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How Axiomatic Design can promote creativity in the design of new products

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Abstract. In product development, creativity is the driving force for doing something that leads to innovation. A typical ideation background has three subsystems: inspiration, dematerialization and recombination. The most basic concepts of Axiomatic Design, *i.e.* domains, hierarchies and zigzagging, as well as the two design axioms, provide a powerful framework to implement ideation, as to make creativity easier when developing a new product. The result of dematerialization is in the functional domain, which is the place where the customer needs are presented by functional requirements and purged of any kind of physical bias. The recombination creates the design parameters, at the physical domain, which are the set of elements of the design object that have been chosen to satisfy the functional requirements, into a new materialization profile of a new product. In this paper, a concrete case illustrating the above-mentioned concepts is presented.

1 Introduction

The success of an innovative new product highly depends on creativity during the conceptual stage of the design process.

On the one hand, creativity can be defined as the ability to produce work that is both novel and appropriate. The economic viability is not an important aspect when looking for new ideas, new concepts and/or even new approaches to deal with existing or emerging problems. On the other hand, innovation refers to the entire process by which an organization generates new ideas and converts them into novel, useful and viable commercial products, services, and business practices.

A typical ideation background is composed by three subsystems: inspiration, dematerialization and recombination [1]. The relations between dematerialization, recombination and the basic concepts of Axiomatic Design will be analysed in this paper.

Section 2 of this paper introduces the concept of ideation framework. Section 3 explains the principles of Axiomatic Design. Section 4 succinctly presents the deployment of a machine aimed to tilt the revolution axis of steel reels from the vertical to a horizontal

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alignment, which is presented as an example. At last, Section 5 contains the conclusions of the present work.

2 The Lean Ideation Framework

The "Lean Ideation Framework" proposed by Marques *et al.* and depicted in Figure 1 represents the aforesaid dematerialization and recombination subsystems that physically behave as being just one [2].

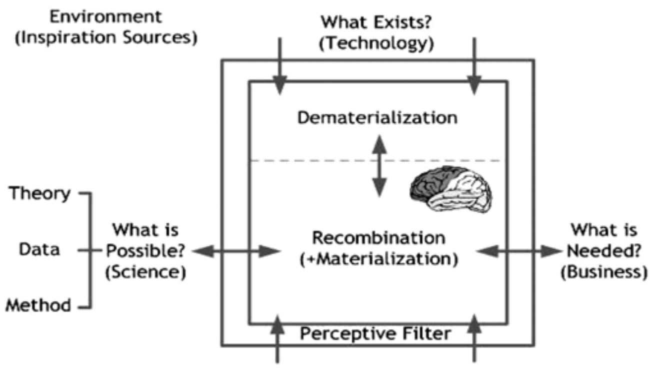

Fig. 1. The Lean Ideation Framework (adapted from [1]).

The inspiration subsystem consists on the available knowledge that exists in the designing environment, which is composed by scientific findings and technological achievements, as well as specific opportunities that depend on the business and the market surroundings. The dematerialization subsystem dissociates by abstraction the physical aspects or the functions embodied in an existent product into elementary functions to be performed by the new product for fulfilling the customer needs. The subsystem recombination is the complement of dematerialization, and is performed when the designer generates, applies and changes the content of the domains of knowledge for a new materialization profile in a new product.

Essentially the designers use the dematerialization phase of the model to release, by abstraction, from the existing concepts. The inspiration phase is driven by necessity, knowledge and technology. In the recombination step the association of new concepts drives the final solution.

3 Axiomatic Design

Axiomatic design (AD) is a theory created by N.P. Suh that mathematically describes the whole design process, according to the mode the human mind operates in the development of the designing activities.

Therefore, AD provides a systematic approach to design that is based on scientific principles, by introducing axioms and theorems, as well as the concepts of domains, zigzag decomposition and design equations, which can be used at the development of all the levels of the design process [3].

According to Suh, "Design, as the epitome of the goal of engineering, facilitates the creation of new products, processes, software, systems, and organizations through which engineering contributes to society by satisfying its needs and aspirations" [3].

3.1 The Design Environment

In the AD terminology, the depiction of the world of any design object is made in any one of four design domains: the customer, the functional, the physical, and the process domains [3, 4]. These domains are shown in Figure 2, and their contents can be described as follows:

"Customer Domain": contains the Customer Needs (CNs), i.e. the attributes that the customer seeks in the product or in the system that must be designed;

"Functional Domain": contains the Functional Requirements (FRs) of the design object. In a good design, they are the minimum set of independent requirements that completely describe the functional needs of the design solution, and which must be defined in a solution-neutral manner;

"Physical Domain": contains the Design Parameters (DPs) of the design solution. The DPs are the elements of the design solution that are chosen to satisfy the specified FRs;

"Process Domain": contains the Process Variables (PVs) that characterise the production process of the design solution, i.e., the variables that allow attaining the specified DPs.

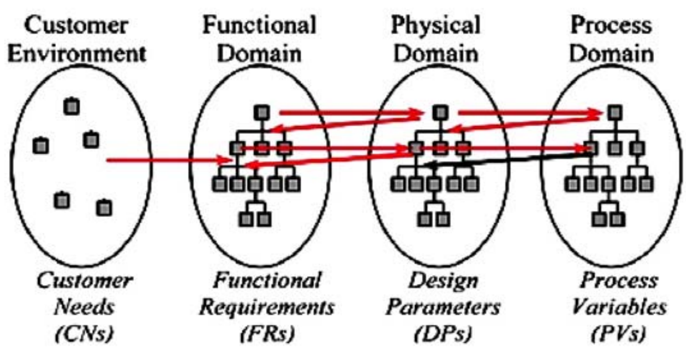

Fig. 2. Axiomatic design domains, their contents and relationships (adapted from [5]).

As shown in Figure 2, for each pair of adjacent domains, the left domain represents 'What is required to achieve, i.e. the goals', while the right domain represents 'How the goals are achieved, i.e. the proposed design solution' [3, 4].

Design is attained by interactions between the goals and the way to achieve them. The goals of the design are specified in the functional domain (where only immaterial items exist), and the way of achieving them is proposed in the physical domain (where the possible real solutions able of performing the specified functionalities are represented).

Constraints are the bounds for the acceptable solutions, and are classified as "input" and "system" constraints [3, 4]. The input constraints are part of the customer needs, while the system constraints are being discovered along the design process.

The mapping between the FRs and DPs can be summarized by equation (1), the "design equation", where {FR} is the "FR vector", {DP} is the "DP vector", and [A] is the "design matrix"

$$\{FR\} = [A]\{DP\} \tag{1}$$

Where $A_{ij} = \frac{\partial FR_i}{\partial DP_j}$. If DP_j disturbs FR_i, then the corresponding design matrix element A_{ij} is non-zero. Otherwise A_{ij} is zero.

3.2 Hierarchies and Zigzagging

Another important concept in AD is the hierarchical decomposition through zigzagging between contiguous domains, as for example zigzagging between the functional domain and the physical domain, in a top-bottom way, beginning at the system level and continuing through levels of more detail, as it is also shown in Figure 2.

After finding the top-level FRs and DPs that appropriately satisfy the general goals of the object under design, one should decompose the design object until a sufficient level of detail is attained at the so-called leaf-level, which means that DPs should not need either redesigning or further decomposition, so that the design could be implemented. The hierarchy established between FRs and DPs represents the design structure, which is also known as the system architecture.

An example of a possible zigzagging path between the functional and the physical domains of the design of an engine is shown in Figure 3.

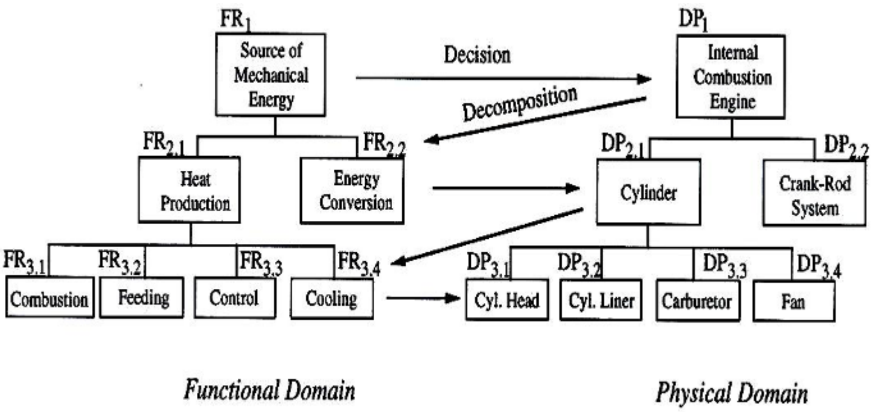

Fig. 3. The zigzag path of the hierarchical decomposition of an internal combustion engine [6].

3.3 The Principles of Design

The underlying hypothesis of AD is that there are two fundamental principles that govern good design practice [3, 4]:

The Independence Axiom (the first axiom):

Maintain the independence of functional requirements.

This means that each FR should be such that adjusting each DP just disturbs the accomplishment of one of the FRs.

The Minimum Information Axiom (the second axiom):

Minimize the information content of the design.

The purpose of this axiom is to help in finding out the alternative design solution that has minimum information, which is the one that has highest probability of achieving the FRs.

The independence axiom and the specific constraints should be applied to the design equation during the decomposition, as to ensure that an "uncoupled" or a "decoupled" design solution is obtained at each level of the design process. Uncoupled and decoupled solutions are characterized by diagonal and triangular design matrices, respectively [3, 4]. Any other shape of squared design matrix corresponds to a "coupled" design solution that should be avoided. Since the design process does not lead to a unique solution, the information axiom should be used to compare the alternative solutions that were previously found and select the alternative design solution with the highest probability of achieving the FRs. [7].

4 An Application Example

An example of a real case where AD was used to the development of a machine design and check the soundness of the selected design solution is as follows.

According to AD, the design main goal must be carefully defined at the onset of the design process. Only after they are clearly stated, one can proceed detailing the appropriate design solutions [8].

In the designing process of a plant to make steel products it was required to rotate the symmetry axle of steel sheet reels from the vertical to a horizontal alignment, as to allow using an existing crane to move away the reels (see Figure 4).

Fig. 4. The design task as defined in the Customer Environment.

The design process starts with the definition of a set of FRs such that the CNs are satisfied. In this case, we have found the following 2nd-level FRs, which are depicted in Figure 5.

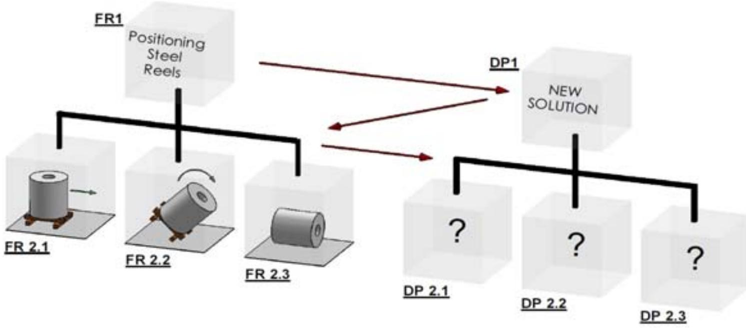

Fig. 5. Functional Requirements that satisfy the Customer Needs.

***FR**$_{2.1}$* – Receive the steel coils that come on motorized roller conveyors.
***FR**$_{2.2}$* – Rotate the axle of the steel reels from the vertical to an horizontal alignment.
***FR**$_{2.3}$* – Keep the axle of the steel in a horizontal alignment.

The design process continues creating solution concepts, at the physical domain, which are capable to perform the required functions.

For each one of the FRs there are several possible solutions that can be defined through different DPs. Figure 6 depicts some possible alternative solutions.

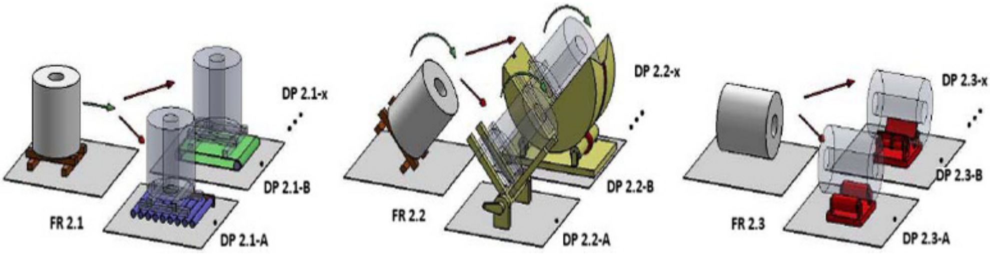

Fig. 6. Alternative solutions that satisfy ***FR**$_{2.1}$*, ***FR**$_{2.2}$* and ***FR**$_{2.3}$*.

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In some specific design solutions, it can happen that the number of DPs is larger than the number of FRs, which makes them "redundant" designs. In such cases, one can use the method followed by Gabriel-Santos *et al.* [9], in which the utilization of system constraints consisting in relationships between some of the DPs, allows clustering the DPs, as to match the number of DPs to the number of FRs.

From the several partial alternative solutions that were generated to satisfy the FRs, one selects the ones that compose the global solution with the higher probability of success. Figure 7 depicts the first higher-level solutions that result from the zigzag decomposition of the new product to positioning the steel sheet reels.

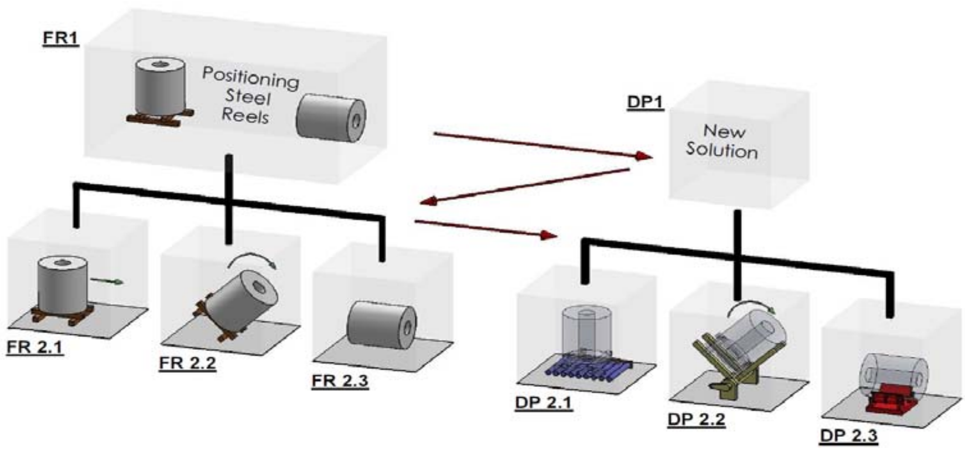

Fig. 7. The first two higher levels of the Functional Domain and Physical Domain of the new product under design.

The design process continues by repeating the procedure described above at the subsequent hierarchical levels, in a top-down sequence, until a level that contains sufficient detail to clearly describe the design object.

After reaching this level, the composition of the selected sub-solutions is performed, in a bottom-up sequence, until reaching the overall solution. In the Simplified Ideation Framework, this procedure is called Recombination, which combines the selected design parameters at the physical domain, thus attaining the materialization profile of the new product.

In this case, we are considering only the first two decomposition levels, so that the global solution is obtained by the composition of the selected sub-solutions, as shown in Figure 8.

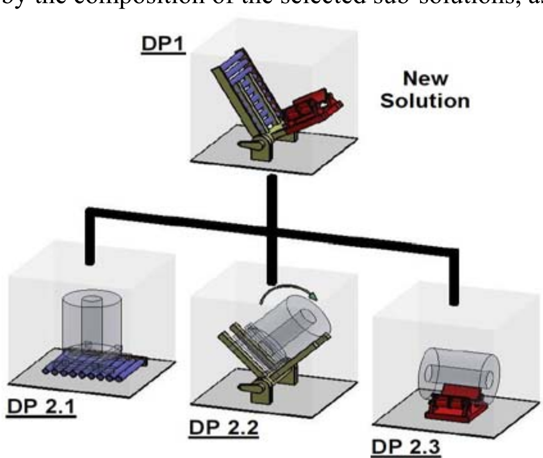

Fig. 8. The global solution resulting from the composition of the selected sub solutions.

Figure 9 shows the new product after being manufactured.

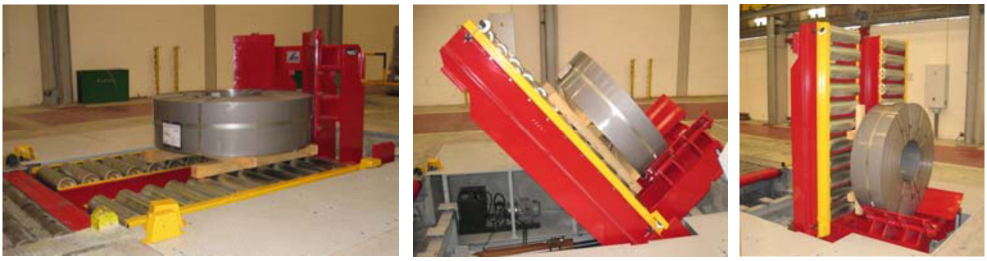

Fig. 9. Three different views of the designed new product rotating steel sheet reels.

As one could see, AD is a powerful tool for evaluating the generated design solutions, through the independence axiom, as well as for selecting the best one among alternative solutions through the information axiom. Additionally, the AD's unique zigzag decomposition technique allows efficiently deploying compound design solutions. However, Axiomatic Design does not offer any specific tool for synthesizing new design solutions.

The synthesis of new design solutions requires creativity, which is related to inspiration, both topics belonging to the scope of the cognitive sciences, as explained, for example, by de Bono [10] and much more extensively by Belous [11, 12].

Therefore the creativity techniques should be used to quickly generate several new design solutions, while AD should be used to quickly and objectively evaluate their efficiency.

5 Conclusions

The main benefits of using AD for promoting creativity in the design of new products are the following:

- It allows to organize and to prioritize the CNs, thus facilitating the minimization of the number of the independent FRs that characterizes the object under design.
- It allows defining the FRs in a solution-neutral environment, i.e., in a way that is not biased by predetermined ideas or existing solution.
- It provides a method to help focussing on the creative aspects of design, while also ensuring functionality, performance, testability, and feasibility of the systems.
- It emphasises an often-weak area of the design process — the complete understanding of the FRs and of their inter-relationships at all the design levels.

Axiomatic Design helps promoting creativity:

- In the problem definition, which is done in terms of solution-neutral FRs, thus creating conditions that facilitate the deployment of the dematerialization subsystem.
- In the separation of the elements of the design process by grouping the design object elements in different design domains according to their nature.
- In defining of the design structure, through the zigzag decomposition that hierarchizes de definition of the design details and facilitates ensuring independence, as prescribed by the First Axiom.
- In systematically dividing compound design problems into several sub-problems, thus facilitating the search for alternative solutions for each of the sub-problems at the different hierarchical levels.
- In selecting the alternative sub-solutions with the higher probability of success, as prescribed by the Second Axiom.
- In quickly evaluating the output of the creativity techniques, which do not provide the means for objective evaluation.

Acknowledgments

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