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A SCIENTIFIC FORMALISM FOR PRODUCT REALIZATION
IN A GLOBAL MANUFACTURING ENTERPRISE:
AN OPPORTUNITY FOR GRADUATE AND UNDERGRADUATE STUDENTS

TOWARDS A CONSTITUTIVE FOUNDATION FOR THE CREATION OF A SCIENTIFIC FORMALISM FOR PRODUCT REALIZATION

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ABSTRACT

History shows that companies that survive in a severe competitive climate are those that are highly adaptable to market and technological changes. Product development is one of the key activities that assure company survival by renewal of its offer to its customers. A scientific formalism has to be created to fulfill two purposes: 1) to ensure that the design and development of a product is successful (the final product must fulfill all the needs with the constraints of costs, delays and resources), and 2) to integrate market and technological changes that will permit the company to survive.

In this paper, eight important issues concerning a scientific formalism of product realization are presented. Concerning the basic design operations: research must explore more deeply the cognitive aspects of designing, especially at the level of embodiment and detail design, as well as collaborative design. There is a need of formalization and interplay between the different product parameters (customer needs, product specifications, product subsystem parameters). The classic project management—control of the project and coordination between project members—has to be rethought for product development and design. Finally, this formalism must permit creativity in design, which is the warrant of the evolution of the products and in this way, the company.

KEYWORDS: product realization, scientific formalism of design, problem solving process, cognitive psychology, change management, product specifications.

1. INTRODUCTION

"[I]f history is a guide, no more than a third of today's major corporations will survive in an economically important way over the next twenty-five years." With this warning, Foster & Kaplan (2001:14) show that companies have to adapt and integrate social and technological changes to survive.

These changes concern new market orientations, acceptation of new technologies, re-organizations, etc. Product realization is one of the most important vectors of change: indeed, this process transforms new needs into reality, carries out the company strategy and integrates technological advances. It has thus to be organized and supported very carefully. The actual state-of-art is a patchwork of "best practices", resulting in prescriptive procedures, and scientific, rigorous but specific and isolated methods. What will be needed to ensure a successful product realization is a scientific formalism that will structure the product development activities so that 1) the product will be as desired and 2) to integrate market and technological changes that will permit the company to survive.

The realization of this formalism addresses numerous research issues. They are

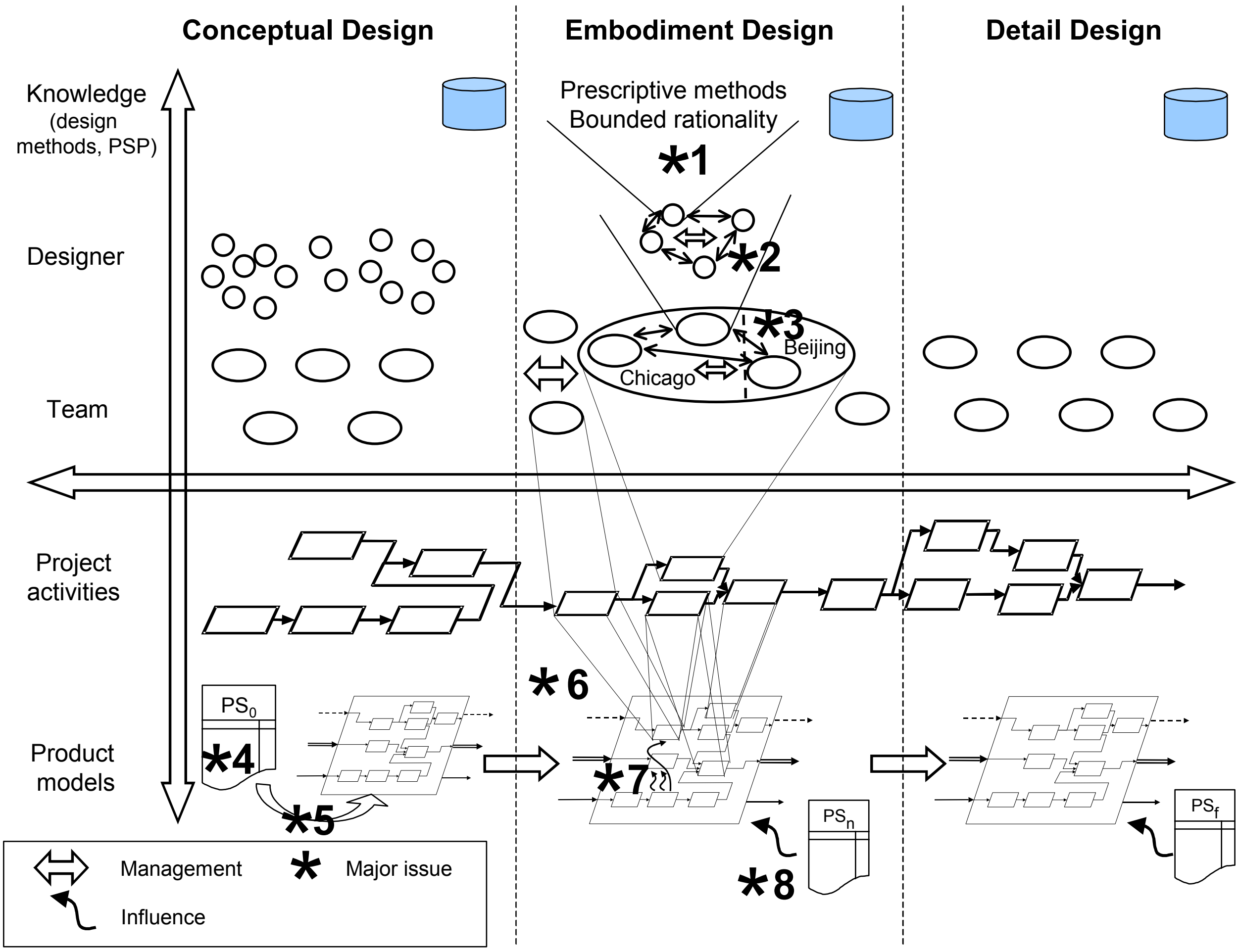

Figure 1 Representation of the major issues towards the creation of a formalism for product realization

developed in this paper considering the description presented in Figure 1. Eight major issues have been developed among the following dimensions: product models, project activities, teams, designers and their knowledge. They have been allocated into three categories: basic design operations, product parameters, and management.

Basic design operations, the first category, are at the core of product realization. They are usually modeled as problem solving processes (Hubka 1976/1982[1], Pahl & Beitz 1996, Olsson 1976). After having developed models of design activities over the last 40 years rational, the next challenge is to integrate the cognitive limitations of the human being. When designing is collaborative, the problem will address group design support and group decision-making. This is presented in the first part of this paper.

[1] The second date of two separated by a slash mark indicates the reference where English translation is available.

In the second category a lack of interplay between the different product parameters customer needs (product specifications, product subsystem parameters) is noticed. This leads to a lack of control, a difficulty of communication between the different actors and difficulty in taking into account the changes, internal and external, that occur during product realization.

The third category of product management needs to be redefined. The classical project organization structure, with a project leader responsible for co-ordination and control is becoming highly complex in global projects where product development members are scattered all over the world. IT technologies will be needed to execute low-valued tasks that are mostly co-ordination problems to let the manager focus on the tasks of controls and major decisions.

Finally, as an extension to the issues concerning a scientific formalism, creativity has its importance for a global manufacturing company. Creativity has to be kept alive and novel ideas exploited. Indeed, formalism helps to rationalize the product realization, that is, to ensure that a need will be fulfilled by the right solution. But rationalization can hinder pioneering findings. The last part will deal with this problem.

2. BASIC DESIGN OPERATIONS

We can distinguish two cases: the design activities made by a single designer (***1**, see Figure 1) and design activities made by a group of designers (***2**). In the first case, rational methods and principles to guide the designer have been developed over the last 120 years (since Reuleaux 1875), but the cognitive limitations of the designers have only been studied for the past 15 years. The integration of human "bounded rationality" to the prescriptive design activities is one of the biggest efforts of the next 20 years. When designers are working together on the same subject, group supports has to be considered, and when they are working separately, it is the harmonization of their results that becomes complex.

2.1. Cognitive perspective on the design process

As summarized in Pahl *et al.* (1999b), when engineering design stopped being considered as "an artistic activity", design methodologies could be developed. Special efforts have since been striving towards normative design procedures, aiming to rationalize and optimize the development of technical artifacts. Methods have been developed for the conceptual as well for the embodiment and detailed design phases; requirements for education, experience, knowledge, reasoning and problem solving ability of the designer have been stated (e.g. Hubka 1976, Pahl & Beitz 1977/1996). This has resulted in substantial improvements in terms of costs, shorter lead-times and higher product quality. However, systematically or based on best practices, present methods have focused on the product technologies, thus neglecting the importance of and impacts by human factors—the designer. Initiated by the increased importance of cognitive sciences, from psychology to artificial intelligence, the designer's way of reasoning has attracted increasing attention during recent decades. There is a consensus that the nature of design processes is based on a problem-solving activity: activities of understanding the task, generating solutions, evaluating and selecting them.

In the conceptual design phase, where problems are ill-defined, a lot of works have been done during the last 15 years. Here are the main findings: Atman *et al.* (1999) and Adams & Atman (1999) confirm the validity of prescriptive methods in the design process. The students who considered more alternatives had a better result quality. Other studies however temper the results. Designers observing the prescribed methodologies will be on average more successful than those who do not (Pahl *et al.* 1999), but prescriptive models "are in conflict with natural cognitive models" according to Condoor *et al.* (1992: 277). These authors list human behaviors and characteristics that contradict rigid procedures: Early appearance and persistence of a core idea; Lack of generation of alternatives; Design fixation; Lack of flexibility; Subjective judgment; Reluctance to change after a design is made; "satisficing". Ball *et al.* (1998:213) complete the picture: failure to search for alternative solutions, marked inclination to stick with early "satisficing" solutions, only superficial modeling and assessment of competing alternatives when such options are actually considered. The claim is that these *human specificities* should be integrated in methodologies. Fricke (1999) noticed that good designers did not suppress their first solution ideas, but did not exploit them until the clarification of the task was complete. His conclusion is that this should be practiced in teaching.

Simon (1996:119) defined the term "satisficing" to refer to procedures that search "good or satisfactory solutions instead of optimal ones". This concept explains why a designer can stop searching, having only the "feeling" that he has reached a sufficient solution or set of solutions (Pahl *et al.* 1999a: 484). Sometimes, solution search stops even without a satisficing one; another phenomenon may be behind this. Ball (1998) uses the hypothesis that an inhibitory memory process can arise subsequent to the recognition-based emergence of a familiar design solution. Pahl *et al.* (1999a) report that research showed that various approaches lead to good solutions; that sub-problem-oriented (opportunistic) procedures are also successful depending on the problem; that methodology is useful but never rigorously followed; the need for more flexibility in methodology, but not in an individual and situation-oriented manner. Eisentraut (1999) confirms this view. The way humans solve problems is not really flexible, whatever the problem may be.

The general conclusion from these findings is that *biases* introduced by human cognition have to be taught, so that the students will be aware of them, and that procedures should be employed in a less rigorous way.

On the other hand, in embodiment design and detail design, almost no research work has been executed. Accumulated experience and practice have led to the application of some basic rules for embodiment design like: *simplicity*, *clarity* and *safety*. Numerous rules can be found in the literature, but still nowadays clarity, simplicity and safety are fundamental to all of them (Pahl & Beitz 1997/1996). These basic rules are supported by *guidelines* based on the constraints of the design, defined during conceptual design. They cover the ranges of "design for X" as well as ways of dealing with some physical and natural effects like corrosion, wear and thermal expansions. Finally, rules and guidelines are completed by *principles*, kinds of *laws* that have been verified by practice and that facilitate the design (Matousek 1963, Leyer 1964, French 1998, Pahl & Beitz 1977/1996). If, for example, "a force or moment is to be transmitted form one location to another, with the *minimum possible deformation*, then the *shortest and most direct* force transmission path is the best" (Leyer 1964, Pahl & Beitz 1997).

While detailing is sometimes considered as a second-order activity in some design process models—because of the "automatism" of certain tasks (e.g. Matousek 1963:5, French 1998:13), this phase is rather like an extension of embodiment design, with the same complexity level. For Hubka (1976:11), detail design overlaps the embodiment design tasks of form-giving, material choice, and manufacturing methods.

The questions that arise concerning embodiment design and detail design concern the designer himself: what he or she performs during an effective embodying activity, if he or she especially applies the basic rules, seeks some support from the guidelines and has in mind the principles during effective embodying and detailing. Has the designer the capabilities – as a human being – to accomplish that? What can be offered to support the embodying and detailing design processes? How are the differences between novices and experts expressed? What characterizes an expert in embodiment and detail design?

Understanding the cognitive activity of the designer is preliminary to a support to design tasks. Computer-based systems for the support of the embodiment design rules, guidelines and principles have been developed in recent years, mostly based on artificial intelligence, expert systems (e.g. Dym 1994, Thornton & Johnson 1996). There is still a long way until all principles and guidelines are integrated into a computer-based design support system. The agenda for the coming years should be: Start and develop research on cognitive activity for embodiment design and detail design, while continuing to study conceptual design; Integrate them into artificial intelligent tools that will support the design activity; Elaborate a strategy to make these tools work with one another.

2.2. Design Groups

The problems identified concern both collaborative and non-collaborative design.

In the first case, much work has been carried out in the conceptual design, which originated the concept of group decision support system (GDSS) for which some computer-supported tools now exist. This is less true for embodiment design or detail design. The problems are not exactly the same: the problems in embodiment design or detail design are relatively well-known (we have already the product concept, some basis, and we know the inputs and outputs of the parts we have to design). The question is how to make people work together on the same product subsystem, and preliminary questions can be: How efficient can it be? Are some parts of design work devoted more to a single person and others to a group?

In the case where people are working alone on different problems concerning one subsystem in which the results are interdependent, the interfaces between (or the functions linking) the sub-problems are of great importance, because they make the integration of the solutions to these sub-problems, possible.

3. THE IMPORTANCE OF PRODUCT PARAMETERS

The product parameters are fundamental for product development and design because they are the basic data on which the product is built, on which calculations are made, and on which solutions are compared and evaluated.

Customer needs are usually written, in a more or less standard way, in form of phrases (functions) where the product to be designed is the subject, followed by an action verb and some complements that refine and limit the action (this grammar is even standardized in Europe, see EN 1325 and EN 12973). To these functions correspond one or more metrics defining quantitatively what the product has to do (the set of these metrics defining the product specifications). One of the first problems concerns this transformation of customer needs into these product specifications: there is no clear way to define without ambiguity the needs and the metrics (***4**). The tool of Quality Function Deployment helps to make them correspond to each other, but not to create them. Qualitative needs are particularly difficult to transform into metrics. A possibility can be the use of fuzzy logic, as in the SPEC method (Yannou & Limayem 2000).

The second problem is to transform these specifications into a technical system (***5**). Here again, some methods exists, as described in Pahl & Beitz (1996) or Ulrich & Eppinger (2000), but these are still heuristics. They are powerful, but just help guide the way to possible solutions: failures are always possible.

Moreover, there is a need to transfer efficiently customer needs to product parameters at every subsystem level. Indeed, needs are changing under product development. It should be possible to pass on these changes to the inputs and outputs of any subsystem of the product. On the other hands, once a subsystem has been partially designed, if its temporary inputs and outputs differ from what was planned, it should be possible to look at the impact it could have on the satisfaction of the customer needs. (***8**)

Finally, the subsystems themselves once designed (at a conceptual or embodiment design level) can influence the functioning of other subsystems—by release of heat, for example. Secondary effects cannot always be planned from the beginning and are not represented in the product system. These changes and new constraints must thus be *dynamically* transferred to other subsystems, so that other designer teams can integrate these changes or reject them (thus forcing re-design of the problematic subsystem); The project manager can evaluate the impact of this unexpected event in term of delays, costs and resources. (***7**)

There is thus a need for formalization and management of the diverse product parameters, prior to a scientific formalism of product realization: customer needs, product specifications, inputs and outputs of product subsystems. This will serve as a support for design and for management.

4. RE-DEFINING PRODUCT DEVELOPMENT MANAGEMENT

Concurrent engineering shows the importance of regrouping the necessary competences around the same project. This gives two aspects of the same problem: 1) know-ing where these competences are (within and outside the company), 2) co-ordinate actions from people who have different backgrounds, cultures, are located at different physical places but have to co-operate and take decisions on the same subjects.

Competence management systems already exist, like KeFax Competence Manager. The results of prior product development projects can be integrated into the designers' profile and soon should be more or less automated. There are however other skills that will be harder to obtain and that have ethical problems. Face-to-face interviews may still be needed before taking people into a project. Surveys are made outside the company to find out new resources (from universities or concurrent companies) and the content of these databases and use can only improve with time. However, parameters are to be defined and developed to ensure you will have "the right man in the right place". This must be one of the characteristics of a global manufacturing company in order to efficiently use a scientific formalism for design.

In the next 10-20 years, half of the engineers graduating from colleges (2-3 millions) will be from China. The cost and time that are needed to gather everybody will be so prohibitive that physical meetings will have to be avoided. The bringing together of the product development team will need to be totally virtual—the so-called virtual enterprise (***3**). That requires two technological efforts. First, the persons must be as close as if they were in the same room, so as they can be as creative, cooperative and talkative as possible. People must be able to see, speak, and laugh together. Technologies already exist that can help but are still relatively constrained and need more development, so that the sensations are the same as in real life. The second and more complicated effort will involve the product itself. Product life-cycle management tools (PLM) are being developed, as those from IBM and Dassault Systems, but they are still incomplete: logistics, packaging (as a part of integrated product development), virtual product testing (Wang *et al.* 2003) are being implemented; they need to integrate the constraints of sustainable development at all the levels.

We imagine that a global manufacturing company will have these tools at its disposal in 2020. The principal work of co-ordination from the management point of view will be the creation of the team, introduction of major strategic changes, and resolution of internal conflicts.

The control part—control if the tasks realized corresponds to the "realization" of the need; decision in case of delays, costs and risks—will be left to the manager. The issue at this level concerns the inadequacy between the management of the project activities, based on the control of costs, delays and resources, and the core of the project: the product (***6**). Project activities and product subsystems do not correspond to each other because project management tools are dedicated to administrative purposes. The actual tools of project management are not adapted to product development.

5. THE IMPORTANCE OF CREATIVITY

Creativity is a core value for a potential global manufacturing company at two levels. First, creativity is to be integrated into production realization methods, because design is the creation of something new, that is, a creative process. At another level, creativity is also what allows a company to pioneer new fields, to break product development continuity in order to adapt itself to new needs or new markets. Indeed the problem of a scientific formalism is that it permits the rigorous and successful resolution of problems *within* this formalism, but can reduce the possibilities of finding out real novel products.

Creativity is one of the domains of cognitive psychology that have shown the least progress: the model of creativity is still that described by Wallas in 1926: 1) Preparation: formulating the problem and making initial attempts to solve it; 2) Incubation: leaving the problem while considering other things; 3) Illumination: achieving insights to the problem; 4) Verification. Even if creative problem-solving methods like brainstorming can enhance creativity, the incubation and illumination phases cannot be controlled. Poincaré (1914) came up with the fuchsian functions during a tourist excursion. New ideas can concern not only the actual project but also possible future projects. Ideas have to be caught, filtered, sorted, evaluated and retrieved for further use. This is the tricky part because it can be difficult to evaluate a novel idea. There can be a problem of intellectual property. There must be interplay and openness between management and designers, but this consideration is fundamental for the future evolution of the company.

However, an alternative way of controlling creativity can be found: by buying technologies, licenses from others or even buying small, creative companies. Indeed the more innovative companies are the small or medium-sized companies and the very large ones, which create innovative results by careful development but especially by the purchase of successful small companies (Andreasen & Hein (1987) after a Booz Allen and Hamilton Inc. study from 1982).

6. CONCLUSION

"By 2020, more than three-quarters of the S&P 500 will consist of companies we don't know today—new companies drawn into the maelstrom of economic activity from the periphery, springing from insights unrecognized today," (Foster & Kaplan 2001:14).

A global manufacturing company that wants to preserve its status for the year 2020 must be adapted to changes. One of the core aspects of adaptation is product development that re-orients the company to new markets and new development. In order to ensure that the designing and development of a product is successful, and to integrate changes during and between different product development projects, a scientific formalism for product realization is needed.

In this paper, eight major issues concerning the creation of this formalism have been developed. They have been regrouped in three categories: basic design operations, product parameters, and management.

The first issue concerns the actual inadequacy between prescriptive models and the human bounded rationality. More research studies are needed to conciliate both.

Group design operations still have to be developed: it concerns collaborative design as well as non-collaborative design.

The realization of the product specifications from customers needs have to be more rigorously formalized.

The transformation from product specifications into a product system suffers the same lack of methods.

The parameters of the product subsystems have to be dynamically modified, along the whole product development.

It must be possible to evaluate the impact of need changes on each product subsystem and execute necessary modifications. Inversely, changes in product subsystem must be evaluated in the light of their impact on customer needs.

Co-ordination between the different teams and designers must be rethought. New needs in a global company appear that current management can hardly fulfil.

Management project tools are concerned with delays, costs and resources but are still not dedicated to the core of the project, the product. There is a need to make correspondences between the product system and the project management.

Finally, a place must be made for creativity: if a scientific formalism ensures successful product realizations, creative ideas will permit a company to discover and take new pioneering roads.

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