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MANUFACTURABILITY AND VALIDATION METHODS IN PASSENGER CAR DEVELOPMENT – AN INDUSTRIAL CASE STUDY

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1. Introduction

To assure competitiveness, companies in the automotive industry are forced to respond to market demands quickly, and to develop and manufacture their products efficiently. While having to keep development and production costs at a minimum, they have to fulfil high quality standards, meet customer needs and legal requirements. Several drivers of production costs and time have been identified and discussed in scientific literature. One issue that contributes highly to the overall development costs and time in serial car production is manufacturability of the product. Manufacturability problems during production ramp-up and serial production may cause delays, necessity of expensive design or process changes, and costly rework. To prevent these problems, designs and processes are usually carefully tested and validated. This article will address the field of methods and procedures for assessing product manufacturability in order to assure the fitness of a product for serial production.

For good manufacturability product and production processes have to be perfectly adjusted to each other to achieve required quality and efficiency levels. Due to the complexity of product and production system, manufacturability problems may cause a variety of effects, from slight deviations from the desired quality and manufacturing efficiency levels up to serious disturbances of production processes and – even worse – product malfunctioning. Corrective measures to reduce the likelihood of these problems are easier and usually less expensive to realise during product development rather than after start of production [Whitney 1990].

Through the late advancements in visualisation, simulation and Rapid Prototyping technologies, the field of application of Virtual and Rapid Prototyping techniques for verification and validation has expanded and many different methods have been developed and applied besides the build of physical prototypes. In order to gain better understanding of the validation of manufacturability, this paper introduces a model of validation methods and provides an industrial case study examining problem types occurring throughout automotive product development and production. The case study examines documented problems during product development and production of a passenger car at a German automobile company.

2. Assuring manufacturability

Manufacturability is an abstract term that describes the quality of a product's design to be manufactured efficiently. An inferior manufacturability would lead to problems and delays during production ramp-up, to necessity of costly product or process changes, and/or to rework.

Swink [Swink 1999] discusses New Product Manufacturability as an abstract construct that consists of several properties concerning product development project characteristics in addition to product

design characteristics. His study shows a negative relation between manufacturability and product complexity. However, the hypothesis that product newness and technological uncertainty lead to poor manufacturability was not supported in his study. The author describes manufacturability with five sub-factors: the product cost goal achievement, product manufacturability goal achievement, product quality goal achievement, number of manufacturing problems in production start-up, and number of product design changes needed in the production phase (reversely coded) [Swink 1999].
In this article, the factor "number of manufacturing problems" will be investigated further. But not only manufacturing problems during ramp-up should be considered to assess manufacturability. Looking at problems occurring during later production phases and during product development may also be interesting. It should be noted that problems detected during product development are usually "predictions" based on validation and verification methods that are anticipated to materialise during production if no changes are implemented. Likelihood of detection as well as information regarding cause and effects of these problems depend on the accuracy applied validation methods represent future real product/process behaviour with.

2.1 Validation and verification

Generally, validation and verification (V&V) comprise all activities carried out in order to test and/or confirm certain properties and functions of an object. The terms "verification" and "validation" are sometimes interpreted differently. Maropoulos and Ceglarek Maropoulos [2010] show different uses and definitions of both terms and point out that they are sometimes used interchangeably in articles and textbooks. Following the ISO 9000 standard, in this article "verification" is defined as the confirmation "that specific requirements have been fulfilled" and "validation" as the confirmation "that the requirements for a specific intended use or application have been fulfilled" [ISO 2005]. Methods for validation and verification of manufacturability always focus on a defined object (complete product, product part, process, etc.) and are carried out to examine this object in the context of certain external factors (process steps, operational statuses, etc.). These methods and procedures aim to detect or predict problems which may hinder efficient manufacturing of the product or even inhibit it completely. In this context, a problem (or "defect" or "failure") may be understood as a deviation of the actual condition from a desired condition [Haberfellner 1994]. In this article and in the context of design for serial production, a problem is defined as a discrepancy between product and production system that obstructs production at desired efficiency and quality levels.
Validation methods aim to reduce uncertainty regarding product/process properties that are tested and in many cases provide information that has not been anticipated. This information serves as basis for further efforts to improve the fit between product and process. The use and quality of validation methods influence the number and quality of defects and problems during production ramp-up. Therefore, a relation of validation efforts and product manufacturability is evident.
In order to reduce the number of defects and to prevent problems within the production processes this relationship has to be taken in account. The aptness of different validation methods to detect/prevent certain types of product/process problems has to be known beforehand in order to configure an optimised method that will reflect all relevant aspects of the abstract property "manufacturability".

2.2 Manufacturability validation methods

A multitude of different validation methods is used to test manufacturability or to gain necessary information to obtain it. These methods can be distinguished by validation object, purpose and type of model that represents the validation object. In this article, the validation object is defined as the object that is to be examined (e.g. a single part, a complete product, a manufacturing process) under certain pre-defined (external) conditions. The validation purpose describes the type of question that is to be answered by the validation method.
Types of representation of the validation object are numerous: besides building a physical prototype and testing it, simulations, virtual mock-ups and rapid prototyping technologies are commonly used in validation processes in the automobile product development process.

- **Virtual models**
  Virtual engineering methods are based on virtual (computer-based) representations of the product or process, so-called virtual prototypes [Weber 2011]. They simulate an object, its properties, behaviour or interaction with other objects before it is physically realised. In addition to the advantage of avoiding expensive physical prototypes, virtual prototypes and virtual engineering methods usually allow the validation of design alternatives and possibly provide test outcomes faster. Even though there have been vast advancements in virtual prototyping and simulation software, and even though virtual engineering techniques (applying analysis methods/tools to virtual prototypes [Weber 2011]) are frequently used in industrial product development, physical prototypes are still often built and tested for design validation of complex products.
- **Physical models**
  During automotive product development, the physical prototype built is still an important source of information. In addition to the use of prototypes for functional tests, valuable information regarding the production process is gathered throughout the building phase. However, physical prototypes are expensive and also have shortcomings, e.g., it takes time to build them, usually several weeks. As a consequence, these prototypes have often been overtaken by design progress, so they usually do not represent the current state. Furthermore, they are not easy to change after having been built.
- **Combinations**
  There are also methods that use a combination of virtual and physical models, like for example augmented reality (AR) based systems. With AR, virtual objects (virtual parts or information) are added to physical objects and displayed together.

Figure 1 shows a scheme of the relationship between the model of a validation object and the properties that it represents.

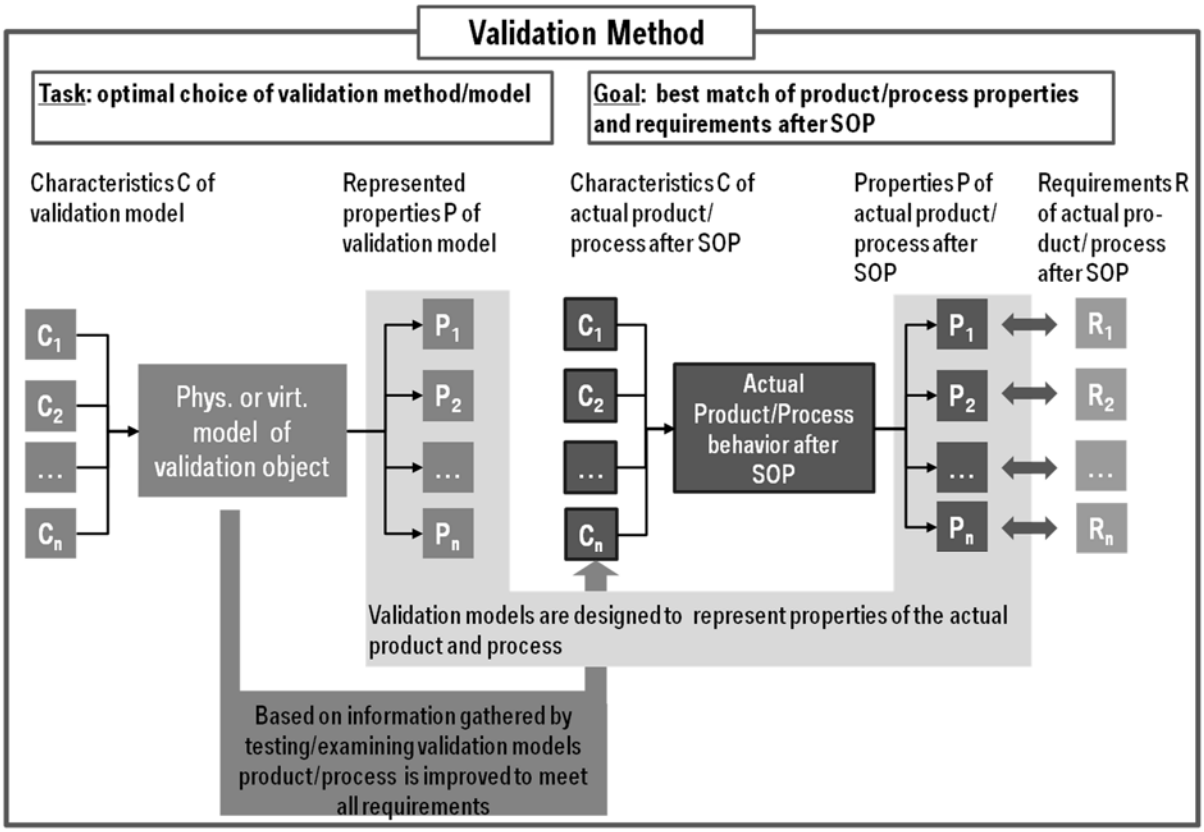

Figure 1. Validation methods

The choice of the design characteristics C defines the properties P that can be derived from the model. These should predict the actual properties of product and/or process after start of production (SOP) as accurate as possible. E.g. the choice of a material (C_1) of the validation model other than the material used in later serial processes may be useful to represent and examine geometric issues (P_1), but may lead to inadequate results when examining assemblability (P_2). Testing and examining the validation model provides information that is needed to adjust design characteristics of the actual product/process in order to create properties that meet the requirements (R) after start of production.
Manufacturability comprises several product and process properties (P_n), which have to be evaluated. At the lowest level, for each single component of a product exist certain requirements that have to be met, and component properties need to be designed and validated accordingly. The complexity grows as assemblies of these components lead to additional requirements, and component interactions may lead to properties that do not necessarily reflect the sum of the component properties. For the identification of component, assembly or product properties that are necessary for the assessment of product manufacturability, detected problems in past development projects provide valuable information.

3. Industrial case study

This study will investigate several aspects of the topic described beforehand. In order to identify product/part properties that are related to the manufacturability, documented manufacturability problems detected during the development process of a passenger car have been analysed. The results of this analysis provide clues that are helpful to improve the applied validation methods. Most validation methods capture only part of the validation object's design properties and are therefore used only for distinctive validation purposes. In order to assure the complete coverage of all possible problems that may obstruct the manufacturability of a design, the scope and capabilities of each procedure have to be known.

3.1 Defining property categories

The abstract concept of the "manufacturability" consists of several sub-properties of a design. These properties are usually tested individually and the absence of problems during a test or during actual production processes indicates manufacturability. Therefore, manufacturability can be assessed by the number of problems that occur when the design is being manufactured within serial production environment and processes. These problems affect different product/process properties and can be distinguished into several property categories, which in turn can be assigned to the validation methods used to assure this property. In order to establish problem categories, several hundred documented problems before and during the production of a passenger car have been analysed for this study. The problem documentation used for this analysis starts four years before and ends about five years after start of production of the product. Throughout its development process, several validation procedures have been applied, such as assessment of virtual models, prototype built and simulations. Since late design or process changes are expensive, it is important to detect manufacturability problems as early as possible.
The product has been chosen for this analysis because of its complete and thorough documentation of applied validation procedures and detected manufacturability problems. A first analysis of this older, however well documented product shows that detected problems lead to the necessity of either product or process changes in order to grant efficient manufacturing. Process-related problems are those that occur due to (currently planned or realised) production processes and lead to process changes or adjustments. Examples are geometric defects due to the use of prototype tools that still need adjustment or problems because of logistic processes. Tool wear and changes of supplier structure are also listed in this category. Product-related problems lead to the necessity of product design changes (including software-related defects).
Since manufacturability can only be reached by creating a perfect match between product and processes, both process- and product-related problems are included in this study. The problem documentation has been analysed in order to establish problem categories and to identify product and process properties that can be assigned to the term "manufacturability". Problems are either caused by product or process issues, but they may affect one or more of the following categories:

- **Geometrical coherency**
  All designs have to be checked for part collisions and malpositioning. As mentioned before, these defects may occur because of the product design but also due to inadequate manufacturing processes.
- **Error prevention**
  Another design property that forms part of the evaluation of manufacturability is the prevention of errors during the assembly process. The likelihood of errors (e.g. mix-up of part variants or assembly order) should be minimised by preventive measures. The likelihood of errors increases if there is more than one product variant assembled in a production line segment.
- **Assemblability**
  This property describes collision-free part assembly. This includes issues like handling of tools and joining forces. Assemblability problems may prolong assembly time and forces or even render it impossible to assemble a product as planned.
- **Appearance**
  Problems that result in compromising the optical or haptic quality of the product and are caused by misfit of product and process are also considered here.
- **(Secondary) Product/Part Properties**
  All problems that compromise secondary product functions/behaviour, such as stability, sound- and water-tightness, etc. are categorised under this topic. These properties are usually not noticed as adding value to the product but cause disapproval or are perceived as a disturbance if not fulfilled and therefore reduce the product value.

The manufacturability problems documented in the problem management system have been assigned to the problem categories listed above; about 67 per cent of all documented problems could be assigned to one or more of these categories. The remaining 33 percent are documented problems that could not be assigned to the above mentioned categories or occurred due to extraordinary external circumstances like machine breakdowns and supplier mistakes. Figure 2 shows the overall distribution of affected product and process properties.

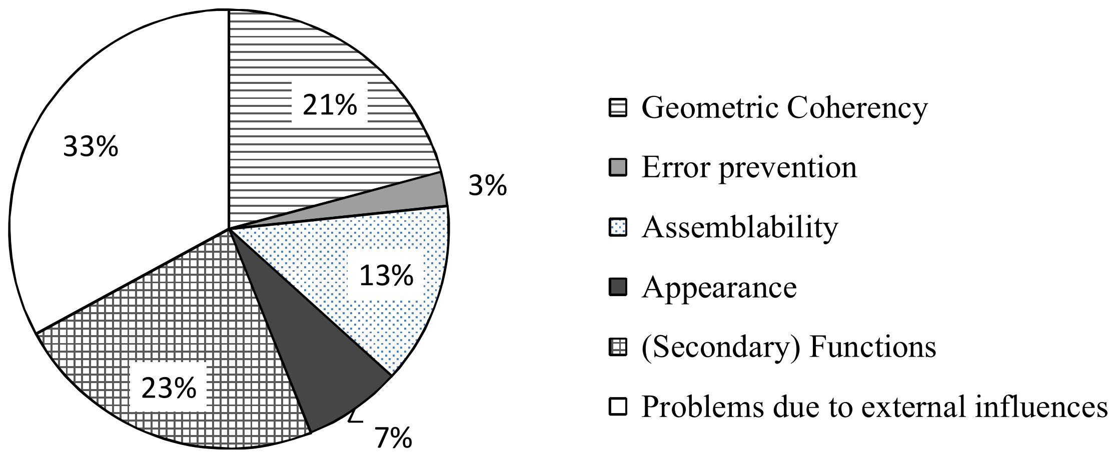

Figure 2. Documented problems

As shown in Figure 2, most underlying issues affect (secondary) product functions and geometric coherency. Since those functions represent a big portion of the overall number of documented problems, a closer look seems necessary. Table 1 shows different types of functions that have been affected by manufacturability problems in this case study.

Table 1. (Secondary) functions

(Secondary) Function	Percentage
Undesired noises	48,4
Usability	2,9
Water-tightness	12,5
Fixation	16,7
Corrosion	1,5
Stability	1,7
Vibrations	1,2
Fixing elements	0,7
Product functions	11,3
Others	3,1

After start of production, when the first cars are built in the serial process environment (and before any design changes due to "face lifts" are introduced), there should not be many problems since they should have been detected by validation methods beforehand. Nevertheless, problems that have not been caught early indicate a potential for improvement of the validation methods used. To do so, the number of problems detected shortly before and after start of production in each problem category will be analysed further in a following study, and the corresponding validation method (validation method that covers that particular property) will be improved according to the results.

A high number of late detected problems indicates potential for improvement of a validation procedure. A low number indicates that the validation procedures applied provided sufficiently reliable and complete information. In case of high reliability of results of validation methods, these can also serve as bases for product/process maturity assessments.

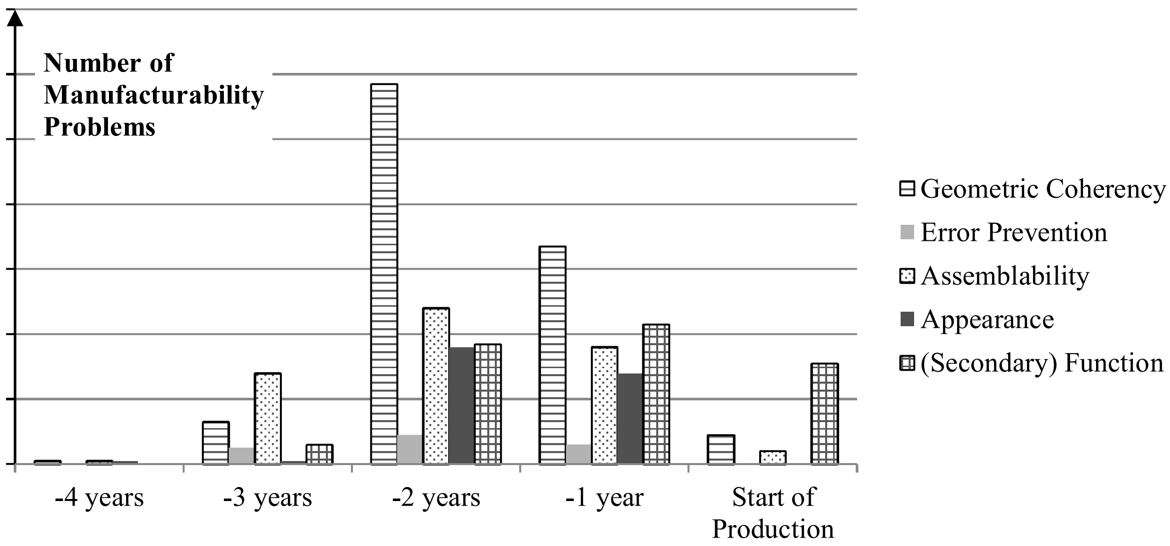

Figure 3. Documented problems over time

Figure 3 indicates that the validation procedures applied to cover (Secondary) functions could be improved, because some problems of this category have been detected very late in the product development process. However, the number of late detected problems regarding Geometric Coherency, Error Prevention and Appearance is relatively low. As a conclusion, improvement efforts should address validation procedures regarding (Secondary) Functions rather than other property categories.

3.2 Product/process maturity and validation methods

Product and process maturity are thoroughly discussed topics among researchers and experts in manufacturing industry. Von Wangenheim et al. provided a literature review that identified 52 models/frameworks describing software process capability/maturity [vonWangenheim 2010]. Other work, such as Jahn [Jahn 2010], focuses on project maturity of product development projects. Weber suggests an approach to assess product maturity based on the evaluation of product properties. The author points out that the confidence of a maturity evaluation is related to the method and information the evaluation is based on [Weber 2007].

Validation methods are designed to prove certain product or process properties, i.e. the fulfilment of certain requirements. If maturity is defined as the completeness of fulfilment of a requirement, then a validation procedure can serve to evaluate product maturity. For the case of validating manufacturability, maturity evaluation can only address maturity from a manufacturing point of view.

4. Summary

A theoretical model of validation procedures has been presented which outlines the dependencies between characteristics of a validation model and the properties it represents. Information gained by testing and examining the validation model serves as bases for improvements of the product/process design. Design characteristics of the actual product/process are adjusted to assure manufacturability, i.e. to create product/process properties that will meet all relevant requirements during production. Currently, validation methods applied in the automotive industry use physical models as well as virtual models or a combination. In a case study a passenger car development project has been examined and valuable information has been extracted through an analysis of documented manufacturability problems. Through data analysis, several problem/property categories could be identified that form part of the abstract term “manufacturability”. Further studies will link the documented and now categorised problems to the validation methods applied in this development project in order to identify potential for improvement. Therefore, an analysis of the applied validation methods will be necessary.

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