	compressor speedLow	t_4	User request is lost
P_5	compressor speedMode..	t_5	Change the working status from ON to OFF
P_6	compressor speedHigh	t_6	higher cooling capacity is required during low compressor speed
P_7	Defrost operation	t_7	lower cooling capacity is required during moderate compressor speed
P_{s1_1}	User request	t_8	higher cooling capacity is required during moderate compressor speed
P_{s1_2}	No user request	t_9	lower cooling capacity is required during high compressor speed
P_{s2_1}	Defrost is needed	t_{10}	Change the program mode from high compressor speed to defrost mode
P_{s2_2}	Defrost is not needed	t_{11}	Change the program mode from defrost mode to high compressor speed
		t_{12}	Change the program mode from low compressor speed to defrost mode
		t_{13}	Change the program mode from moderate compressor speed to defrost mode
		t_{14}	Defrost time has expired
		t_{15}	Defrost temperature > Defrost maximum set temperature

B2. Smart Washing Machine

A new generation washing machines, namely smart WM (sWM), is produced with different program modes to reduce water and energy consumption. In this work, four program modes are assigned to sWM such as *regular*, *long*, *express* and *special* modes. These program modes have different operating cycles (*water fill, heat, wash, soak, rinse, spin, softaner, drain, etc.)* All program modes have different washing durations, therefore different water consumption rates and power profiles. Power consumptions of sWM at different program modes are given in Fig. 6. Difference between energy consumption rates of these program modes demonstrate that selection of the appropriate mode is crucial for energy savings. User can select the program mode depending on the type and contamination of the laundry and can also define the desired working time intervals for sWM.

Since, program modes of sWM is dependent on the type and dirtiness of the laundry, MC cannot interfere with the program modes of sWM. However, it can interfere with the working modes of sWM.

PN model of sWM and the peripheral devices are given in Fig.7. In this PN model, user remote controller (sensor 1) is modelled by $P_{\text{sensor1}} = \{P_{s1\_1}, P_{s1\_2}\}$ and $T_{\text{sensor1}} = \{t_3, t_4\}$, where places P_{s1_1}/P_{s1_2} correspond to user request existence/absence.

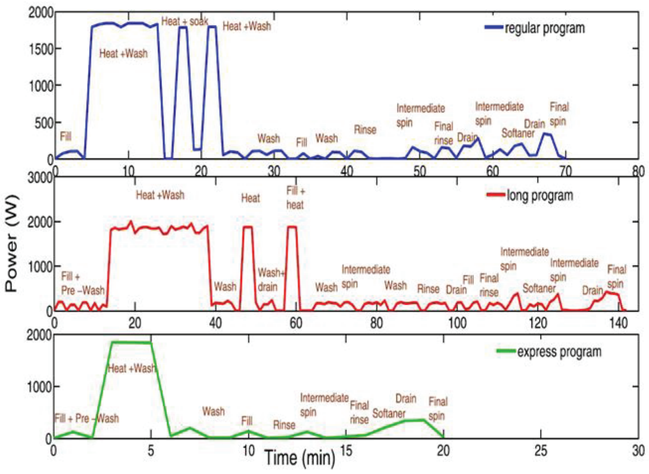

Fig. 6. Power consumptions of sWM at different program modes.

The status of this component is represented by the marking vector as $M_{\text{sensor1}} = [P_{s1\_1}, P_{s1\_2}]^T$. Timer sensor (*s*ensor 2) is modelled by $P_{\text{sensor2}} = \{P_{s2\_1}, P_{s2\_2}\}$ and $T_{\text{sensor2}} = \{t_5, t_6\}$, where places P_{s2_1} /P_{s2_2} correspond to “Time is in the desired time interval / Time is out of the desired time interval”. The status of this sensor is represented by $M_{\text{sensor2}} = [P_{s2\_1}, P_{s2\_2}]^T$. In this PN model, the third sensor is dirtiness sensor. This sensor is modelled by $P_{\text{sensor3}} = \{P_{s3\_1}, P_{s3\_2}\}$ and $T_{\text{sensor3}} = \{t_{16}, t_{17}\}$, where places P_{s3_1} /P_{s3_2} correspond to “too dirty / slightly dirty”. PN model of sWM consists of $P_{\text{WM}} = \{P_1, P_2, .., P7\}$ and $T_{\text{WM}} = \{t_1, t_2, t_7 ..., t_{15}\}$. Places $P_1/P_2/P_3$ correspond to on /standby/off working modes, while places $P_4/P_5/P_6/P_7$ correspond to *regular /long/express/special program modes* of sWM. $M_{\text{WM}} = [0\ 0\ 1 \mid 0\ 0\ 1\ 0]^T$. The mathematical model of the entire frame in Fig.6 consists of $P = P_{\text{WM}} \cup P_{\text{sensor1}} \cup P_{\text{sensor2}} \cup P_{\text{sensor3}}$ and $T = T_{\text{ref}} \cup T_{\text{sensor1}} \cup T_{\text{sensor2}} \cup T_{\text{sensor3}}$. The status of the entire model is represented by $M = [M_{\text{WM}}|M_{\text{sensor1}}|M_{\text{sensor2}}|M_{\text{sensor3}}]^T$. In Table II, places and transitions of petri net model of sWM are given.

When the user requests, the working status of sWM is set to standby. When the time reaches the time interval set by user, the working status is changed to on and sWM starts to operate. User sets the program mode to *long*, but the dirtiness sensor detects that the laundry is not so dirty, so the local controller of sWM change the program mode from *long* to *regular* in order to reduce water and energy consumption. User sets the program mode to *regular* or *express*, but the dirtiness sensor detects that the laundry is too dirty, so the local controller of sWM change the program mode from *regular* or *express* to *long* in order to increase the user comfort.

MC does not intervene in the program modes of sWM because the selected program mode depends on the type and contamination of the laundry, but if the home power consumption exceeds the permitted level, MC may interfere with the operating mode of the device within certain constraints, delay the start of operation. PN models of other home appliances (air conditioner, dishwasher, TV, water heater, coffee machine, coffee-machine, etc.) are ready and they will be shared if requested.

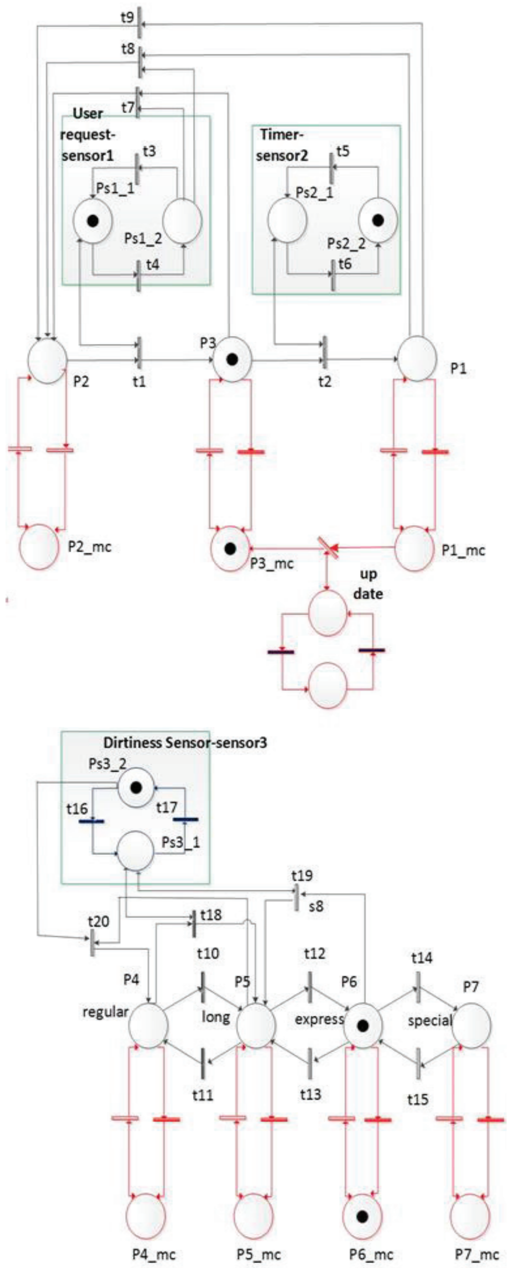

Fig. 7. Petri Net model of smart washing machine.

TABLE II. Places and Transitions of sWM Petri Net Model

Places		***Transitions***	
P_1	working status-ON	t_1	Change the working status from OFF to STDBY
P_2	working status-OFF	t_2	Change the working status from STDBY to ON
P_3	working status-STDBY	t_3	User request is received
P_4	Regular program mode	t_4	User request is lost
P_5	Long program mode	t_5	Time > Set starting time
P_6	Express program mode	t_6	Time > Set finishing time
P_7	Special program mode	t_7	Change the working status from STDBY to OFF

Places		*Transitions*	
P_{s1_1}	User request	t_8	Change the working status from ON to OFF
P_{s1_2}	No user request	t_9	Completed the washing program
P_{s2_1}	Time is the desired time interval	t_{10}	Change the program mode from regular to long by user
P_{s2_2}	Time is out of the desired time interval	t_{11}	Change the program mode from long to regular by user
P_{s3_1}	Too dirty	t_{12}	Change the program mode from long to express by user
P_{s3_2}	Slighty dirty	t_{13}	Change the program mode from express to long by user
		t_{14}	Change the program mode from express to special by user
		t_{15}	Change the program mode from special to express by user
		t_{16}	Too dirty is detected
		t_{17}	Too dirty is not detected
		t_{18}	Change the program mode from regular to long by sensor
		t_{19}	Change the program mode from express to long by sensor
		t_{20}	Change the program mode from long to regular by user

All new devices (sensors, appliances, actuators, etc) and features, which are integrated to the smart home system, can be modelled by Petri Nets to show their working principles and their interactions with the smart home system. Before installing the real appliances and smart home system, proposed models allow designers to understand whether smart home appliances and system work well. Consequently, models of smart appliances are useful tools to develop and improve smart appliances and smart home systems. In addition, after the real system is installed, these Petri Net models can be used to monitor the operation status of all appliances and smart home system. Some faults can be traced by using these models.

In this study, Petri Nets modelling is proposed for modelling the smart home appliances. The properties of these Petri nets models (reachability, boundedness, liveness, reversibility, coverability persistence, and etc.) are not been addressed.

IV. SIMULATION PROGRAM

In this study, in order to simulate the considered smart appliances and smart home system, a simulator program based on Keysight Vee and Matlab has been developed. The Graphical User Interface (GUI) of this simulation program is shown in Fig. 8. It serves as a dashboard for customers to monitor the status vectors of the appliances, communication status with MC, power consumptions of appliances, status of grid tariff and total power consumption of SH.

Users can enter their request by clicking on the appliances' icons or user interface icon. When the user clicks sWM icon, the sWM control panel in Fig.9. is appeared. User can select the program mode of sWM and set the operating time interval.

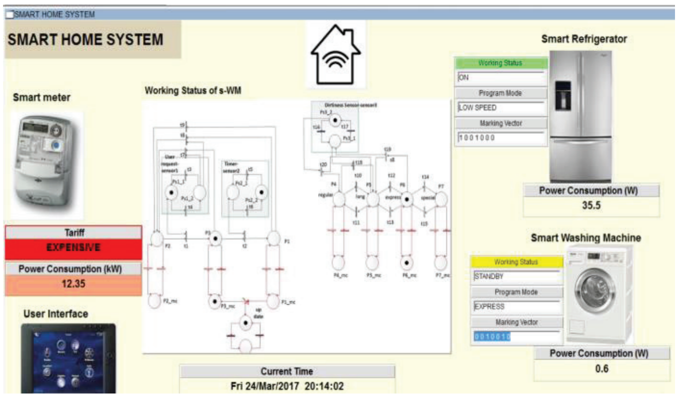

Fig. 8. Graphical user interface of simulation program.

It is assumed that an EMS module could be integrated to SH. For this reason, an EMS activation button is added to the control panel of smart appliances. If user select the EMS activate button, the MC may interfere with the operating mode of the device within certain constraints, delay the start of operation. If the EMS activate button is not active, MC cannot interfere the working status of sWM. By using "Learning" button, users may integrate new s-WM to the SH system. All real power measurements and program features are added to simulator database. Users also monitor the working status of sWM by using the same control panel.

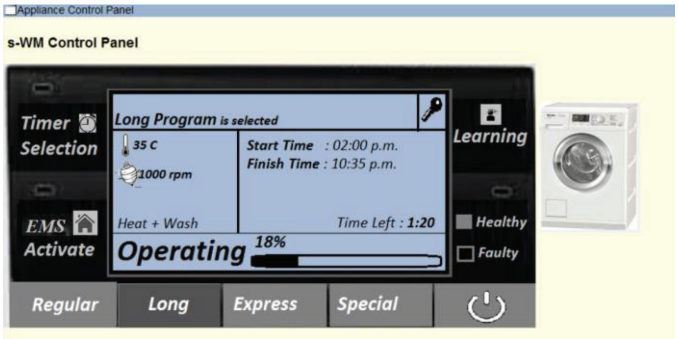

Fig. 9. Control panel of sWM.

V. CONCLUSION

Technological developments that affect human life make people's life easier. Recently, we have started use smart systems in our homes and factories. User expectations about home appliances and user habits have been changing. Smartness in our lives is very crucial to improve user comfort and reduce energy and water consumption. Home appliance manufacturers, research institutes, users are developing solutions for these purposes.

In this study, smart home appliances and their integrations to smart home system are considered. PN models of two of the smartest appliances, i.e., refrigerator and washing machine, are introduced to show their working principles and their interactions with the smart home system. Before installing the real appliances and smart home system, proposed models allow designers to understand whether smart home appliances work well. A simulation program based on Keysight Vee and Matlab is developed to simulate the proposed models. Consequently, models of smart appliances are useful tools to develop and improve smart appliances and smart home systems. In future work, more than one smart house will be modeled using Petri nets to integrate with the others in the same neighborhood. These Petri Nets models will be expanded to include smart grid components and renewable energy resources used in domestic areas.

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