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VALIDATION OF PRODUCT REDESIGN BY INTEGRATING FUNCTIONAL REASONING AND AXIOMATIC DESIGN

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ABSTRACT

This paper describes the development and validation of a new product version made by a Calabrian company, leader in the sector of mechanisms for windows and shutters.

Up to now, the designers of this company have operated on the basis of their know-how, employing the trail-and-error method. However, they were conscious that decisions made during the conceptual design phase profoundly affect the quality of the industrial product and the productivity of the company, leading to costly mistakes. Then, they decided to consult the authors to have a "scientific" validation about a new product version, with the aim to limit the investment risks for the firm.

For this purpose two design approaches were applied: a functional design and the axiomatic design. Both methodologies were employed to help designers to structure and understand design problems, thereby facilitating the synthesis and analysis of design requirements, solutions, and processes.

In particular, representing the new product in a design space where its functional structure can be analyzed in term of functional blocks connected by functional links, it was possible to verify if all functional requirements were satisfied correctly. Later, the morphology of the new product was verified, checking its functional surfaces, in order to establish if the product was able to perform the functionality for which it was conceived.

At that point, it was necessary to verify if the modified version of the product was really better than the old one. This check was performed applying the axiomatic design, providing this theory a rational basis to evaluate the alternative proposed solutions.

The paper has the aim to verify the advantages of the combined use of both design theories in order to have a better control of the whole conceptual design process.

Keywords: Axiomatic Design, Functional Analysis, Product Development, Redesign Process.

1 INTRODUCTION

Cooperation between University and Firms is one of the most important factors that can support the economical development, stimulating innovation and competitiveness of industrial products. So University must not restrict its own activity in high education for people (managers and technicians) that work in Firms, but must cooperate with Firms in searching systematically the most suitable way for solving technical problems.

In the ambit of a collaboration between the Department of Mechanical Engineering of the University of Calabria and a Calabrian Firm, leader in the sector of mechanisms for windows and shutters, the present case of study has been developed, consisting in the redesign of a device that allows a discrete number of orientation to the shutter slats.

The study has started with the analysis of the currently used device, as-is, employing the functional analysis. In fact an accurate interpretation of any problem in functional terms, gives to the designer the right elements to thing on the possible solution [Cross, 2001]. The functional approach has been clarified by several authors, starting from Pahl and Beitz [Pahl and Beitz, 1996] till to Ulrich and Eppinger [Ulrich and Eppinger, 2003], from Otto and Wood [Otto and Wood, 2001] to Stone [Van Wie et al., 2004]. Also the authors of the present paper have proposed a functional model [Bruno et al., 2003], that place the classic functional net in a 3D space, in which the solution comes to an embodiment. The principal intent of this model is to drive towards the embodiment of a solution by means of an abstract/linguistic functional level, till to arrive to a rough geometric form that each single component (or a part of it) must have so it can perform the task for which it has been conceived.

The present paper deals with the application of the functional approach operating in a fashion callable "Reverse Functional Analysis", for analyzing the functionality of the current device, identifying on each component the function or the functions it performs, and arriving to draw a functional net of the whole device. Then, following a BOTTOM/UP sequence, the functional net is traced back till to an early level of abstraction, completed with all the interactions among the functional blocks and with the outside. This "old version" of the device was analyzed, correlating each Functional Requirements with its or their own Design Parameters, and a decoupled Matrix Design was obtained. Considering the high number of elements and a foreseeing conflict with the Second Axiom of the Axiomatic Design Theory [Suh, 1998], a new product version was searched formed by the lower possible number of elements.

So, re-examining all the functions, a new functional net was searched, emphasizing new functionalities and new principle of solutions. Enlarging the domain of the solutions, not confined to the use of only "rigid elements", but considering also the elastic behaviour of the material, a new device was developed. Also this latter was verified with the Axiomatic Design, and being formed by only two components it is reasonably to say that it reaches a better index related to the Information Axiom.

The paper describes all the steps followed during the redesign process and emphasizes how functional reasoning and axiomatic design are able to guide and suggest a right way to the designer.

2 GENERAL CONTEXT

The study is related to the devices that allows the orientation of the shutters. A sector that appears so modest requires to the involved designer a particularly remarkable inventiveness. A firm operating in this sector, in order to maintain the position reached in the marketplace, must have a fully populated portfolio of products, each characterized by a proper mechanism to fulfil the extremely various kind of user needs. In fact, if some manufacturers offer knobs or rotational handles to orient the shutters, other use levers of various kind that activate mechanisms on sight or hidden into the aluminium section.

Common elements to all typologies of solutions is the space, very small, available for assembling the mechanisms, that require designer to check complex tolerances chains. Furthermore, regardless to the way in which the orientation is made, it is important to consider that some users prefer to orient slats continuously, while others prefer to choose the orientation among a certain number of predefined positions. Generally, these latter are limited to 5 or 6 positions: all open, all closed, plus 3 or 4 angular positions equally spaced in the range of 90 degree. So, together to the lever, a mechanism is required to orient the slats in these predefined positions. To this latter category belongs the mechanism under investigation, reported in Figure 1.

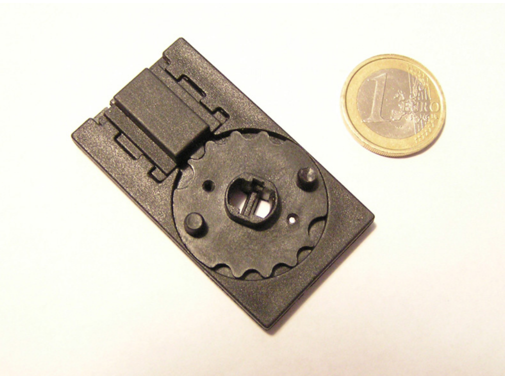

Figure 1: Image of the current device

The mechanism, though runs correctly, presents some drawbacks in the production phase. In fact it is constituted by a high number of parts, in particular: five moulded parts in Nylon PA6; two screws and one spring (see Figure 2).

The high number of moulded parts does not allow to rationalize to the best the exploitation of injection mouldings and, requires a considerable time for the assembly (about 40 seconds for a skilled worker).

Therefore, the designers of the firm aimed to a radical improvement of the current mechanisms with the purpose to optimize the injection mouldings and to reduce the assembly time rather than improve the performance of the product.

3 FUNCTIONAL ANALYSIS OF THE DEVICE AS-IS

Before the redesign of the device, the authors considered essential to perform a functional analysis of the current device.

First of all, it was important to clarify that the user, operating by a lever, modifies the inclination of a single slat of the shutter. The same inclination is transmitted to other slats by a pair of rods in aluminium.

The device allows a snap rotation in a series of predefined positions for the orientation of the slats of a shutter. Only one device is required for the entire shutter.

Obviously, the device must oppose the suitable resistance to slats rotation in order to allow a easy usage, but sufficiently adequate to prevent the autonomous rotation of slats under the effect of the wind.

For the current device, the snap rotation is obtained by a gearwheel, with the sprocket profile shaped by arcs of circles, and by a pin that fit in the space between two adjacent teeth. When the user operates on the lever, the gearwheel turns and, overcoming the resistance of the spring, draws back the pin. Then the pin is pushed by the spring and snaps into the next space, defining in this way the next position for the orientation of the slats of the shutter.

In particular, the components of the current device are: a box, a gearwheel, a wheel-plate to fix the gearwheel, a pin, a slide for the pin, a spring and two self-tapping screws to fix the wheel-plate to the gearwheel. The slide is fixed to the box by clicks.

In the following figure an exploded diagram of the current device is shown.

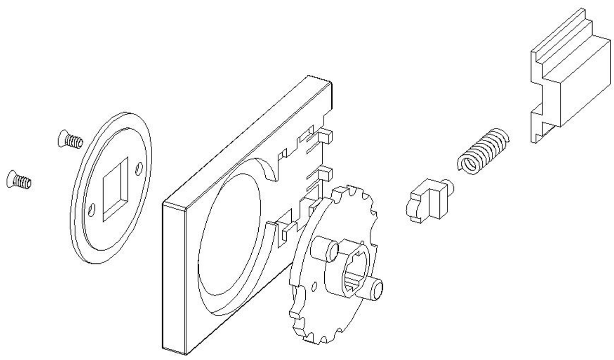

Figure 2: Exploded diagram of the current device

In the same figure, it is possible to observe the pins on the gearwheel for the coupling with the aluminium rods that are linked with every slat of the shutter.
In table 1, the functions, performed by every component of the device, are reported.

N	Components	Functions
1	Box	Connect the device to the aluminium section House the gearwheel House the wheel-plate Guide the rotation of the gearwheel Fix the slide
2	Gearwheel	Connect to the rods Define angular positions Connect to the wheel-plate
3	Slide	Lock on the box Hold the spring Lead the pin
4	Pin	Block the rotation of the gearwheel
5	Wheel-plate	Connect to the gearwheel
6	Spring	Push the pin in the hollow of gearwheel
7	Screws	Fix axially the wheel-plate to the gearwheel

Tab. 1 – Functions of the current device components

The high number of components employed for this device cannot be reduced if the described functioning is adopted. In fact, it is not possible to combine more components in a single one, unless to introduce more complex injection moulding set up.
Therefore, in order to reduce the number of components, an alternative way to obtain the snap swing is required.

3.1 REVERSE FUNCTIONAL ANALYSIS

In order to generate an idea to obtain the snap swing in a different way, the functional analysis of the current device has been performed with the aim to stimulate the inventiveness of the designers.
In this way, it was possible to identify the functional requirements of the device and, with this analysis was recognized where to operate in order to combine some functions and reduce the number of components.
As already presented by the authors in a previous work [Giampà et al., 2003], the functional analysis can be performed either in TOP/DOWN way (following the design process from the problem to the solution) or in BOTTOM/UP way (when it is necessary to reconsider some done choices or to analyze an existing product).
In any case, the elements of the "design space" are: the functional blocks (which represent the functions or the sub-functions), the links (which represent the relations among functions) and the geometrical archetypes (that are rather simplified geometries of the real components where the functional surfaces can be recognized, i.e. the surfaces by means the components perform their function).
The link can be: the energy flow, the material flow, the signal flow and the force contact. In the case in examination the material flow and the signal flow are absent.
Following the BOTTOM/UP process, the authors started from the identification of the functional surfaces on the archetypes and of the functions performed by every component.
The device has two different behaviours as shown in figures 3 and 4. In figure 3 the current device is represented, in the design space, when it is actuated by the user. It is possible to recognize the links acting among the functional surfaces: the energy link is represented in red (this link depicts the energy flow that, overcoming the resistance of the spring, gives a rotation to the gearwheel) whereas the force contact among parts is represented in blue.
In figure 4, the device is represented when the energy stored by the spring is transferred to the pin in order to block the rotation of the gearwheel in the required angular position of the slats of the shutter. In this case, the energy transferred by the spring is transformed in the translation of the pin and in the force contact between the same pin and the gearwheel.

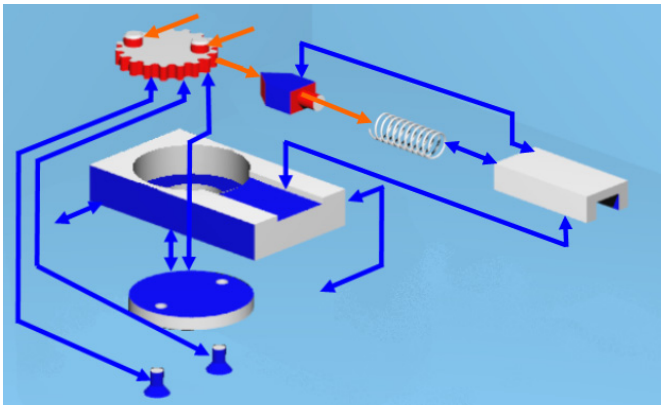

Figura 3:The current device actuated by the user

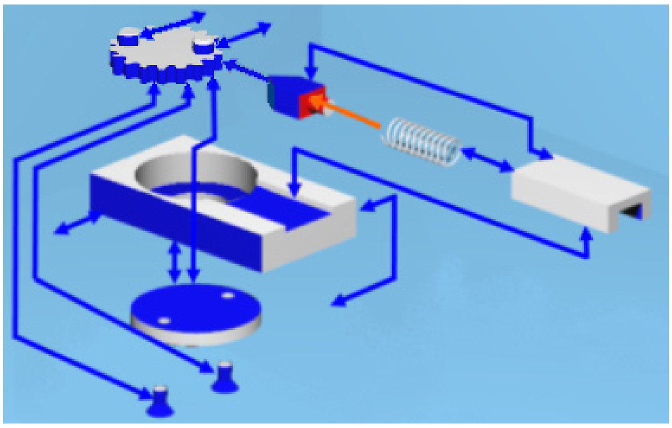

Figura 4: The energy of the spring acts the blocking

Going backwards in the Reverse Functional Analysis, the functional net shown in figure 5 is obtained.
In it the device is represented with a high level of abstraction, where there are not archetypes, but only functional blocks with related functions.
The authors have considered to not continue further the Bottom-Up process. In fact it is not essential to reach to the functions at an higher level, or even to reach to the macro-function of the whole device (this macro-function could be expressed as: "Effect a snap swing"), in order to start a reasoning that could lead to a different original solution.

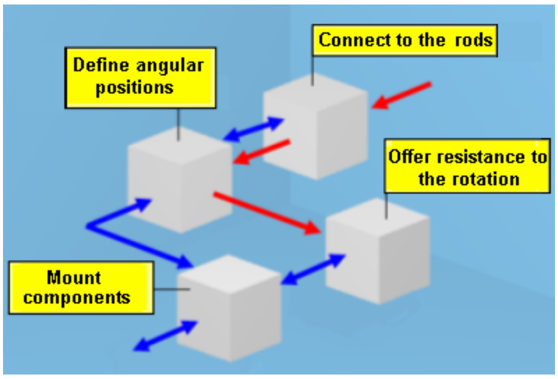

Figure 5: A backward step in the Reverse Functional Analysis

3.2 AXIOMATIC DESIGN OF THE CURRENT DEVICE

Axiomatic design is a general methodology that helps designers to structure and understand design problems, so facilitating the synthesis and analysis of suitable design requirements, solutions, and processes.
In the present case study, the authors have applied the Axiomatic Design in order to evaluate and choose between two design alternatives (the current device and the new one designed with the help of the functional approach) in a checkable way.
The authors consider that the creative phase of the design process, in which a suitable solution is generated, can be well supported by the functional approach. Nevertheless, the axiomatic approach can be more useful in a later phase when the designer has to analyze alternative solutions to recognize which one satisfies better the design requirements.
The axiomatic approach provides a rational basis for evaluation of proposed solution alternatives and the subsequence selection of the best alternative by two design axioms: the first axiom is the independent axiom, and it focus on the nature of the mapping between "what is required" (FRs) and "how to achieve it" (DPs). It states that a good design maintains the independence of the functional requirements (FRs). The second axiom is the information axiom and give a measurement of the quality of the solutions, or better how the FRs are fulfilled.
Analyzing the current device on the basis of the first axiom, it is possible to recognize that this solution is already an acceptable design. Referring to figure 5 the functional requirements can be so listed:

FR_1= Mount the components;
FR_2= Define angular positions;
FR_3= Offer resistance to rotation;
FR_4= Connect to the rods.

Taking into account the functionalities of each components, these requirements can be so decomposed:

FR_{11}= Connect the device (box) to the aluminium section;
FR_{12}= House the gearwheel in the box;
FR_{13}= House the wheel-plate in the box ;
FR_{14}= Guide the rotation of the gearwheel;
FR_{15}= Fix the slide on the box;
FR_{16}= Connect gearwheel and wheel-plate between them;
FR_{17}= Hold the spring;
FR_{18}= Lead the pin;
FR_{19}= Fix axially wheel-plate to gearwheel

FR_2= Define angular positions;

FR_{31}= Block the rotation of the gearwheel ;
FR_{32}= Push the pin in the hollow of gearwheel ;

FR_4= Connect to the rods.

A set of design parameters DPs, related to the FRs, have been identified in such a way that each specific DP satisfies its corresponding FR without affecting other FRs.
This leads to a diagonal matrix, that proves the complete independence of the FRs.
The DPs are the following:

DP_{11}= External dimension of the box;
DP_{12}= Depth of gearwheel housing;
DP_{13}= Depth of wheel-plate housing;
DP_{14}= Coupling tolerance;
DP_{15}= Coupling tolerance;
DP_{16}= Dimensions of the coupling;
DP_{17}= Length of the slide;
DP_{18}= Internal dimension of the slide;
DP_{19}= Screw dimensions;

DP_2= Angle between two adjacent teeth of the gearwheel;

DP_{31}= Dimension of tooth;
DP_{32}= K (elastic constant) of the spring;

DP_4= Dimension of the pins that connect the gearwheel to the rods.

In the Table 2 the design matrix of the current device is shown.

	DP_{11}	DP_{12}	DP_{13}	DP_{14}	DP_{15}	DP_{16}	DP_{17}	DP_{18}	DP_{19}	DP_2	DP_{31}	DP_{32}	DP_4
FR_{11}	X	0	0	0	0	0	0	0	0	0	0	0	0
FR_{12}	0	X	0	0									0
FR_{13}	0	0	X	0									0
FR_{14}	0	0	0	X									0
FR_{15}	0				X								0
FR_{16}	0					X							0
FR_{17}	0						X						0
FR_{18}	0							X					0

FR_{19}	0								X				0
FR_2	0									X			0
FR_{31}	0										X		0
FR_{32}	0											X	0
FR_4	0	0	0	0	0	0	0	0	0	0	0	0	X

Tab. 2. Design matrix of the current device.

4 NEW DEVICE DEVELOPMENT

The aim of the authors is to employ the functional analysis to support the development of a new mechanism with a smaller number of components. Since the global function and the related design requirements must remain the same necessarily, the number and the type of the sub-functions for the new mechanism have been clarified.
Reasoning on the functional net of the product shown in Figure 5, it was decided to combine several functions in a few archetypes and then in a fewer number of components. The functional analysis was used, in fact, as a reasoning tool in order to stimulate the inventiveness of the designers towards the formulation of different design alternatives. The 2-D scheme shown in Figure 6 reproduces that of Figure 5 and represents an attempt to merge more functions, enhanced by dashed lines.
Actually, the first two functions ("define angular positions" and "connect to the rods"), were already, in a certain sense, merged together and carried out by the gearwheel.
So, it was necessary to focus on the functions: "mount components" and "offer resistance to the rotation". The final idea was to conceive a box, that would have allowed the gearwheel to cling to it without use of others parts and that would have offered the required resistance to the rotation of the gearwheel, generating the snapping movement.

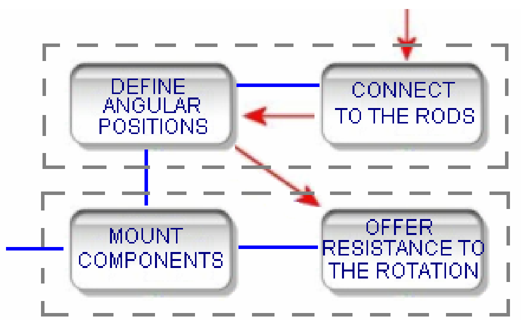

Figure 6. Functional net of the redesigned device

In order to achieve this aim, the sequence to assemble the components and the mode to obtain the snapping movement (that could not be determined by a pin driven by mean of the action of a spring) have been turned upside down, necessarily. Even if in the initial product version, the design principle or concept (even if implicit) was to assume all the components as rigid elements, in the new solution the guideline has been that to make use of the elasticity property of the material.
The adoption of this concept has actually expanded the domain of the possible shapes and of the types of the functional surfaces present on a components, allowing a larger flexibility in finding solutions. Therefore, now the box can be modeled not as completely rigid, but with some elastically deformable zones.
So, on the new box the pin, that blocks the gearwheel, has been arranged on a deformable portion of the box, that bends due to the elastic behavior of the material. The concept to take advantage from the elastic behavior of the material has been extended also to the gearwheel that can now be fixed to the box by means of a trigger (i.e. a carved end hinge that guarantees the alignment of the two components) on which a ridge has been arranged in order to prevent the disassembling.
In the following Figures, the 3D model of the new device (Figure 7) and its exploded views (Figure 8) are shown.

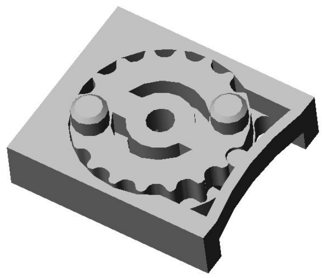

Figure 7. 3D Model

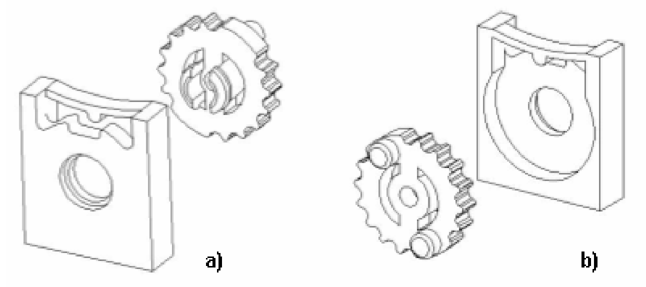

Figure 8. Exploded view: a) front view, b) back view

The new functions related to the two parts are reported in table 2.

N	Components	Functions
1	Box	Connect the device to the aluminium section House the gearwheel Fix the gearwheel axially Guide the rotation of the gearwheel Block the rotation of the gearwheel by the pin Push the pin in the hollow of gearwheel
2	Gearwheel	Connect to the rods Define angular positions Connect to the box

Tab. 2 – The functions of parts of the new device

4.1 AXIOMATIC DESIGN OF THE NEW DEVICE

For the new device, the functions are almost similar to those of the current device. The FRs of the first level can be considered

identical to those previously listed. But they must be decomposed in a different way, because now they are associated to new components.
So, taking into account the functionalities of these new components, the FRs are:

FR_{11}= Connect the device (box) to the aluminium section;
FR_{12}= House the gearwheel in the box;
FR_{13}= Guide the rotation of the gearwheel;
FR_{14}= Connect the gearwheel to the box;
FR_{15}= Fix the gearwheel to the box;

FR_2= Define angular positions;

FR_{31}= Block the rotation of the gearwheel by the pin;
FR_{32}= Push the pin in the hollow of gearwheel;

FR_4= Connect to the rods.

The corresponding DPs are:

DP_{11}= External dimension of the box;
DP_{12}= Depth of gearwheel housing;
DP_{13}= Coupling tolerance;
DP_{14}= Notch width of the central pin on the gearwheel;
DP_{15}= Toroidal section of the trigger;

DP_2= Angle between two adjacent teeth of the gearwheel;

DP_{31}= Dimension of tooth;
DP_{32}= Section of the deformable portion of the box;

DP_4= Dimension of the pins that connect the gearwheel to the rods.

As can be noticed there is a reduced number of either FRs and DPs. These can be put in relation by means of the following design matrix:

	DP_{11}	DP_{12}	DP_{13}	DP_{14}	DP_{15}	DP_2	DP_{31}	DP_{32}	DP_4
FR_{11}	X	0	0	0	0	0	0	0	0
FR_{12}	0	X	0	0					0
FR_{13}	0	0	X	0					0
FR_{14}	0	0	0	X					0
FR_{15}	0	0	0	X	X				0
FR_2	0					X			0
FR_{31}	0						X		0
FR_{32}	0						X	X	0
FR_4	0	0	0	0	0	0	0	0	X

Figure 10. Design matrix of the new device

This matrix is no longer triangular, because there is a more strict interrelation between some design parameters. In any case, it remains decoupled, and the corresponding design solution can lead anyway to a successful product.
At this point can be said that both devices satisfy the first axiom.
In order to investigate more deeply their differences, it is necessary to compare the devices on the basis of the second axiom, choosing the best as that with the minimum information content, which leads to the maximum probability of success.

Considering the characteristic of the devices, both have the same probability to satisfy FR_2 and FR_4 because this requirements are satisfied in the same way. Concerning FR_1, the box of the current device has to mount more components than the new device (6 instead of 1) therefore the probability to satisfy this requirements is certainly highest for the new device because the faultiness is directly connected with the number of components to be mounted.
Regarding FR_3, the two devices meet the requirements in two different ways: the current device by a spring and a pin, the new device by the elastic behavior of the material by which the box is made. Even in this case can be considered in advantage the redesigned device. Moreover, since for the requirement FR_3 the current device employs 4 components whereas the new device employs only 2 components, the probability that this requirement is also satisfied is certainly highest for the new device rather than the old one.
In summary, in a qualitative way, it is possible to affirm that the new device has greater probability to satisfy better the requirements than the old version.

5 CONCLUSIONS

In this paper an experience has been reported in which the Axiomatic Design and the Functional Analysis have been employed to guide the redesign of a device.
This work has been the outcome of a collaboration among the University of Calabria and a firm leader in the sector of windows and shutters.
By means of the functional approach, the authors have analyzed the current device employing the Bottom/Up approach.
Reflecting on the functions performed by the device and decomposing them in new sub-functions, a highest simplification of the number of components was achieved.
The axiomatic design has confirmed the validity of the revised device, that is already on-stream and has had a positive effect on the industrial productivity. In fact, the reduction of the number of parts, in addition to increase the probability of success of the new product has simplified and optimized the injection moldings, even if the global difficulty to manufacture the new components is equivalent to those of the old version.
Besides, the assembly time are vanished and the assembly does not require a skilled worker.

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