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ASSESSMENT OF THE RESPECTIVE BENEFITS OF 'AXIOMATIC DESIGN' AND 'NEW PRODUCTS DESIGN METHOD' FOR THE DESIGN OF A BIOMECHANICAL SIMULATOR.

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ABSTRACT

In this paper we present a comparative study of two design methods: Axiomatic Design and New Products Design. In order to compare them more closely, we applied the two approaches to a single industrial project (design of a biomechanical simulator). This experiment enabled us to collect empirical evidences to better understand the specificities of each method, and we were thus able to accurately identify their respective benefits and primary application fields. Our long-term goal is to elaborate a didactic tool supporting the choice of a design method for a particular application project.

Keywords: Axiomatic design, NPD method, assessment, integration, engineering, innovation.

1 INTRODUCTION

When a designer starts a new industrial project, s/he first has to choose the relevant methodological approach to ensure an optimized development and a successful achievement. This choice is not straightforward, especially for someone with little experience or for a student. Indeed, many design methods have been formalized by experts with great authority, and have shown their effectiveness and reliability in several industrial applications. But facing a particular project, it is sometimes uneasy to choose which one of all these excellent approaches to prefer.

Part of our research concern is to define the scope of different design methods, identify their primary application fields and respective benefits. Our long-term goal is to rationalize the adequacy of design methods to particular application projects. We thus expect to build a didactic overview of design engineering, potentially useful to students but also to practitioners and researchers.

But how can we compare different design methods? One comprehensive solution could be to carry out a careful state of the art about the application of design methods to several industrial contexts. Although this strategy would be very rich and instructive, we believe that an experimental approach could be more powerful to accurately examine the specificities of each method. Such a view requires applying several design methods to the same projects.

The present study comes within this framework, since we decided to apply two design methods to a single industrial project in order to compare their respective benefits.

1.1 INDUSTRIAL CONTEXT

This study is grounded on a request from the field of car racing. The needs analysis can be summarized by the formulation of Portero [1]: "Racing pilots' performance is partly determined by their acquisition of visual information under load factor. It may be disturbed by cervical pathologies, either acute or chronic, and by fatigue as well". Unfortunately, the neck solicitations depend on the type of vehicle (F1, F3, Champ car, Formula Campus, etc.), the type of circuit and the duration of the race (endurance, grand prix, etc.). It is then particularly difficult to adapt muscular training to race characteristics.

Our industrial partner requested us to design a simulator enabling both to predict pilots' fatigue for a given circuit and to adapt their training consequently. The goal of such a system would be, first, to allow amateur pilots (gentlemen drivers) to participate or not in the race, and secondly, to plan race strategies (pilots' turn, specific physical training). The simulator has to reproduce the pilot's environment and the solicitations on neck, arms and legs muscles. With the simulator, the pilot must experience real conditions of solicitation, position and concentration.

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1.2 CHOICE OF DESIGN METHODS

To design the biomechanical simulator, we chose two methods that seem appropriate, the "New Product Design Method" and the "Axiomatic Design": the first one because it is likely to provide many tools to improve creativity and innovation; the second one because it is known to enable a scientific control all along the design process.

The comparison of the two approaches at different levels of the design project is expected to demonstrate their respective contributions and application domains.

2 NEW PRODUCTS DESIGN METHOD

The New Products Design (NPD) method, initiated by Duchamp [2], is based on the integration of expert skills into a multidisciplinary team. It provides methodological tools and processes to enable a multidisciplinary collaboration from the very early stages of design instead of a progressive integration decreasing the degrees of freedom of each contributor. The emphasis is put on the pluralism of the team, which is composed in accordance with the needs of the project (engineers, human factors, interface experts, graphic designers, marketing specialists, etc) [3]. This culture tends to improve group creativity and the likelihood to design real innovations on the one hand; and favors identification of all the functional and stylistic aspects on the other hand. It is assumed that too homogeneous teams are not so efficient on these two dimensions.

The NPD method is decomposed into four domains, themselves split into several steps formalizing the necessary transitions and deliverables to ensure the good progress of the study. The global process of NPD is presented in figure 1. In addition to this process, the NPD method integrates many tools (e.g. technological watch, functional analysis, brainstorming, analogy) helping the design team to manage the mapping between the different domains. It also provides a definition of the deliverables required (e.g. functional specifications for the need translation). Finally, the NPD method emphasizes the importance of taking users into account during the design process, notably with the evaluation of intermediate artifacts (e.g. rapid prototyping, simulation, user tests, subsequent feedbacks).

2.1 PRELIMINARY COMMENTS

The NPD method and the Axiomatic Design both consist of four domains and the two first ones are identical. Each domain can itself be decomposed into transition phases and deliverables whatever the method. Transitions can occur in two directions: downwards or upwards (feedback loops) and the goals are the same. The two approaches were validated by many successful industrial projects, and were published at the same period (1990). At the first sight, they seem quite equivalent. However, our study will clarify a few differences between the two methods.

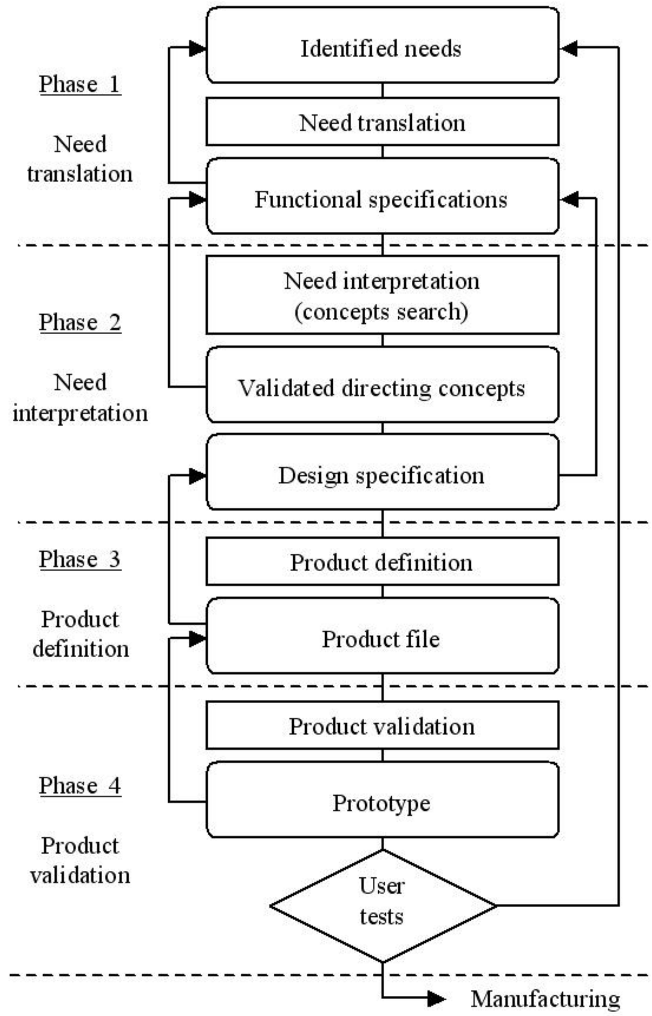
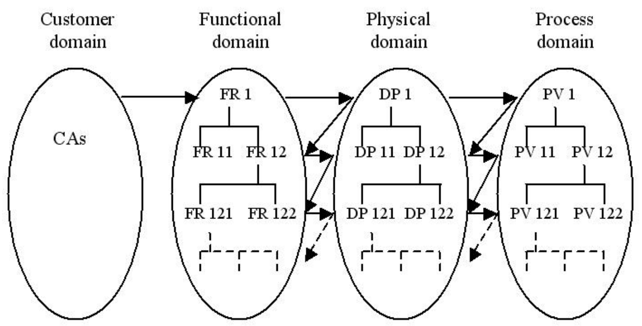


Figure 1 –New Products Design Method, Aoussat [4].

2.2 FRENCH-AMERICAN APPROACH

A comparative study of NPD and Axiomatic Design was previously carried out by Acuna [5], who worked on "scientific design methods, a Franco-American approach". The first step of his work consisted in establishing a diagnosis on the two design methods. For this purpose, Acuna applied Axiomatic Design and the NPD method on distinct projects. The diagnosis was then used to elaborate a principle of combination: Acuna stated that each domain of the Axiomatic Design can be supported by other tools or design methods. Figure 2 summarizes the integration of several methods into the Axiomatic Design process, which resulted in the so-called "Franco-American approach" – NPD being the French part; Axiomatic Design and Taguchi's method forming the American one.



NPD; Statistics	NPD; Statistics	1st and 2nd domain; Taguchi method; Products line; Statistics	Taguchi method; Products line; Statistics

Figure 2 – Integration of other methods into Axiomatic Design [5].

In this combined method, Axiomatic Design gives a structure to the whole process. But other tools and methods are used within each domain to optimize the development and the result. For example, in the customer domain, Acuna suggests using the NPD method as well as statistical tools to support Axiomatic Design; in the process domain, one may use Taguchi's method, products line and statistics.

To sum up, Acuna studied several design methods in various contexts in order to provide a new generic model. Conversely in the present study we wish to go deeper into each method and identify more accurately their specificities. The strength and originality of our study lies in the application of both methods (Axiomatic Design and NPD method) to a single project.

3 STEP-BY-STEP COMPARISON

Just before going through the comparison of Axiomatic Design and New Products Design method, we briefly describe the design team formed for the biomechanical simulator project. The team includes three full-time participants:

- A PhD candidate in Biomechanics who works on a numerical model of cervical spine in order to identify the parameters affecting neck fatigue (heat, vibrations, helmet features, etc.).
- A master student working on data acquisition (acceleration measure) on several cars and circuits to establish a database.
- Another master student in design engineering who works on the neck stimulator design.

The team also includes a Professor in mechanic, a researcher in Ergonomics, the director of a car racing institute and a coach for pilots.

3.1 CUSTOMER NEEDS AND FUNCTIONAL REQUIREMENTS

Needs identification

Figure 3 highlights the correspondence between the Need translation phase from NPD and the first two domains of Axiomatic Design (customer and functional domains). The two methods seem rather similar. Indeed, the "identified need" in NPD method is equivalent to the "Customer Attribute" in Axiomatic Design. Both methods state that it is a key stage for the rest of the project. It is crucial to identify the primary need, otherwise the designer can follow the wrong way. The "need translation" is symbolized by the mapping between the "customer domain" and the "functional domain". Finally, NPD first phase ends with the functional specification file, which corresponds to the FRs (Functionnal Requirements) in Axiomatic Design's second domain.

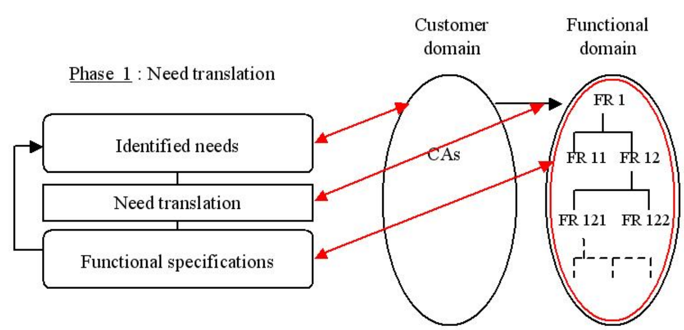


Figure 3 – Comparing the need phase in NPD method (left) and Axiomatic Design (right).

However, the previous analysis is not sufficient to fully understand the two approaches. In this respect, the concrete application of each method reveals the first differences between NPD and Axiomatic Design.

The need as it was initially formulated by the customer was: "we need a neck muscular training machine". In Axiomatic Design, Suh [6] specifies that the designer's task consists in asking the right questions to the right customers, at the right time. Thus, we met the people primarily concerned with the need: several pilots, one physical preparation coach and the director of the institute. NPD method provides several tools, adapted from the field of Value Analysis, to help formalize the answers: one of them is known as the "bête à corne" (APTE terminology [7]), another one is a series of predefined questions (fig. 4) helping to identify the real underlying issue behind customer's request, then to divide it into sub-issues. In our case the underlying issue appeared to be "How to evaluate and to train the pilots?" and the sub-issues are: "How to reproduce real racing conditions?" and "How to evaluate the fatigue?"

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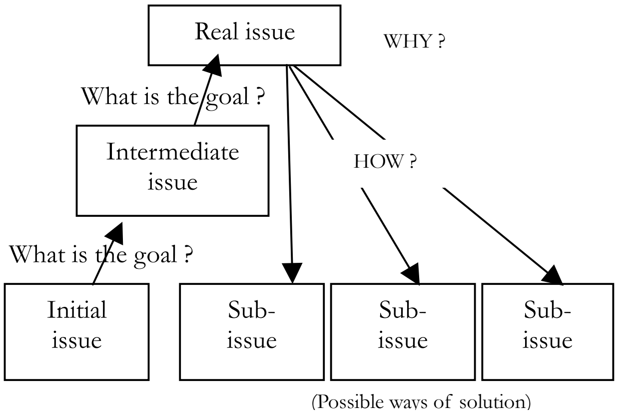

Figure 4 – Decomposition of need identification.

Needs translation

The next step is the needs translation, which consists in connecting the customer needs to the functional domain. To do so, functional requirements must be identified. The functional requirements (FRs) are defined as a minimum set of independent requirements characterizing the design goals. In Axiomatic Design, this step relies on different tools (Quality Function Deployment, House of Quality, Pugh Matrix, Taguchi Loss Function, benchmarking, etc.) but Suh [6] explains that they are efficient only for re-design or improvement of existing systems but not for new products design.

Now let us focus on NPD method. The pluralism of the multidisciplinary team and its inner interactions tend to widen the effective vision of the functional domain. A functional analysis (APTE method [7]) enables the identification of all the functions reflecting customer needs and needs intrinsic to the product lifecycle. Then, octopus diagrams highlight functions related to use, transportation, installation or end life recycling. This tool is very powerful and enables to exhaustively characterize the system by relevant functions.

For the simulator, two approaches are presented: they are different but at the same time they depend from one another. The whole simulator, except the module in charge of neck muscle stimulation, will be designed and manufactured by a subcontractor who will work on the basis of our functional specifications. This partner will be in charge of the choice of technical solutions for his field of expertise. On the contrary, we wish to keep a scientific control over the design of the module reproducing neck solicitations. We will thus work on two approaches in parallel. First, we will write functional specifications for the entire simulator. We will use the NPD method rather than Axiomatic Design, because the continuous zigzagging exchange which should be performed between the functional domain and the physical one becomes impossible in case of subcontracting. Secondly, we will simultaneously develop the core module concerning the neck using the two design methods, to highlight their respective contributions for this stage.

Deliverables

The functional analysis had a great contribution to the achievement of the functional specifications file. As previously seen, this document is a key tool to share information in case of a clear separation between the functional and the physical domain (subcontracting). However, when a continuous contact between the two domains is possible, Axiomatic Design hierarchies enable to avoid the formalism of the functional specifications file. This document is indeed standardized (AFNOR X50-151 [ch.4]) and its elaboration can involve a temporal constraint. Moreover, it is sometimes difficult to define the functions of a device we do not know anything about at this stage. Actually, the subcontractor often needs to call his customer all along the design process. In this case, the approach gets closer to the axiomatic design zigzagging.

The muscular exciter of the neck, called the stimulator, is less detailed in the functional specifications file since we will entirely design it, contrary to the other modules. We elaborate on this part of the study thereafter because it involves a parallel investigation of the functional and the physical domains. Indeed, there are various ways of evaluating the pilots' muscular fatigue: we will be able to define the functional requirements of this evaluation only once the technical solution for reproducing the solicitations is defined. The first functional level can be defined by the two requirements FR1 and FR2:

FR1: reproduce real solicitations
FR2: evaluate tiredness

3.2 FROM THE FUNCTIONS TO THE PRODUCT

At this stage, it is again possible to compare the two methods. The first phase is the need interpretation, which consists in finding directing concepts (first level of design parameters in the Axiomatic Design hierarchy) that have to be validated by the design team. This process will highlight new differences between the two approaches. In the NPD method, it is divided into two steps (phase 2 and phase 3, fig. 5): design specifications are directly created after the validation of the directing concepts, and the product is then defined and formalized into the "product file". The Axiomatic Design approach considers that the designer does not *a priori* know how many stages will be necessary to obtain the product definition. There is actually no separation between the two documents (design specifications file and product file). The designer works by zigzagging between the two domains, thus progressing in the hierarchy. The functions do not all have the same number of hierarchical levels, some of them require three lower levels, other ones need five or more levels to define the whole system. This is why it is hard to formalize everything in a rigid document.

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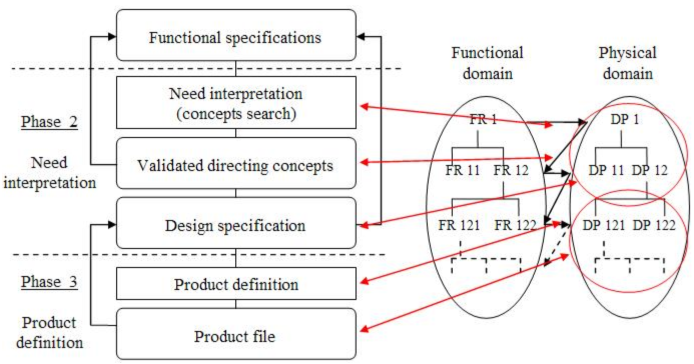

Figure 5 – Comparing the mapping between the functions and the products in NPD method (left) and Axiomatic Design (right).

In this example (fig. 5) we link (arbitrarily) the design specifications file to the two first hierarchical levels, and the product file to the following levels. The actual distribution will depend upon the projects. But the main difference comes from the tools associated to the two approaches. NPD method fully helps the design team to find concepts. The tools provided for this phase are of several types; for example the brainstorming or the analogy method for enhancing creativity, the product cards, the FMECA (Failure Mode Effects and Criticality Analysis) for the product definition, etc. The Axiomatic Design approach does not include tools for the mapping between these two domains but gives advice called corollaries, which formalize the skills and knowledge of an expert designer. For example corollary 2: "Minimization of FRs" recommends minimizing the number of functional requirements and constraints; or corollary 6: "Largest tolerance" encourages specifying largest allowable tolerance in stating functional requirements. A strong characteristic of Axiomatic Design is the high level of control on the intermediate results obtained on the basis of the axioms.

Our strategy was thus to search concepts with the NPD tools and then, to test the results with the axioms.

Concepts search

As previously mentioned, we will design the module for neck muscles stimulation, the rest of the simulator being built by a subcontractor. Our concept search is thus concerned only with the neck stimulator.

Despite the innovative properties of the project in the car racing field, we carried out a benchmark on different domains such as the aerospace engineering, the medical environment, the military equipment. This technological watch enables the introduction of various concepts into our project. The creativity sessions are also an important milestone for innovation. These sessions are divided into a sequence of tools: First of all, a team has to be carefully chosen for the creativity. It should be composed of quite different peoples, some of them belonging to the design team, some others being unaware of the project. An animator ensures the proper course of the session but does not participate directly in the concepts generation. For the present study, the creativity team included pilots, sportsmen, specialists in physiology, in mechanics, student and experienced engineers, a coach for pilots and a journalist. Several creativity tools were used (e.g. initial discharge of preconceived ideas, brainstorming, analogies, phonetic plays, inversions, etc.). We were careful never to ban any idea, even if some of them were technically not feasible.

Several ideas thus arose to meet the functional requirements of the neck exciter (i.e. FR1: reproduce real solicitations, and FR2: evaluate tiredness):

DP1a: Use gravity force?
DP1b: Use electro-stimulation?
DP1c: Use acceleration in translation?
DP1d: Use centripetal acceleration?
DP1e: Use a gyroscopic effect?
DP1f: Apply a mechanical force on the head?
Etc.

DP2a: Blood analysis?
DP2b: Use electromyography?
DP2c: Measure heart rate and breadth?
DP2d: Measure head movements?
DP2e: Measure concentration?
Etc.

Given that various concepts may be relevant for each one of the two functions, a matrix (tab. 1) was built to evaluate the compatibility of design parameters with one another. The goal here was not yet to test the concepts with regards to the first axiom but rather to examine spatial, physical and technological compatibility. None of our concepts was given up; we just studied concept combinations. For example, the use of electro-stimulation is not compatible with the use of electromyography for fatigue evaluation because of space incompatibility.

	DP2a	DP2b	DP2c	DP2d	...
DP1a	1	1	1	1	
DP1b	1	0	1	0	
DP1c	1	1	1	1	
DP1d	1	1	1	1	
DP1e	1	1	1	0	
…					

Tab. 1 – DPs compatibility.
1=compatible parameters, 0=incompatible parameters.

Mapping to the physical domain

According to the NPD Method, a concept is valid when it satisfies the functional specification file. If we now refer to the Axiomatic Design, the concept has to satisfy not only the functional domain (Functional requirements and Constraints) but also the first axiom. The second axiom will be used to choose the best concept among all the acceptable ones. Let us take three significant examples:

If we use gravity to reproduce the acceleration, it is easy to understand that the maximum lateral acceleration (pilots in

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horizontal position on one side) is 1g. It is thus impossible to reach the desired values: up to 5g of lateral accelerations to reproduce Formula 1 solicitations. This solution does not satisfy the functional requirement.

We now use an electro-stimulator to simulate the stress on neck muscles. According to the literature, this solution seems possible; we thus follow up our analysis:

FRs (level 2)	DPs (level 2)
FR11 : Reproduce longitudinal forces	DP11 : Electro-stimulator (ES) on the appropriate muscles
FR12 : Reproduce lateral forces	DP12 : Electro-stimulator (ES) on the appropriate muscles

Tab. 2 – Second level of the hierarchy, second concept.

The muscles of interest are not the same according to the direction of forces. But the physiology specialist we met said that the muscular network on the neck is too dense to isolate just one of them, thus the result is:

[FR]=[A][DP]	DP11: ES on good muscles	DP12: ES on good muscles
FR11: Reproduce longitudinal forces	1	1
FR12: Reproduce lateral forces	1	1

Tab. 3 – Matrix [A], second concept.

The system appears to be a coupled design because each design parameter affects the two functional requirements. The first axiom (maintain the independence of functional requirements) is violated. This solution is given up.

Third concept: the head is submitted to mechanical forces to reproduce the effects of acceleration. Two cases must be distinguished: first, the stress can be applied via two jacks brought under control in position and associated springs transforming the displacement into force. Which gives:

FRs (level 2)	DPs (level 2)
FR11: Reproduce longitudinal forces	DP11: System {jack + spring} A
FR12: Ro reproduce lateral forces	DP12: System {jack + spring} B

Tab. 4 – Second level of the hierarchy, third concept.

[FR]=[A][DP]	DP11 : System {jack + spring} A	DP12 : System {jack + spring} B
FR11: Reproduce longitudinal forces	1	1
FR12: Reproduce lateral forces	1	1

Tab. 5 – Matrix [A], third concept.

The concept is coupled because the head movement in a direction involves a parasitic displacement in the perpendicular direction (Fig. 6).

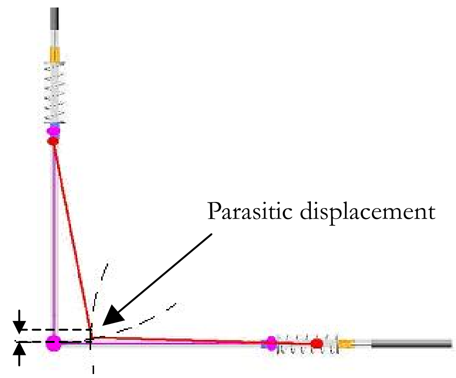

Figure 6 – Description of the parasitic displacement.

However, if we refer to chapter 4.7 of « the principles of design » [8], according to the theorem 8: « Independences et tolerances » : A design is an uncoupled design when the designer-specified tolerance is greater than $(\sum(\delta FRi/\delta DPj)\Delta DPj, j=1, i\neq 1, n)$, so that the non-diagonal elements of the design matrix can be neglected for design considerations. This is our case, this solution is thus uncoupled.

[FR]=[A][DP]	DP11 : System {jack + spring} A	DP12 : System {jack + spring} B
FR11: Reproduce longitudinal forces	1	0
FR12: Reproduce lateral forces	0	1

Tab. 6 – Matrix [A'], third concept.

This solution is thus being currently studied but the previous analysis enabled us to identify a first potential problem. Indeed, the concept considers that the pilot keeps the head upright whereas he actually often anticipates a curve by turning the head inwards.

Another possible solution could be to apply the solicitations directly with jacks brought under control in pressure (proportionally with the force function of the piston surface).

FRs (level 2)	DPs (level 2)
FR11: Reproduce longitudinal forces	DP11: System {jack} A
FR12: Reproduce lateral forces	DP12: System {jack} B

Tab. 7 – Second level of the hierarchy, fourth concept.

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[FR]=[A][DP]	DP11 : System {jack} A	DP12 : System {jack} B
FR11: Reproduce longitudinal forces	1	0
FR12: Reproduce lateral forces	0	1

Tab. 8 – Matrix [A], fourth concept.

This system is thus also being studied; it enables the pilot to freely position his head in a curve.

Various ideas (presented in this paper or not) were thus produced and proved appropriate. They are still currently being studied. We develop several concepts in parallel; some of them are abandoned when new hierarchical levels are determined. Among those which will remain, we intend to select the best one by means of the second axiom, which is the most powerful tool for this purpose.

From the engineering point of view, we may underline the usefulness of the tools provided by NPD method, such as the creativity sessions for the search of innovative concepts. We may also underline the effectiveness of the first axiom to evaluate the solutions generated.

4 CURRENT RESULTS

This study is still in progress at the current time. We are now experiencing a slight slowing down of the project due to the continuous identification of interesting issues put into evidence by our design methods. These very relevant issues are likely to condition the success of the future product; we thus have to carefully consider them.

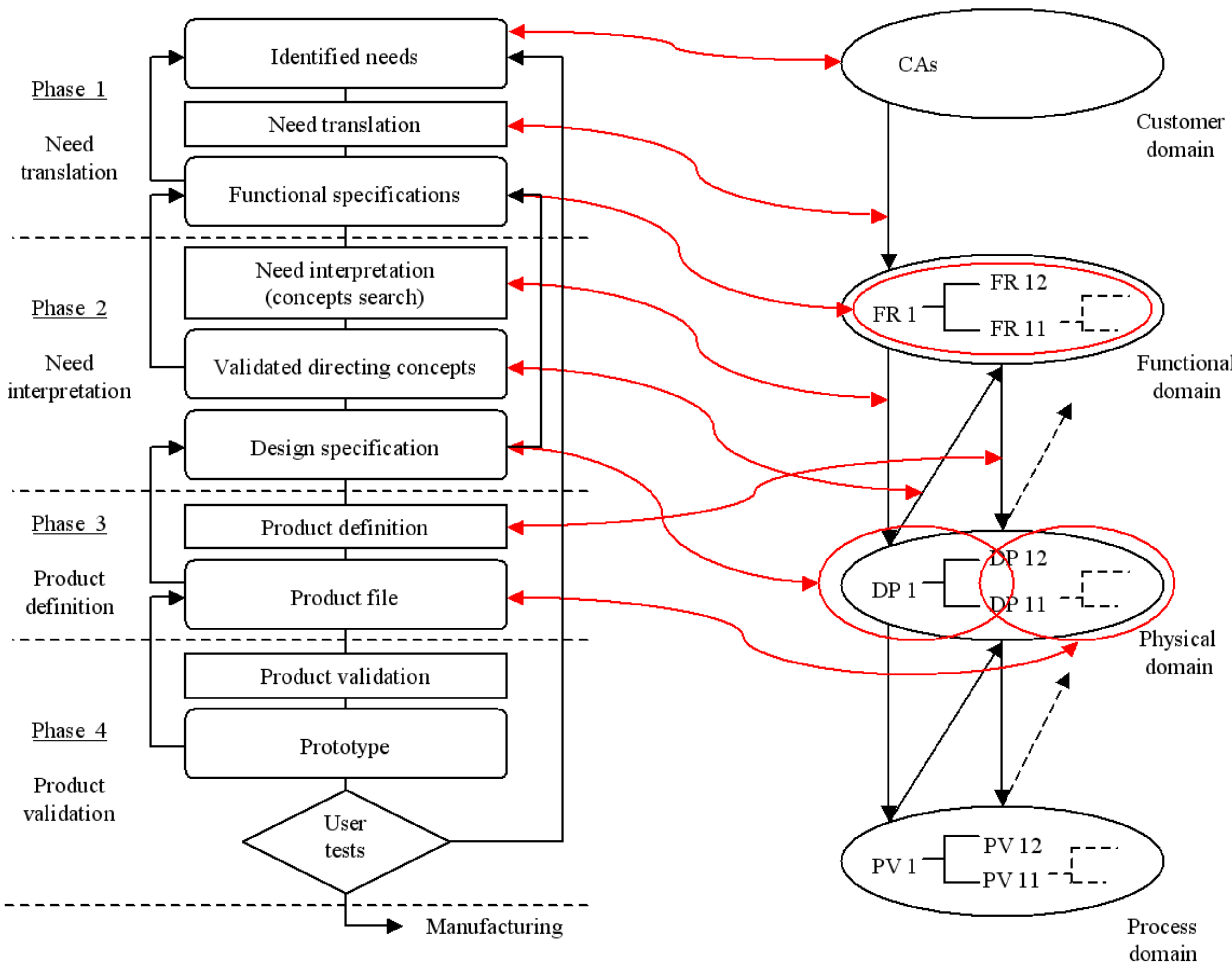

Figure 7 – Comparing the two method.
NPD method (left) and Axiomatic Design (right).

4.1 FUNDAMENTAL DIFFERENCES BETWEEN AXIOMATIC AND NEW PRODUCTS DESIGN METHODS

Regarding the needs analysis, the tools provided by NPD method are highly relevant. However, the design specification file, essential in most cases, is quite a heavy, time-consuming tool. Axiomatic Design does not recommend any particular tool for this stage but has the advantage of performing the needs interpretation in parallel with the search of technical solutions. The associated drawback is that it makes some situations hard to manage, notably in a subcontracting context.

The application contexts of NPD and Axiomatic Design thus appear to be complementary: NPD process may be especially recommended for projects including a subcontracting partnership, whereas Axiomatic Design may be easier to handle when a single design team is in charge of the whole project. Anyway, the two methods never appeared incompatible.

Regarding the generation of innovative technical concepts, NPD includes many methodological tools enabling to structure this stage. Axiomatic Design may thus appear weaker for the creativity dimension. Conversely, the latter is more powerful to evaluate intermediate results and technical solutions because they have to satisfy the axioms in addition to the functional requirements.

In summary, one could say that Axiomatic Design is more focused on the domains: designers are not closely guided within the domains but their control on intermediate results is increased. New Products Design method is more focused on domain transitions and puts an emphasis on efficient tools to manage these transitions.

Finally, we may underline the flexibility of Axiomatic Design as compared to the NPD method (at the current stage of our project). Axiomatic Design appears to enable a smoother progress into the detailed design, the deepest levels being considered progressively all along the process.

4.2 SIMILARITIES

Figure 7 recapitulates the correspondences between Axiomatic Design and the NPD method. The application of both approaches to a single project highlighted their complementarity.

5 CONCLUSION

In this study we investigated two methodological frameworks of design engineering, namely Axiomatic Design and New Products Design. They were both used in the context of a single industrial project: such a strategy enabled us to identify the respective benefits of each method more accurately and rigorously than if we had compared them in different contexts. Of course, this study alone is not sufficient to draw definitive conclusions on the methods, and further data are needed to strengthen our findings.

The present study nonetheless brought a few interesting results. It showed that Axiomatic Design and NPD method are complementary approaches, regarding the tools provided as well as the application fields (see section 4.1). The differences we identified may seem obvious to expert designers, but our study offers an empirical demonstration and a more tangible foundation for these differences. Our results may be useful to non-expert designers, e.g. students or specialists of other scientific fields. Design engineering being a more and more multidisciplinary domain, we need some didactic references e.g. to exemplify a process or to justify the choice of a design method in a particular project.

Regarding the industrial project (design of a biomechanical simulator for car racing pilots), the implementation of two different methods in parallel may have seem useless and inefficient at first sight. However, each method actually had a real contribution to the project and the time investment was balanced by the quality of results. At the current stage of the process, the main design issues have been identified and the tools necessary to solve them and validate the solutions are available to the design team. The final benefit of this study will thus surely go to the industrial project.

This study also opened up many paths for future research. First, we will achieve the current project and complete our findings about Axiomatic Design and NPD method for the remaining phases (e.g. process definition, user tests). Then we could initiate new projects and perform new comparisons of these approaches with other existing methods and tools. In this respect, we may mention that Axiomatic Design was previously compared with TRIZ [9]. The final goal of this data collection will be to progressively draw a comprehensive map of existing engineering methods.

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