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Modularity and Configuration Applied to Product Integrating the IoT Technology

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Abstract. The growth of the IoT (Internet of Things) offers a large number of opportunities for new product development. The adoption of IoT technologies improves the operational efficiency of products and their interaction with humans. The variety of sensors and communication protocols, the increased number of cloud infrastructures and services, not forgetting security challenges induced by the IoT technologies lead the designers to make complex choices in the configuration of an optimal IoT solution. Modularity and design for configuration represent an efficient solution for the design of products adopting the IoT technologies. This paper applies the model of configurable product design, conceptualized as multi-layer fuzzy models, to the product integrating the IoT technology. The layer models are the fuzzy product specification layer, the fuzzy functional network layer, the fuzzy physical layer, and the fuzzy constraint layer. The model discerns the consensual elementary solutions that create common ground for moving toward a global solution. The case study shows the configuration of a connected houseplant sensor.

Keywords. Design for configuration, modularity, configurable products, product modeling, multi-layer models, Internet of things

Introduction

The number of objects connected to the Internet, already far greater than the number of people online, is constantly growing. With 8.6 billion cellular IoT connections in 2018, estimates for 2022 are around 22.3 billion cellular IoT connections[2] according to the Ericsson Mobility Report (2019). This exponential growth in the Internet of Things (IoT) opens up an era of creating new services that can bring significant changes to society, the economy, and the environment, as well as a host of business opportunities. The adoption of IoT technologies in various fields such as smart cities, smart transportation, smart logistics, smart industry, smart metering, and smart grids improves their current operational efficiency of products and their interaction with the population [1][2][3].

However, the customers are no longer passive buyers of the products because they can participate in the customization of their goods prior to purchase. Companies that can provide customization and increased product variety improve customer satisfaction and achieve a significant competitive advantage. To face this societal challenge, the design

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[2] https://www.ericsson.com/en/mobility-report/reports - June 2019

of products adopting the IoT has to be optimized according to the dynamic and individual requirements of the customers. The variety of sensors and communication protocols, the increased number of cloud infrastructures and services, and of course security challenges induced by the IoT technologies lead designers to make complex choices in the configuration of an optimal IoT solution.

Modularity and design for configuration represent an efficient solution for the application of IoT technologies. Fodor revived the idea of the modularity of mind, although without the notion of precise physical localizability [4]. According to Fodor, modular cognitive systems fulfill certain criteria: (1) Domain specificity: modules only operate on certain kinds of inputs, (2) Informational encapsulation: modules need not refer to other psychological systems in order to operate, (3) Obligatory firing: modules process in a mandatory manner, (4) Fast speed: probably because modules are encapsulated and mandatory, (5) Shallow outputs: the output of modules is very simple, (6) Limited accessibility, (7) Characteristic ontogeny: there is a regularity of development, and (8) Fixed neural architecture.

These criteria are also valid in equal measures for modular technical systems [5] and intelligent systems integrating IoT technologies [6]. The main criteria for product modularity are component separability and component combinability [7]. These are coupled with other criteria such as commonality, function binding, interface standardization, and loose coupling [8][9][10][11][12][13].

Design for configurations uses the principles of modularity, as individual products are not developed anymore, only whole product families or product spectra [14]. Design for configuration is the design process, which integrates explicitly customer requirements and the services involved in the product realization process, such as manufacturing, assembly, maintainability, etc. to intelligently synthesize or generate the components, the modules, and the final product belonging to a virtual family of products [15][16][17][18].

Indeed, the product modeling process is characterized by several domains that participate simultaneously in the development of configurable products. Each domain has a particular view of the product. The design for the configuration process is also characterized by many degrees of freedom and possibilities due to the individualized requirements of the customers. Therefore, design for configuration takes into account: (a) the different views of the product, (b) the great number of product variants generated by the process, (c) the user-oriented characteristic of the configurable products, and (d) the possibilities and uncertainty of the design process. A fuzzy multilayer network of multiple fuzzy models, which correspond to the multiple views of a configurable product, allows an intelligent and adaptive way for product configuration [19].

Considering multiple views of the configurable product design, the fuzziness of handling imprecise design information and the modularity, a fuzzy multilayer network of multiple fuzzy models can be applied to the product configuration adopting the IoT technologies. In spite of some research that deals with the conflict resolution problem [20][21][22][23], there is a need to integrate methods that can reach consensual solutions during design configuration. The proposed approach uses the concept of consensus as the overlapping of customer perspectives and designer perspectives to converge toward a final solution.

The paper is organized into three sections. In the first section, the fuzzy multilayer network model for configuration is proposed. The second section presents the computing models for configuration. Finally, the third section describes a case study.

1. Fuzzy multilayer network model for configuration

The fuzzy multilayer model is composed of the following four interacting layers: the fuzzy product specification layer, the fuzzy functional network layer, the fuzzy physical solution layer, and the fuzzy constraint layer (Figure 1).

The fuzzy product requirement layer. A relationship exists between the set of product functions and the set of requirements, which indicates in what degree a requirement is accomplished by the set of functions. A fuzzy relationship can be defined between the set of functions and the set of requirements. The fuzzy relationship is characterized by the membership function, which takes values between 0 and 1.

The fuzzy functional network layer. The fuzzy functional network is used to represent the functional structure of a product. The functional structure of a product consists of functional elements and their interrelationships that involve decomposition and/or dependency. Usually the functional structure of a product is indicated by a crisp representation. In a functional network layer, the product functions are symbolized by nodes, and their relationships are symbolized by edges. Each edge is characterized by a membership function, which takes the value of 1 if there is a relation between the two considered functions, or the value of 0 if there is no relation.

Given the set of functions of a configurable product, it is considered that the relationships between the functions have different degrees of interaction. The variation of the degrees of interaction between the product functions leads to different functional configurations of the product. The degrees of interactions between functions can vary according to the functional configuration chosen by a user. So, different functional configurations can emerge during the design of the configurable product. To describe the interactions inside the fuzzy functional network, a fuzzy relationship is defined between each couple of product functions in the set of product functions. The fuzzy relationship is characterized by the membership function which takes values between 0 and 1, and represents the degree of interaction between each couple of functions.

The fuzzy physical solutions layer. Each function in the set of product functions corresponds to different product modules. Each module in turn has some alternative solutions. Each physical solution can satisfy the set of functions to a certain degree. This aspect implies that the relationship between the set of functions and the set of physical solutions has a fuzzy character. The fuzzy relationship defined between the set of functions and the set of solutions is characterized by the membership function. It takes values between 0 and 1 and denotes the satisfaction degree of a function by the set of physical solutions.

The fuzzy constraint layer. The integrated design is characterized by various activities that are involved in the process, where each activity has its own view of the product. The fuzzy constraint model defines the specific constraints of each activity that are integrated during the design process of the product. The existing process capabilities impose constraints on the product realization which reduce the number of possible product variants or configurations. The set of physical solutions must satisfy the set of constraints. So a fuzzy relationship exists between the set of solutions and the set of constraints, indicating that each physical solution satisfies the set of constraints to different degrees.

A fuzzy relationship is defined between the sets of constraints and the set of solutions. This relationship is characterized by a membership function that can take values between 0 and 1. The values indicate to what degree each physical solution satisfies the set of constraints.

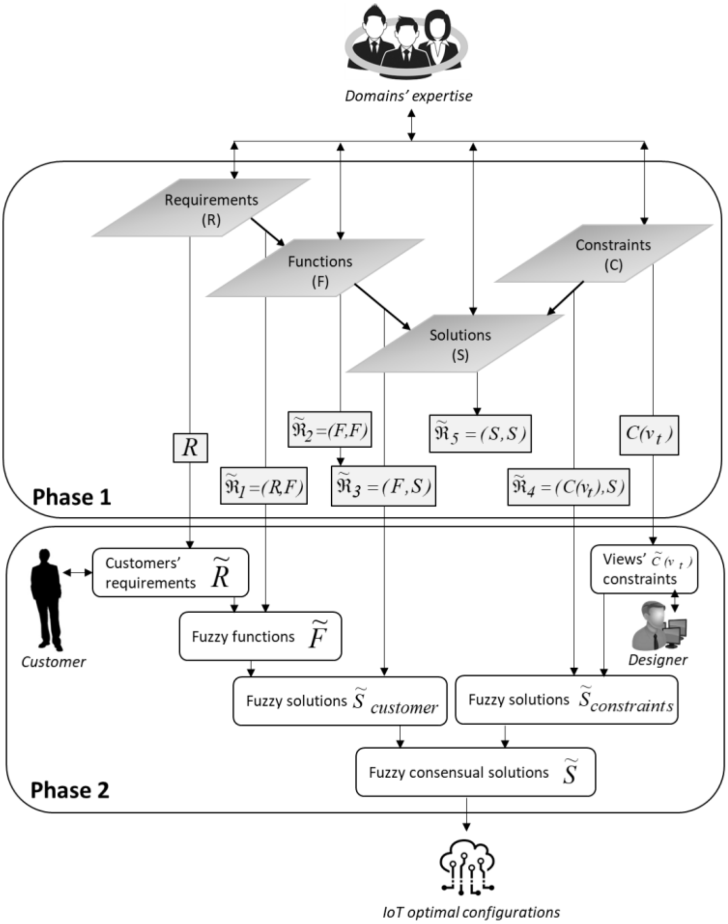

Figure 1. Fuzzy multilayer network model for IoT product configuration.

2. Configuration based on the fuzzy multilayer network model

Configuration starts with the definition of a requirement in the requirement domain. A customization requirement is manifested by the customer's choice of customizable requirements. The customer perceived value of each requirement indicates the degree of customer satisfaction in the requirement domain. Simultaneously, in the process domain, a constraint is manifested by the expert's choice of process constraints [15]. The expert's perceived value of each process constraint indicates the degree of expert satisfaction in the process domain.

Therefore, to satisfy customer requirements and process constraints, the mapping from the requirement to the solution, as well as the mapping from process constraints to the solution is applied. It yields a set of consensual solutions from both domains: requirement and process constraints. Then, this set of consensual solutions can be distributed in modules to form configurations [23].

Optimal configurations can be than generated using some limits of acceptability for objective function values. Limits of acceptability, whether communicated formally or established informally by experience, are familiar to engineers in the industry. It permits the early release of a possible set of configurations. Details for these phases are given below (Figure 1).

Phase 1: Building fuzzy relationships in product configuration. In this phase, different engineering design models, necessary for the configuration of a product, are built within and between domains. These models are expressed in the form of the fuzzy relationships. Table 1 shows the formal building of these fuzzy relationships and the meaning of associated membership functions.

In order to assess the membership functions, linguistic values are used. The following set is used to express the evaluation of actors: *E={*e_0*=worst,* e_1*=very poor,* e_2*=poor,* e_3*=fair,* e_4*=good,* e_5*=very good,* e_6*=excellent}*. Each actor chooses a linguistic value from the set *E* to express his/her evaluation. Table 2 represents the reference value as well as the interval-value for each linguistic value. In this way, the actors can assign a *degree of membership* or a *degree of belief* to each design parameter.

Table 1. Phase 1: Fuzzy relationships in product configuration.

Given

Four heterogeneous and distributed domains: (a) requirement, (b) functional, (c) solution, and (d) process constraint and their data consisting of:

1 Universal set of requirements $R=\{r_i\}$, $i \in I_R$, $I_R=\{1,2,\ldots,n\}$; *these are customer requirements.*

2 Universal set of functions $F=\{f_i\}$ $i \in I_F$, $I_F=\{1,2,\ldots,m\}$; *these are the functions of the product and they are designed to satisfy customer requirements.*

3 Universal set of solutions $S=\{s_i\}$ $i \in I_S$, $I_S=\{1,2,\ldots,q\}$; *a solution is a designed physical object.*

4 Universal set of constraints $C(v_t)=\{c_{1t}, c_{2t},\ldots c_{lt}\ldots c_{r_t t}\}$ for the process view v_t , c_{lt} is the constraint number l for the view number t and r_t is the number of constraints for the view number t ; *A constraint is a restriction or a requirement of a view on any solution.*

Build

Fuzzy relationships in engineering design consisting of:

1 Fuzzy relationship between requirements and functions $\tilde{\Re}_1=(R,F)$.

Its membership function $\mu_{\tilde{\Re}_1}(r,f)$ *indicates to what degree a requirement can be accomplished by the universal set of functions.*

2 Fuzzy functional network model $\tilde{\Re}_2=(F,F)$.

Its membership function $\mu_{\tilde{\Re}_2}(r,f)$ *indicates the degrees of interaction between functions.*

3 Fuzzy relationship between functions and solutions $\tilde{\Re}_3=(F,S)$.

Its membership function $\mu_{\tilde{\Re}_3}(f,s)$ *indicates to what degree a function can be fulfilled by the universal set of solutions.*

4 Fuzzy relationship between constraints and solutions $\tilde{\Re}_4=(C(v_t),S)$.

Its membership function $\mu_{\tilde{\Re}_4}(c,s)$ *indicates to what degree a solution satisfies the universal set of constraints* $C(v_t)$ *for process view* v_t .

5 Fuzzy relationship between universal set of solutions $\tilde{\Re}_5=(S,S)$.

Its membership function indicates the degrees of affinity between solutions.

Table 2. Linguistic values.

Linguistic value	Reference value	Fuzzy interval
worst	0.05	(0, 0.15)
very poor	0.2	(0.1, 0.3)
poor	0.35	(0.2, 0.5)
fair	0.5	(0.3, 0.7)
good	0.65	(0.5, 0.8)
very good	0.8	(0.7, 0.9)
excellent	0.95	(0.85, 1.0)

Phase 2: Searching the fuzzy set of consensual solutions. In this phase, a designer, using the fuzzy relationships from Phase 1, customizes the product based on (a) customer perceived value of each requirement and (b) specific process domain constraints involved in its production, such as manufacturing, assembly, maintainability, and so on. Both particular customer's requirements and specific process domain constraints are fuzzy [15]. The result is a fuzzy set of alternative physical solutions, called fuzzy consensual solutions, which satisfy both customers' requirements and specific domains' constraints. The proposed model considers consensus as the overlapping of perspectives. The part or the fragment of a design solution which receives the maximum degree of consensus is called here consensus nucleus. Discerning the consensus nucleus as an overlapping of perspectives can help designers create common ground needed to move toward the final solution.Table 3 shows the formalization and different steps of this phase.

Table 3. Phase 2: Searching the fuzzy set of consensual solutions.

Given

1 Fuzzy set of customers perceived requirements $\tilde{R} = \{(r_i, \mu_{\tilde{R}}(r_i))\}$ over R

2 Fuzzy set of perceived constraints for process view v_t $\tilde{C}(v_t) = \left\{\left(c_{lt}, \mu_{\tilde{C}(v_t)}(c_{lt})\right)\right\}$ over $C(v_t)$

3 Fuzzy relationships in engineering design $\tilde{\Re}_1 = (R,F)$, $\tilde{\Re}_2 = (F,F)$, $\tilde{\Re}_3 = (F,S)$, $\tilde{\Re}_4 = (C(v_t),S)$

Find

1 Consensual fuzzy relationship between functions and solutions $\tilde{\Re}_3^C = (\tilde{\Re}_2, \tilde{\Re}_3)$ with membership function:

$$\mu_{\tilde{\Re}_3^C}(f,s) = \mu_{\tilde{\Re}_2 \circ \tilde{\Re}_3}(f,s) = \max_f \min[\mu(f,f), \mu(f,s)], \ \forall f \in F, \forall s \in S$$

2 Fuzzy set of functions $\tilde{F} = \{(f_i, \mu_{\tilde{F}}(f_i))\}$ over F with membership function:

$$\mu_{\tilde{F}}(f) = \mu_{\tilde{R} \circ \tilde{\Re}_1}(f) = \max_r \min\left[\mu_{\tilde{R}}(r), \mu_{\tilde{\Re}_1}(r,f)\right], \ \forall r \in R, \ \forall f \in F$$

3 Fuzzy set of solutions $\tilde{S}_{customer} = \left\{\left(s_i, \mu_{\tilde{S}_{customer}}(s_i)\right)\right\}$ over S satisfying customers perceived requirements, with membership function:

$$\mu_{\tilde{S}_{customer}}(s) = \mu_{\tilde{F} \circ \tilde{\Re}_3^C}(s) = \max_f \min\left[\mu_{\tilde{F}}(f), \mu_{\tilde{\Re}_3^C}(f,s)\right], \ \forall f \in F, \ \forall s \in S$$

4 Fuzzy set of solutions $\tilde{S}_{constraints}(v_t) = \left\{\left(s_i, \mu_{\tilde{S}_{constraints}(v_t)}(s_i)\right)\right\}$ over S satisfying perceived constraints for the process view v_t, with membership function:

$$\mu_{\tilde{S}_{constraints(v_t)}}(s)=\mu_{\tilde{C}(v_t)\circ\tilde{\Re}_4}(s)=\max_{c}\min\left[\mu_{\tilde{C}(v_t)}(c),\mu_{\tilde{\Re}_4}(c,s)\right] \quad , \forall c\in C(v_t),\ \forall s\in S$$

5 Fuzzy sets of solutions $\tilde{S}_{constraints}=\left\{\left(s_i,\mu_{\tilde{S}_{constraints}}(s_i)\right)\right\}$ over S satisfying all fuzzy constraints $\tilde{C}(v_t)$, $t\in T$ with membership function:

$$\mu_{\tilde{S}_{constraints}}(s)=\min\left[\mu_{\tilde{S}_{constraint(v_1)}}(s),\cdots\mu_{\tilde{S}_{constraint(v_t)}}(s)\cdots\mu_{\tilde{S}_{constraint(v_u)}}(s)\right] \quad , \forall s\in S$$

6 Fuzzy set of consensual solutions $\tilde{S}=\left\{\left(s_i,\mu_{\tilde{S}}(s_i)\right)\right\}$ with membership function:

$$\mu_{\tilde{S}}(s)=\min\left[\mu_{\tilde{S}_{customer}}(s),\mu_{\tilde{S}_{constraint}}(s)\right] \quad , \forall s\in S$$

3. Case study

In the U.S., houseplant sales have increased 50 per cent in the last three years (2017-2019) to reach $1.7 billion, according to the National Gardening Association[3]. In France, according to a study conducted by Kantar TNS[4] on 7,000 households, 75% of people bought a houseplant in 2016 which represents 21.2 million of households in the country.

Flourishing is an IoT concept composed of several smart houseplant sensors allowing people to monitor the health conditions of houseplants at any time and in any place. It is based on a dedicated cloud service, allowing houseplant sensors to connect to an outsourced server by using a Wi-Fi connection. These sensors gather condition data, such as the soil moisture, ambient temperature, humidity, and light. The visualization and the monitoring of houseplants' condition is realized through a web interface. The system is also able to inform users in real time concerning the houseplants' conditions (e.g., sun exposition, ambient temperature, etc.) or to send alert messages if the conditions required to preserve the houseplants' health need to be improved (e.g., need watering).

Fuzzy customer requirements. Flourishing is a concept intended for young customers, who are very busy and inclined to use new technologies in their daily life. Moreover, the system has to be accessible through a smartphone and must be able to adapt its recommendations according to the characteristics of different types of houseplants.

Fuzzy functions model. The Flourishing sensors have to be placed in the houseplant pots. The sensor must be able to gather condition data, such as the soil moisture, ambient humidity, temperature, and light. The data must be hosted on a server that is remotely accessible through a smartphone. The sensor must use electric energy and a Wi-Fi connection.

Fuzzy constraint model. The solution must allow an easy and ergonomic interaction with the houseplant through the web interface. The solution should also allow for easy connection to the Wi-Fi router of the customer.

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[3] https://www.bloomberg.com/news/features/2019-04-11/the-one-thing-millennials-haven-t-killed-is-houseplants

[4] https://www.tns-sofres.com/publications/les-achats-de-vegetaux-d-ornement-et-pour-le-potager-bilan-2016

Fuzzy consensual model. The solution is composed of two parts: (1) a web service and (b) the connected sensors. The web service includes a website, two databases (MySQL and InfluxDB), a Raspberry Pi version 3 (server), and an Internet router with a Wi-Fi connection. The MySQL database allows for storing data, such as user accounts, houseplants and houseplants characteristics. The InfluxDB database allows for storing the data from the connected sensors. Through the web interface, the customer can monitor the health condition of the houseplants. The user can add or remove a houseplant. It is possible to manage several houseplants by monitoring in real time the condition of the houseplants (watering, light, temperature). The sensor is composed of consensus modular components: a Wi-Fi module NodeMCU ESP8266 (7.79€), an ambient temperature and humidity sensor KY015 (2.99€), an ambient light sensor DFR00026 (2.99€), a soil moisture sensor SEN13322 (3.99€), a RGB LED WS2812B (0.99€), resistors, and cables (1€) as presented in Figure 2.

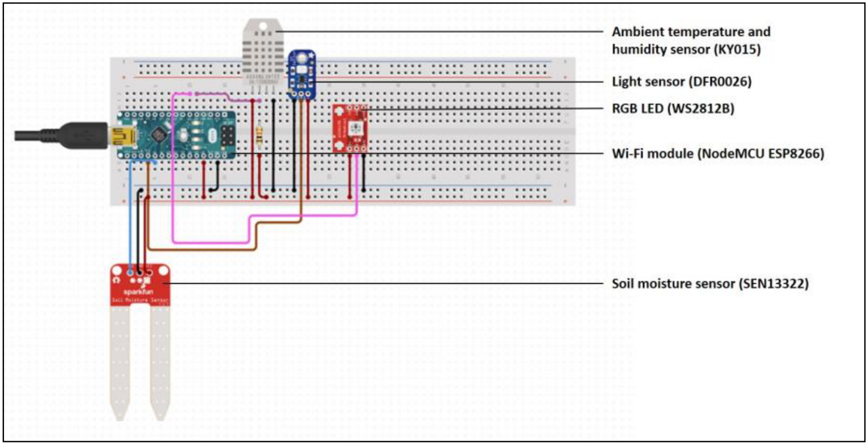
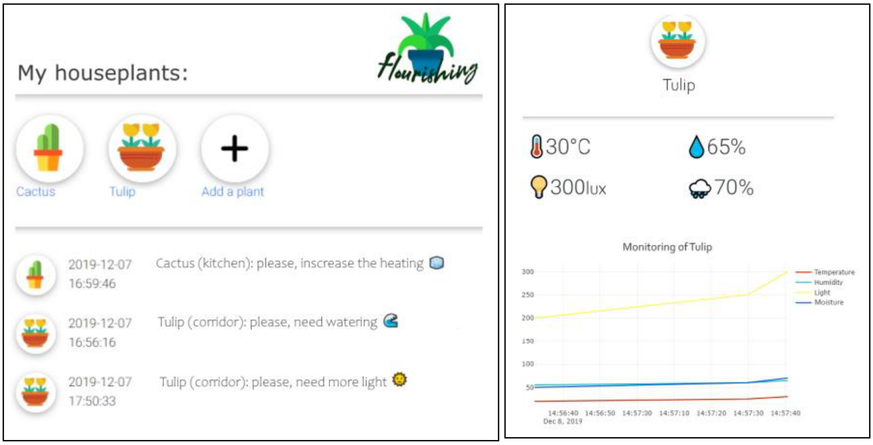


Figure 2. The architecture of Flourishing sensors.

The dashboard (Figure 3, left side) displays all the received alert messages. For example, on December 7, 2019, the houseplant asked to "increase the heating". The monitoring interface (Figure 3, right side) makes it possible to visualize data about ambient temperature, humidity, soil moisture, and light, all in real time.



2019-12-07 16:59:46 Cactus (kitchen): please, inscrease the heating

2019-12-07 16:56:16 Tulip (corridor): please, need watering

2019-12-07 17:50:33 Tulip (corridor): please, need more light

30°C 65%

300lux 70%

Monitoring of Tulip

Figure 3. Dashboard with alert messages (left) - Houseplants monitoring interface (right).

4. Discussion

We assumed that consensus is the overlapping of actors' perspectives in an uncertain design situation or context. Consensus is used for working out an agreement during configuration conflict resolution.

Conflict situations in design emerge when at least two incompatible design commitments are made, coming from different actors (customer, designers) for a given subject, or when a number of actors have a negative opinion regarding the commitments asserted by the others [20][21][22][23]. Propagation of conflict, as well as backtracking without common ground for a solution, or a partial solution where the perspectives converge, can quickly lead to uncontrolled scenarios in product configuration adoptiong IoT technologies. Therefore, discerning the consensual elementary solutions creates common ground for moving toward a final global solution.

In addition, disciplines and transdisplines taking into account the subjective nature of the opinions of actors, formalized using fuzzy set theory, often reflect latent conflicts in actors' commitments. Therefore, consensus is particularly useful when uncertainty is assumed, but the rational decision-making process is required.

5. Conclusion

Modularity and design for configuration represent an efficient solution for the application of IoT technologies. The modularity offers the flexibility in design for configuration of products adopting the IoT technologies.

The fuzzy multilayer network model for configuration allows for the transition from market study into physical solutions. The approach allows for the synthesis of the best consensual solutions for the application of IoT technologies, also arguing the reason for the choice or design of a new component.

Although the fuzzy multilayer network represents the configuration in a integrated perspective, it also has some limitations, particularly its complexity for complex products. The final consensual solution is sought for a given IoT product in the situation where customers have fuzzy targets on product modules selection. To maintain coherent results, the fuzzy multilayer network should be updated dynamically.

The following questions of interest should be investigated: Is a stable solution, which results from the values of membership functions and from the computation on the fuzzy multilayer network, part of continuous change or an island sorrounded by instability? Would a small quantitative change in the membership functions of the fuzzy multilayer network, or in the degree of customer satisfaction in the requirement domain, or in the degree of expert satisfaction in the process domain, alter a solution slightly, produce very different new solutions, or perhaps leave no solutions at all? For the future, the challenge is also to develop a computer-aided integrated platform for a configurable product design integrating the IoT technologies.

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