SYSTEMS ENGINEERING BASED APPROACH FOR PRODUCT AND PROCESS CONCURRENT DESIGN

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ABSTRACT

This paper deals with the concurrent design of a new product and the process to obtain it. The presented approach is based on the use of the principles defined by the Systems engineering community. The attention is called on a point of peculiar interest: the upstream design step, where are shown the necessary relations established between the product upstream design and the process upstream design. The electrochemical oxygen microsensor example is used to illustrate this design step of a new product.

I. INTRODUCTION

The goal of this paper is to suggest a formalisation based on Systems Engineering methods for product and manufacturing process concurrent design. The use of these techniques can be a valuable aid to point up the interactions between product design and process design. These interactions are particularly significant since the product is an innovative technology product like micro or nanosystems.

Let us consider two points: on the one hand, it's obvious that system complexity is increasing, and quite difficult to take into account all the system with all its details. On the other hand, in order to reduce the costs and the time to market of new products, as micro/nano-systems, it is now necessary to know how to carry out the concurrent design of the « Product » and the « Process ».

These two points are intensively taken into account by Concurrent Engineering which suggests the development of new product using a global approach [Prasad 95]. All the tasks of the project are performed in parallel reducing the time-costly sequential operations, among others, for very large project, or less (cf. the research project ENHANCE of the European Aeronautic product development, or the contribution of [Eversheim et al. 02]).

An other way to hit cost and time to market reductions for an innovative product is obtained when applying the principles of the Systems Engineering [Buede 99]: « *an interdisciplinary approach and means to enable the realisation of successful systems* » as defined by INCOSE[1]. Systems Engineering is based on several processes such as « V-life cycle » and « Requirement Modelling ».

It could be recalled in few words that the V-life cycle is defined to separate the problem area from the solution area, using an iterative cycle based on four steps. The Specification step defines in a detailed and rigorous way all the requirements the system needs to respect. The Design step consists in designing the technical tree structure to obtain the lower level components by an iterative decomposition. The Integration step is assigned to build the system by its components composition. Finally, the Validation step is needed, for each requirement, to check the conformity of the integrated system with all the defined specifications.

Because of the difficulty to separate the product from the manufacturing process [Abadi et al. 03] [Leibrandt et al. 98], it seems useful to work with the same basic process in both cases.

For this, the second quoted process, « Requirement Modelling », helps to solve this difficulty. This is one of the different processes used by Systems engineering approach. It is a helping tool for the control of the system development and for the control of its evolution during all its life. The way in which the steps of this general process follow on from each other is shown on figure 1. The first step concerns the users needs capture. The objective of this step is to explore, collect and understand the need of the system. This task is performed simultaneously with the analysis of users and stakeholder needs and expectations. The second step is the requirements analysis: the activity of this process consists in the translation of the stakeholder needs into system technical requirements, and to do the technical analysis of them. The third step includes the verification and validation step of the technical system requirements. Verification addresses whether the system, its elements, its interfaces, satisfy their requirements. Validation confirms that the system will satisfy the user's needs. This process analyses the quality of each requirement and the coherence of the set of them. Finally, the fourth step has a modification activity. A corrective action may be necessary, consequently to the activities of the different processes performed during the global cycle of requirement treatment.

[1] International Council on Systems Engineering

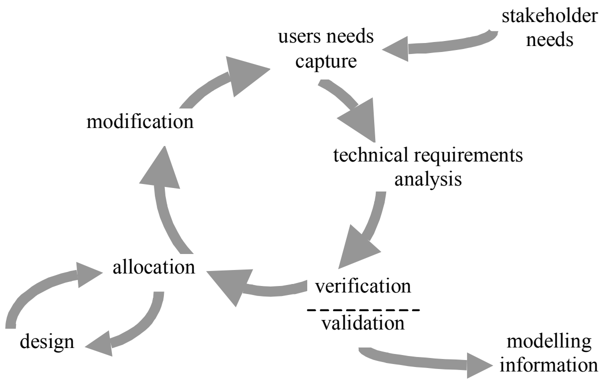

Figure 1. Requirement Modelling

This introduction was necessary to explain the two basic processes used by our approach. The second section of the paper shows the main aspects of our approach for the « product » and « process » concurrent design. The third section details an example selected to illustrate the use of the approach and to point up the interactions between the two processes. Finally, the fourth section concludes the paper.

II. APPROACH

In aim to reduce the costs and time to market of new system products, it is essential to run in parallel the product design and the process design processes [Cohen et al. 96] [Duhovnik et al. 01].

Our approach is primarily Top-down, and it associates in parallel (figure 2): Product design, Process design, Project management.

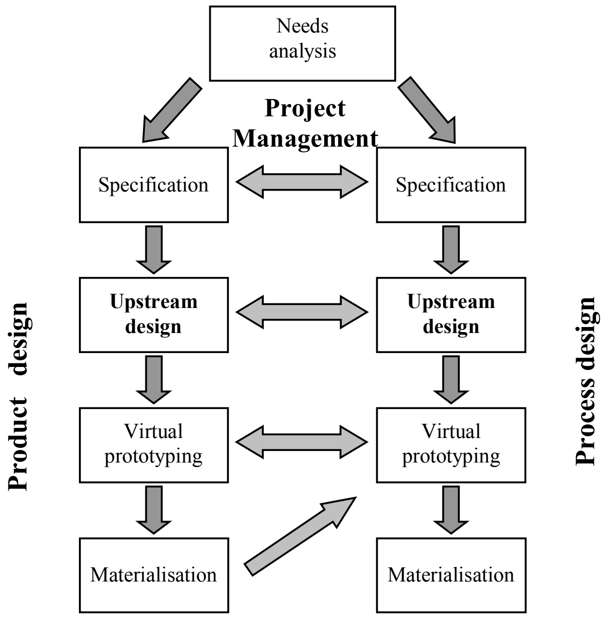

Figure 2. New product design methodology

Generally, a project begins with a phase from upstream study which determines the feasibility of the project and defines its high level objectives. This phase of needs analysis consists in exploring with all concerned parts the various aspects of the problem field.

II.1. Specification level

The specification phase consists in defining in a detailed and rigorous way the requirements needed to be respected by the system [Meinadier 02]. This phase is placed in the field of the problem to solve, independently of the chosen solutions. The requirements to define can be selected from two classes [Meinadier 98]: functional requirements or non-functional requirements.

The finality of the requirements definition step consists in deriving from the exploration of the problem field, all the requirements to which the solution will have to conform. These requirements are translated into technical requirements from system or subsystem needs.

The following step is the Requirements verification and validation step. The verification of the requirements modelling consists in making sure formally that the transformation process of the stakeholder needs into technical requirements is correctly applied. The validation of the requirements is made up of evaluation activities, with the objective to make sure that the technical requirements are the best translation of the problem. During this validation process, some mistakes can be pointed out to the designer, like the lapse of memory or the fact that some stakeholder needs are not taken into consideration. These deductions imply a new iteration on the requirements analysis process [Meinadier 98].

The processes of the specification level for product design and process design will not be more detailed in this paper, we will focus on upstream design. However, it is necessary to indicate which is the information needed by the design level. This information will be associated to the requirements of the product upstream design and the process upstream design processes.

Thus, in the case of the product specification, this information is gathered in a "product specification file", including technical data and information on costs and time to market expected values. Information resulting from the process specification relates to the production cost, production rate, and time to market, among others.

Now, we will consider the upstream design level detailed on figure 3. The next three parts will explain the chosen approach to obtain the reference frame of requirements.

II.2. Product upstream design

The product upstream design process is based on the requirement modelling process. The specification file constitutes the starting base for the design process (figure 3, left part).

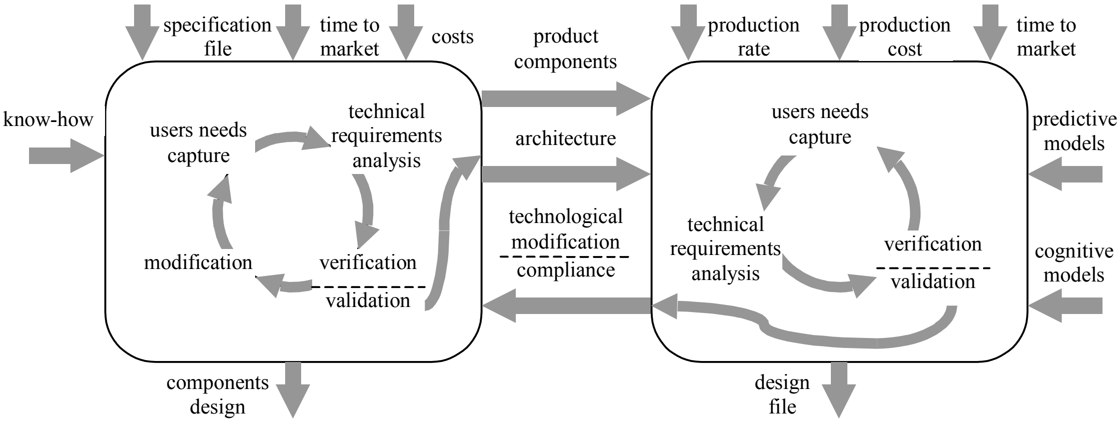

Figure 3. Product (on left) and (on right) Process upstream co-design

The first step of the process relates to the users needs capture. It is an important step because there are a lot of technical information, from the functional class (e.g. “dimensioning of the product”) and non-functional class (e.g. “the cost”). Moreover, the know-how of project manager is useful to be ensured of the realism of these needs, and to refine them if necessary.

The second step of the process consists in translating stakeholder needs into system technical requirements. The most important result of this step is the initial creation of a design file containing the characteristics of the product: its architecture, the needed components and their characteristics, etc.

The third step is verification/validation of the technical requirements. On the one hand, the verification consists in evaluating each technical requirement to ensure that it would have the quality representation of the users need from which it is the translation. On the other hand, it would be checked that there is no contradiction among the expressed requirements. Validation is based on the stakeholder needs, which led to requirements description. The question here is to ensure that each stakeholder need would be taken into consideration.

The technical requirements verification/validation failing involves to return on the requirements analysis step. At the end of this step, the product design process is achieved and the product design file is transmitted to the manufacturing process upstream design, which will analyse it. This process answers either by a continuation development acceptation or by a modification request. The second situation is associated to a technology modification request or to a non-conformity problem. This implies a new capture of the users needs.

II.3. Process upstream design

This design process is based on the requirement modelling process (figure 3, right part).

As the product design process, the starting step of the process is the stakeholder needs capture. However, in addition to the stakeholder needs, this step has to take into account the information transmitted by the product system design process, by way of the product design file. This set of needs is analysed and refined and is presented to the next step.

The requirements analysis step is developed to ensure of the feasibility of the needs. For this, the activity is based on the experience feedback, realised by predictive and cognitive models and constituting the know-how for project manager. A set of system technical requirements is then available.

The verification/validation step can lead to conclude that some technical requirements don't respect the initial needs: a new iteration is carried out within the design process, as an « internal feedback ». When these iterations are ended, the result of this step is transmitted to the product design process in various terms: either the product associated to the design file proposed is feasible, or it is feasible with some compromise of realisation, or it is not feasible. The product design process will react consequently to these « external feedback ».

When the product is realisable, it is then possible to continue the development of the process design. The virtual prototyping level can be started with all the information defined above: the objective is to obtain the best knowledge of the manufacturing process, before its effective realisation.

II.4. Product and process co-design

The concurrent design consists in binding the two design processes as suggested in figure 3.

The product design process is a “major” of the design movement and provides a design file expressing a set of technical requirements that the process design task would have to take into consideration.

The process design task considers:
1) the product design file proposed is the description of a feasible product: it is then possible to pass to the following level,
2) the product detailed in the design file is not feasible: the upstream design processes will have to be reactivated for the elaboration of new technical requirements,
3) the product is feasible if some compromises are respected. The product design process checks the acceptability of them for the stakeholder needs it must honour, and gives a new product design file with more precise design information. This induces a new iteration between the two design processes.

When no more iteration of this development level is necessary, it is possible to refine the two branches of design, while evolving the level of virtual prototyping.

III. EXAMPLE

The presented approach will be illustrated by the following example: an electrochemical oxygen microsensor [Dilhan et al. 95]. The sensor is an essential component for measurement and regulation: it converts the observed phenomenon in an electric signal. LAAS-CNRS interest in these problems is to consider that microsensors constitute an economic challenge for the ten next years. It was decided to open a prospective thought of electrochemical microsystems for production, an other domain interested by concurrent engineering [Ohtomi et al. 02]

III.1. Analyse of the users needs

This first step is based on an interview of the users to know their needs. The designed microsensor has to be able to measure the oxygen rate dissolved in water and that according to an electrochemical principle and the smallest size as possible. These users needs can be translated into terms of cost, quality and functionality.

III.2. Specification level

In this level, we can distinguish the product specification and the process specification.

- product specification
From the data provided by the analysis step of the users needs, we deduced non-functional information (time to market, cost) and functional information (dimension of the microsensor, measurement range, temperature of use) collected in a specification file.

- process specification
Based on the previous specification file, among others, this step gives some information concerning the process, as the annual rate of production, the production cost, the increase in the production rate, and the satisfaction of the customers.

III.3 Product upstream design

- users needs capture
This step collects the stakeholder needs and the product specification file. The main information are time to market, selling price, life span, and the functional information collected in the specification file.
- requirements analysis
The translation of the stakeholder needs into system technical requirements for the dissolved oxygen microsensor is mainly based on the knowledge and the know-how of the design team. Previous works, usage of paste-ups or simulations lead the design engineer to define the structure of the sensor (figure 4) and to dimension its elements such as the two electrodes and the volume of the electrolyte.

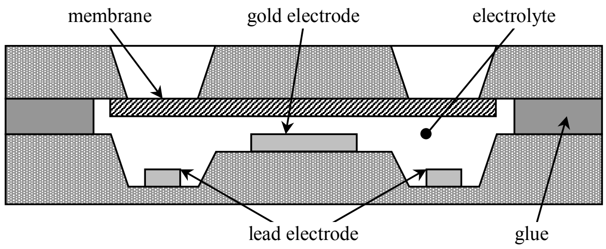

Figure 4. Electrochemical oxygen microsensor

The components of the system are: first electrode, second electrode, electrolyte, porous membrane. The electrodes are immersed in the electrolyte, and a permeable membrane with oxygen separates these elements from the solution to measure. The oxygen contained in the solution diffuses through the membrane towards the electrolyte, and the two electrodes are consumed by chemical reactions. These chemical reactions induce the creation of an electric current between the electrodes, which value is in proportion with the number of oxygen molecules of the solution.

- technical requirements verification
Each technical requirement is analysed, to verify its conformity with the user need. For instance, a functional user need is the reduction of the dimension of the sensor: the technical requirement is to realise a microsensor no much greater than a few cm^3.

- technical requirements validation
Is there any contradiction between several technical requirements ? For instance, is the compatibility of the silicon parts and the porous membrane sufficient for insuring of the best quality ? When all the answers are positive, the product design file is closed and is available for the process design task.

III.4. Process upstream design

- users needs capture
For this step, the information is coming from two origins:
- users needs coming from the specification level: production cost, production rate are some of them,

- the product design file provided by the product upstream design.

- requirements analysis

The translation of the users needs into system technical requirements may lead to various possibilities in terms of choice of components, implementation or assembly techniques. There are two techniques of implementation of the microsensor, called « dry engraving » and « wet engraving ». When the first is expensive, precise and with a relatively short time of realisation, the second is not expensive, less precise, and has a realisation time greater than the other. In the same way, different assembly modes are available, and the fastest and most judicious technique must be adopted.

- technical requirements verification/validation

The conclusion of the verification/validation step is the execution of different feedback loops.

- ***Internal feedback*:**

necessary to choose the assembly mode of the microsensor, because several alternatives are possible: serial assembly and parallel assembly. The chosen technique will be based on parallel assembly, because the production will be faster, even if this implies some synchronisation in the production technique.

However, the second technique lends itself better to a faster production because the two parts can be carried out in parallel before to be stuck sets.

- ***External feedback (between processes): modification***

for the oxygen microsensor a problem is detected concerning the precious metal electrode, because the initial technical requirement is to made it from silver. Working techniques for this metal are relatively expensive. Then a proposition is made to the product design process to reformulate the need, i.e. to propose to work with another metal, if possible. This proposition is evaluated by the other process, which defines new modelling requirements and proposes the use of gold.

- ***External feedback (between processes): choice***

because of the two techniques of implementation, it is necessary to propose to the product design process to choose between « dry engraving » and « wet engraving ». This information is sent with the entire characteristics dimension, to define the use of the most suitable technique. New technical requirements will be defined for the product design, taking into account the dimensions suggested by the process design.

When the requirements verification/validation step is ended, both product and process are designed. It is possible to start the next level of development called « virtual prototyping » which will allow the design teams to know with a lot of detail the manufacturing process before its effective realisation.

IV. CONCLUSION

This paper shows a Systems Engineering based approach for a new product design and the concurrent design of the process to obtain it. The Systems Engineering approach and more particularly the "requirement modelling" process permits to clarify the interactions between product design and process design which are necessary in the case of new technology product like micro/nanosystems.

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