Example of a New Smart Kitchen Model for Energy Efficiency and Usability

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***Abstract* — The paper presents the design, the implementation and the evaluation of an innovative smart kitchen called E-Kitchen where the technology is intended to make everyday life easier increasing comfort, energy efficiency, usability and safety. E-Kitchen is a kitchen environment, completely redesigned according to User-Centered Design approach, which implements a home automation system based on ZigBee communication technology. It integrates several devices: smart household appliances, devices connected with smart plugs, sensors, lighting systems. A qualitative usability assessment, which involved final users, highlighted that adopted solution is able to enhance the accessibility and usability of the kitchen especially for the elderly. Moreover, it allows to increase the users' energy awareness and it contributes to increase energy saving.**

Keywords-Smart kitchen; user centered design; accessibility; context and energy awareness.

I. INTRODUCTION

Nowadays, the kitchen is the main room of the house, a multifunctional space where people spend a lot of time to prepare and cook meals, to eat them and store the supplies. Moreover a kitchen can be regarded as a space for the family members to meet together and pass time during lunch and dinner preparation.

In particular, it was estimated that the kitchen is the room where the family spends the majority of the time (35%) [1]. The kitchen is also the space more "dangerous": more than half of the domestic accidents happen in the kitchen (55%) [1]. No other room of the house is so dangerous, because in any other room the frequency of accidents is always less than 10% [2]. The main cause of trauma and incidents is due to the everyday use of devices and tools of kitchen, such as knives, oven, small appliances and cookware. Most of them occur for distraction and scarce prevention. The kitchen and in particular the worktop, have often insufficient lighting and this causes loss of visibility so increased risk of accident. Furthermore, the space above the worktop is often full of accessories and all kinds of objects, making everyday tasks more difficult and dangerous.

The kitchen is also the space with the higher number of "machine elements" and the room that consumes more energy in the house. It estimated that kitchen appliances, including refrigerators, freezers, oven, and dishwashers, account for nearly 27% of household electricity use [3]. Therefore, the necessity of reduce the energy consumption of a kitchen becomes a priority. In most home automation systems, control is given by user that establishes manually all parameters. In this way, the behaviors and actions become central for energy saving. For this reason, awareness and feedback about electricity consumption is a key aspect to save energy.

Our main focus has been to create a smart kitchen where user is central element of system design. In particular, it was attempted to make more comfortable and safe the kitchen environment through the inclusion of a series of technological interact smart and high usability solutions. Technology becomes a support and a tool by which to ensure a better livability of the kitchen in terms of safety, comfort and well-being. In particular, it has been developed a smart system that allows to coordinate the appliances and sub-systems in order to optimize energy consumption, increase energy efficiency, and improve the usability of the kitchen.

This system is managed through a web user interface, which gives information on the functioning and energy consumption of all devices in the kitchen, allows to set and control all household appliances in a simple and intuitive way and gives information and alerts in case of situations of warning.

The paper is organized as follows. Section 2 summarizes some of the approaches presented in literature about sensor in smart homes, smart appliances, energy management and intelligent control systems. Section 3 gives the description of system and highlights the innovations. Section 4 reports the results of the experimental assessment of e-kitchen environment. Finally, some final considerations are provided in Section 5.

II. RELATED WORK

Smart home can be defined as “a house which comprises a network communication between all devices of the house allowing the control, monitoring and remote access of all applications and services of the management system” [4]. There are a wide number of scientific works focused on smart home, but they investigate only one aspect such as smart object and sensors. Scientific research on kitchen environment is still at the beginning and it has often analyzed as part of the smart home [5].

Many studies of sensing systems have been developed for monitoring and controlling of environmental parameters of a house. Ding et al. [6] make a state of the art of sensor technology most commonly used in smart home. The work highlights the strengths and limitations of different sensor technologies and focuses on the opportunities from the

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perspective of technical, clinical and ethical. It emphasizes that there is not a generic perfect mix of sensors: each case must be evaluated independently and designed for the specific needs. Muñoz et al. [7] present a system that allows to control the house through simple and unobtrusive sensors, and a multi-agent architecture. This system gives the possibility to supervise the state of the house and occupants, and gives instructions and guidelines through an alert assistant. Similar work is that of Stander et al. [8] in which a sensor system provides an overview of the whole kitchen. The system, through a sensors infrastructure, monitors the status of the room and obtains information about the various devices.

On the other hand, many studies are focused only on smart appliances, in order to make them intelligent so as to make life more safety, convenient and comfortable. An example is the study on a smart fridge [9] which detects the amount of foods stored inside it (i.e., milk bottles, fruits, bread, drinks, water bottles, or the quantities of irregular shape, such as vegetables, meats, etc.). Moreover, if the amount of food is less than a set value, it can communicate automatically with the food supplier by web and order the needed food. In addition to detection capability, the refrigerator implements a control system of the gas oven installed in the kitchen. The system controls remotely the switching on and off of device.

In the recent years, this kind of development is being taken up by the major commercial players. For instance, at the last Consumer Electronic Show (CES 2015) Bosch [10] presented a refrigerator with built-in camera that allows to look inside when the user is not at home, making meal choices and grocery shopping easier. Even Whirlpool [11] and LG [12] have introduced on the market the first smart appliances such as refrigerators and ovens that communicate with the internet and could be controlled remotely by mobile phone.

The research focus is also on optimal energy load management strategy for household appliances. Arghira et al. [13] present a method that predicts the consumption of each appliance, to estimate how much energy can be saved. This research is based on dynamic demand-side management, and allows energy saving due to the different cost of energy and the maximization of renewable energy. Nistor et al. [14] propose a control system of household appliances to reduce energy loads. The system is made up of a central hub which communicates with the different devices and it is programmed according to user needs. The system can manage the functioning of the devices through various algorithms. According to user preferences, the shifting and interruption of appliance operation, permit save energy at the system level. Frederiks et al. [15] say that in order to save on domestic energy consumption, is necessary to act on user behavior. Only by understanding and managing the psychological motivations we can encourage a more responsible consumption of energy.

All of these studies focused on the technical aspects and marginally consider the end user preferences and characteristics. For this reason, the introduction of new appliances not always leads to an increase in usability. In fact, the user often uses only a minimum percentage of functions. However, it is possible to find several works focused on human-machine interaction but for only one aspect. An example is provided by the development of help and user guides in food preparation. Ficocelli and Nejat [16] have developed an assistance system in kitchen's daily activities as research of recipes, help during the preparation and guidelines to a healthier behavior. Chen et al. [17] presented a system that, once recognized the food, provides information about calories and nutritional values.

Almost all of the research is focused on one of the three aspects that characterize the smart kitchen: internal communication network, intelligent control systems, and home automation and do not consider the usability of the whole system. Our work has been focused in the development of a smart kitchen in terms of physical and cognitive ergonomics in which technology will be completely invisible to not limit the use of the environment. In this way, the kitchen itself will become an interface through which the system will communicate information and alerts (visual communication), and the user will be supported by an "artificial intelligence" in the management of household appliances.

III. SYSTEM'S GENERAL DESCRIPTION

E-Kitchen is a new concept of "innovative kitchen" (Figure 1) in which the technology is intended to make everyday life easier increasing comfort, efficiency, usability and safety.

Figure 1. E-Kitchen prototype.

The system was designed through the study of three main interactions (Figure 2): human-environment, human-machines and machines-environment. The study of these three aspects has allowed to obtain a kitchen usable and accessible highly, that implement a smart home automation system.

In particular, the work on machines-environment interaction permitted to achieve:

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- the control of devices to ensure the safety of the environment,
- the control of operating parameters of devices,
- the possibility to manage the status and self-diagnosis and auto repair,
- the monitoring and optimization of energy consumption.

Figure 2. E-Kitchen structural represantion.

The second level of interaction (human-machines) is related to the usability of the "machines" and focused on the study of:

- an highly usable user interface to allow communication/visualization of information,
- system software based on User Centered Design.

Finally, the human-environment interaction has been analyzed to improve:

- the functionality and ergonomic layout,
- the system integration,
- the possibility to monitor user behavior and activate alerts in case of need or assistance.

In this way, it has been developed a kitchen environment in which there are multiple systems that contribute to transform a kitchen in “smart kitchen”. E-Kitchen is structured in three systems: kitchen system, the "smart" devices system and, finally, the home automation system.

A. Kitchen

An innovative kitchen layout has been developed to allow a perfect integration between technology, design and ergonomics. In accordance with ergonomic approach, an innovative layout has been designed, to prevent any risk to the user during daily operations. In particular, the depth of the working top has been increased according to the specification deduced from ergonomics (Figure 3) and the results of an ethnographic analysis, which involved 20 people aged between 50 and 85. In fact with the current base cabinets, deep 60 cm, the wall units are too close to the user's face causing the narrowing of the visual field and increasing the risk of collision. Moreover, the results of the behavior analysis showed that connections of water and sanitary system greatly influence the layout of the kitchen and often lead to bad design.

The worktop 80 cm deep has been then designed to obtain a more open space, a greater freedom of movement and a perfect view on the working plane. On the other hand, the additional space has been very useful to design the expansion of sanitary vacuum which can accommodate pipes. So, the layout of the kitchen can be separated from connections of water and sanitary system thanks to this added space.

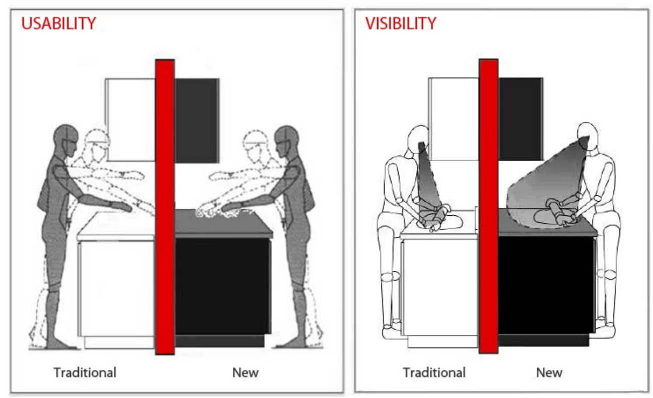

Figure 3. New worktop improve usability and visibility.

Ethnographic analysis also revealed many accessibility issues related to the interaction user-cabinets. To solve these problems the kitchen is also equipped with some electromechanical systems to improve its accessibility.

Devices have been inserted on the back of the wall cabinets to obtain an extra storage space. It makes accessible an additional space, always handy and useful for storing everyday items (e.g., dishes, utensils and small appliances such as coffee machine). Similarly, facilitator systems are included in the lower drawer of base cabinets, to facilitate easy access to users with limited mobility (Figure 4).

Figure 4. Electromechanical systems: the wall unit device (on the left), the system for base cabinet (on the right).

B. Smart devices system

The kitchen is equipped with a lot of devices. Figure 5 describes the architecture of E-Kitchen communication network and shows all the elements which constitute the intelligent system.

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The network is realized through ZigBee technology. It provides communication from/to any appliance or device and from/to the Gateway. The Smart Gateway is able to communicate with the outside through connection to the Modem-Router. A Power Meter ZigBee (SmartPlug) installed downstream of the energy meter provide to measure the global consumption of the house and to send data to the Gateway.

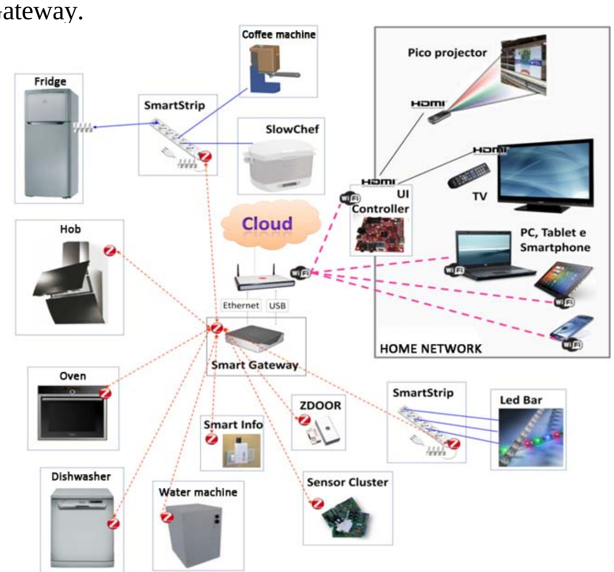

Figure 5. E-Kitchen communication network

Household appliances which provide smart service (i.e., oven, dishwasher and hood) are equipped with communication interfaces based on ZigBee standard. Other devices (i.e., the fridge) are connected through Power Line Communication (PLC) and ZigBee standard. For the conventional appliances (i.e., the coffee machine), which are not capable to communicate with system by themselves, ZigBee smart plug have been used in order to monitor energy consumption and to turn devices on/off remotely.

In the E-Kitchen system, standard sensors (i.e., temperature and humidity) and non-standard sensors (i.e., air quality) have been implemented to identify emergency situations: for example, light sensors are used to detect when room becomes too dark, and temperature sensors are used to control kitchen hob. All the sensors use the ZigBee and Bluetooth standards.

Led lights have been inserted under the wall cabinets and under the base cabinets of the kitchen. They permit to transform the kitchen into a real user interface able to communicate information and alerts. There are two kinds of led strips: white to illuminate the worktop and red for seeing information. The white lights can be automatically activated when the home automation system detects a low level of brightness in the environment. The red lights are exclusively remote controlled and are used to manage the information (e.g., warnings or alarms) that the system sends to the user.

C. *Home automation system*

The home automation system enhances the usability, intuitiveness and safety of the kitchen environment. The hub of such system is the Smart Gateway, which manages all the information. It connects smart devices of Home Area Network (HAN) to the modem/router Telecom Italia [18] to make them available outside the home automation network, through the internet (Figure 6).

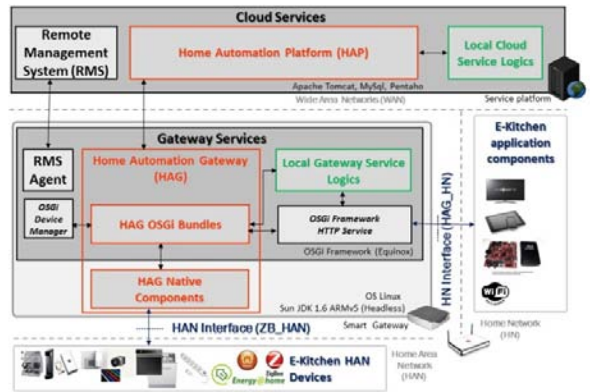

Figure 6. Hardware architecture.

The Smart Gateway is composed of Home Automation Gateway (HAG) and other local application bundles. HAG is constituted by a set of native components and some bundle included in OSGi framework (HAG OSGi Bundles). HAG permits local application bundles (Local Gateway Service Logics) and applications of devices of Home Network (E-Kitchen application components) to interact with HAN devices and access to storage data of Home Automation Platform (HAP). HAP is a platform in a cloud service that gives network storage service of data collected by the devices of the HAN. The stored data can be accessed from the HAG or other logic network application (i.e., Local Cloud Service Logics that can process the raw data sent by the gateway and store new data).

A web-based User Interface Controller has been developed that allows the user to manage and interact with the E-Kitchen environment. The controller software architecture is realized by two parts: Logic Unit (LU) and User Interface (UI) (Figure 7)

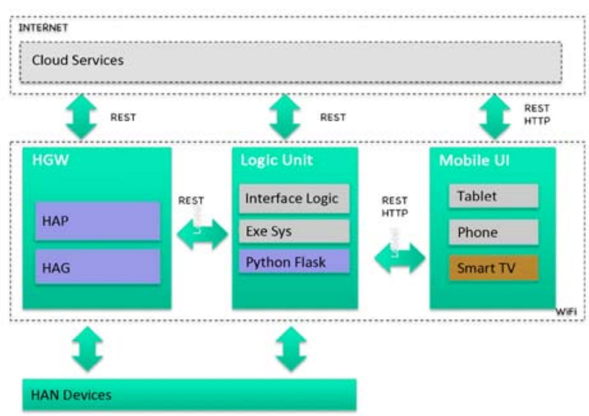

Figure 7. E-Kitchen software architecture.

The LU manages the communication to/from the home gateway and it is involved to execute logic management

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system based on events and store data. In particular, the LU processes all the information provided by system, it elaborates that information and operate events through a decision-making algorithm in order to support the user. It is also managed by the user through the UI.

Figure 8. E-Kitchen User Interface.

The UI is a web application developed in Cloud Services, which manages the interface visualization and user interaction with the system. The interface is visible and accessible at any time and can be displayed on PC, Smart-TV, Smartphone or Tablet (Figure 8).

The Graphical User Interface has been design according to User-Centered Approach. The design process consists of the following steps:

- collection of project requirements and user needs;
- definition of a concept design solution;
- construction of a paper-prototype;
- evaluation of the design solution with usability experts and identification of improvements;
- construction of full functional high fidelity prototype (figure 8);
- design evaluation with users, which is described in the following paragraph.

IV. EVALUATION SYSTEM

A preliminary usability evaluation have been carried out to assess E-Kitchen system in terms of usability and acceptability, with focus on the impact of additional features. It has been chosen to use the methodology well-known as thinking aloud [19] to understand in more detail the choices made by users during the course of the assessment.

In order to carry out a qualitative assessment focused on global characteristics rather than on individual aspects, usability tests have been based on tasks scenario. Each scenario has been designed in order to allow evaluation through the observation of interaction between the user and the whole system.

In the evaluation, there have been tested two different ways of interaction: direct (without the help of the user interface) and mediated by the user interface visualized through a tablet. At the end of the evaluations, user impressions were gathered through interviews conducted by evaluators and questionnaires.

The following objective parameters have been collected during the test by using the form reported in the figure 9:

- (C) Completion of the task (S / N);
- (E) Number of errors made by user during the interaction with household appliances;
- (I) Number of errors in the use of the interface;
- (O) Capacity error correction (S / N);
- (H) Reference to the instructions.

User recruitment is based on three main aspects: familiarity with the kitchen, age and ability with technology. The users have to be able with the kitchen: they have to be skilled in performing operational tasks (e.g., food preparation) inside the kitchen. The distinction based on the age has been defined according to the difference between adults and elders, where adults are intended between the ages of 30 and 50 years, and elders over 65 years. Intermediate characteristics (age between 51 and 64) were not considered because they are easily deducible from the behaviors detected in extreme groups. Users under the age of 30 were not considered in the test. According to the ability with technologies, the users are divided into two groups: high ability (HA) for users which use frequently computers, smartphones and tablets and scarce ability (SA) for who uses them less than once per week and with reduced functionality.

According to these definitions users were divided into three groups (Table 1) according to the following characteristics:

1. Adults (30 to 50 years) with HA;
2. Elders (over 65 years) with HA;
3. Elders (over 65 years) with SA.

To improve the assessment, users with minor limitations in vision, hearing and fine motor, have been involved, because such limitations are widespread in a large portion of elderly people.

Five subjects for each of the two categories of elders (with and without ability with technologies) and five users in the first group have been selected.

Tests have been conducted by two researchers. Performance data have been collected through diary study and Video Interaction Analysis (VIA).

TABLE I. USERS GROUPS

Groups	**Criteria**		**N°**
	Principal	*Limitations*	
G1	Adults (30 to 50 years) with HA	None	5
G2	Elders (over 65 years) with HA	View, Hearing, Fine motricity	5
G3	Elders (over 65 years) with SA	View, Hearing, Fine motricity	5
		Total	**15**

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N°	Main Task	Object of verification	C	E	I	O	R	H
1	Search a recipe	Is the user able to perform the task? Does he/she need to consult the instructions?	Y N	☐ ☐	☐ ☐ ☐	Y N	☐	☐ ☐ ☐ ☐
Put ingredients out of the fridge								
2	Alert Fridge door open	Is the user able to understand the meaning of the alert?	Y N	☐ ☐	☐ ☐ ☐	Y N	☐	☐ ☐ ☐ ☐
3	Program the oven	Is the user able to perform the task? Does he/she need to consult the instructions?	Y N	☐ ☐	☐ ☐ ☐	Y N	☐	☐ ☐ ☐ ☐
4	Start the cooking	Is the user able to perform the task? Does he/she need to consult the instructions?	Y N	☐ ☐	☐ ☐ ☐	Y N	☐	☐ ☐ ☐ ☐
5	Alert term cooking and off oven	Is the user able to understand the meaning of the alert? Does he/she need to consult the instructions?	Y N	☐ ☐	☐ ☐ ☐	Y N	☐	☐ ☐ ☐ ☐
Serve the dish								
6	Program and start the dishwasher	Is the user able to perform the task? Does he/she need to consult the instructions?	Y N	☐ ☐	☐ ☐ ☐	Y N	☐	☐ ☐ ☐ ☐
7	Alert lack water dishwasher	Is the user able to understand the meaning of the alert? Does he/she need to consult the instructions?	Y N	☐ ☐	☐ ☐ ☐	Y N	☐	☐ ☐ ☐ ☐

Figure 9. Evaluation form.

Few examples of the scenarios used during testing are:

- Preparing a meal: the user must prepare a meal using a recipe. Tasks: selection and consultation of a recipe, finding the ingredients, start and setting the oven, check the status of cooking, preparation, programming and starting the dishwasher, management of any warning.
- Alarm management: the user manages unexpected alerts of system. Tasks: understanding the alarm, solve the problem.
- Power Management: The user manages the consumption after an overload warning and checks energy consumption in a given period. Tasks: programming one or more appliances, choice between automatic or manual management of overload, manage an overload alarm, and check the consumption in a given period.

A. *Evaluation Discussion/Results*

Users have positively assessed the layout of the kitchen and the additional space of the worktop. During the preparation of the meals they have expressed positive opinion about the use of the kitchen.

During the interaction with the User Interface through tablet positive impressions were collected from the users.

Instead during the direct interaction with the devices, by the majority of subjects, it was reported some difficulties to find right information for programming dishwasher and oven. In particular, 11 of 15 subjects have required the support of the researchers more than once and repeated the task once before do it correctly. In this case, the task has been evaluated by users as difficult. As regards the ability to program the oven, 7 of 15 users have utilized researcher instructions, and evaluation of task difficulty was better than dishwasher. This can be due to the characteristics of household appliances interfaces: instead of UI system, the dishwasher in particular presents a really poor button-interface, which is not able to suggest the correct sequence of action necessary to set up a program.

In the management of alarms (i.e., overload warning, ambient alarm, error or alerts of appliances) users have reacted to system alert without difficulty. All users have used the interface to get information and instructions to resolve the problem. Data collected during observation of user performances and answers given by users to questionnaires showed that light signals and user interface allow to identify the problem immediately and to react properly.

As regards the reading of energy consumption through the interface, users have completed the task without using the researchers' instructions or making mistakes and they have supplied very positive feedback in the activities. Through the questionnaire, users have highlighted the importance of knowing energy consumption in real time or and historical ones.

V. CONCLUSIONS

This paper presents the design of an innovative smart kitchen.

The results of a qualitative experimentation with final users has shown that it is accessible and highly usable for users with some limitations such the elderly. In general, it emerged that the new smart kitchen system is able to improve the usability of household appliances, such as oven and dishwasher, as regards the programming and controlling operations, compared with a "traditional" kitchen. At the same time, it shows how the introduction of smart technologies in the kitchen environment improves the usability also for users with scarce attitude to technology.

The main innovation of E-Kitchen is the ability to govern rationally and in an intuitive manner the functions of all the appliances that find place in the kitchen: it improves the use and the control of the devices, it reduces malfunctions and it makes them more easy to manage.

The work is not definitive: the smart kitchen will be evaluated with a greater number of users in order to verify this first qualitative evaluation. Moreover, a field study will be conducted to assess the ability of E-kitchen system to enhance the users' energy awareness and, in order to understand if it is able or not to contribute to increase energy saving and to demonstrate its benefits with respect to other proposals in the literature. Anyway, it is reasonable to assume that the system allows to save around 3% of money, in term of energy bill, because the system gives the possibility to shift the appliances program when the energy rate is low.

An additional effort will be focused on the development of E-Kitchen to make it commercialized at a sustainable cost.

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