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A smart home information management model for device interoperability simulation

Andrea Capitanelli[a,]*, Alessandra Papetti[a], Margherita Peruzzini[a], Michele Germani[a]

[a]*Department of Industrial Engineering and Mathematical Sciences*
Università Politecnica delle Marche, Via Brecce Bianche 12, Ancona 60131, Italy

* Corresponding author. Tel.: +39-071-220-4797. *E-mail address:* a.capitanelli@univpm.it

Abstract

Numerous smart home systems have been created in the recent years, but they still lack of high interoperability and research has been focused on single smart technologies instead of the system interoperability as a whole. Furthermore, available systems are usually strongly technology-oriented and they neglect the user's satisfaction and the benefits' analysis. In addition to this, modern systems impose the intelligent management of a huger amount of data, which needs to be properly coordinated to achieve higher performances and offer new energy-control services.
This paper defines an information management model to improve device interoperability in smart homes. It allows selecting and classifying the devices, visualizing their data model, aggregating the necessary data according to the desired service functions, and finally defining a set of rules to coordinate device operations according to user preferences and external events. A case study focused on washing machines is presented to demonstrate the methodology implementation; it allows designing and developing an energy-control service for the selected device and optimizing its functions according to the users' needs and preferences as well as the constraints of the use scenario. Finally, the benefits achieved with such a new service are evaluated in terms of energy consumption, costs reduction and user satisfaction in a simulated home environment that represents practical scenarios of use.

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1. Introduction

The recent advances in home automation and communication technologies offer many opportunities to the creation of innovative solutions for smart homes. As the residential sector is one of the most energy-intensive [1], there is a strong interest in the exploitation of smart devices connectivity to improve energy efficiency and reduce the related costs [2, 3]. In fact, smart homes can make several objects cooperate each other to achieve higher performances and allow the users improving safety, comfort and quality of life, saving energy and reducing the operating costs.

For this reason, the system should be conceived according both to the devices' technological features and the users' needs and skills. However, the existing systems are usually strongly technology-oriented and aim to increase the potentiality of a single sub-system or service neglecting the achievement of the expected benefit-cost ratio for the final user. Furthermore, although numerous system architectures have been proposed, the simulation of their behavior on practical cases is neither investigated nor detailed in literature.

In order to overcome these limitations, all the device typology within the smart home and their mutual relationships have to be considered, and the information flow and the user interaction with each device have to be analysed in order to properly model the home environment and define a set of rules for its management [4]. Therefore, understanding which functions a certain device is able to perform when connected to the network and what information generates and sends is fundamental.

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For this purpose, the presented approach aims to design a smart home data model able to define how the system functionalities can be performed, which information is required for each functionality, how to carry out the selected functionalities by a proper service system and which benefits will be provided to the final user. At the end a suitable management model can control the smart home devices by a set of rules and algorithms and provide the expected services.

Furthermore, the paper presents how the proposed rules are validated by their application in a simulated home environment where several devices intelligently interoperate to provide optimized energy-control services. Different scenarios are proposed to show how such a model aims to customize the system design according to several users' habits and needs. The case study focuses on a smart washing machine able to intelligently schedule its work in order to save energy and money. Simulation is focused on the analysis of benefit-cost ratio for the final users and compares the different scenarios on the basis of practical results. In particular, the simulation results show the users' benefits in terms of reduced energy consumption and expenditure. Such a simulation can demonstrate that the proposed model is a valid way towards the creation of a standard for smart devices interoperability.

The remainder of the paper is organized as follows: Section 2 provides an overview of the existing smart home system for devices interoperability and information management; Section 3 describes the proposed methodology to design a smart home information management model; Section 4 illustrates the approach implementation by a practical case study focusing on the "Device scheduling" function for washing machines and the user benefits are evaluated in a simulated home environment considering different scenarios of use.

2. State of the art

The smart home is a special place where all the sub-systems are interconnected allowing the users to save energy, to reduce operating costs and to improve safety, comfort and quality of life [5]. It implies creating a distributed system with many entities working together about the home dwellers and managing the interrelations between different sub-systems (i.e. home automation, digital entertainment, assistive computing, healthcare, surveillance, energy management). Furthermore, the spread and the growing intelligence of home devices impose the management of a huger amount of data than in the past whose flow has to be well coordinated in the communications inside the smart home and outward [6]. This issue becomes particularly important with the introduction of household appliances (washing machine, dishwasher, etc.) due to their complexity (i.e. numerous programs, settable functions, interaction with external home conditions and events). In this context, the proper data management must be associated with the definition of a proper architecture able to make all smart home devices interoperable and to guarantee a correct information exchange.

There are many possible typologies of architectures to build a Smart Home System (SHS) [7]. Traditionally, a SHS is built with central managed architecture where the sub-system interconnections can be guaranteed by a residential gateway. It is required for the integration between devices and sensors that differing in terms of connections and communication protocols, and serves as a bridge between the Home Area Network (HAN) and the external networks (i.e. Internet) [8]. Thanks to the residential gateway it is possible to have interoperability inside the HAN, it means an integrated environment with a lot of devices that cooperate each together as a single entities, exchanging data and providing high-quality services. In the recent years many SHS are proposed, but they do not have a high degree of interoperability and are usually strongly technology-oriented [9]. Nowadays, in most cases the information exchange takes place vertically between gateway and single device or between devices of the same sub-system [10]. The lack of a high-level system design does not allow offering advanced services and fully exploiting the system capabilities and potentials.

In this context, a robust approach to design a wide range of smart home functionalities is compulsory. Such an approach should be able to start from a high-level system analysis considering not only the technological requirements of the system, but also the user needs and skills [11]. Some studies recently explored smart home user-centred design, but they usually focused on specific aspects of the design, in particular on the user interfaces [12, 13]. Contrarily, a user-centred design approach for interoperability has to analyze the characteristics of the users interacting with the system and to define the proper functionalities to fulfill their needs and offer optimized services. In this direction, a recent study explored the smart home experience and highlighted the main characteristics of smart home users [14]. Whereas, other projects highlighted the characteristics of the residential electric consumption by country, providing an energy database of average device use and potential savings [15, 16]. Both aspects are fundamental to provide high-level services by exploiting smart home capabilities, but they are usually studied separately. Indeed, a joint approach is necessary: starting from a high-level system architecture and the specific users' requirements, a dynamic and interoperable environment characterized by explicit but flexible relationships between home devices, significant information, home events, and management rules must be firstly modeled and then simulated.

3. Simulating the smart home information management model

3.1. Design methodology

The research approach aims to define and simulate a smart home data model able to properly manage the following aspects: devices' smart functions, device interoperability, user interaction with smart devices and functions, smart devices' information flow, and rules required to perform the system functionalities.

The adopted methodology can be summed up in six main steps (Fig. 1):

1. Identification of the service users' needs in the smart home for the specific context of use;
2. Definition of a set of smart home functionalities to satisfy the service needs for the specific context;

3. Classification of smart home devices and their characteristic information which consider both data generated by the devices themselves and external data;
4. Definition of a general information management model correlating the information categories with the device classes (Matrix 1);
5. Definition of a set of intelligent rules and tasks to perform the service functionalities;
6. Integration with Matrix 1 in order to establish which devices and data is required by a specific rule (Matrix 2) to provide the desired services.

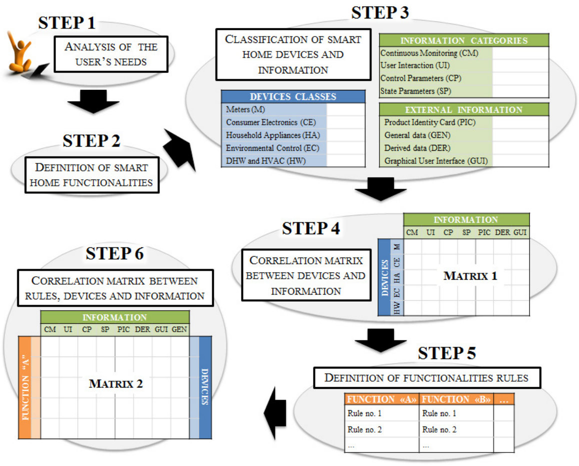


Fig. 1. Smart home information management model

3.2. The correlation matrices for system design

The design of the high-level system requires a holistic and user-centred approach and focuses on the service user's needs satisfaction to support the design of an intelligence-based information management tools. For this reason, the first step concerns the analysis of the user's needs in relation with a specific context of use (e.g. elderly people living alone, young married couple with an active lifestyle, a family with two little babies, etc.). Such an analysis is carried out by involving sample users and investigating their habits and behaviors by different techniques such as interviews, questionnaires, and brainstorming sessions. At the end, a list of users' needs for the implementation of useful services supporting people in the specific context of use is defined.

The second step consists in the identification of the smart home functionalities able to satisfy the identified user's needs. Some general aspects like energy, comfort, security, safety and product care are considered as well as standard functions related to the system management and possible preset scenarios. Table 1 shows examples of functionalities for each category investigated in the present research.

Step 3 aims to provide an overall vision of the smart home in order to create a general information management model. For this aim, smart home devices are identified and displaced in five homogenous classes (Table 2) according to the typology, treated data, and home interaction modalities. Renewable energy systems are included in the meters category as the information provided by the dedicated meters, neglecting the specific system parameters. Data model classification considers four main categories (Table 3): they allow eliciting the relations between the information generated by the smart home devices and their functions.

Table 1. Smart home functionalities categories

Energy	Devices scheduling Home historical consumptions analysis
Comfort	Heating automatic regulation Home environmental conditions monitoring
Security	Leaks detection Intrusion detection
User safety	Mobility monitoring Fall detection
Product care	Device remote maintenance Product use analysis
System management	Scenario creation Device installation
Scenarios	"Out of home" "Holiday"

Table 2. Smart home device classification

Meters (M)	Electricity, gas and water meters and control and safety systems (e.g., electrical safety, gas leaks, water leaks). Also meters of renewable energy systems (e.g., photovoltaic, micro-wind turbine) are included.
Consumer Electronics (CE)	Entertainment systems (e.g., TV, game console, audio equipment and players) and small household appliances (e.g., coffee makers, electronic cutters or graters, toasters).
Household Appliances (HA)	Major household appliances such as refrigerator and freezer, oven, hob, hood, washer, dryer, and dishwasher.
Environmental Control (EC)	Lighting, doors, windows, alarm system and sensors, window curtains and shutters.
DHW and HVAC (HW)	Domestic Hot Water devices (DHW), Heating, Ventilation and Air Conditioning devices (HVAC), and all the devices and sensors related to their functioning (e.g., sensors of indoor/outdoor temperature, humidity sensors).

Table 3. Smart home information categories

Continuous Monitoring (CM)	Information continuously monitored when the devices are turned on. They mainly consist of resources consumption data (e.g., energy, water, etc.), which can be used to provide a feedback to users and companies.
User Interaction (UI)	Information regarding the user-product interaction and characterizing the users' behaviours (e.g. selected options, duration of use, time of use, frequency), which can be used for statistic analysis and post-processing.
Control Parameters (CP)	Functional parameters that are continuously analysed and compared with target parameters. Such data are used to predict problems, detect conditions, and supervise device functionality and user security.
State Parameters (SP)	Information regarding the status of home devices, which is used to monitor a particular scenario or to carry out device remote control.

The model also considers four extra categories of data (Table 4) that are not directly generated by the devices but provided by external entities (e.g., utilities, manufacturing companies), elaborated by the system or sent by the users by means the Graphical User Interface (GUI).

Step 4 considers the above-mentioned information categories and matches them with devices classes: as a result a correlation matrix expressing the relationships between devises and information is populated (Matrix 1). In this phase, the “General data” category is not considered because it comprehends data not directly linked to a specific devices class. Table 5 shows an extract of Matrix 1.

Table 4. Smart home external information categories

Product Identity Card (PIC)	Device reference information provided by the manufacturing company (e.g. datasheets, standard consumptions, etc.). They are fundamental for the products care and do not depend on the smart home.
General data (GEN)	Data generated by external entities (e.g. building typology, occupants’ characteristics, economic indicators, fees of utilities, climatic conditions) that contribute to define the analysed scenario.
Derived data (DER)	Data derived from post-processing elaboration and statistics analysis (e.g. average time of use, average expenditure over the time, use frequency), which can be used for realizing specific service functionalities. They are considered external as they are usually produced by partners’ elaborations and software systems.
Graphical User Interface (GUI)	Data generated by the users as remote settings of the proposed smart home functions (e.g. on/off, close/open, show details, set parameters, etc.).

Table 5. Correlation matrix between system information and device classes

MATRIX 1		**INFORMATION**			
		Continuous monitoring	**User interaction**	**Control parameters**	**…**
DEVICES	**M**	Gas consumption Power consumption Water consumption	Shutting on/off gas Shutting on/off water Shutting on/off power	Electrical overload Short circuit Gas flow rate Gas pressure Water flow rate …	…
	CE	Power consumption	Delay start Turning off time Turning on time	Volume	…
	HA (WM)	Grid frequency Power consumption Water consumption	Delay start Eco wash on Easy iron on Extra rinse on …	Cycle time Cycle phases time Detergent level Door lock …	…
	…	…	…	…	…

Step 5 consists in the definition of the intelligent rules managing all the relations between devices, information and events in order to realize the desired service functions by executing a set of tasks.

Finally Step 6 considers the interaction between the smart home and the ecosystem actors (i.e., users, energy utility and company technical staff). In particular, a correlation matrix (Matrix 2) is created to define the rules sequence of a specific service function and the necessary information and devices. In this way, only data directly related to a specific rule are considered and each row of the matrix represents a subset of data from Matrix 1. An example is shown in the case study. The last step is the core of the methodology as it allows understanding what devices can be used to realize a certain service function, which data have to be managed and how each specific device will collect data from the other devices and will make data available for the interoperable system. Such a model is general as it can govern different SHS architectures, different ecosystems and different services with the same correlation matrix.

3.3. Simulating the smart home information management model

When the information management model is completely designed as described in the previous sections, it can be executed in a simulated environment, which reproduces different scenarios of use to effectively validate the system information exchange and the achieved benefits. The simulated scenarios consider the selected devices and data and execute the defined rules according to the designed model to simulate the expected behaviors of the devices and finally estimate the achieved benefits.

The simulating environment has been realized as a Matlab application. It is able to model the considered devices by a set of equations expressing their effective behaviors, which are taken from literature and from field tests. The tool has some databases containing known data (i.e. home features, the weather conditions, the tapping profile of the hot water, etc.) and an excel interface to set the desired data according to the energy management model proposed.

4. Case study

This section presents how the proposed approach can be implemented to design the “Washing Machine scheduling service” as a simplified practical case, which is able to point out clearly the effective benefits of the methodology. The first part of the case study shows how the user can easily select the desired service function as well as the devices involved, and how the system visualizes the data model and identifies the rules to perform the selected functions in practice. In the second part the proposed rules are validated on two application scenarios by estimating the potential benefits of the optimized energy-control service in terms of energy saving, costs reduction and user satisfaction.

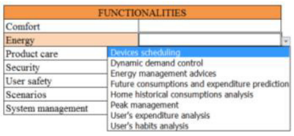
4.1. The Washing Machine scheduling service

The “Washing Machine scheduling service” is included in the “Energy” field and contributes to the satisfaction of the user’s need of money saving (Step 1). It is realized by applying the “Device scheduling” functions (Table 1) of the general information management model (Step 2).

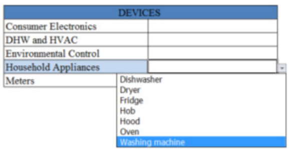
Step 3 consisted in the selection of devices involved in the selected function. There are five device classes related to the energy category and each device class contains a group of devices. In this case the Washing Machine is selected, but the service takes into account other devices always in operation such as the fridge, the water circulation pump and the devices in stand-by status. In Step 4, all data concerning the washing machine operation and the other involved devices are listed and classified considering also the external information categories in order to create the Matrix 1. Step 5 introduced a set of intelligent rules for the WM scheduling function that are correlated with data, devices, and external events. The proposed structure is composed by a set of tasks that describe step by step the function operations. A tool for function design and rules definition is in developing to automate and speed up the process. It will allow designing a function, save it in a database and reuse it for future analysis with automatic recognition of the device information. Step 6 consisted in linking Matrix 1 with the WM scheduling function tasks. Only data and events related to the selected function are kept for the case study, while other information is not shown as reported in Matrix 2 (Fig. 2). In particular, the rules to perform the "Device scheduling" are listed on the left, whereas the relations between devices and rules are specified on the right. It is worth to notice that this step shows how the proposed model easily defines the rules to manage a set of tasks to carry out the intelligent scheduling.

These rules are valid for all washing machines, homes and users, because the goal is to create a standardized model. Obviously each user can obtain different benefits from this service in relation to his/her habits. The user's benefits evaluation allows comparing different scenarios of use depending on the specific users' habits and behaviors and assessing the advantages of such an approach.

1) "DEVICE SCHEDULING" SELECTION



2) "WASHING MACHINE" SELECTION



3) MATRIX 2 RELATED TO THE WASHING MACHINE SCHEDULING FUNCTION

	DEVICE SCHEDULING	CM	UI	CP	SP	PIC	SP	GEN	DER	GUI	
RULES	If the parameters are conform with the start condition, Then do next step. Else send the message to user.				Open/Close door; Cycle phases in progress; Detergent and load presence; On/Off		Open/Close door; Cycle phases in progress; Detergent and load presence; On/Off				HA → WM
	Calculate the latest time for the cycle start according to the user setting and considering a tolerance.		Set time to finish; Set special function; Set program; Set spin speed; Set temperature								HA → WM
						Standard phases cycle					HA → WM
	Schedule the device start to minimize the energy expenditure for the user considering the other devices scheduling and according to the priority rules and user needs.					Standard power consumptions					HA → WM
		Power consumption						Expected renewable electricity produced			M → E
			Delay start; Set time to finish; Standard phases cycle time			Standard power consumptions				Scheduled start time; Set time to finish	HA → DW HA → DR
			Scheduled on/off time			Standard power consumptions				Scheduled on/off time	CE
			Scheduled on/off time			Standard power consumptions				Scheduled on/off time	EC → L
			Scheduled on/off time			Standard power consumptions		Expected outdoor temperature		Scheduled on/off time	HW
								Current energy price; Energy price ranges; Max power available; Expected energy price; Priority rules; Current time			
	Turning on the device at the scheduled time.										

Fig. 2. Simulation of the information management model for the "Washing Machine scheduling service"

4.2. Service simulation and benefits evaluation

Simulation allows estimating the benefits achieved by the proposed service model and optimizing or customizing the general model for particular user or users class. For this purpose, two real use scenarios are compared in the simulated environment. The tool considers the electrical energy data of the washing machine, the consumption of other devices always in operation (i.e., fridge, water circulation pump) and the stand-by power consumption.

The simulation tool exploits the rules defined by the model and described in Matrix 2 (Fig. 2), evaluates the user's benefits and produces a report. It allows verifying and evaluating the service quality that will be implemented in a real Smart Home. The case study simulates a one-year lifetime to highlight the differences between a user and the other. It simulates devices operation and takes from real database the external data, i.e. weather data, representing a real condition where the system needs to know in advance the weather forecast and device set program to calculate the better device scheduling. The simulation result consists of an assessment of the potential benefits that can be achieved by the "Washing Machine scheduling service" operated by the home energy manager.

Two different use scenarios are analyzed; they vary for number of users, habits and locations:

a). a family of 4 people who lives in Ancona (Italy);

b). a young couple who lives in Torino (Italy).

In both cases there is a contract with the energy utility of 3 kW as maximum power available from the grid and a photovoltaic panel with a surface of 20 m^2. As far their habits are concerned, there is a different use of the washing machine in the two scenarios that brings to different energy consumption, hours of use and preferences for the programming. The family (scenario a) normally does 6 cycles per week during the day as shown in Fig. 3, whereas the couple (scenario b) does averagely 4 cycles per week. In Fig. 3 data characterizing the two scenarios are shown: number of cycle per week, cycles enabled for automatic scheduling, time horizon for scheduling, cycles with fixed start time, washing temperatures, load of clothes.

a

CASE 1 - FAMILY

External Information	
City	Ancona, IT
Users typology	Family
Users numbers	4
Max power avaiable	3
PV surface	20

Washing Machine						
Energy label class						A
WM cycles per week						6
Cycle	Now	Sched.	Cycle start	Cycle end	Cycle temp.	Load
1	08:00	Yes	08:00	18:00	60 °C	5 kg
2	08:00	Yes	08:00	18:00	40 °C	5 kg
3	16:00	Yes	08:00	18:00	40 °C	5 kg
4	19:00	No	-	-	40 °C	5 kg
5	20:00	No	-	-	60 °C	5 kg
6	20:00	yes	08:00	18:00	40 °C	5 kg

b

CASE 2 - COUPLE

External Information	
City	Torino, IT
Users typology	Couple
Users numbers	2
Max power avaiable	3
PV surface	20

Washing Machine						
Energy label class						A
WM cycles per week						4
Cycle	Now	Sched.	Cycle start	Cycle end	Cycle temp.	Load
1	08:00	Yes	08:00	19:00	40 °C	4 kg
2	08:00	Yes	08:00	19:00	40 °C	4 kg
3	19:30	Yes	08:00	19:00	60 °C	4 kg
4	19:30	No	-	-	40 °C	4 kg

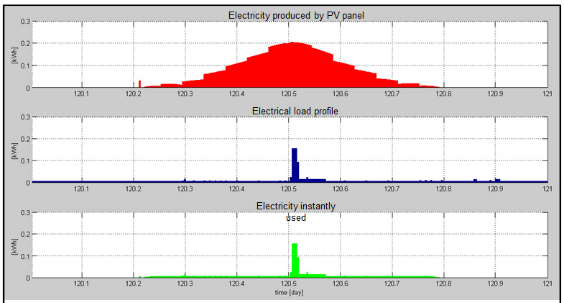
Fig. 3. (a) Family input data; (b) Young couple input data

The simulation results show the benefits achieved in the two scenarios as shown in Fig. 4. Three cases are considered:

1. current situation,

2. adoption of the “Washing Machine scheduling service” according to the user preferences,
3. adoption of the “Washing Machine scheduling service” in an automatic modality.

For all of them, the average electricity price is 0,20 €/kWh and it is considered for the calculation of the user expenditure and saving. Government incentives are not considered to evaluate the effective benefits achieved by the service implementation. Results highlight that the family (scenario a) does many washing cycles and spends more money than the couple (scenario b), but it can obtain more saving from the service. Energy consumption costs before and after the scheduling are the same, but the service allows optimizing the washing times and exploiting the low cost energy taken from the PV solar panel, since other devices consumption remains unchanged. The automatic modality (case no. 3) brings to the highest saving to the user. This leads to an increased use of renewable source and consequently to a reduced environmental impact and operating costs for the consumer.



FAMILY Cases	WM electric consumption [kWh]	Total electric consumption [kWh]	Electricity from the grid [kWh]	Electricity from the PV panel [kWh]	Expenditure [€]	Saving [€]	User effort
Current	255,91	1203,14	733,60	469,54	146,72	-	-
After Sched.	255,91	1203,14	652,33	550,81	130,47	16,25	*
Max	255,91	1203,14	586,18	616,96	117,24	29,48	***

COUPLE Cases	WM electric consumption [kWh]	Total electric consumption [kWh]	Electricity from the grid [kWh]	Electricity from the PV panel [kWh]	Expenditure [€]	Saving [€]	User effort
Current	144,05	1091,28	635,67	455,62	127,13	-	-
After Sched.	144,05	1091,28	577,08	514,20	115,42	11,72	*
Max	144,05	1091,28	552,79	538,49	110,56	16,58	***

Fig. 4. Simulation report

The case study shows that each kind of user achieves different benefits by exploiting the same service accordingly to the different habits and requirements. For this reason, also other variables have been considered – not reported in this paper – (i.e., different energy price ranges, absence of renewable energy system). Furthermore, it is worth to notice that the benefits are more significant performing the “Devices scheduling” function for all the Smart Home devices in order to realize a set of scheduling services of the different devices, or enhancing such service with other energy-oriented functions to reduce global consumptions i.e. “Energy management advices” and “Home historical consumption analysis”.

5. Conclusions

This paper presents a methodology for designing and simulating a smart home information management model able to perform system functionalities according to user’s needs, devices typology and information flow. In particular, it defines a model to set the most proper rules to manage each system function and to provide end-user services. The case study focuses on washing machines and applies the proposed approach model to the “Devices scheduling” function: in particular it creates a model for the so-called “Washing Machine scheduling service” and assesses the related benefits in terms of energy consumption and expenditure reduction obtained in a simulated home environment. The research shows the main advantages of the proposed model: flexibility, modularity and scalability, adaptability to different SHS architectures and ecosystems, and highly customization of functionalities and services to satisfy a wide range of users.

Future works will consider the implementation of a smart home system prototype, the testing of the most common functionalities in different contexts and the evaluation of the achieved benefits in terms of environmental impact, performances, operating cost and user’s satisfaction.

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