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Multi-layered functional analysis for smart homes design

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Abstract

The conception of smart homes exceeds the boundaries of a simple design process. It becomes mainly a managerial, multidisciplinary process in which added value depends on the measure in which these answer, in an adequate manner, to a set of requirements raised by a target group of users and stakeholders with specific needs.
The paper proposes a methodology for functional analysis of smart living spaces that combines a multi-level approach for its structure with FAST (Functional Analysis System Technique). A generic functional scheme for a smart living space is defined and explained, and then, for illustrative purposes, this scheme is customized for the functional analysis of two smart systems of the mentioned space: illumination, and safety/security.

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Keywords: Smart homes, Functional analysis, User oriented development

1. Introduction

In today's economic world the design and development process is bound to cope with the pressure to continuously improve products and services. The architectural and construction fields are no exception in this respect. Increasing customer and user demands and market competition, raising requirements for sustainability and inclusion, plus the rapid progress of knowledge and technology, all together lead to an increase of the complexity and, implicitly, of the difficulty of decisions in the mentioned field (The World Bank 2015)

In the actual architectural and urbanistic landscape, smart technologies are more and more present both at the large-scale of smart cities (National League of Cities 2017) that are using ICT for building an infrastructure to continuously improve the collection, aggregation, and use of data to improve the life of their residents", at the medium scale of smart buildings, able to adapt their characteristics and facilities for optimizing the energy consumptions and functional costs, and at the small scale of smart spaces and smart objects, highly connected and capable to interact in an intelligent way with the life of their inhabitants.

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A smart living space and its component objects have the ability to fulfill multiple and complex functions, to process complex information, to communicate with the residents, with each other and with people or equipment from the outside, to learn from events and to take autonomous decisions in certain situations having the objective to protect or facilitate the everyday life of those who live there. Such attributes, when associated with the home space, nominates it as intelligent or smart.

The approach in conception and development of such smart homes far exceeds the boundaries of a simple design process. It becomes mainly a managerial, multidisciplinary process in which many different types of skills (space and form architecture, functional design, software development, communication systems and others) converge to generate solutions that are able to meet the needs and requirements of certain target group of users and stakeholders.

The added value of such a solution comes from the functions offered by the living space and the measure in which these manage to answer, in an adequate manner, to a set of requirements raised by a specific need (e.g. those of a person with certain disabilities). In this context, function identification and analysis becomes a critical component for the resulted value of the entire design-development process.

The paper proposes a methodology for functional analysis of smart living spaces that combines a multilevel approach for its structure with FAST (Functional Analysis System Technique). A generic functional scheme for a smart living space is defined respectively explained, and then, for illustration, this scheme is customized for the functional analysis of three smart systems of the mentioned space: illumination, shading, safety and security.

2. Background

The present paper intersects two conceptual spheres that are required to be briefly presented and explained to provide a knowledge base for the subsequent presentation of the specific contribution. These two concepts are smart spaces (particularly smart homes) and functional analysis.

2.1. Smart living spaces

Starting from the characteristics of human intelligence that some associate with the individual adaptive capacity (Sternberg & Salter 1982; Binet 1905) and the ability to acquire, store, combine, compare and use information in new contexts (Humphreys 1979) along with the maturation of ICT (Information and Communication Technologies), direct correspondences between the characteristics of human intelligence and the characteristics of modern technologies can be identified. (Acampora et al. 2013) identify for all smart living spaces a number of common features:

- *Context aware:* exploiting the contextual information;
- *Personalized:* to the individual needs;
- *Anticipatory:* anticipating the individual needs without a conscious intervention.
- *Adaptive:* to the changing needs;
- *Ubiquitous:* integrated into the everyday environment.
- *Transparency: e*mbedded in an unobtrusive way in the daily life.

The first mention of "smart house" dates back to 1984, being linked to the name of a working group of the US National Association of Home Builders, aiming to advocate for the inclusion of automation in home design (Aldrich 2003). The modern intelligent house, however, takes shape only from the beginning of 21st century, once the involved technologies (processing power, miniaturization, integrated systems, communication technologies, etc.) reach the required maturity. Being an emerging field, "intelligent houses" and their definitions are very varied in the scientific literature, but one cannot yet identify a comprehensive and universally accepted definition. However, to provide an overview, one can consider a smart living space, a ubiquitous processing application (Alam et al. 2012), which integrates advanced sensory, communication, automation and control technologies (Vimarlund & Wass 2014) to form a smart and context aware system (Alam et al. 2012), which anticipates and adapts to the needs of residents to enhance their comfort, safety and entertainment (Aldrich 2003), energy efficiency (Saad al-sumaiti et al. 2014) and health (Reeder et al. 2013).

(Aldrich 2003), a work oriented on the history and sociological implications of the emergence of intelligent houses, proposes a hierarchy of homes by degrees of intelligence:

1. Homes containing intelligent objects functioning in an intelligent manner;
2. Homes containing intelligent and connected objects communicating each other
3. Connected homes: to internal and external networks, thus forming interactive systems that can be remotely controlled from both inside and outside.
4. Learning homes: behavioral patterns are identified allowing functionality adaptation (intelligent thermostats that learn the residents' timetable to adjust the temperature accordingly)
5. Attentive homes: Activities and location of residents are constantly recorded and the information is used to anticipate the user needs and react accordingly.

These technologies have a wide applicability and have the potential to completely change the paradigm of modern living. A first search that preceded this paper, has identified 6 functional categories in which intelligent solutions with already existing or emerging technologies can be integrated, namely: Illumination and shading; HVAC (heating and ventilation); Safety and Security; Multimedia/entertainment/communication; Health; House maintenance.

2.2. Functional analysis

Functional analysis is a critical step in the design process when maximizing the value of a new product / service (also applies to a process, system, or organization). This involves identifying and placing of product-related functions within functional models that allow understanding of the product / function relationship versus user's and other stakeholders need / expectation level, a relationship that determines the degree of satisfaction for the product.

The function is defined by (EN 1325 2014) as "the effect of the product or its constituents". A function determines the satisfaction of the user to the extent that he responds to a need in the performance conditions expected by him. The need is defined by the same standard as "something necessary or desired by the user".

A SAVE document (SAVE 1998) more clearly explains the concept of function by stating that it is a function that makes a product, structure or service work and sellable.

In line with the definition of function as "the effect of the product or its constituents" (EN 1325 2014), the description of the functions is done in as simple a format as possible (noun, verb) designating "who does" and "what to do" to determine the "effect" mentioned. In view of the subsequent analysis process (relative to the needs / requirements specification and performance level), a function must be expressed in measurable or translatable terms directly in the measurable parameters (SAVE 1998).

For the purpose of their differentiated treatment, functions are classified according to several criteria. The first one divides the functions into two categories: basic (or main) and secondary. Functional models refer in addition to subsets, such as upper and lower order functions as well as dependent and respectively independent functions.

The basic function it the function that provides the primary purpose for which the product is designed and, in this respect, the condition that must be satisfied is to ensure its operation. A product may have more than one basic function. Once set for a particular product, the basic function no longer changes in its development, the loss of this function causing the cease of product utility and, implicit, the disappearance of its value.

Secondary functions provide support for the base function.(SAVE 1998) states that the main function alone is not capable to "sell the product"; for that purpose, a product needs secondary functions to provide technical, managerial, aesthetic support, etc. Secondary functions are specific to a particular design solution. Changing the design may cause the support functions to be canceled or changed.

The way in which a secondary function relates to stakeholders' expectations in a particular context of conception determines their attitude toward it. In this sense, there may be secondary functions more or less desired (depending on the value they represent for stakeholders) or even undesirable, some of which could be considered even deleterious.

In the study of secondary functions, it is frequently used to decompose the whole product studied in its components and designate their functions.

It is important to note that a function that appears as a secondary within a product may show a basic function character when a part (sub-assembly) of that whole product is analyzed individually.

In a functional model, the path of the basic function, containing functions directly related to it, is called the "critical pathway" or "logical pathway" and functions in this chain are also called critical functions.

Secondary functions can be deployed independently or dependent on each other, dependent ones may be part of another function (activities), its consequences, or conditional upon its triggering.

As secondary functions support the basic function, some secondary functions (dependent or independent) can support other secondary functions (usually in the critical pathway).

3. Proposed research

The proposed approach operates with two key concepts, one from each of the conceptual spheres presented in the previous section. The approach operates by adapting an established functional analysis method, "Function Analysis Systems Technique" (FAST) on the multi-layered structure of the smart home, as established and described by (Amiribesheli et al. 2015). A short introduction into these two concepts is necessary to better understand the proposed method.

3.1 The layered structure of a smart home system

To describe highly complex and dynamic systems, such as a smart home these must be broken down into their constituent parts, which, in turn, have to be arranged in conceptual models. Building a multi-layered model for the smart home is an approach used mostly in developing the software aspects of the system. The model chosen as the basis of the approach (Amiribesheli et al. 2015) describes the functional structure of the intelligent living space as being divided into 4 distinct layers, each with its own specific functions and solutions (both hardware and software). The information pertaining to the surrounding environment is collected from the physical layer with the help of sensors. The collected information is transmitted through the communication layer to the processing layer, responsible with storing and processing the data. From there the data is transmitted to the interface layer where the users have access to it.

The physical layer

The physical layer contains two distinct classes of components. Firstly, it contains all sensors embedded into the living environment. Depending on the types of sensors and their configuration, these allow the smart home to gather information about the living environment and the inhabitant's state and activities. The data is gathered in a raw unprocessed state and is transmitted via the communication layer to the information-processing layer. Secondly, it contains actuators, which are the main way in which the smart home can exert an influence on the environment and its inhabitant. The actuators are the class of components with the largest variety of possible technical solutions.

The communication layer

The communication layer contains all the wired or wireless networking infrastructure and protocols linking the components and layers amongst themselves. These facilitate the two-way communication between the physical and processing layer, or the communication between different systems inside or outside the smart home environment. For an optimal configuration of technical solutions, it is important to take note of the various communication protocols specific to each component as the choice for one protocol (ZigBee, Z-wave, etc.) can drastically limit the ulterior options for other linked components.

The data processing layer

The processing layer is the main core of the smart home. This layer receives the information from the sensors and the user interface and processes it to facilitate the basic functions for which it was intended. As opposed to classical robotic systems, which receive and react to the user's direct input, a smart system, through its processing capabilities, interprets the command as a part of a larger context in which the command is not the only variable, and identifies the optimal reaction considering all other variables. (Chan et al. 2008) Depending on its complexity the processing core can be reactive/programmatic (a lower degree of smartness) or, by way of its processing algorithms, it can be attentive/intuitive (a higher degree of smartness) (Aldrich 2003). The processing core is also responsible for centralizing, storing and preparing data for output to the user interface.

The interface layer

The interface layer is, beside the physical layer, the second point of contact between the smart home and the user/inhabitant (the other being the physical layer). It contains all direct control methods and terminals, whether they be local or remote.

3.2 „Function Analysis Systems Technique" - FAST

Developed in 1964 by Charles Bytheway as a stage of his „Value Analysis" method, FAST consists of a graphical representation of the way in which the functions of a product or process are linked and work together to acomplish its intended result. Since then, FAST has become the primary technique for functional analysis within the „Value Methodology" framework.

The FAST technique is a representation of the component functions of a product or process in a block diagram in which the position of each element has a semantic value and a hierarchic / causal relationship with the other linked functions. Each element of the diagram represents a function (primary or secondary) noted on the diagram as a simple statement (noun + verb). The arangement of the elements representing functions in the critical path (the path that is linked directly to the basic function of the analysed system) is set up directionally indicating a How/Why/When logic:

- *From left to right* one can observe a process of functional decomposition from the system's basic function (indicated on the very left of the diagram) to secondary functions of lower order, down to the last level of functions, which are still part of the analysed system. With each step, one understands **how** the function on the left is enabled or supported by the function on its right.
- *From right to left* the process is reversed, becoming one of functional recomposition from lower order functions up to the basic function, explaining their purpose (**why**)
- *Vertical* positioning of the elements highlights functions happening simultaneously (**when**) with functions on the critical path. These can be represented either above the critical path if they happen independently (or they offer support) of critical functions or below the critical path if they are a consequence of critical functions.

Because of the great variety of systems, which can be successfully described by the FAST method, one can find a wealth of different approaches to the structure and composition of the FAST diagram.

3.3 Proposed approach

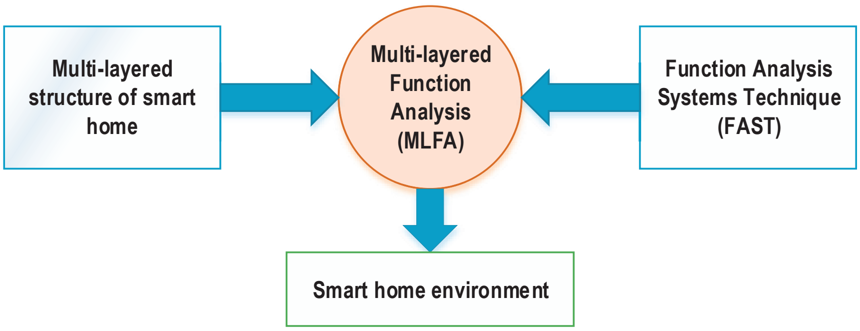

Figure 1 - MLFA structure

As previously stated, the approach proposes applying and adapting the FAST method to the multi-layered structure of the smart home (as seen in Fig. 1). From a formal point of view, the MLFA analysis follows the basic logic of a FAST diagram (at the base of the arrow is a lower order function than at the tip of the arrow, maintaining the "how/why" relationship between the two), but it forgoes the left / right orientation of the critical path for a curved path. This change allows the critical path to conform to the layers while at the same time illustrating the input and output points of the system (in the physical and interface layers). This curved versus straight critical path is illustrated in Figure 3. This adaptation results in a more detailed look at the relationships and dependencies between the analysed functions and their relationship with the whole environment.

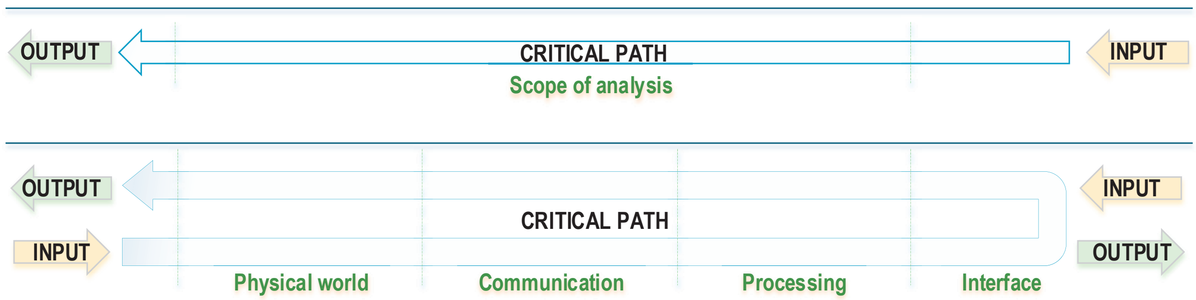

Figure 2 - FAST versus MLFA critical path configuration

Once the formal and structural aspects of the of the MLFA analysis have been determined, a study of the public database at www.smarthomedb.com was undertaken. This database is publicly maintained and updated by volunteers and it contains, at the time of writing, 1193 commercially available smart home products, their costs, and 28442 possible connections between them. As such, it is the most comprehensive public database of commercially available smart products and their functions. In studying the gathered data certain similarities can be observed between all the analysed systems and solutions, when applying the multi-layer model to them. These similarities have been grouped and illustrated in a generic MLFA diagram (Fig 3) of a smart home system. Main functions have been marked with blue, secondary supporting functions, with yellow and the basic functions with green. As previously stated, the functional logic of a FAST diagram has been kept; so there is a causal relationship between each pair of linked functions. Of particular interest is a main function present in all of the systems, "external communication". This refers to the ability of the system to communicate with other systems in the smart home or outside of it, creating a network of systems which brings tremendous added value to the whole environment with minimal effort, by enabling functions which the system would not have had or would have been difficult and expensive to implement. By embedding such a function into a discrete system it enables it to access primary and secondary functions from a different system, drastically increasing the complexity of the possible solutions.

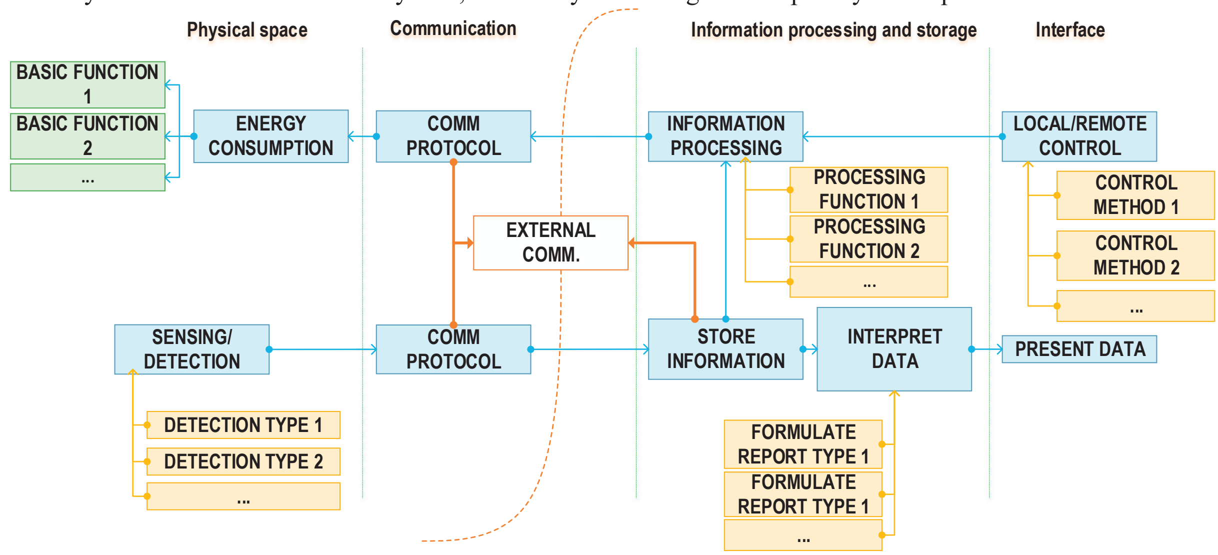

Figure 3 - generic MLFA analysis on a smart living environment

The proposed diagram can be adapted and applied to any process or system of a smart home environment. MLFA has been applied to two systems frequently found in smart homes: lighting and safety/security (Figures 4 and 5). In addition to the classes of functions found in the generic diagram the analysed systems present certain functions unique to them. Due to the very high speed of smart technologies development, the proposed diagrams are not and cannot be exhaustive, rather they illustrate the application of the proposed analysis on 2 specific systems. Since the diagrams illustrate what a prospective fully equipped smart system would be capable of not all of the identified functions in the specific systems have to be present for a system to be considered smart.

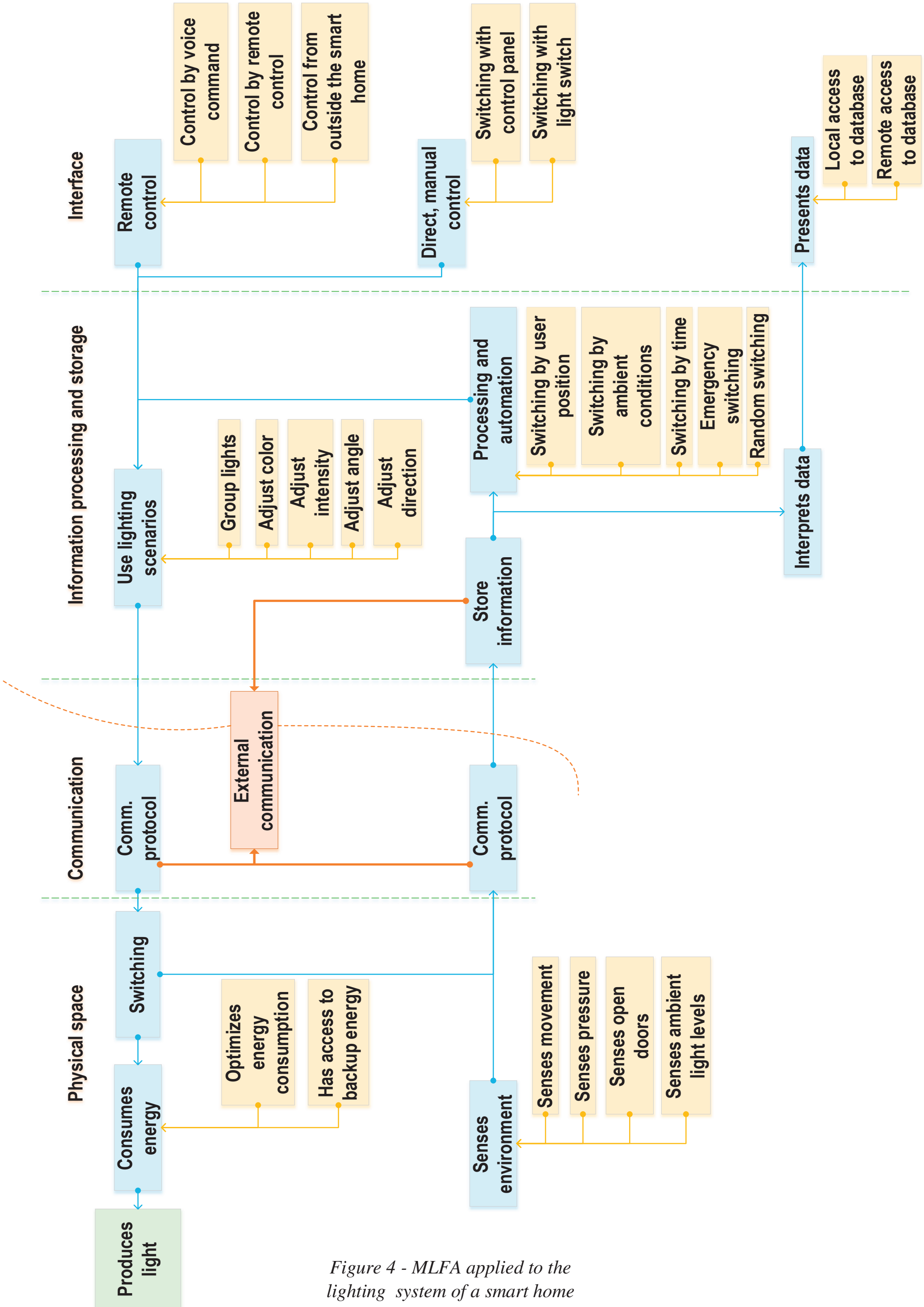

Figure 4 - MLFA applied to the lighting system of a smart home

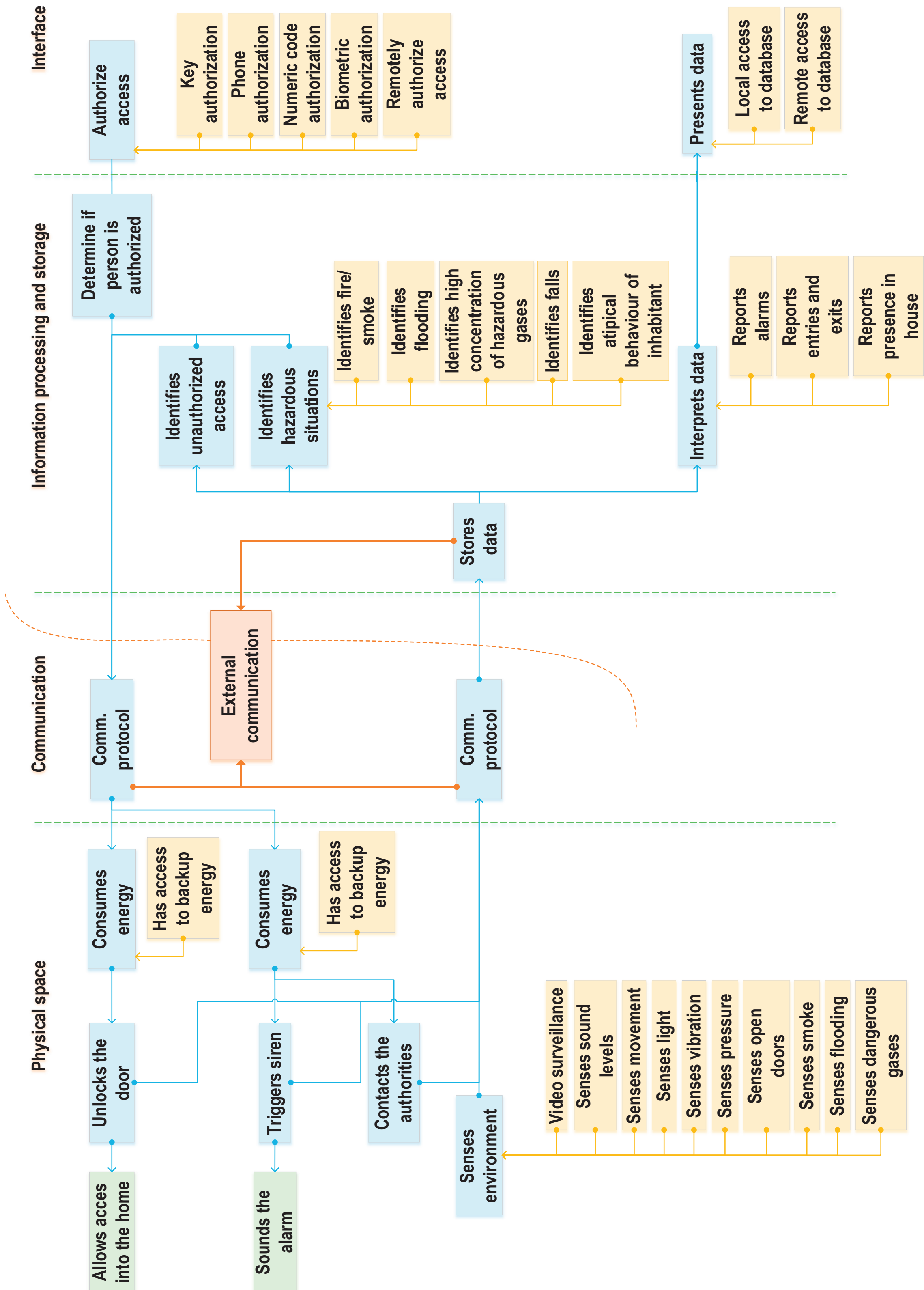

Figure 5 - MLFA applied to the safety/security system of a smart home

3.4 Applying MLFA on specific smart systems – observations

The smart lighting system has three main purposes in a fully equipped smart system: ambient lighting, navigation lighting and emergency lighting (Hamernik & Tanuska 2012). Ambient lighting refers to the general light intensity and quality in a space, important for general mood and adequate to the different activities performed in the space. Navigation lighting is purely utilitarian in nature, it enables the inhabitant to navigate safely inside the environment and identify all features of the space. Security lighting is triggered automatically in emergency situations. The last two are especially important in an Ambient Assisted Living context where the inhabitant has to cope with certain impairments.

The safety/security system has two basic functions: controlling access into the living environment and reacting in emergency situations. Possible reactions range from notifying the inhabitants, authorities or next of kin, sounding an audible alarm or triggering reactions in other smart systems implemented in the house. The sensing component related to a safety/security system tends to be more complex than the one present in a lighting system. While the lighting system reacts mostly to presence (movement sensors, pressure sensors etc.) the safety/security system needs more information to evaluate complex situations such as fall detection, seisure detection, personal identification for authorisation purposes etc.

Elaborating a MLFA diagram for two specific systems leads to a few important observations:

- The main functions determined in the generic diagram will be broken down into several other main functions, with varying interactions, specific to the analysed system. This is especially true for the data processing function, which will change in complexity and configuration on a system-by-system basis. For example in the safety/security system "data processing" is broken down into determining a persons authorization and identifying hazardous situations. Such decompositions can not be integrated into a generic diagram since they will change as new functions become commercially available.
- Security lighting is a relevant example of a function which gains value because of the lighting system's link with other smart systems in the house. Detecting emergency situations is a specific function of the security/safety system which employs more complex sensors and behavior analysis algorithms. A typical smart lighting system does not present such advanced functions, but if the external communication function is implemented in both systems then the safety evaluation functions can trigger emergency lighting if needed.

4. Conclusions

A general tendency has been identified to direct smart home research on specific technological solutions and components (Queirós et al. 2013) (Vimarlund & Wass 2014). According to their reviews 87% of studied papers concentrate on specific technologies, to the detriment of study and innovation of complete integrated systems for smart living, and the management and development of such systems. At the same time (Henkemans et al. 2009) observes that the current smart spaces market is dominated by suppliers, whose approach is to force specific solutions into the market instead of a systemic approach based on the client's needs. This leads to a series of solutions which are economically inefficient, do not present the optimal combination of functions to adress the client's needs and are difficult to use and live with. These aspects, together with the ever-increasing speed of technological innovation and spread of smart technologies, will need to be controled by managerial approaches which promote economical efficiency and user-oriented development if large scale adoption of smart technologies is to be achieved.

The first step towards configuring an optimal smart environment for its inhabitants is identifying the functions which a system can perform with current, commercially available technologies. The proposed approach adapts an established functional analysis method, FAST, to the complex and multi-layered structure of a smart environment to create a diagram which lists and describes the relationships between these functions. The research presented in this paper yielded a generic functional diagram which can be used to analyse any smart system inside an intelligent environment.

Future directions of research will integrate this approach in a broader value methodology context, by integrating the functions identified into a value map, a bi-dimensional diagram where each function is defined by the benefits it brings to the user and the costs of implementation. The result of such an analysis can be used as decisional support for generating customized solutions that are able to meet the needs and requirements of certain target group of users and stakeholders with increased financial efficiency. Another possible direction will be integrating the MLFA into the methodology proposed by (Popescu et al. 2015) which uses the AHP method and a series of cascading QFD matrixes to corellate the needs of disabled patients with the technical characteristics of a prospective ambient assisted living environment which is tailored to the inhabitants unique combination of needs and disabilities.

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