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AN APPROACH TO VERIFICATION AND EVALUATION OF EARLY CONCEPTUAL DESIGN SOLUTIONS

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1. Introduction

The design process is often metaphorically described in terms of alternating divergent and convergent phases. The principal purpose of the convergent activities is to reduce the number of alternative solutions until finally only one or a few solutions remain. The final goals of the convergent events are to come to a decision. A decision is usual, or at least should be, preceded by a comprehensive evaluation of the alternative solutions. Nevertheless, the following decision has a major impact and influence on the direction of the remaining design process.

This paper focuses on how the technical feasibility and reliability of a conceptual solution can be estimated with a higher degree of certainty. The fundamental thought of this work is to understand and be able to describe the way different parts of a system interact, both within the closed system as well as in contact with the surrounding environment. The essential point of the matter is how the information about the solution is represented. Because of parameters and geometry not yet being defined, limited resources, etc. the available amount of information about the conceptual solution will be limited. Thus, the ability to process the information largely depends on what kind of information is available and how it is structured. The working hypothesis, which this paper is based on, could be defined as:

> *The ability to process available information, with focus on increasing the understanding, is strongly affected by the ways in which the early design solutions are modelled or represented.*

The representation could be made in different ways depending on the purpose. A particular representation fulfils special needs of analysing, understanding, and communicating a solution in a special phase of the design process. The goal of this paper is to present a way of modelling, which may use qualitative information to predict or simulate not-intended behaviour.

2. The nature of evaluation

In the evaluation activity the information about a solution is processed in order to increase the understanding of the alternative solutions and their relate to each other. Evaluation methods are here defined as methods that contribute with enhanced information to the decision-making activity.

2.1 Concept and product evaluation

Depending on the status of the design process, the alternative solutions are defined at different detail levels. In the early phases when the solutions are characterised by non-quantifiable, unclear and incomplete information, they are often addressed as concepts. Later in the process when the solutions are more quantifiable, detailed and concrete, they are denoted as products. The difference in characteristics reflects the possibilities of conducting a proper evaluation on each level respectively.Ullman (1997) distinguishes between concept and product evaluation. For the concept evaluation, the goal is to use the least number of resources on deciding which concepts have the highest potential for becoming a quality product. The difficulty is to choose which concept to spend time developing when the information that the selection is based on is strongly limited. Product evaluation, however, more is to determine, with certain validity, the performance of the product and compare it with the specification. The performance is here interpreted as the measure of function.

2.2 Approaches of evaluation

To ensure the objectivity of the evaluation, the solutions have to be examined from different perspectives, which not always could be treated in the same way to be meaningful. In effort of reducing the number of solutions, one could distinguish two principal approaches, namely:

- Selection of the fittest solutions
- Exclusion of the improper solutions

The *selection of solutions* often designates as a determination or estimation of the “worth” for the alternative solutions by how well they fulfil the given task. A common interpretation (i.e. method) of this approach is to compare the solutions with characteristic criteria, which have often been derived from the design specification. The outcomes depend mainly on how well thought out the criteria are, in extent and objectivity, and the knowledge and the understanding of the respective solution.

The *exclusion of solutions* focuses on the limitations of a solution, e.g. their shortages or disadvantages. This kind of problems could either be rather serious and disqualify the solution immediately, or they may become potential risks in the future, needed to be illuminated and taken care of. The results from this kind of evaluation may be interpreted in different ways. The detected negative effects of the solution may be seen as a measure of the reliability, but it also, in the extension, may be seen as an obstacle of the task to be satisfactory fulfilled.

The natures of the two evaluation approaches differ regarding how the solutions could be compared to each other. In the first case, the solutions are evaluated from the same base, with the same criteria. A comparison is, in other words, relatively easy to execute. In the second case, a comparison is more complicated. The alternative solutions could be derived from different base-technologies, each with their own set of problems. This indicates that the base for the evaluation has to origin from the solution, rather than from the task.

Table 1. Examples of evaluation approaches in prevalent design theory and methodology

Author	Evaluation characteristics
Roozenburg & Eekels (1995)	• Overarching description of different kind of methods • Pays regard to both relative and absolute judgements • Discussion on the risks of only relying on the result of the evaluation • Taking into account the decision-makers role in making a decision • Recommend a multi criteria approach
Pahl & Beitz (1996)	• Describes two way of conducting the evaluation, strict and clear methods – first a reduction followed of a selection • Multi criteria approach (user value analysis) – absolute judgement • Distinguish between technical and economical values
Ullman (1997)	• Differentiate between concept and product evaluation • Pays regard to both relative and absolute judgements • Four different techniques to reduce the number of concepts: feasibility judgement (gut feel), technology readiness assessment (state of the art), go/no-go screening, and multi criteria approach (decision matrix method (customer requirements))
Ulrich & Eppinger (2000)	• Principally relative judgements • Multi criteria approach (concept screening and concept scoring)

2.3 Prevalent Design Theories

In the prevalent design theories (see Table 1) the concept evaluation is often approached and dealt with in a similar way. The common approach is based on the selection of the fittest. This kind of methods sets the focus on the possibilities of the solutions to fulfil the task, and take no, or little, considerations to the limitation that each solution has, like weak spots, etc.

There exist several methods for investigating the reliability of new products, which are not directly labelled as evaluation methods, rather as verification or validation methods. The most common ones are Failure Mode and Effect Analysis (FMEA), and Fault-Tree Analysis (FTA).

FMEA is a qualitative procedure for identifying potential failure modes and for estimating their effects on the product performance. The procedure consists of several steps that are fulfilled by using a standard FMEA chart. In the FTA the influence of faults and disturbances are systematically investigated. By looking at each of the separate parts or subsystems and assuming that a function failure has occurred, the potential causes of the failure are investigated. This method gives a graphical structure showing various Boolean combinations of faults and incidents that result due to the main failure. (e.g. Voland 1999, Pahl & Baitz 1996)

FMEA and FTA are, in their simplicity, useful tools to identify failure and failure mechanisms for detailed and concrete product ideas, but they are normally best suited after the conceptual design.

However, most authors in design science emphasise the importance of an early prediction of the reliability of a solution. Some of them approach the problems in terms of interaction between systems (Ulrich & Eppinger 2000 and Liedholm 1999), the sensitivity in variations of the input of a system (Robust design), effect chains (Chakrabarti 1999), and others. Nevertheless, there are still very few practicable methods that are aimed for the designer to use in the early phase of the design process.

2.4 Conclusions

The commonly used evaluation methods are relatively simple and stand-alone methods, which do not require a particular representation of the solution. By organising the information in a more systematic and structured way, the ability to process the same amount of information becomes more comprehensive. Thus, the foundation of the decision-making may be more solid.

3. Models of representation

The input to the evaluation activities is the prediction of the behaviour and properties of the solutions, often designated as simulation (Rooznenburg & Eekels 1995). The prediction is usually executed by means of an imitating system – a model, which resembles the actual system in certain respects. Roozenburg & Eekels (1995) distinguish four different kinds of models with consideration to their type (material and symbolic) and function, see Table 2.

Table 2. Four type of representation models, adapted from Roozenburg & Eekels (1995)

Type of models	Descriptions
Structure models	The models are based on the visualisation of the structure of an object or process. All the models have a qualitative nature because the rules, according to which the properties of the models are interpreted, in terms of properties of the original, are not explicit and formal, but intuitive. Examples are flow or circuit diagrams, qualitative graphs or a functional block diagram, sketches, dummies and simple manikins.
Iconic models	Iconic models are material models by means of which experiments can be conducted. In such models, the properties of the original to be studied are represented by the same properties of the model. Examples are pictures, drawings, dummies, mock-ups, scale models and prototypes.
Analogue models	In an analogue model, a property of the original is represented by another property of the model. This other property must behave in the same manner or in a known relation to the represented property of the original.
Mathematical models	Mathematical models represent the original by means of symbols. The models may describe the behaviour of a system in terms of physical or chemical first principle or by a clever supplementation and rephrasing in order to make an unknown factor disappear.

By evaluating the reliability, in the meaning of detecting potential conflicts from qualitative information that has not directly anything to do with the realisation of the desired functionality, the whole solution has to be described in an objective way. The iconic and analogue models are more suited to verify a particular functionality of the solution; i.e. they are not able to represent the wholeness.

Mathematical models may represent the whole solution, but since these models by definition cannot handle qualitative information they are not suitable in the early phases of the design process, at least not in a general case. Thus, the kind of model that suits the purpose best seems to be a structural model, which may describe the different part as well as the wholeness of a solution.

4. Representation proposal

In order to enable a description and derivation of different properties and phenomena originating from the system a concept representation based on the *systems theory* is proposed. According to Hubka & Eder (1988) a generalised model of a system may be defined as a finite set of *elements*, whereby certain definite *relationships* exist between the elements, and to its environment (Figure 1).

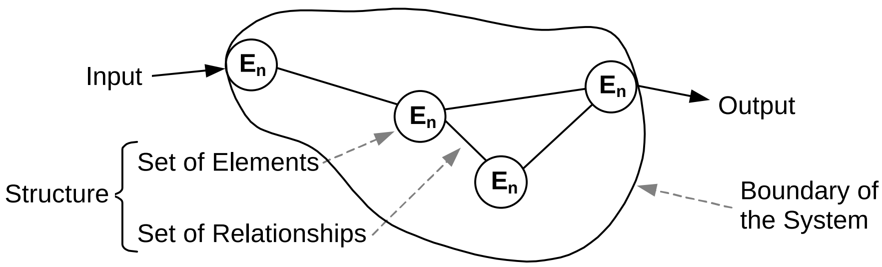

Figure 1. A general system model, after Hubka & Eder (1988)

4.1 Elements

When defining a structural model in order to evaluate a generic solution there are at least two main approaches to distinguish between. (1) From an abstract and functional perspective the solution may be described with an organ model, where the elements of the system are represented by organs (Hubka & Eder 1988 and Andreasen 1980) or function carriers (Pahl & Beitz 1996). I.e. each element in the model realises a particular function. (2) For a more concrete and behaviour oriented model the elements may origin from the physical structure, i.e. a function may be realised either within an element or in co-operation between two or more elements.

4.2 Relations

Every artificial system serves a certain purpose. This purpose or functionality is, as mentioned above, realised by the elements defining the structure model. In the case where more than one element is involved the relation between them become very important for an accurate realisation. For the intended behaviour, i.e. functions, the elements and relations are designed to suit the purpose. Concerning the rest of the behaviour, either positive or negative, it may be described in the same way.
Generally, the content of the term *relation* often includes both the relation itself and the effect it causes. To be able to understand the system behaviour and discuss its reliability it is of great importance to patently distinguish between the cause and the consequences of a relation. By examining the nature of relations, it is possible to distinguish between effectuating relations and non-effectuating relations. The effectuating relations may give rise to effects depending on the physical properties of the elements, while the non-effectuating relations do not generate any real effects. They rather work as indicators that determine or describe the status of the system; e.g. its spatial, time or logical behaviours. The non-effectuating relations may also determine the potentials for an effect to occur or not.

4.2.1 Effects

The effect of an effectuating relation may be grouped after its orientational features (see Figure 2).

- *Single-acting*: the effect of the relation only, or mainly, affects one of the participating elements. I.e. an output from one element may become an input to another element, for example the output torque from a motor becoming the input to a gearbox.

- *Double-acting*: the effect of the relation affects both the participating elements, i.e. interactions between elements, for example a screw joint where the elements mutually affect each other.
- *Non-oriented*: the effect of the relation does not have any particular orientation, i.e. the effect is not directed towards any particular element but may affect any element or system in its surrounding which is sensitive to its influence, or in contrary being affected. The relation between a non-oriented effect and the set of elements in the system, or the surrounding, may be regarded as a *second order relation*. Examples may be vibrations from the contact between the ground and the wheels of a car, propagating trought the frame. A non-oriented effect can also origin from a single element. In that case, it is comperable with incidental interactions in accordance with Ulrich & Eppinger (2000) and Liedholm (1999).

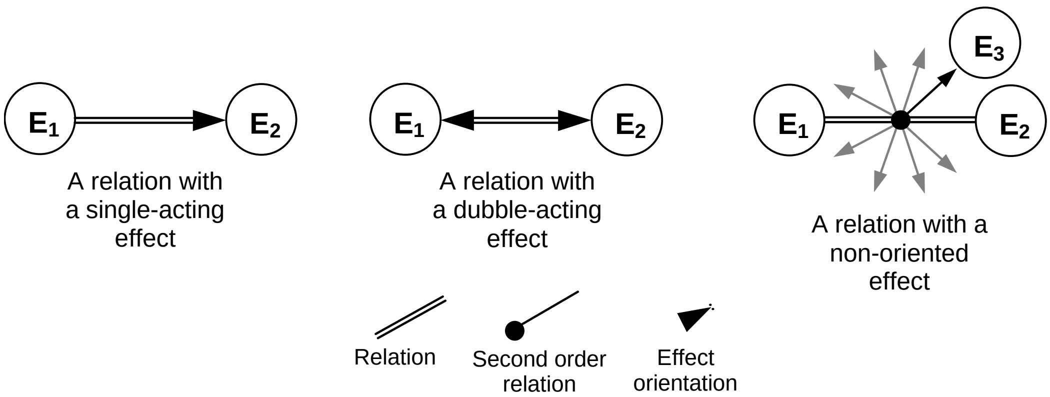

Figure 2. Orientational features for an effect of a relation

The effects can be either intended or unintended. The intended effects contribute to the realisation of the functionality for a system while the unintended effects are by-products of the choice of solution and its properties, which will give the system its final behaviour. In most cases, the unintended effects cause no harm to the system, but occasionally they can cause potential conflicts, and some times even obstruct a part of the functionality.

The oriented effects (single- and double-acting effects) may be both intended and unintended, while the non-oriented effects mainly are unintended. An oriented effect is strongly connected to its effectuating relation; thus, it is relatively simple to deduce the cause and the concequence. For a non-oriented effect, however, this connection is much more vague, consequently they are more difficulty to take into consideration.

4.3 Example of non-oriented effect and second order relation

Two elements in a system have a relation in form of a physical contact. Every physical contact implies friction in some way. Depending on the relative motion of the contact area friction energy will arise, i.e. a work will be done and be transformed into heat. The magnitude of the friction energy depends on several factors, e.g. the magnitude of the perpendicular force in the contact areas; the material properties; the surface structures; the magnitude and direction (alternating or not) of the motion, and the friction constant.

The *relations* between the different elements in this case are the physical contact (*effectuating*) and the relative motion (*non-effectuating*). The *effect* of these relations may be friction energy transformed into heat (*non-oriented*). This is an effect that not could be deduced from a single element, but becomes one in the superior system. The generated heat in turn may interact with another element or system in its surrounding. The effect of this *second order relation* may become critical depending on the non-effectuating relations between, and the properties of the affected elements, like spatial relations, sensitivity of the affected element, the amount of heat, etc.

5. Conclusions and Discussion

The goal with this paper has been to draw the outlines for a concept representation which improv the basis for evaluation and decision-making in the early phases of the design process. It has been approached by providing a more nuanced description of a system, which increases the possibilities of understanding and communicating the solutions.

The major distinctions from prevalent design theories are the widened meaning and definition of the term *relationship* in the *systems theory*. It implies an increased possibility of describing different phenomena that origin from the connection between the elements, like natural frequency, wear, assembly costs, etc., in a more objective way, which earlier have been difficult to embrace.

By using a representation that is focusing on the relations between the different elements within a solution and how they influence each other, the possibilities of detecting potential problem areas will increase compared to the use of an arbitrary representation. If the traditional evaluation methods (often based on the principle: *selection of the fittests*) are used together with a systematic search for potential conflict areas within the solutions (i.e. a method based on the principle: *exclusion of the improper*) the validity of the evaluation result will be higher. In other words, the probability of choosing the “right” concept will be increased since more aspects have been taken into consideration.

A proposal of a concept representation does not alone contribute to an improvement of the evaluation activities for the individual designers. It should rather be considered as a first step towards a more elaborated methodology. To be useful as a method it has to be able to: (1) identify the relations and their potential effects in a systematically way; (2) estimate the potential risks of an unintended effect; and (3) eventually propose a way of prevent or alleviate the consequences of the effect.

One possible way of conducting a systematic identification of the relations may be to study the participating elements and their physical properties. By mapping them together, some of the relations, depending on the concretisation levels of the elements, may be detected. The appearance and the potentials of the effects mainly depend on how the different relations relate to each other. To neutralise the consequences of the effect one can either change conditions for the effect or change the effectuating relation.

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