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OBJECTIVE-ORIENTED PRODUCT REALIZATION: FUNDAMENT FOR A SCIENTIFIC FORMALISM FOR PRODUCT REALIZATION

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ABSTRACT

The need for a scientific formalism for product realization is the translation of a need onto a product which is developed right in time, at the right costs, and fulfills the specifications set out for the product. To achieve this, most existing methods focus on the customer, or on a key technology as the backbone of product development. In this paper, we claim that efforts must be directed towards the development of a formalism that considers the objectives and constraints of all *the stakeholders that are touched by the product development process. In this way, we shall reach the goals of developing the "right" product. This essay presents this objective-oriented product realization. Then the product development organization that seems the most adequate to support our objective-oriented product realization is discussed. Finally, the implications of this formalism on the design process, which is the core activity of product realization, are developed. An in-depth study of the design activity is needed, in order to develop tools that will support the application of the formalism at all decision levels.*

1. INTRODUCTION

During the past thirty years, the pace of product renewal has constantly quickened, and the product life cycle has been constantly shortening, putting the product realization process at the heart of company strategy. Not only is the customer more and more demanding, but also more and more stringent constraints are imposed on the product, be they environmental or even political. There is every chance that these trends will continue for the next fifteen years, up to 2020 and even beyond that date. Thus the strength and even the survival of a company will more strongly than ever depend on its capacity to develop products that are the realization and fulfillment of all the needs and constraints that have been attributed to them during their development.

Customer needs and legislation are not the only matters that product development addresses. It must be ensured that the final product corresponds to the strategy and vision of the company, generates profit, considers production requirements, and takes into account suppliers specificities… All the stakeholders must be present and all efforts must be made so that their demands will be met at the end of the product realization process. All these factors are of course contradictory, change during time, or must be changed due to the technical limitations of the product. Thus there is a need to integrate all these requirements in order to acquire an overview of the objectives to fulfill.

Our assumption is that this integration is possible, if all requirements, specifications or demands are seen as sets of objectives and constraints. Thus the whole product realization process could be seen as the sequence of activities that leads to the fulfillment of *objective functions* and *constraints*. According to this assumption, product realization can be formalized by the integration of all the specifications and factors that influence the product development into objective functions that will be concretized by the final product.

This assumption, the possibilities that this view offers as well as the research issues that this view addresses, will be developed in the first part of this essay. Then, the re-organization of product development that it will lead is discussed in the second section. Finally, the last section will focus on the implications of such a view for the design process, which remains the core activity of the product development process.

2. OBJECTIVE-ORIENTED PRODUCT REALIZATION

2.1. The objective-oriented product realization approach

The actual approach to product development is structured towards the satisfaction of the needs of the customers (client or final users) [1]. This view was introduced when the offer began to be superior to the demand. The major challenge of product realization shifted from having a product technologically reliable to a product that satisfied the demand. Now this market-oriented culture is deeply rooted in most of the large companies. However, customer satisfaction is just one of the objectives — or constraints — of the company (which by the way fulfills the objective of making profit). Other stakeholders that take part in the product realization process have different objectives that must also be fulfilled. The production department, for example, may need to make its installations profitable; packaging and distribution departments or suppliers put other constraints on the products. These objectives and constraints are of course already taken into account, but not in a structured and formalized way. Some are taken into account at a strategic level, before product development; others, on the contrary, very late in the process. Because of this, the company may need to modify the product during its development, forget requirements, etc. This leads to loss of time and money. Therefore, all the requirements of every stakeholder, active participants or passive participants in the product realization process, should be present in the list of product specifications, as objectives or constraints, and the stakeholders should be considered the same way, as kinds of customers.

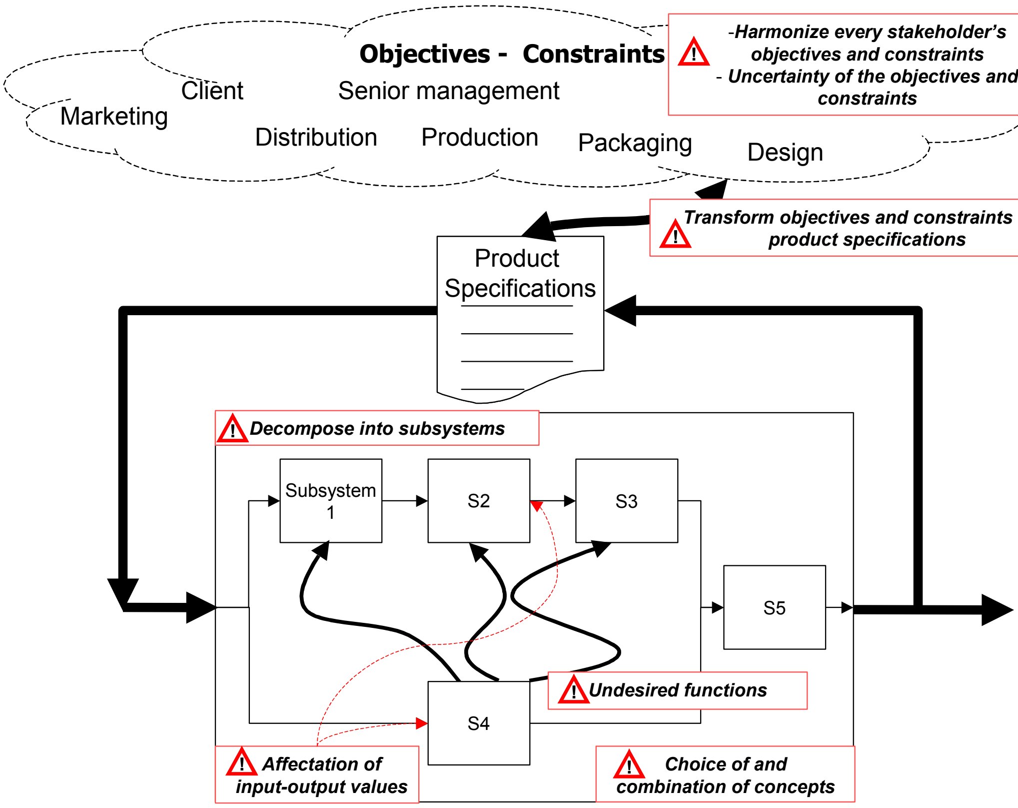

Figure 1. Representation of the issues that a scientific formalism should cover.

Following the preceding assumption (stakeholders as customers), the objectives and constraints can be understood as the definition of the user's "need" and "constraints" used for example in the value analysis. A *need* is what is "necessary or desired by the user" (standard EN 1325); this can be extended to all stakeholders of the product realization process. One objective is the determination of intentions, the end that one foresees. The product is then the means to attain objectives, be it use, or sales. The advantage of reasoning in terms of objectives is that it gives a description of the product-to-be that is independent of the means employed to attain these objectives. It is also independent of the form, solution principle or technique that the product-to-be might have (except, for example, if the strength of a company is the use of a key technology).

The objectives can then undergo the same operations as the customer needs. They can be transformed into specifications ([2],[1],[3]), or refined [4]. The product concepts can be evaluated and selected ([5],[1],[3],[6]).

One of the major research issues is then to harmonize the different objectives and constraints of every stakeholder, so that they can be handled on the same plane. Moreover, the techniques that handle needs and specifications still need improvement. [7], for example, showed the limits of validity of the House of Quality.

2.2. The fulfillment of the specifications

The fulfillment of the objectives and constraints of all stakeholders is one of many steps that must be formalized. As we shall see, each further step towards the realization of the product must be encompassed into a rigorous formalism.

The transformation of needs into product specifications, described above, is a second step towards the design of the product. The specifications are constituted by metrics that give the technical requirements the product must fulfill. The analysis of the problem (fulfilling the technical requirement) leads very often — if not always — to its decomposition. The fact that we now have the specifications that derive from the objectives and constraints of all the stakeholders makes the problem even more complex. [6] describes an array of methods that helps in that decomposition: logical, general, or physical (p. 35). But this decomposition, so far, is still performed by the help of heuristics, and thus each decomposition depends on each designer's experience and can be questioned.

The sub-problems often correspond to a physical phenomenon or action (store energy, receive signal…). A set of solutions for each sub-problem can be found in design catalogues like [8]. Then the possible solutions can be combined with the help of the morphological matrix [9]. The problem here is that the possible combinations are increasing exponentially (5 sub-systems with 5 solutions each gives already 3125 possible product concepts). How to choose the best combination? This is still left to the designers. Efforts have been made to rationalize the decision: in [10], designers rank the sub-solution by performance and risk. But this ranking is still left to the designer.

Then the development of each sub-system is left to one designer, or a team of designers. The product specifications must somehow help to determine the inputs and outputs of the subsystems that interact with the environment. Other subsystems are only present because of the nature of the first ones (e.g. need of energy storage, need of signal filtering…). The problems that come up here are those of interfaces between subsystems. How can a designer put a value on the different inputs and outputs early in the process? What is the probability of this value being correct? What is the risk and what are the consequences of an incorrect value? Some work has been done in this area [11], but this needs to be further developed.

Another problem that appears is that of unplanned or "undesired" functions. Once a subsystem is sufficiently developed, undesired functions may appear, like heat [12][13]. This can be a new input to subsystems that depend on this one, or give a new input to subsystems that were considered as independent before. This new input can in turn change the design of the other subsystem or create the need of a new interface component (insulation). This becomes a decision problem. When and based on what criteria should other teams be informed of the changes?

Optimization is a problem that must be addressed. The optimization of each subsystem separately is worthless and can even be dangerous, as every subsystem may sooner or later have new inputs. Moreover, optimization in one subsystem can lead to worse results in another subsystem. The optimization can then only happen at an aggregated level, the product level. Then at the product level, optimization is only needed if this is a part of the product specifications (e.g. to be the lightest). Concretely, this case should be avoided during the setting of objectives or translation into specifications, and replaced by a threshold, as optimization is always time- and money-consuming.

In both cases, there is a need to describe the impact of each change in each subsystem for the whole product. Except for trivial cases (e.g. [14]), it is not possible to express this impact analytically; simulation or prototyping are the only, time- and money-consuming ways.

2.3. Mass Customization

If the product as a system changes during the design process time, the objectives are also time-dependent. The economic, political, and environmental situations evolve, suppliers disappear, customer trends change. The strength of a company will depend on its capacity to develop products by taking into account the needs and constraints of changes during their development. The quantitative objectives, instead of being studied as values, can be seen as sets of intervals. Thus this can limit the number of decisions to transmit the changes to the designers. (The qualitative objectives, modeled for example by the help of fuzzy logic, are less sensitive to small changes.)

Finally, the last point that companies need to consider for year 2020 is the extended mass customization that will occur during the coming years. Actually, mass customization is managed through modular product architectures and platforms [15]. But it cannot be excluded that the demand of personalization of each product will be higher and changing. These new requirements will need to be integrated into the development of the product and its subsystems at a higher pace. The management of these changes and their boundaries (what is possible, what is not) must be formalized in the objectives the product must fulfill.

3. THE RE-ORGANIZATION OF THE PRODUCT DEVELOPMENT PROCESS

The application of a scientific formalism that allows the realization of a product by taking into account the objectives of all the actors of the product development process requires a re-organization of the work and place of these stakeholders.

In most companies, the product development process is no longer sequential. Most of the tasks that could be put in parallel are put in parallel. This "parallelization" concerns mostly the tasks of product design (electric, mechanic, electronic) and the task of process design (manufacturing and assembly) [16][17]. These are the tasks which contribute mostly to the realization of the product. Nevertheless, other tasks are fundamental for the product development. To production and design department, [18] added marketing. [19] considered even the role of managers. Recently, an empirical study reported in [20] emphasized the need of integrating packaging development in product development.

The idea behind integrated product development is that all actors who play an important role for the realization of a product be present. This notion should be enlarged to include everybody who is touched by the product development process.

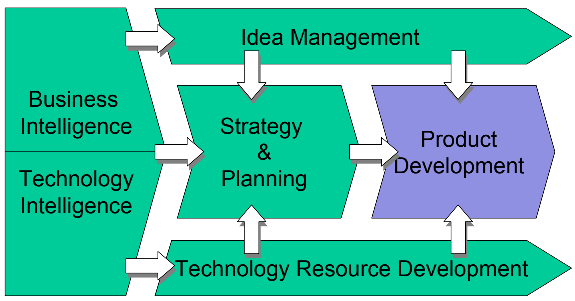

Figure 2. Innovation and Product Development Process at TetraPak®.

Figure 2 shows the innovation and product development process at TetraPak®, Sweden. It is typical for a large company to have a well-developed policy concerning the choice and orientations of future products, due to the costs that every new technical system will imply for both the product and the process. But strategy and planning should not occur only *before* product development. Once the objectives and constraints have been formulated, the senior management team should see itself, not as exterior to the product development process, but as a part of it. Packaging, distribution, and even the client should be inside this system. Figure 3 could be an example of a product development organization in the year 2020.

This change in organization represents more a shift of mind than a total restructuring of the company's activity. The core of the product development remains the design process, seconded by process design and development. But because the changes of objectives of every stakeholder affect all the others, the decisions must be taken with preliminary dialogue, and each stakeholder must have a clear representation of his implication in the product development process.

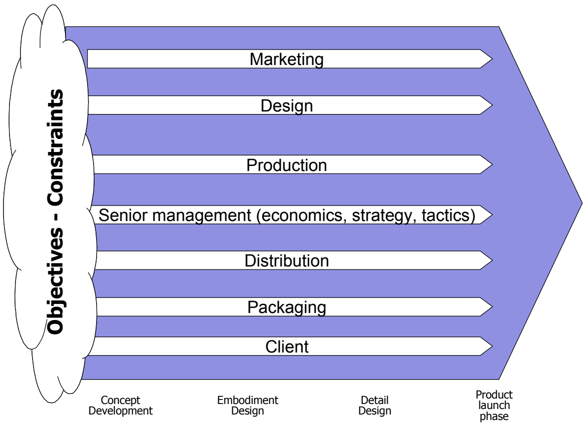

Figure 3. The necessary reorganization of the product development process.

As mentioned before, design remains the core activity of product realization. While the scientific formalism will help in taking the best decisions and developing a product that fulfills the objectives of everyone, the act of creation of the product or its subsystem remains human. As the quantity of information grows, the constant evolution of its content will challenge the design engineers (designers for short). The following section presents what the characteristics of their work will be, the technology that will be needed and the research issues that this new way of working will address.

4. THE IMPROVEMENT OF THE DESIGN PROCESS

Designers are used to working with fixed specifications, or at least specifications that do not change often. This is going to change during the coming decades, and that has an impact at two levels of the design process: at the level of collaboration, designers need to exchange information and make decisions more often; at the level of the single designer, the designer needs to integrate this new information in his daily work, change its current design analysis or synthesis, and this demands a challenging new ability to apprehend design work.

4.1. Collaboration between designers

At the collaboration level, the most usual model of designer collaboration is the decision model. This research area is already at an advance stage nowadays, and is one of the fundaments towards the development of a scientific formalism for product realization. Designers may co-operate while designing, or not [21]. Then the designers' decision-making activity can be modeled by decision theory or game theory [22]. A recent study gave the conditions for which the collaboration may lead to a convergence or to a divergence, depending on the specifications the designers receive [23].

There already exists a physical separation between design engineers and production engineers: the latter follow the delocalization of manufactures, while the former often remain, as their work is strategic for the company, in the headquarters. It will not be long before designer teams will be split all around the world. This has already begun for large companies. Thus collaborative design will be achieved through computer interfaces, and no longer face-to-face. Decision-making needs to be modeled through this framework [24]. Some studies already show that the process of design is slowing down and that there is a need to develop technologies that will recreate the work atmosphere of face-to-face [25]. Others try to develop decision-making models that are not solely based on rationality [26].

The decision-making models of collaborative design have two purposes. First, they help to understand the designers' work. They give a description of the actions the designers take when working at a collaborative level. Secondly, these models, used as a simulation tool in daily activity, can help these designers forecast the consequences of the decisions they make. Research work will still be needed concerning the propagation of the decisions and their impacts on each subsystem (this is not obvious, as undesired functions need to be considered) and on the whole product.

4.2. The design process of a single designer

Designers work together most often at the beginning of the design process. They must, with all other stakeholders, transform the objectives and constraints into product specifications (as long as this step is not formalized by an algorithm). Then, during the concept development phases, creative methods often demand that the designers work together. Otherwise, most of the time, the design activity is performed by single designers who have a part of the product, or a part of a part, to develop.

This activity is rather modeled as a problem-solving process. The traditional view in the problem-solving literature is that of the "phase theorem", which means that a problem is solved rather sequentially. This idea was first developed by Dewey in 1910 [28], who proposed a five-step model: 1) a felt difficulty, 2) its location and definition, 2) suggestion of possible solutions, 4) development by reasoning of the bearing of the suggestion, 5) further observation and experiment leading to its acceptance or rejection. In the field of mechanical engineering design, as well as in any other field, the problem-solving processes are described in this way (see e.g. [6], [29]). The designer has to understand the problem, generate solutions, evaluate them, refine them, and finally decide to choose them. This decision is transmitted further to other designers working on other subsystems, and we come back to the collaborative design activity developed in the last section.

But the problem-solving process used during design is far from being fully understood. The assumption about the phase theorem is even being questioned. As described in [30], "the descriptive facet of the [phase] theorem suggests that problem solvers follow a certain sequence of phases. Its prescriptive facet suggests that problem solvers are more likely to succeed if they follow a certain sequence of phases." (p. 48). However, though widely accepted, the validity of both the prescriptive and descriptive models is also being questioned [30]. No study has so far been conclusive, and we do not even know if the problem-solving process models in the literature represent the actual process-solving process or if they are "implicit schemata of how problems are, and should be, solved" [30] (p. 48).

The assumption that most activities in design can be modeled as a problem-solving process can also be questioned. This is, however, a well and widely accepted assumption. Even Simon in [31] presents the problem-solving model: "intelligence", "design", and "choice" (which can roughly correspond to: "problem understanding", "solution generation, "evaluation-decision"), using the word "design" to describe the core of the problem-solving process. However, the assumption that the design activity is a problem-solving process has been recently challenged in [32]. Design is rather seen as including problem solving, rather than being a special case of problem solving; design problems should be seen as projects to handle with an infinite number of problems, rather than just problems. Design thus needs to be seen from another perspective. The rationale behind this claim is developed in [32]. The implications are that the modeling of a design activity as a problem-solving process may not be sufficient to describe it.

The claim developed in [32] should be investigated in further studies. This could even open a new opportunity to develop a formalism that could include the single steps of the design process.

The validity of the sequentiality of the problem-solving activity may be discussed, but this model is nevertheless the one used to describe design activity observations. Numerous studies have been undertaken these last fifteen years to try to model this process. In [33] and [34], it is shown that the number of "jumps" between different problem-solving steps, or the number of iterations during the problem-solving process, has a statistically significant impact on the design quality. We know from cognitive sciences that the problem-solving process performed by an expert is different from that of a novice [35]. The expert tends to design following the systematic methodology classically proposed in textbooks (e.g. [6]), but becomes *opportunistic* when he or she is faced with a more difficult problem, that is, the expert then actively uses past experience to solve the problem [36]. When and why does a designer stop designing and know he or she can now take a decision? Simon in [37] explained that the approach of the designer is that of designing "satisficing" solutions. When the designer is about sure the solution fulfils the requirement, he or she stops, evaluates the solution and makes a decision. This action of "bounded rationality" considerably hampers the search for possible solutions. Other restrictions, due to human limitations, also apply to the designer: design fixation (early appearance and persistence of an idea) [38], lack of flexibility in a designer's thinking behavior, superficial assessment [39]. Recently Eder [42], following Schön's *Reflective Practitioner* [43] improved Hubka's model of the problem-solving process [29] by adding the characteristic way of "reflecting over" that the practitioner has when solving a problem.

These findings and others coming from cognitive sciences (e.g. memory limitations [40]) define the technological needs for the support of the design process: memory support by sketching [41]; need to support the designers focusing on the specifications rather than on the solutions; need to support the decision of incorporating product specification changes in the design activity; need to develop knowledge-based systems that can support the novice without overloading him or her (because of memory limitations).

4.3. The need of a comprehensive study

The findings described above now need to be placed in their contexts. Most of the studies were experiments. The designers were observed while designing; their comments were transcribed and analyzed, following the verbal protocol analysis described in [44]. There is a need now to go into the field and observe the designer at work: field studies are required to know how to couple the design work with decision-making in collaborative design, how to transfer information from objectives and constraints to engineering specifications that can be handled by the designer in his or her daily work.

The designer can be observed within a three-level model: 1) the elementary, operational, cognitive activities during design, especially problem solving (sequential or not); 2) the tactics and strategies used during all the design activities (including decision-making); 3) the designer in his or her context. The two first levels can be observed under controlled experiments, while the third needs to be studied "in the field", either directly by means of ethnography or indirectly by interviews or surveys. Figure 4 represents a four-level study model of the designer's activities. The elements of the fourth level of study (induction, deduction, abstraction, perception, pattern recognition, attention, intelligence, etc.) are not design-specific [29], and thus are beyond our scope here.

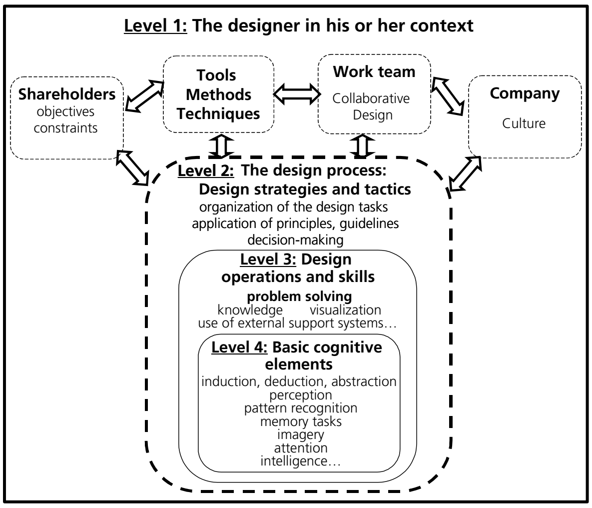

Figure 4. The four-level study model of the designer's activities.

This study must be considered as a pendant of the research work that must be addressed towards the development of a scientific formalism for product realization. The results it should give — a descriptive model of the design and decision-making process through the whole product development process — should help in the development of tools that would support the implementation and use of this formalism.

5. CONCLUSION

In this essay, it has been shown that product realization must be based on the fulfillment of objectives and constraints from all product development stakeholders. In this way the chances are optimized to have the desired product at the right time and cost and with the right specifications.

Each step of the use of the objectives and constraints towards the development of design problems — translation of objectives and constraints into specifications; decomposition into sub-problems, etc. — must be rigorously formalized, while these steps are still actually heuristics.

The product development process must be reorganized correspondingly. Integrated product development seems to be the best organization through which decisions and changes can be taken and applied.

At the design activity level, the decisions made and taken during collaborative design must be adapted to this formalism. Finally, the supports and limitations that concern the single designer have been mentioned. An in-depth multilevel study of the designer has been proposed, in order to get acquainted with the specific needs that such formalism will entail.

Design education has not been mentioned. The formalism developed in this essay integrates tightly the design process and the product realization process. It will be more difficult for the students to learn and assimilate such concepts. Special efforts must be invested in design engineering education, as we know from experience that the designer may learn several design techniques during a lifelong carrier, but that the way of organizing and sequencing his or her activities will tend to change more slowly and more difficultly, and is thus greatly determined by what has been learned at the university.

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