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INTERDISCIPLINARY DESIGN OF AN ASSISTIVE PRODUCT FOR PERSONAL MOBILITY WITH THE USE OF AN EXPANDED MODEL OF AXIOMATIC DESIGN

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Abstract: *This article presents a model for product design in an interdisciplinary way with participation of the university, private company and the user. The proposal was implemented in the design of an assistive product for mobility according to the ISO9999: 2007 standard. The structure considers the user as the central axis of the design process. In the application, the interdisciplinary team was made up of engineers, industrial designers, an occupational therapist and a psychologist. In the model, the creative phase of the design process is supported with the Theory of Inventive Problem Solving -TRIZ and the analytical phase, with an expanded model of Axiomatic Design, which involves perceptual requirements. In the design of the assistive product, four main requirements were found: the first, to move the technical system; the second, to carry the user; the third, to switch between sitting and semi sitting positions; and finally, to fold the system. It is concluded that the model favors the interaction of disciplines and organizations from the moment of the conception of the problem and not in sequential stages. This contributes to an integrated view of the problem from an ergonomic, technical, aesthetic and commercial point of view. The use of the theory of inventive problem solving contributes to the systemic analysis of the problem, to the technological surveillance of the product and to the determination of the product requirements. Finally, the use of the expanded model of axiomatic design structures the design process, takes into consideration in a rational way the perceptual requirements, and facilitates the transition from the conceptual design to the manufacturing of the product.*

The application of the proposed model in an assistive product for mobility made it possible to conceive a technical system that gives more autonomy to the user that changes the propulsion paradigm, that favors the standing position and which does not use external sources of energy to perform different functions.

Key-words: *Expanded model of Axiomatic Design, TRIZ, Assistive Products for mobility, ISO9999*

1. Introduction

There are different methods for the design of products, some prescriptive and others descriptive (Cross, 1998). Within the prescriptive models, Pugh's proposal (1991), which considers important the work of various disciplines, proposes the following phases: Identification of needs, Definition of specifications, Conceptual design, Detailed design, Production and Sale (Pugh, 1991). Meanwhile, Pahl and Beitz refer to the stages of Planning, Conceptual design, Embodiment design and Detailed design (Pahl & Beitz, 1995). On the other hand, there is another product design theory, Axiomatic Design, which is also known as rational design. It has a descriptive characteristic as well as a prescriptive characteristic. The descriptive characteristic refers to the recognition of the creative and analytical phase in the process of design. The prescriptive characteristic refers to the strict compliance of the two axioms from which its name is derived. The two axioms are the Functional Independence Axiom and the Minimum

Information Content Axiom which helps verify the quality of the design (Suh, 1991).

Along with the theories, there are various supporting techniques for the design process in each one of the stages of the models by phases. However, in the interdisciplinary collaborative design, the mere technique does not contribute to the cooperative work in the project. Additionally, in the industry, it is not frequent the use of methods and techniques as demonstrated by studies in England (ARAUJO et al 1996), Japan (Fujita & Matsuo, 2005) and Sweden (Janhager et al, 2002).

Several authors state that the creation of multidisciplinary project teams for product design broadens the product vision, ensures low cost production, considers in a better way aspects associated to the product's life cycle and the products are expected to have a better market acceptance. However, the authors suggest to carry out more empirical experiences to validate the potential of interdisciplinary work teams (Peeters et al 2007; Rafols & Meyer, 2006).

From the point of view of innovation, cooperative work is seen as desirable by all the organizations in order to learn, use and share the logic of other fields of knowledge through processes of interaction that go beyond the use of techniques from other disciplines under a single discipline approach (Hosnedl & Dvorak, 2008).

This article proposes and applies a model for product design involving interdisciplinary teams from the University, the long-established industry, the technological-based industry and the user, with the support of the State. Thus, with the model presented in this paper, we obtained results of interest for all participants and the design of innovative products. The company from this relationship creates new business opportunities, the university finds new opportunities for applied research and the State fulfills its role in promoting research and strengthening the economy by being supportive to business. Additionally, the state benefits from the results of research in society by generating new social development programs of impact. In the proposed model, the common point is the Social Need from a multidisciplinary and multi-organizational perspective, rather than market orientation as traditionally product design is focused in an enterprise level. The model of interaction of the different participants takes as theory of reference the Axiomatic Design along with the inventive solving solution strategies TRIZ and the use of techniques such as fuzzy logic for the dealing with the subjective requirements of the product (Ulla, 2004).

The paper is organized as follows: the first part presents the Expanded Axiomatic Design Model (MADA). This section presents the characteristics of interdisciplinary interaction of business-university-state-user and the structuring of the design process in its creative and analytical parts. The creative part is worked with the Theory of Inventive Problem Solving (TRIZ) and the analytical part with an extension of the original model of Axiomatic Design Suh (1991). Then, we present an application of the Expanded Axiomatic Design Model in the design of an assistive product for mobility to promote the social inclusion of people with disabilities. Finally, the results and a discussion of the application are presented.

2. Characteristics of the Work-State University-Enterprise in product design

Many authors have expressed the need of working together State-University-Industry taking as reference Sabato's model and the triple helix model (Etzkowitz & Leydesdorff, 2000). Numerous studies analyze the tensions generated by these relationships due to the different interests each of the actors have, their differences in organization, working mechanisms, promotion and tradition, among others (Siegel et al., 2003, Mora-Valentin et al. 2004; Freitas, 2007). For product design, universities have a set of knowledge of their own due to their diverse range of disciplines and professions, which would broaden the vision of a problem when used together (Pugh, 1991; Cuervo & Asakawa, 2008). In turn, the consolidated company has a current knowledge of the market, knows the production process, brand recognition and channels of supply and logistics, all of which should be exploited to a higher innovative value process supported in these abilities. However, some companies are reluctant to apply new knowledge, overestimating the achievements obtained over the years in rigid and functional administrative structures. These difficulties do not favor the absorption and implementation of new knowledge, nor of cooperative work to develop new business opportunities (Cohen & Levinthal, 1991). In turn, the State has resources that can be assigned to innovation and has a robust structure to meet the necessities of citizens. These resources can be directed to the generation of new products or innovative services which allow compliance with the obligations of the State with society.

This suggests an approach to innovation through inter-organizational cooperative work, which must identify and structure the existing capabilities of organizations and carry out processes of coordination and reconfiguration of these capabilities. In the same way, it is suggested that from a perspective of the product axiomatic design, it can be possible, on the one hand, to enhance the productive and technological capabilities, and on the other hand, enhance the capabilities that enable the display and reconfiguration of the existing ones.

3. The process of ideation with the theory of Inventive Problem solving TRIZ

TRIZ is a set of techniques to encourage invention, developed by the team of Genrich Altshuller in the former Soviet Union in 1946. TRIZ is best known for having reviewed more than two million patents as its information source, and its main concepts are: Contradictions, Ideality and Technical System Evolution. The key concepts of the theory are the Ideality TRIZ, ARIZ, Contradictions, Substance-Field Analysis, the laws of Evolution Systems and Base of Knowledge of the Effects and Inventive Principles (Goel et al., 1998). Nowadays, the TRIZ theory is used worldwide in the industry and the university (Cavallucci, 2008).

3.1 The technique of the nine windows in Triz

The nine windows (multi-screen scheme of thinking) is a TRIZ technique used to visualize a system, which has a Principal Function on an object, as part of a hierarchical structure and with temporal behavior. This way of analysis helps to understand a problem in a disaggregated manner and to identify issues associated with the problem that are not obvious from a purely functional analysis. In turn, it allows stating some hypotheses of evolution through the identification of the behavior of a set of parameters that are involved in the problem from the past. Figure 1 shows the diagram of nine windows, where the horizontal axis represents time, being the center the current time, with the past to the left and the future to right. The vertical axis represents the vision of the problem. The center is the technical system that plays some role. The lowest level is its composition (the subsystem) and the upper level is its context (supersystem) in which it is immersed.

3.2 The matrix of contradictions

The technique of the nine windows allows the systemic analysis of the problem which is an input for using the technique of the matrix of contradictions. A contradiction is defined in TRIZ as a situation in which a particular parameter which describes a quality of a system is affected negatively when trying to improve another. The matrix of contradictions is a technique to resolve such conflicts making the system to evolve from its current state.

Altshuller suggested a crossing matrix of parameters in conflict that contains a set of inventive principles to overcome them. The parameters originally proposed were 39 and the inventive principles, 40.

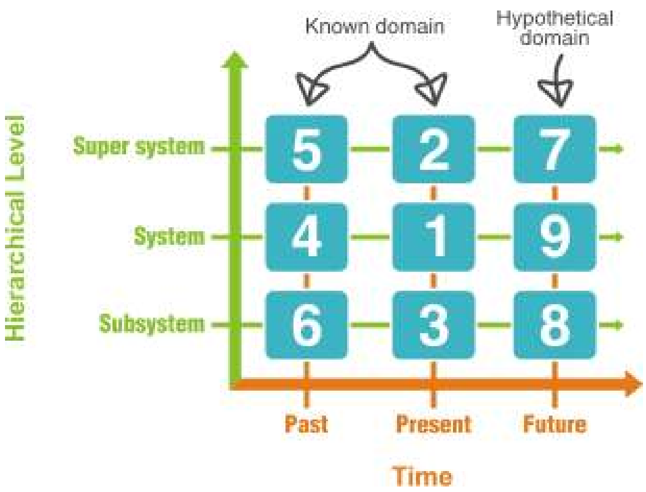

Figure 1: Nine Windows Diagram. Source: INSA, 2007

In the analysis of a problem, using the technique of the nine windows, achieving an ideal future state will depend on overcoming a conflict in the present. These conflicts arise when trying to improve a parameter in the technical system another parameter is worsened. Thus, with the contradictions identified, the inventive principles suggested to overcome this contradiction are looked for in the matrix. Figure 2 shows the contradiction of the parameter strength with the parameter weight of stationary object.

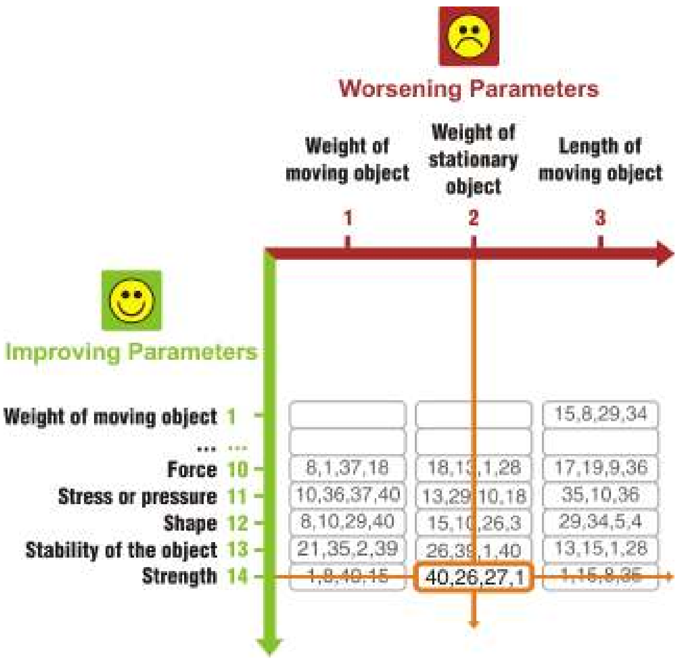

Figure 2: Example of the Use of Contradiction Matrix Source: The Authors

4. Support products according to standard ISO9999: 2007

According to the standard ISO9999: 2007, a support product is any device, instrument, software, technology or equipment, specially made or commercially available to prevent, compensate, control, mitigate or neutralize the disability of an individual. The standard establishes a classification into three hierarchical levels (class, subclass, and divisions), according to the function they provide; Figure 3 shows a conceptual map which details the class 12 standard, corresponding to product support for personal mobility.

5. Axiomatic Design

Axiomatic Design is a proposal of Nam P. Suh who defines a strategy for the design of products accompanied by a sound scientific basis to ensure the success of the design. Axiomatic Design has four domains: customer domain, functional, physical and process.

In the customer domain, the attributes and customer needs are characterized as customer attributes (CAs). In the functional domain, the CAs are converted into a set of functional requirements (FRs). In the physical domain, a set of design parameters (DPs) are chosen to satisfy the functional requirements (FRs). And finally, in the process domain, a set of process variables (PVs) are selected to manufacture the DPs of the physical domain. Figure 4 shows the four domains mentioned.

5.1 The design equation

Mathematically, the Functional Requirements (FRs) can be treated as a vector {FR} with m components. Similarly, the Design Parameters (DP) are a vector {DP} with n components, where each element A_{ij} of the matrix relates a component of the vector {FR} with a component of the vector {DP}. This is expressed by the design equation:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ \vdots \\ FR_m \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \vdots & \vdots & & \vdots \\ A_{m1} & A_{m2} & \cdots & A_{mn} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ \vdots \\ DP_n \end{Bmatrix} \quad (1)$$

The *content of information* (I) of a design can be defined quantitatively as the logarithm of the probability *(p)* of satisfying the functional requirement (FR) specified.

$$I = \log_2 {}^{1}/_{p} \quad (2)$$

6. Expanded Model of Axiomatic Design

A model of management in initiatives of collaborative innovation between the University, the industry, the state and the User is proposed for product development. Note that two types of firms are part of the initiative. On the one hand, there is the long established industry and on the other hand, there is the new technology-based industry. Also, the participation of the user is explicitly included. Figure 5 presents the proposed model in which the participants, their current capabilities and potential for collaboration, the learning process and the contribution which is obtained by the cooperative work in the relationship are identified.

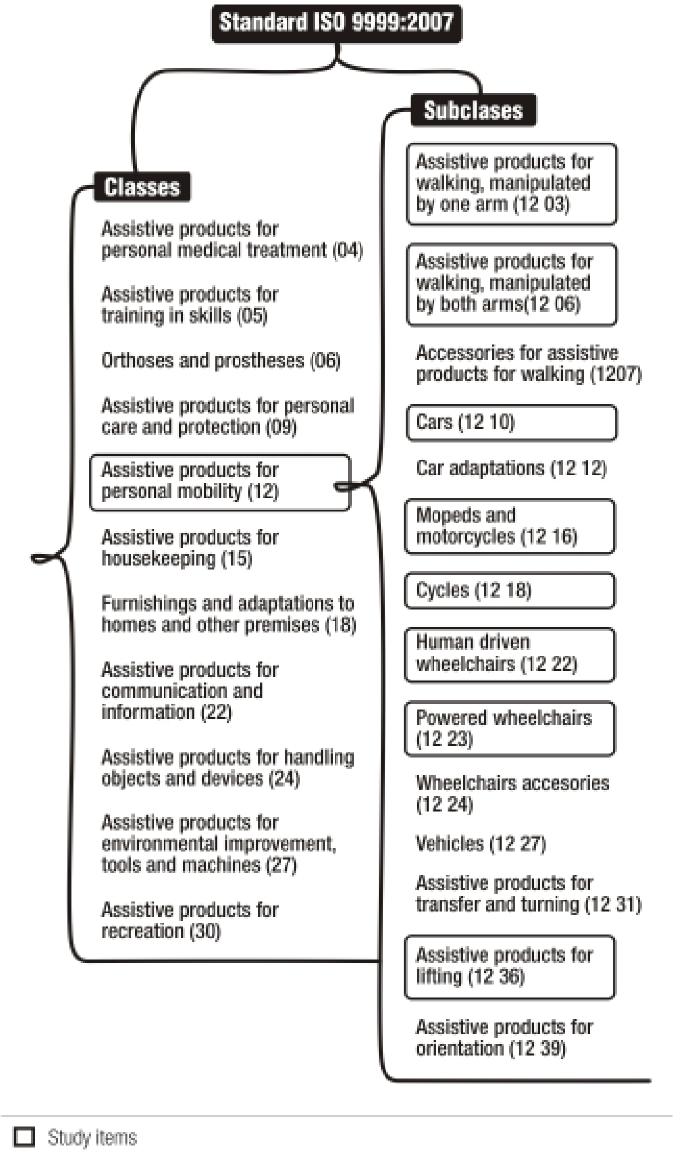

Figure 3: Assistive Products Classification Standard ISO: 9999, 2007 Source: The Authors

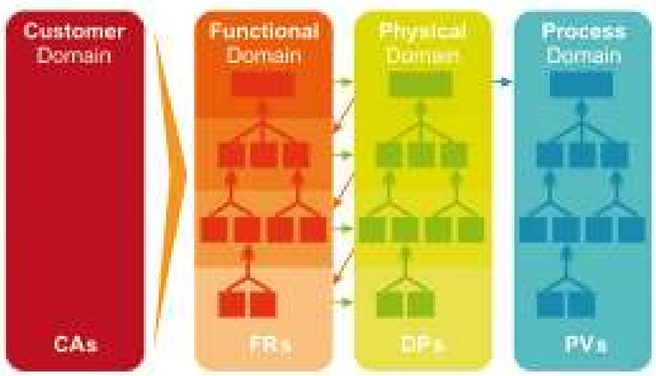

Figure 4: Axiomatic Design Domains Source: The Authors

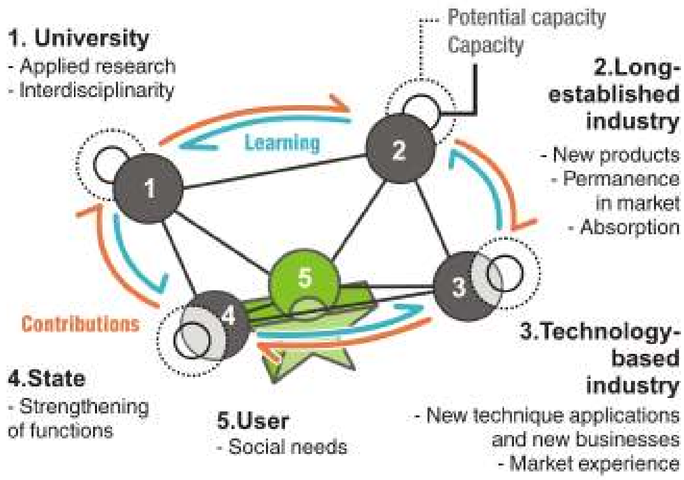

Figure 5: Participatory Model of Planning and Transformation of capabilities. Source: Aguilar-Zambrano J. et al, 2009

MADA consists of three parts as shown in Figure 6. The first part is the conformation of the team, the second is the systematic analysis of the problem, where a hierarchical structure is determined and the third includes the structuring of the design process for the lower levels or detail levels in where the compliance of the two axioms that defines the axiomatic design are constantly verified.

6.1 Composition of the design team of multidisciplinary nature taking into account the social need

A model of management in initiatives of collaborative innovation is proposed between the University, the Industry (a long-established one and a new technology-based one), the State and the User for product development. In the participative model, the center of convergence is the social need which is associated with the user. Thus, not only innovative products are developed, but all actors are favored with the increase of their own capabilities because of the results of the relationship.

6.2 Determination of the functional and nonfunctional requirements of the product

The problem is studied through the technique of the *Nine Windows* of Theory of Inventive Problem Solving, TRIZ.

This tool allows a systematic analysis of the problem, and at the same time, provides an evolutionary view of it. The results obtained using the technique allow to form the first level of the hierarchical tree of Axiomatic Design determining first-level requirements and their Design Range (Rd). The Product Constraints (Cs) are formulated and the Design Parameters (DPs) are associated to each requirement.

Requirements are of two types: functional (FRs) under the classical definition of Axiomatic Design, and non-functional or perceptual (NFRs), both NFRs and FRs arise from the Contradictions (CTs) that appear in the analysis of the problem when an ideal future scenario is proposed to solve the problem and cannot be achieved with the current system or product. Design Parameters (DPs) also arise from the contradictions found and are proposed through the use of the Contradiction Matrix TRIZ.

6.3 Formulation of the lower levels of the hierarchical tree and evaluation of the axioms of Axiomatic Design

Design Parameters (DPs) of the first level give origin to the requirements of the lower levels, for which Design Ranges are determined and are associated with new DPs; this iterative process (zigzagging), between the functional and physical domain of Axiomatic Design forms the hierarchical tree of the product. During the process of formulation of the Design Parameters (DPs) the design equation is set up. This equation is the relationship between DPs and requirements (FRs and NFRs) which is used to evaluate the first axiom of the design.

7. Application of MADA in an assistive product for mobility to promote social inclusion

The MADA was applied in the design of an assistive product for mobility (ISO999: 2007) for people who have a lower limb motor disability. The project involved three universities, a technology based company, a set of users and the State financed its development.

7.1 Conformation of the design team with a multidisciplinary nature taking into account the social need

The social need, which is an essential part of the model, was the need to favor the social inclusion of people who had motor disabilities.

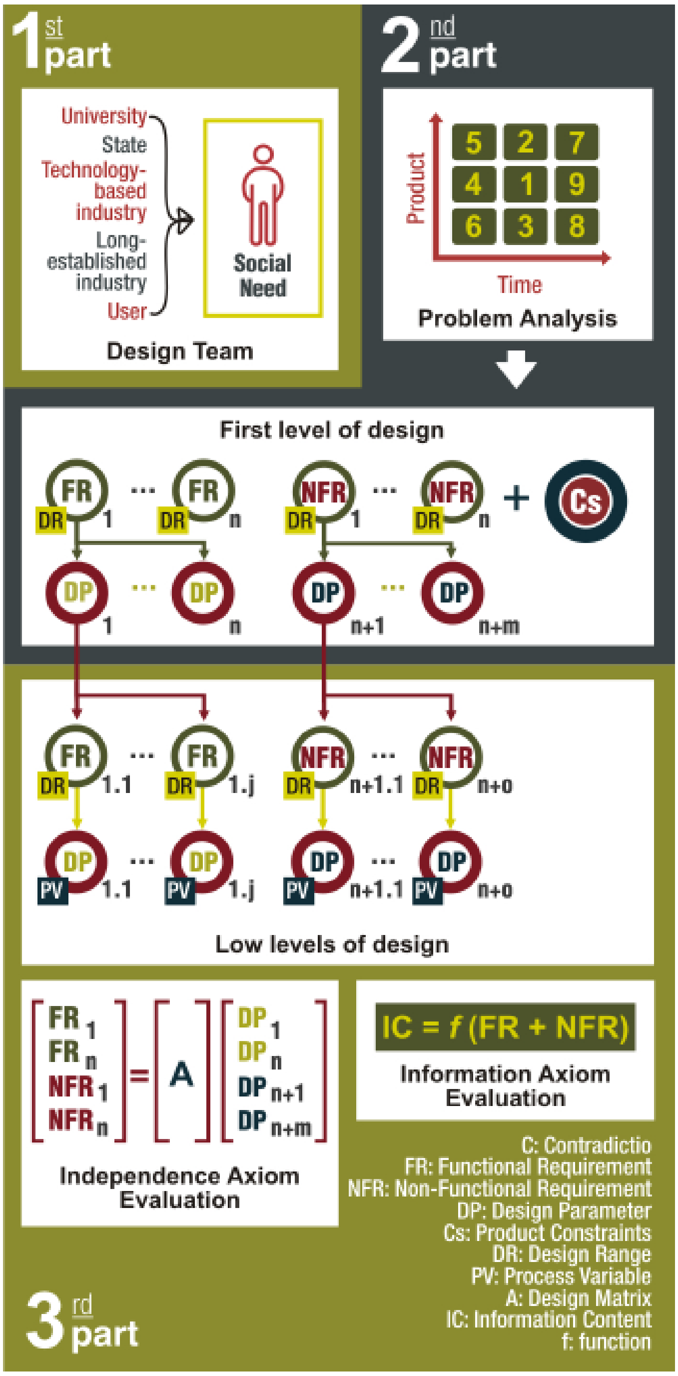

Figure 6: Expanded Model of Axiomatic Design

From the identification of the social need, a multidisciplinary and multi-organizational design team was formed with the following structure: User: two people with motor disability. University: professionals in different disciplines: electrical, electronic, mechanical and industrial engineering, industrial design, occupational therapy and psychology from in the Pontificia Universidad Javeriana-Cali and Universidad del Valle in Colombia, and Universidad Politécnica de Valencia in Spain. Technology-based company: an engineer from a company that designs and manufactures products for rehabilitation, Rehabitec Ltda. State: the main financial institution of research projects in Colombia, the Administrative Department of Science, Technology and Innovation - COLCIENCIAS. Long- established Company: There was no involvement of this firm due to the absence of industries producing these products in the country.

7.2 Determination of functional and nonfunctional requirements of the product

We used the technique of TRIZ Nine Windows for the systemic analysis of the problem. The inputs for these Nine Windows were: the implementation of the Laws of Technical Systems Evolution; the evaluation of commercial products, prototypes, articles and patents of the assistive products for mobility of class 12 considered in the standard ISO9999: 2007, and the development of a product's user profile through two consultation tools based on the International Classification of Functioning, Disability and Health (ICF).

The application of the technique of the nine windows TRIZ made possible to determine a set of Functional Requirements (FRs) and nonfunctional requirements (NFRs) as summarized below:

FR1: To complete the power supplied by the user.

FR2: To transmit the energy to move the Technical System.

FR3: To maintain the dynamic equilibrium of the Technical System

FR4: To allow the user to control the direction of the device

FR5: To allow the user to control the braking device.

FR6: To allow the user to access to the minimum space designed for the transit of the pedestrian.

NFR7: To maintain the user at a temperature that does not generate discomfort.

FR8: To reduce pressure points that could lead to pressure sores

FR9: To allow the user to get into and out of the device

FR10: To allow the user to use stairs.

FR11: To allow the user to move through different terrains.

FR12: To allow the adaptation of the device according to the level of injury, keeping the balance.

FR13: To allow the user to change between sitting to semi-sitting position.

Subsequently, based on an analysis with the use of Independence Axiom only four Requirements were proposed:

- FR1: To move the technical system.
- FR2: To carry the user
- FR3: To change between sitting and semi sitting posture
- FR4: To reconfigure the assistive product for easy folding and transport.

To determine the Design Parameters of the Functional Requirements, the tool used was the Contradiction Matrix of TRIZ.

The Design parameters selected for the requirements of the first level are shown in Figure 7.

7.3 Formulation of the lower levels of the hierarchical tree and evaluation of the axioms of Axiomatic Design

Low-level requirements depend on the DPs of the previous level. For example, for FR2, in the first thirteen requirements mentioned above, the low level FRs and DPs are the following:

FR2: To transmit the energy of the person for the displacement; DP2: Lever easily removable in each ring

FR2.1 To connect to and disconnect from the fulcrum; DP2.1 Connector at the interior of the ring

FR2.2 To connect to and disconnect from load point; DP2.2 Ratchet

FR2.3 To have a pushing point; DP2.3 Ergonomic handle

FR2.4 To allow to alternate pushing direction; DP2.4 Selector of direction

The relation between each FR and its respective DP must be described with its attributes as it is shown in Table 1.

Table1: Class functional requirement and design parameter

FR1.1	To drive along horizontal and inclined planes
Design range	Min: 0 degrees.
	Max: 15 degrees
DP1.1	Driving system with gears activated by a lever.
Justification	The angle is the way to measure the inclination of the slope. The minimum value corresponds to horizontal planes and the maximum value corresponds to the limit value according to standards of electric wheelchairs.

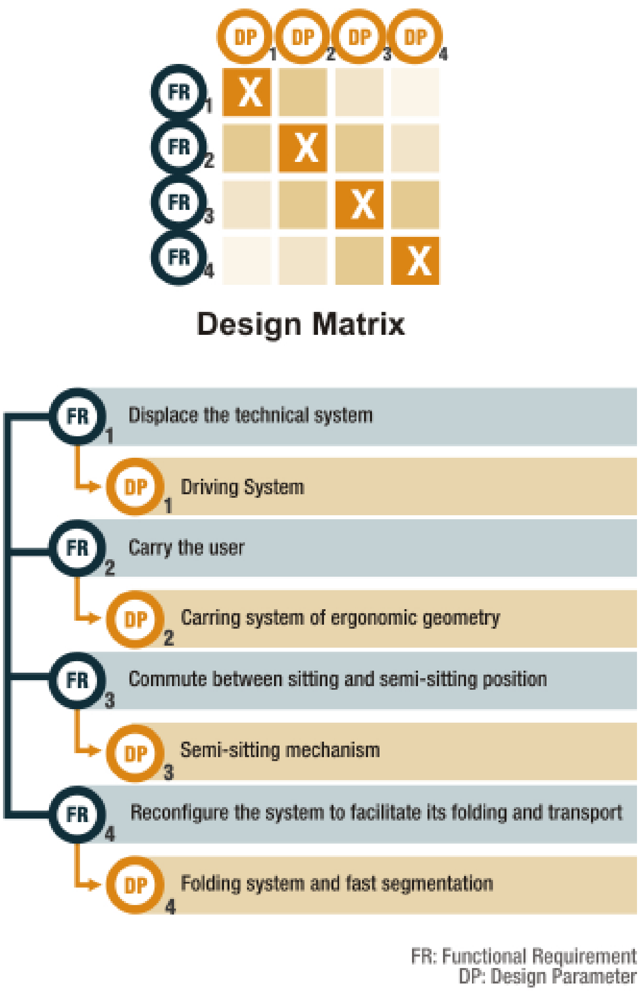

Figure 7: First Level Functional Requirements

The design product is shown in Figure 8.

Figure 8: Representation of the design based on the four last requirements.

Table 2 shows the final evaluation of the information content for the product designed in the project with the use of the equation (2) of Information Content

Table 2: Information content of functional requirement of first level

FR	**Rank**					**Information Content**
	design			system		
	minimum	maximum		minimum	maximum	
1[b]	1,46	0,55		1,71	0,53	0,374
2[c]	75	100		75	100	0
3[d]	0	80		0	64	0
4[e]	30	50		40	70	1,584

Note. Units: [a]bits, [b]m / s, [c]KG, [d] degrees, [e]percentage of volume reduction.

8. Discussion

This type of approach to product design made it possible that the disciplines involved generate value for areas of knowledge. In this way, the industrial design was enriched with functional methods from engineering and with the ways of approaching the user from psychology. In turn, engineering had a better approach to the social need through psychology and occupational therapy. Psychology handled problems associated with interdisciplinary working groups; on the other hand, occupational therapy made possible to integrate technical knowledge to tackle problems both of social inclusion and of human functional independence.

Systemic analytical work made possible to recognize a broader vision of the problem and in turn, identify its constraints since it considers different qualities such as functional aspects of the products together with features of the context that prevent social inclusion of people with disability.

The extended model of axiomatic design is enriched with the principles of the theory of inventive problem solving TRIZ since it made possible solve functional requirements through design parameters obtained from the use of these principles.

The application of axiomatic design, with the use of the first axiom, made possible to decant the functional requirements of first level since when setting up the low hierarchical level of the first approximation, the system was coupled.

The measurement of information content of the design makes possible to have a certainty of its quality because it represents the degree of compliance of the design proposal with respect to the requirements demanded. However, the process can consume a lot of time because of the amount of calculations involved in greater detail for the inferior levels of functional requirements in designs with multiple levels of hierarchy.

The matrix design makes possible to have a clear view of the product design because it provides information about both, the requirement and the design parameter that satisfy it and provides information on the degree of coupling between the functional requirements.

The assistive product for mobility that was designed has innovative features compared to products currently on the market which is a contribution of the interdisciplinary work. In the same way, it emphasizes the integration of engineering and industrial design in the support of technical aspects as well as ergonomic aspects, respectively.

9. Conclusions

The approach to the problem of social inclusion with an interdisciplinary participation, made possible to make the design of the product from the user's inquiry, the analysis of context and application of the technology to favor innovation.

The design process with the use of Expanded Axiomatic Design Model made possible to improve the product respect to the quality because all the configuration of the product and the functional relations between its components is known. Thus, the product can be improved in a structured way to ensure its operation without much change.

The design of this assistive product for mobility has innovative features compared with other products in the market. This was achieved by the participation of the user in the design process and the participation in a structured way of the disciplines using the Expanded Axiomatic Design Model.

The designed product is a device that favors the functional autonomy because it has features that make possible that users reduce the efforts on terrains with slopes without needing help of other people and to reach objects in higher places than they would be able to reach with traditional wheelchairs.

Theory of Inventive Problem Solving TRIZ has been applied in new way integrating it to the Expanded Model of Axiomatic Design. One advantage of this integration is the reduction of the complexity of the design because of the reduction of couplings between the FRs Functional Requirements due to the selection of the design parameters with the use of the principles of TRIZ.

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