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Important Aspects of Early Design in Mechatronic

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Abstract: *The aim of this article is to provide a general overview of an integrated product development focused on the important aspects and new ways in system engineering and mechatronic design. First, the chapter introduces fundamental definitions and continues with requirement and concept evaluation techniques. Only some phases of the development process are presented in this paper (i.e. Analysis/ Certification, Specification/ Validation). The design approach presented in this paper is combined with a SysML modeling approach which is ongoing joint research topic of TUT and TKK.*

Key words: Mechatronic, system design, Integration, SysML, Dimensional analysis

1. THE DESIGN PROCESS

According to Otto and Wood [1], product development process is the entire set of activities required to bring a new concept to a state of market readiness. This set includes all the activities from the original idea or needs, to the business analysis, marketing efforts, engineering design, development of production plan, and validation of the product design.
A design process is the set of activities within a product development process. This set includes refinement of the product vision into technical specifications, concept development, embodiment engineering of the new product.
Neither the product development process nor the design process includes the manufacturing process. Nevertheless, the design of the manufacturing process is a part of the product development process.
The design tasks efforts' which are required from a design team can vary greatly according to the type of development project.

2. DESIGN STAGES

Innovative products require an interdisciplinary combination of mechanical engineering, electrical engineering and information technology. The term "mechatronics" is the expression of this. The VDI 2206 guideline [2] deals with the development of a modern mechatronic product in its entirety. In this way it creates an essential basis for the communication and cooperation of experts in the disciplines involved. This is where most of the deficiencies of mechatronic product development process are to be found in practice. VDI 2206 guideline promotes interdisciplinary cooperation, which has proven to be an important factor in the success of the development of mechatronic systems. On the next chapter the early stages are briefly covered and new aspects are pointed out.

3. PROBLEM ANALYSIS AND CERTIFICATION

The *problem analysis and certification* phases are summarized in figure 1. This phase represent the first phase of the V cycle (presented in red in figure 1). The first part of the product development problem consists to know what to develop. Laws such as the S curve presented in figure 2 are useful tools to answer to this type of questions. For example if many existing products are already present on the top right of the green curve (S curve). It can make sense to try developing a totally new product. Making an initial economic evaluation is also necessary in order to take a go/no go decision at the early stage of the development process. Performance criteria such as cash-flow, break-even point, return on investment and investment risk need to be evaluated.

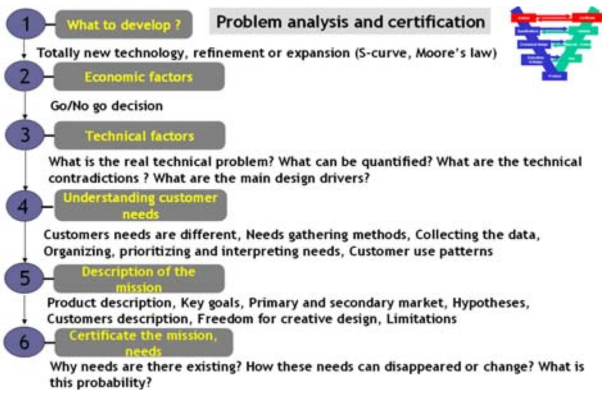

Fig. 1. Schematic summary of the product analysis and certification

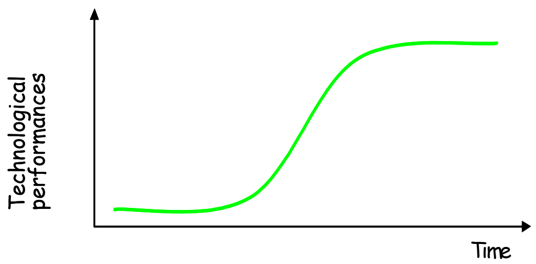

Fig. 2. Schematic summary of the product analysis and certification

4. ESTABLISHING & VALIDATING PRODUCT REQUIREMENTS

When the problem is properly understood, analyzed and when the existence of the initial needs are certified then the *product requirements* can be defined. The figure 3 provides a summary of the fundamental tasks needed to achieve this goal and presents the position in the V cycle. In order to create the product requirement list, the concept of function needs to be first understood. This is a concept which is used during the reasoning process. A function is defined in this paper *as an interface between the available inputs and the desire outputs of the products* [3]. Several types of functions exist, here we present two of them, the *overall function* of a product or service and the *service functions* of this product. To establish functions, useful tools exist, e.g. *APTE graph* (figure 4).

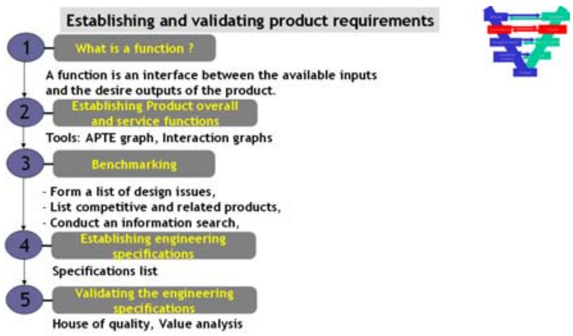

Fig. 3. Schematic summary of the tasks needed for establishing requirements and there validation

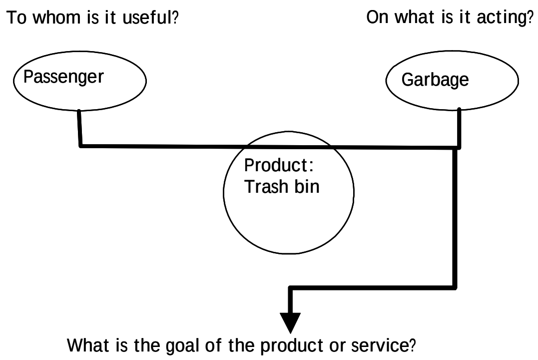

Fig. 4. APTE® graph [4]

When all the functions of the future product have been defined and when benchmarking have been conducted, it is possible to establish a requirement list.

In order to use new System Modeling Language (SysML) it is possible to define requirements with special *Requirement diagram* or additional diagrams (e.g. *Use Case*) for better understanding and structuring. However the graph and list (textual description) have to remain linked as using long text in graph is not rational.

The list is a source for the graphical representation and decomposition. Objects in graph are linked with requirement list by the unique *ID* field. In figure 5 the initial requirement model is decomposed in basic level. In this figure it is seen that different stereotyped requirement classes can be used to separate the different requirements. On the next cycle the decomposed requirements are opened in the separate diagrams. Requirements related with the *environment, locomotion, energy consumption* and others will be later described in more detail in a separate diagram. The figure 6 shows *Energy Subsystem* decomposition. Final requirement item are then connected with test case and model item showing how particular requirement is checked and archived in final design.

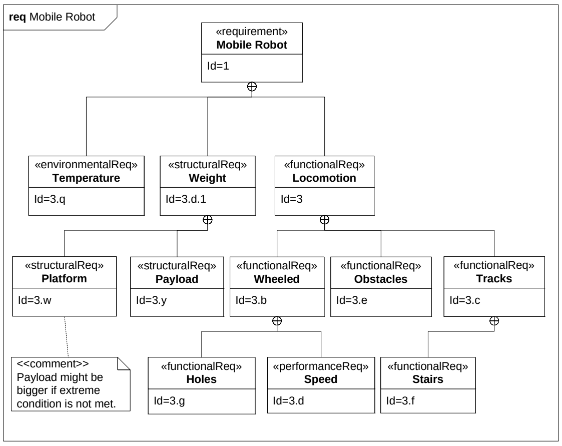

Fig. 5. General requirement hierarchy

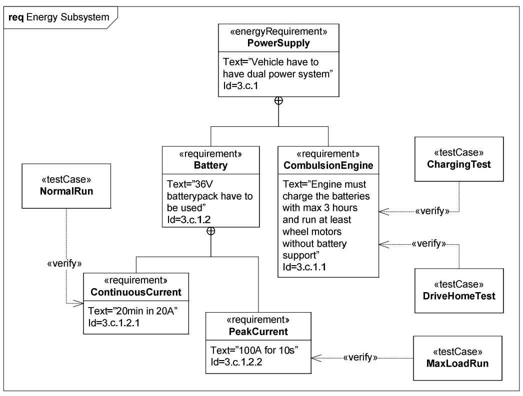

Fig. 6. Decomposed requirements

In the requirement engineering stage the context and relationships with the environment have to be specified. It gives the good overview for the non-technical people showing the system its main functions and external relations. Here it is possible to use either the *Block Definition* diagram or the *Use Case* diagram. The complete approach to describe the application specific requirements with SysML is developed in [5].

5. Creation and evaluation of product concepts

The next stage in the product development process consists of creating and evaluating concepts of solutions. The figure 7 presents a brief summary of a classical approach which can be used to create and evaluate concepts.

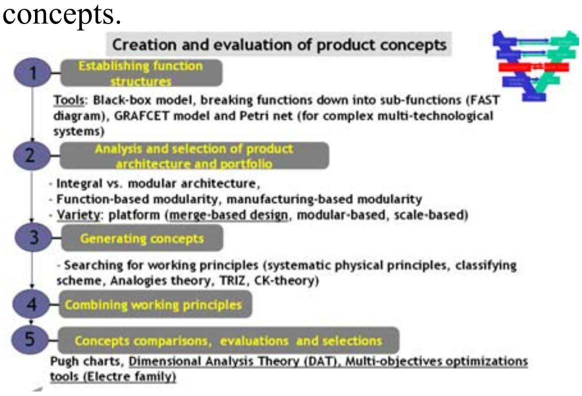

Fig. 7. Summary of the creation and evaluation of product concepts

The first task consists of establishing function structures. Function structures can be modeled using a black box model. The functional structure can be established using the FAST diagram which helps to split the overall function into sub functions such as technical functions.

When functional structures have been established, it is important to analyze what type of architecture we would like to develop. The scope of this activity is wide and we are not treating phases 2, 3 and 4 in this article.

We are providing a special attention in this chapter to the Concepts comparisons; evaluations and selections (phase 5). This is due to the fact that very seldom in literature coherent scientific methods are presented to solve this issue. Our perspective is to use dimensional analysis as a key tool for creating early models of concepts, for comparing concepts and for ranking concepts.

5.1 Dimensional Analysis Theory (DAT) in brief

DAT is dealing with two main aspects, similarity analysis and aggregation of descriptive variables. The Vashy-Buckigham theorem, also known as the Π theorem, is the central element of DAT. Several well known Π numbers have been developed, especially in fluid mechanics and thermodynamic (i.e. Reynolds number). The theorem demonstrates that the physical description of a phenomenon can be reduced to its minimum set of variables by combining the dimensions involved in this description in order to obtain only dimensionless variables.
A dimensionless number is a product which takes the following form:

$$\Pi_i = y_i.(x_1^{\alpha_{i1}} x_2^{\alpha_{i2}} x_3^{\alpha_{i3}}) \qquad (1)$$

Where $\{x_1, x_2, x_3\}$ is called the *repeating variables* set and $\{y_i\}$is called the *performance variables* set [[6]]).

The table 1 proposed by Butterfield [[6]] list the variables governing a system. *V* is denoted as the independent variables, that are assumed to govern the system, *R* contains the variables selected from *V*, which have distinct dimensions other than 0 ($R \in V$). *P* contains variables not in *R* which have been placed in this group because the dimensions of some of these variables repeat the dimension of the variables in *R*. Input and Output variables of a module are to be put in this set. *P* constitutes *the performance variables set*. *O* is the set of variables having already zero dimensions (i.e. a physical dimension 1). *D* is a possible set of *m* independent from basic or composed dimensions. *Q* is a set of variables selected from *R*, from which a dimensionless group cannot be formed. The list *Q* is the *repeating variables* list. The selection of the set *Q* is not unique.
Nevertheless, for making the appropriate choice, rules can be applied. A variable of interest, whose behavior is to be reasoned about, should not be included in *Q*. Dimensional richness (e.g. MLT^{-2} is richer than L) is the criterion for including a variable in *Q* set. Given several variables with the same dimensional representation, only one should be included in *Q*. Thus, the input and output variables of the module studied should not be added to this set. In addition, in order to be able to form dimensionless numbers, it should be checked that [A] is non-singular (det (A) ≠ 0).

Table 1. Table for the selection of the repeating and performance variables.

<table>
<tr><td colspan="2"></td><td colspan="9">V</td></tr>
<tr><td colspan="2"></td><td colspan="5">R</td><td colspan="2" rowspan="2">P</td><td colspan="2" rowspan="2">O</td></tr>
<tr><td colspan="2"></td><td colspan="3">Q</td><td colspan="2">S</td></tr>
<tr><td colspan="2"></td><td>v1</td><td></td><td>vm</td><td></td><td>vo</td><td></td><td>vp</td><td></td><td>vn</td></tr>
<tr><td rowspan="5">D</td><td>d1</td><td colspan="3" rowspan="5">A (mxm)</td><td colspan="6" rowspan="5">B(mx(n-m))</td></tr>
<tr><td></td></tr>
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<tr><td>dm</td></tr>
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Once a matrix is formed, its rank is computed. This calculation has two goals: checking if the amount of dimensions in *D* equals the minimum number of independent dimensions, and setting up the amount of repeating variables needed. For example, if we have listed three dimensions occurring, L, M and T, and if the rank of [*D*x*V*] is 2, then we need to recombine the three dimensions into two independent ones, say L and F [$M.L.T^{-2}$]. Thus, this example requires only two repeating variables to create all the dimensionless numbers. The matrix [*D*x*V*] should then be recomputed according to the new found dimensions.
Having selected the *Q* set, it is possible to express the dimension of the performance

variables (from *P*) as a linear combination of the dimensions of the variables in *Q*.
Π numbers can be created by solving the equation:

$$A.q=p \qquad (2)$$

Where *p* is the vector expression of the dimensions of a *performance* variable from the set *P* and *q* represents the exponents of the linear combination of the dimensions of the *Q repeating variables*. These exponents applied to the dimensional basis *Q* and will thus provide the same dimension than the performance variable of interest. Π numbers constitutes key elements of the multi-objective evaluation approach developed below.

5.2 Multi-objective evaluation and comparison

The process of evaluation in design is multi-objectives. In the example presented below we have to compare two technologies providing the same function. In the literature, several decision making techniques have been developed. All of these methods require performance criteria for ranking solutions. The remarkable property of the Π numbers compared with all the other approaches is the fact that the weighting of the variables which composed the Π numbers is automatic and based on the principles governing the law of physics. These principles are included in the fundamental system of quantities, which is the base of the DAT method. This is the fundamental advantage of the approach because it creates a coherent continuum covering all the design stages.

In the design process, we consider the target values as the set of values describing the expected behavior of an artifact. The concept of target values is different from the concept of *Ideality*. Target values are used to provide a functional coverage zone when ideal provides the compass to orient design improvements. But, how to compare solutions implemented using different technologies but starting from a similar functional description?
The similarity principle is a solid scientific answer to this issue. The concept of similarity is the second pillar of DA. Similarity refers to the equivalence between things or phenomena that are actually different. For example, under particular conditions there is a direct relationship between the forces acting on a full-size work machine and those on its small-scale model.
Dimensional analysis provides a *similarity law* for phenomenon under consideration of different scale. In that specific problem, dimensionless numbers take the following forms (see table 2).

Table 2. Dimensionless groups of two machines having different scales

Machine A	Machine B
$\Pi_{A_1} = A^{\alpha} B^{\beta} C^{\chi}$	$\Pi_{B_1} = \left(\frac{A}{a}\right)^{\alpha} \left(\frac{B}{b}\right)^{\beta} \left(\frac{C}{c}\right)^{\chi}$
$\Pi_{A_2} = D^{\delta} E^{\varepsilon} F^{\phi}$	$\Pi_{B_2} = \left(\frac{D}{d}\right)^{\delta} \left(\frac{E}{e}\right)^{\varepsilon} \left(\frac{F}{f}\right)^{\phi}$
$\Pi_{A_3} = G^{\varphi} H^{\gamma} I^{\eta}$	$\Pi_{B_3} = \left(\frac{G}{g}\right)^{\varphi} \left(\frac{H}{h}\right)^{\gamma} \left(\frac{I}{i}\right)^{\eta}$

In order to meet the similarity conditions, the parameters of the two machines should be such that π_{Ai} and π_{Bi} are equal. The equations 3, 4 and 5 present the similarity conditions where:

$$\Pi_{A1} = \Pi_{B1} \ (3), \ \Pi_{A2} = \Pi_{B2} \ (4), \ \Pi_{A3} = \Pi_{B3} \quad (5)$$

Therefore, we derive the following similarity conditions in this specific example:

$$a^{\alpha} b^{\beta} c^{\chi} = 1 \ (6), \ d^{\delta} e^{\varepsilon} f^{\phi} = 1 \quad (7),$$
$$g^{\varphi} h^{\gamma} i^{\eta} = 1 \quad (8)$$

However, our problematic in design situation is slightly different. Indeed, different solutions created to implement a specific function can differ radically on most of their describing aspects. The technologies used can be totally different (e.g. a mechanical watch or an electronic watch). The amount of dimensionless numbers necessary to model each solution can also differ, as well as the descriptive attributes and their exponents.

Nevertheless, in a design perspective none of the concept of solutions is *real*. This is the major difference with the experimental use of DAT. Consequently, we can imagine transferring a concept of solution B into the design space of the concept of solution A by creating a *virtual concept* of solution A' which behave in a similar manner than the concept A but in the design space of the concept of solution B (i.e. with the same descriptive attribute). In this article, it is not possible to develop the entire mathematical machinery used for comparison, selection and evaluation of concepts, nevertheless interested readers can refer to [3] for more detailed description.

6. CONCLUSION

This article has presented a small part of an integrated design procedure for the development of Mechatronic structures. The procedure is a synthesis of existing approaches which can be supported by a new System Modeling Language (SysML). The mechatronic system design integration with SysML is covered in [5]. We have not been able to develop in an extended manner all the parts of the development process. Interested reader can then refer to the book chapter referenced below in order to obtain more complete information. Parts not treated in this article emphasize on evaluation. This aspect is fundamental and is often under evaluated when using the V cycle models.

8. REFERENCES

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