THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Visualizing the Effects of Geometrical Variation on Perceived Quality in Early Phases

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ABSTRACT

In a perfect world, geometrical variation in a manufacturing process would not exist. Every component produced in a series would have the exact same dimensions and, when observed by a trained eye, look exactly identical. However, the world is not perfect and neither are manufacturing processes.

When developing new products, this fact must be considered since a product, in most cases, consists of several components that are assembled together. The geometrical variation may impact the function of the product, the ability to assemble the product and the aesthetics of the product. Geometrical variation may thereby affect the customer's perception of the overall quality of the product. That is the reason why the visual appearance of the relationships between components, also defined as split-lines, in many cases is of exceptional importance in the automotive industry. Perceived quality of split-lines is one of several aspects of perceived quality, which is an overall quality as perceived through the human senses.

This thesis is concerned with methods for simulating and evaluating perceived quality in early phases of the product development process. Early simulation and evaluation of perceived quality can minimize the number of corrections in late phases, increase quality and save both time and money. The potential for savings is of substantial importance as projects in the automotive industry are conducted with consistently decreasing budgets and tighter time plans.

The thesis elaborates on methods for performing non-rigid variation simulation in early phases when data maturity is low. These are placed in a proposed framework for managing and supporting evaluation of perceived quality in general during the development process based on the maturity of the data available. Some activities in the framework are widely used in the automotive industry while others are based on recent research in the area.

The thesis reports on several case studies that highlight different aspects in the framework. It shows how mesh morphing can be used to predict component variation and component stiffness in very early phases by using historical inspection data and design solutions as input. This facilitates a way of visualizing the effects of geometrical variation on perceived quality in very early phases by utilizing reference data linked from previous projects.

Another study was performed to investigate the applicability of non-FEA-based deformation methods for simulation and visualization of effects of geometrical variation on perceived quality. Results showed that many of the involved engineers and managers endorsed the alternative of taking decisions based on simulated results from the method. They also emphasized the advantage of having the possibility to visualize expected scenarios early on in the development phase. Based on results from this study, a follow-up study was performed to show how the method could be applied in industry.

Also included in this thesis is a study showing that evaluators perceive rigid and non-rigid visualizations differently. This further supports the need of non-rigid simulations and visualizations for correct judgments of the virtual models. Unfortunately, most non-rigid simulation models are more time demanding to build, compared to rigid ones, and may consequently not be applied in all cases. Therefore, a study has been conducted to investigate in which vehicle areas non-rigid variation simulations are recommended.

These results are expected to support and improve the work with perceived quality in the industrial development process, and they expand the body of scientific knowledge in the research field.

Keywords: *Geometrical variation, perceived quality, tolerance analysis, geometry assurance, non-rigid, variation simulation, product development, visualization and evaluation.*

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Forslund, A., Forslund, K., Kero, T. and Wagersten, O., (2011), "Robust Design and Quality Assurance". *Entering the Tiger’s Cave – Perspectives on Japanese and Swedish Product Development.* D. Bergsjö, Ed., Chalmers University of Technology, Department of Product and Production Development, Göteborg, Sweden, p 37-44.

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Paper A
Wagersten initiated the idea, with the support from Wickman. The method was developed by Wagersten and Wickman. The work was planned and carried out by Wagersten, with support from Wickman. Wagersten and Wickman wrote the paper. Söderberg contributed as reviewer.

Paper B
Wagersten initiated the idea, planned and carried out the research. Wagersten wrote the paper. Söderberg contributed as reviewer.

Paper C
Wagersten, Forslund, Wickman and Söderberg initiated the idea and developed the main framework. Wagersten wrote the paper with Forslund, Wickman and Söderberg as reviewers.

Paper D
Wagersten initiated the idea with support from Wickman. Interviews were carried out by Wagersten and Wickman. Wagersten performed analysis and wrote the paper. Lindkvist implemented the evaluated method in the CAT-software. Söderberg contributed as a reviewer.

Paper E
Wagersten and Lindau initiated the idea of the paper. Lindkvist developed support for the CAT-software. Wagersten and Lindau wrote the paper together. Söderberg contributed as a reviewer.

Paper F
Wagersten initiated the idea with support from Wickman. The case study was performed by Wagersten and Wickman. Söderberg contributed as a reviewer.

Paper G
Wagersten and Wickman initiated the idea of the paper. Wagersten, Wickman and Forslund performed the study. Wickman and Wagersten performed the data analysis and wrote the paper together. Söderberg contributed as a reviewer.

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1 INTRODUCTION

This chapter provides a short introduction to the research documented in this thesis, the project goals, the research questions and a brief outline.

It is always advantageous to place emphasis on the early phases in a product development project. This may avoid, or at least reduce, the range of changes and rework in late phases, where such unwanted activities are costly and time consuming (Ullman, 2003; Pahl and Beitz, 2007; Ulrich and Eppinger, 2004). In the study by Koen et al. (2001) it was identified that the work in early phases plays a key role in the product development process. In Figure 1, the typical characteristics of early phases are depicted in accordance to von Hippel (1993). Herstatt and Verworn (2001) describe these characteristics, speaking in the terms of "fuzzy front end" instead of early phases (more established in the automotive industries). The degree of freedom in design and influence on project outcomes are high, whereas costs for changes are low. This advantage is limited by the fact that the amount and certainty of information is low compared to later stages of the development process. Therefore, sound decisions cannot be made unless necessary information is gathered.

This also affects the work around virtual prototypes. Traditionally, iterations of tests to explore the solution space have been accomplished with the help of physical prototypes rather late in the development process. This has been associated with time consuming and expensive activities. Hence, many efforts are made to minimize the number of prototypes throughout the development chain, especially test series but also physical mock-ups that are costly and time-consuming to build. This is also an important aspect in the concept of front-loading (Thomke and Fujimoto, 1998; Thomke and Fujimoto, 2000, Morgan and Liker, 2006), partly aiming to facilitate verification and validation as early as possible. This, in turn, forces decisions to be

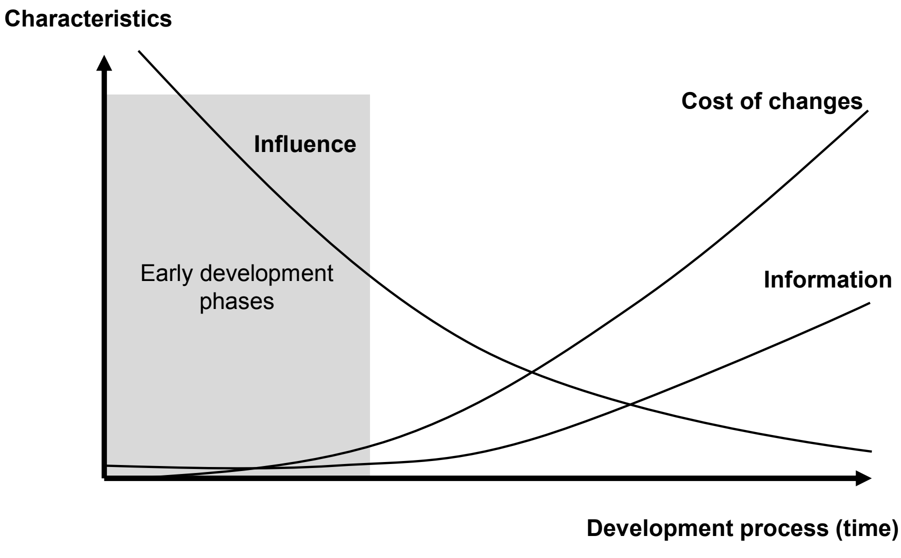


Figure 1. Evolution of influence, costs of changes, and information during the innovation process (von Hippel (1993), modified by Herstatt and Verworn (2001)).

made earlier which puts an increased focus on the work with virtual prototypes in early phases.

In a development project, numerous models for simulations and testing activities are performed in different areas and for various purposes. One important factor necessary to predict, both for technical function aspects and user-related aspects, is the effects of geometrical variation. An overview of the major contributing factors to geometrical variation in an assembly has been initiated by Söderberg (1998), depicted in Figure 2. Part variation (i.e. component variation) stems from factors related to the tooling and the manufacturing of components, and is limited by tolerances on drawings and CAD (Computer-Aided Design) models, that define the allowed spread of variation. Assembly variation originates from the assembly process and precision. Finally, the design concept can have impact on the final variation. With a robust design concept, the final variation in important areas can be suppressed.

Furthermore, geometrical variation may in turn affect customer experience of the product since the appearance of relationships between visible components, also defined as split-lines, is in many cases of exceptional importance. Through early visualization of non-nominal product concepts, where effects of geometrical variation are presented, the perceived quality of product split-lines can be evaluated in a virtual environment.

Front-loading aims at shifting simulation activities to an earlier stage of the development process. However, the conceptual styling models, available in early phases are less mature compared to the final engineering models where information regarding detail design is available. This, in turn, impacts the work of performing virtual evaluations to assess the final perceived quality of split-lines. For instance, in immature styling models, design parameters such as material selection, material thickness, locating scheme, design and position of reinforcements and flanges are rarely defined. These parameters may influence the deformation behavior of a

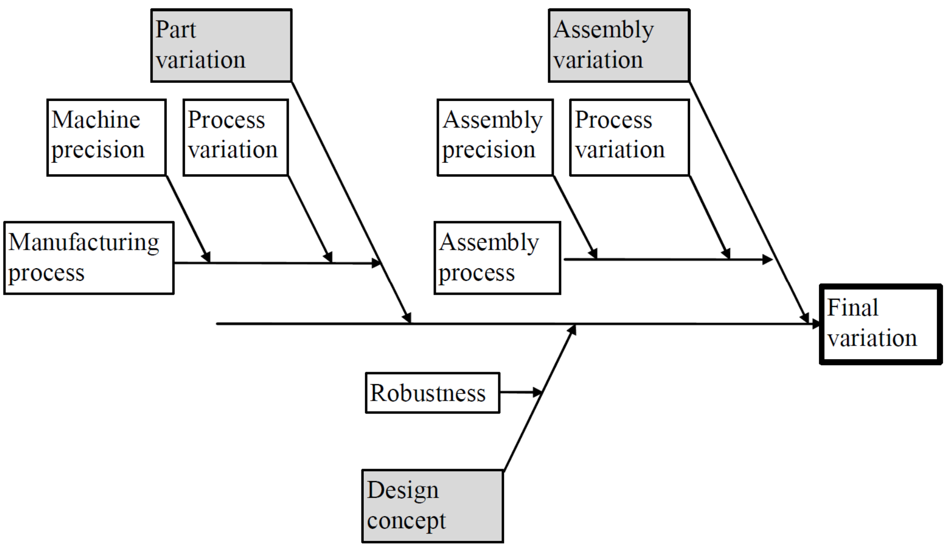


Figure 2. Major contributors to geometrical variation (Söderberg, 1998).

component, and as several of the visible components on a vehicle are in fact non-rigid, the effects of variation on the final perceived quality are dependent on the component behavior.

The work in this thesis is aimed to support and structure the work around simulation and visualization activities to better facilitate early judgments of perceived quality of split-lines. To further overcoming the issue with immature models in early phases, this work also presents and proposes methods and tools aimed to support the possibility to perform simulation and visualization activities of non-rigid components. It will also highlight the importance of taking component behavior into account to increase the reliability of visualization models for perceived quality evaluations.

1.1 PERCEIVED QUALITY OF SPLIT-LINES

When components are assembled into a product, the division between components is defined as a split-line. In many cases, the product design does not allow contact between components in these split-lines. The gap size that occurs in these divisions originates from the effects of geometrical variation, over-slam, dynamic movement, swing clearance and other factors requiring space.

The final variation in these split-lines is limited by so-called aesthetical geometrical requirements. Examples of such requirements are allowed maximum and minimum gap and flush-size, and non-parallelism. In Figure 3, contributors to the final perceived quality of split-lines are illustrated, described by Wickman and Söderberg (2010). Examples of unwanted effects that may arise, stemming from geometrical variation, are extremely wide gaps, non-parallelism and asymmetry in the split-lines. Furthermore, the visual sensitivity of different split-lines affects the degree to which the geometrical quality is made visible to the customer or, whether it actually influences the quality perceived by the customer. The final factor affecting the perceived quality of a split-line, covering unintended exposure of design details, is described as detail execution. Geometrical variation and detail execution are to some extent correlated. Geometrical variation, resulting in wide gaps and large flush, may reveal such details to the customer and is thus an important factor.

Focusing specifically on the evaluation of product experience of split-lines, which is the case in this research project, two essential circumstances have largely contributed to this evolvement, tolerance management and virtual reality visualization.

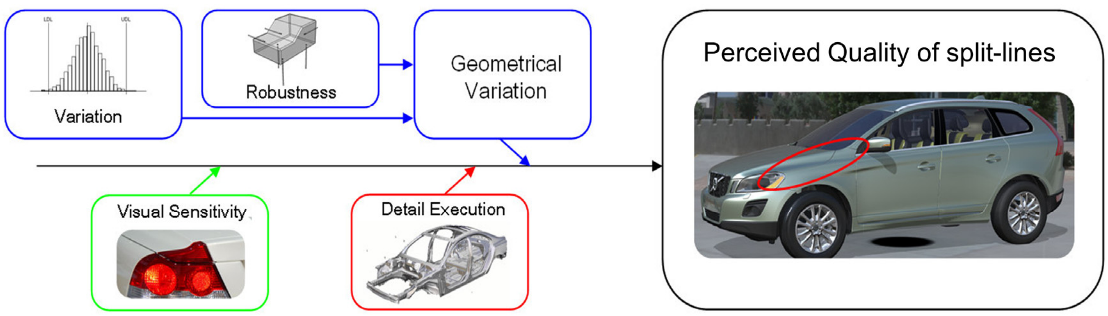


Figure 3. Contributing factors to perceived quality of split-lines (Wickman and Söderberg, 2010).

1.2 ROBUST DESIGN AND TOLERANCE MANAGEMENT

Component variation in mass-production will vitally impact the customer's perception of product quality in many cases. Furthermore, as products generally consist of several components that are assembled together, the effects of variation will propagate throughout the product. In most cases, improved manufacturing methods for the purpose of delimiting geometrical variation are not financially defensible, since small improvements will be very costly compared to what may be gained from a variation perspective. Therefore, this issue needs to be grasped through more economically viable methods.

The implementation of so-called robust design methods has been widely spread at many companies performing product development. Robust design is a concept applied to minimizing the effects of variation (Taguchi et al., 1989), here referring to geometrical variation. Further, as Phadke (1989) states, the fundamental idea of robust design is to minimize the effects of the sources of variation without eliminating the actual sources. In practice, this may be realized by executing smart design solutions that withstand variation in a robust sense.

One of the more basic issues to deal with, when it comes to suppressing the effects of geometrical variation in a product, is to handle the positions of the locating points. The locating points can generally be defined as the fixation points of one component onto others in an assembly. By spreading the locating points, the effects of variation propagation may be suppressed, resulting in a more robust design. Managing locating points is one of several issues included in the field of tolerance management. In recent years, an increased number of tools to support tolerance analysis on component- and assembly-level have been developed. Many of these analysis methods have been implemented in computer software, defined as CAT (Compute-Aided Tolerancing), that use methods such as Monte Carlo simulation and FEA-based simulation.

As well as focusing on component and product design to increase the perceived quality, one may also focus on the styling of the product. Just as the engineering design may provide a less variation-sensitive product, robust activities may be adapted to the styling of the product. This interplay between design and styling has an impact on the visual sensitivity (Wickman and Söderberg, 2001), or later, the visual robustness (Dagman, 2007; Forslund, 2011), an important contributor to the final perceived quality.

1.3 VISUALIZATION AND EVALUATION OF PERCEIVED QUALITY IN PRODUCT DESIGN

Using virtual reality software facilitates realistic visualization of product concepts in early phases of a product development project. This is an important contributor to achieving high perceived quality. To support the work with aesthetical geometrical requirements during the development phase, evaluation activities are implemented. In general, different styling and design concepts are evaluated to get a visual impression of the final product. To achieve the high performance of the foundation in terms of geometry models, this is performed in a high-end visualization software that renders the product in a realistic way. Taking it one step further, Maxfield et al. (2000a) and Wickman et al. (2003) have presented methods for how to combine CAT software with high-end visualization software. This facilitates visualization of so-called non-nominal assemblies where effects of geometrical variation are included. Currently, however, showroom interfaces can be integrated in the software, as seen in Figure 4.

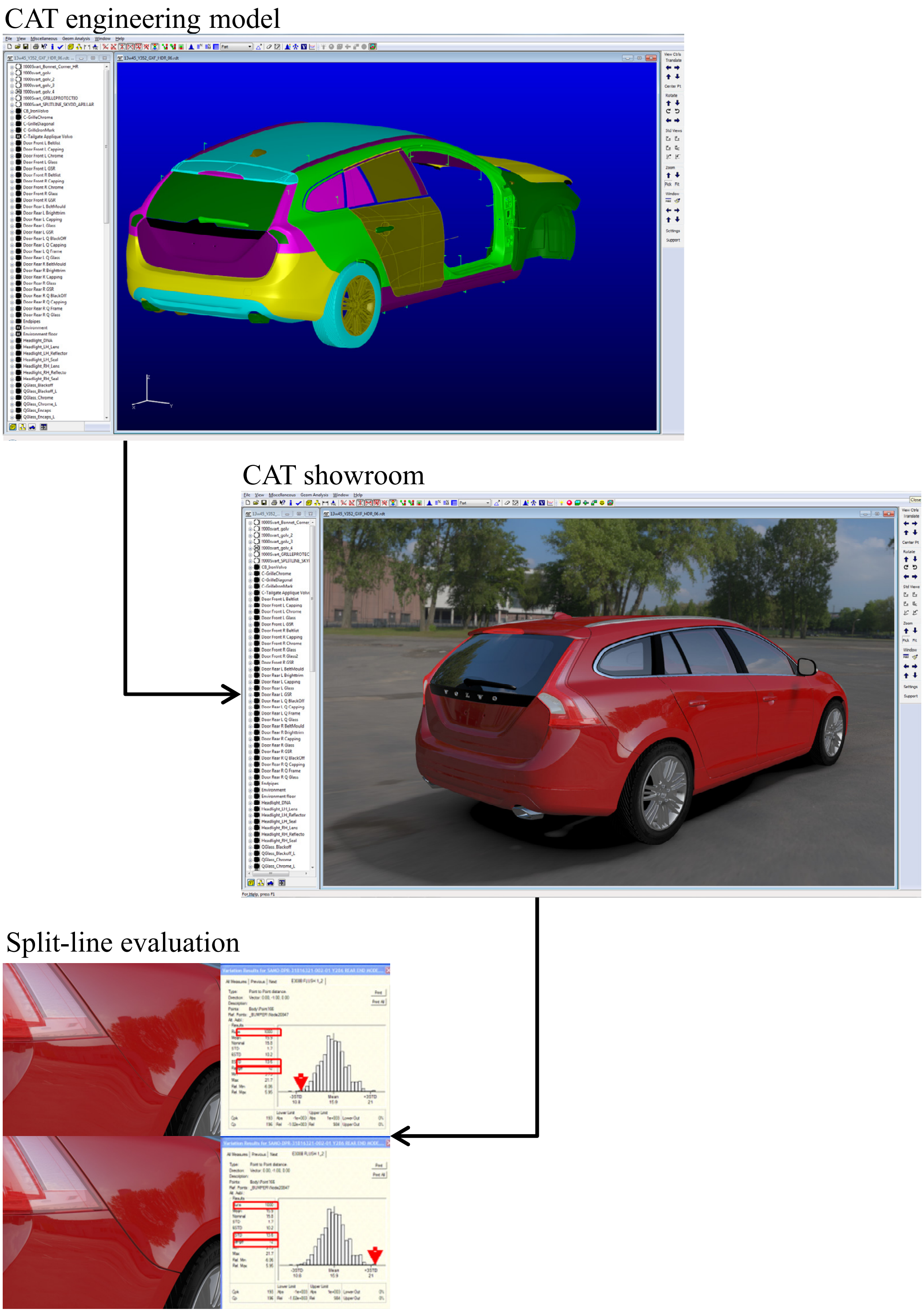


Figure 4. Example of virtual evaluation of perceived quality of split-lines in CAT-tool RD&T.

Here, the effects of geometrical variation are simulated using a CAT-tool to achieve statistically reliable results. To reach the realism of a physical vehicle, visualization of the simulated model is performed. Finally, the evaluation can be carried out. The evaluation may focus on different objectives and serve different purposes. For instance, it could either be to support the aesthetical requirement definition or to analyze the detail execution of the split-line by focusing on visible details or effects inside the actual split-line. In addition, the visualization activity is a superior tool for analyzing the visual robustness of proposed concepts.

1.4 CAD DATA MATURITY DURING PROJECT EVOLVEMENT

When performing perceived quality visualization and evaluation activities through a virtual prototype, product-defining digital CAD models, e.g. geometrical models, are required. These models are released at different stages in the product development process. In the context of product styling and engineering design, this is often defined as geometrical data. There are basically two variants of geometrical data that are considered. The two variants are also related to the maturity of the data. In the early conceptual phases, the data is defined as styling data and these are the geometrical models originating from different styling proposals.

Later in the product development process, when focus has changed to the detailed design of components and assemblies, the geometrical basis is defined as engineering data. This is a more substantial basis in terms of level of detail. Figure 5 shows the difference in maturity on styling data and engineering data respectively.

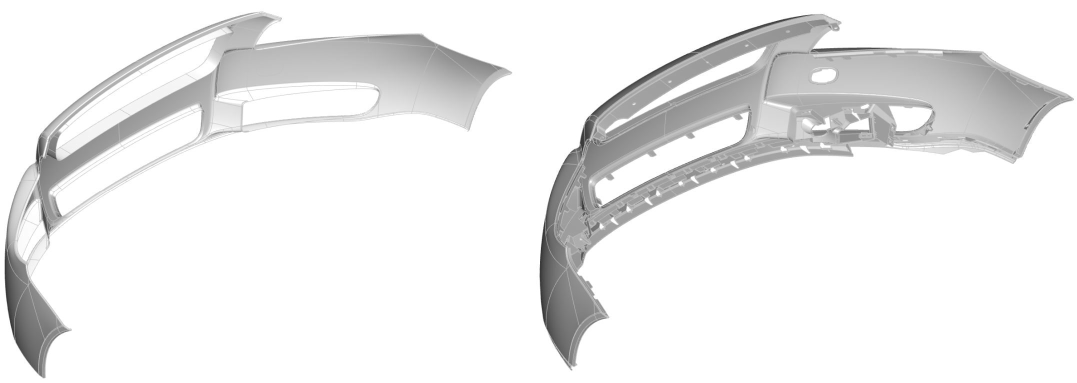


Figure 5. Level of detail on styling data and engineering data respectively.

1.5 PURPOSE AND AIM OF THE RESEARCH PROJECT

The main objective of this research project is to develop tools and methods for early variation simulation and visualization, with a focus on non-rigid components, for the purpose of evaluating perceived quality. In addition, this research project aims at exploring the area and detecting and evaluating important factors that have a large impact on the objective described above. Consequently, the underlying parameters and ingredients affecting the variation simulation and visualization of non-rigid components need to be identified and managed. The aim of this research project can be summarized by the following bullet points:

- Support and improve the work with perceived quality in the development process by proposing efficient work procedures, tools and methods.
- Support perceived quality evaluations through non-rigid variation simulation and visualization where rigid simulation is not sufficient.
- Propose efficient methods for the visualization of deformed components to support perceived quality evaluations.

1.6 RESEARCH QUESTIONS

In this research project, one main research question has been defined. The question is stated as follows:

"How can variation simulation and visualization of split-lines be performed, to support early perceived quality evaluation, when complete engineering CAD data is not available?"

In order to answer the major research question, the following underlying sub-questions have been identified:

RQ I - Process:	How can a process for simulation and visualization be defined, in order to support early perceived quality evaluations based on immature data?
RQ II - Tools/Methods:	What tools and methods are needed to predict geometrical variation and component behavior to support early perceived quality evaluations based on immature data?
RQ III - Focus:	What vehicle areas should be focused on when performing early non-rigid perceived quality evaluations with respect to geometrical variation?

RQ IV – Visualization: What is the difference in how non-rigid and rigid components are perceived when evaluating perceived quality through visualization?

As Williamson (2002) states, it may in some cases be advantageous to break down the major research question and frame sub-questions. Such specific questions, that all fall within the scope of the major question, will help the researcher to make manageable or easily researchable chunks. Moreover, Powell (1997) emphasizes that these questions should include a complete coverage of the main scope and not introduce issues beyond it.

1.7 ASSUMPTIONS AND DELIMITATIONS

This research project is a collaboration between a company in the automotive industry (Volvo Cars), and the Department of Product and Production Development at Chalmers University of Technology. The base for this research therefore stands upon the grounds that are found in the automotive industry. However, it is the author's desire that the results from this research also can be adopted by other areas of business that have a similar approach and attitude to perceived quality. Other assumptions and delimitations are listed below.

- This work is specifically concentrating on early phase when data maturity is low.
- It focuses on visualization of the effects of geometrical variation. This visualization allows interpretation by humans that numerical representation cannot provide.
- The work does not investigate how perceived quality can be measured quantitatively.
- There is a discrepancy between how objects are perceived in a physical environment compared to a virtual one. This discrepancy is not explored further in this thesis.

1.8 RESEARCH SETTING

The research of this thesis was conducted in the Geometry Assurance & Robust Design group, whose activities are illustrated in Figure 6. As seen by the figure, the research project focuses on the concept phase, marked by the red boundary. However, the research group addresses the whole product development loop.

The project is set in the Wingquist Laboratory VINN Excellence Centre. Apart from Geometry Assurance & Robust Design, there are three other related research groups, namely: Systems Engineering and PLM, Geometry and Motion Planning, and Automation.

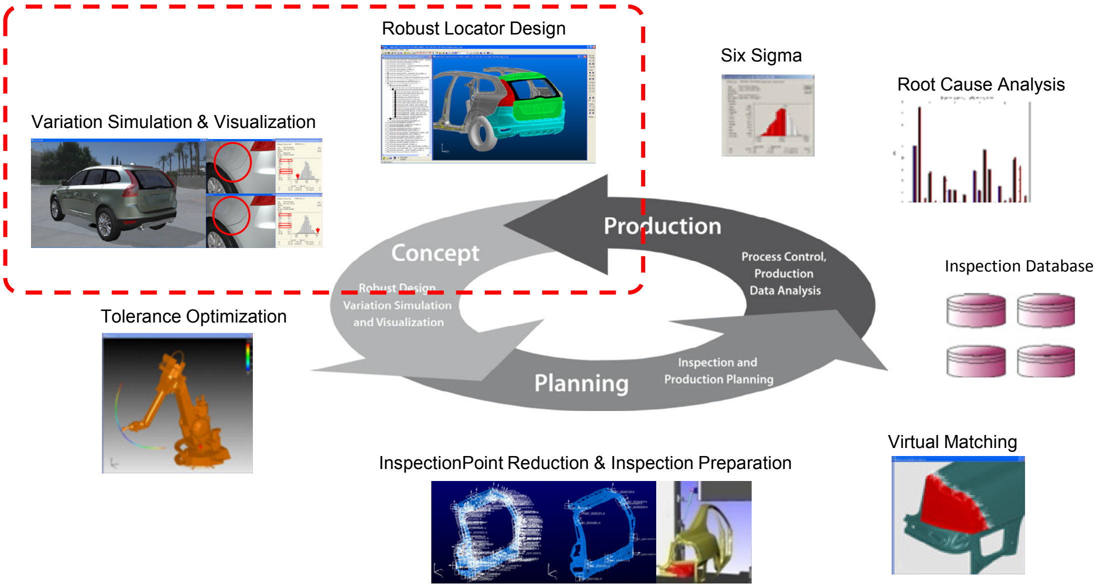


Figure 6. Geometry assurance activities within the scope of Wingquist Laboratory.

The project is also part of the ProViking program, with a focus on product realization (product development, manufacturing, product support and maintenance in a life-cycle perspective). The main focus in ProViking is on industry with manufacturing and development, operating in Sweden. The program is supported by the Swedish Foundation for Strategic Research.

1.9 The Volvo Cars Industrial PhD Program

The Volvo Cars Industrial Ph.D. Program (VIPP) was started in 1999. It aims to increase competence and support research within Volvo Cars strategic areas. It also helps to create a stable network between the company and academia. The target is to have approximately 30 research students studying a wide range of topics continuously. There are advisors within the company and at the university, where each student is connected to a research group. A review committee that consists of university representatives has been appointed to evaluate the results of the Ph.D. candidate and the content and quality of VIPP. An important element in the program is the annual VIPP conference, where the candidates present their work.

1.10 Thesis structure

The following structure has been chosen to present the thesis:

- **Chapter 1** has presented a brief introduction to the research included in this thesis and also information regarding the project in general.
- **Chapter 2** will discuss the research methodology applied and used during this research project.
- **Chapter 3** presents the frame of reference, the theoretical foundation on which this research has been built.

- **Chapter 4** emphasizes the results achieved in this research project. It also gives a short summary of the papers with a focus on the results.
- **Chapter 5** will examine the research questions and discuss the industrial and scientific relevance. It also discusses the validity and the verification of the results achieved in the project.
- In **Chapter 6**, conclusions are followed by suggestions for future work.

2 SCIENTIFIC APPROACH

This chapter briefly outlines design science and engineering design as a science. Additionally, it discusses the research approach and methods applied in this research project.

2.1 DESIGN SCIENCE

In the mid 1960s, strong forces promoted a desire to produce works of art and design on the values of science. In Cross (2002), the author gives a short historical review of the first definitions of design science, from this important milestone to definitions presented by researchers, such as Hubka and Eder (1996). Cross tries to clarify the difference between the terms design science and the science of design. Briefly, Cross suggests that design science implies an explicitly organized, rational and wholly systematic approach to design, whereas the science of design is the actual study of design, including principles, practices and procedures (Cross, 1984), very much like the later definition by Simon (1996).

The definition of design science by Hubka and Eder (1996) reads: "a system of logically related knowledge, which should contain and organize the complete knowledge about and for designing." Additionally, the authors have presented a scheme of how to structure design-related knowledge. The approach described by the authors, depicted in Figure 7, emphasizes the need to also consider design process statements as well as statements considering the technical system.

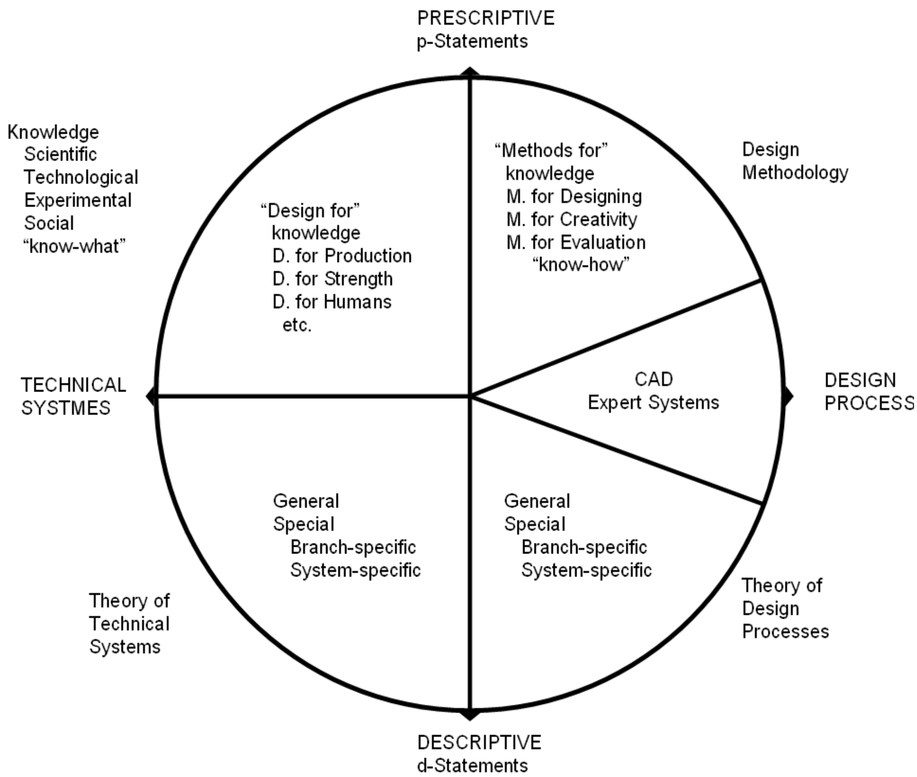


Figure 7. The dimensions of design science (Hubka and Eder, 1996).

Prescriptive statements refer to knowledge focused on practice (in other words, ways of working with either the technical system or the design process). Descriptive statements comprise current theories of the technical system, or the design process or future theories. The figure shows how object-related to process-related knowledge reaches from a West-East direction. With the similar approach, descriptive to practical knowledge reaches in a South-North direction.

2.2 DESIGN RESEARCH AND DESIGN RESEARCH METHODOLOGY

Andreasen (2010) discusses the evolution of design research, the current situation and how to lead the area into a desirable condition. The author describes the areas as explicitly defined and well-defined. At the same time, Andreasen emphasizes the need for consolidation by taking measures in a number of important areas, such as to ensure research directed at industrial practice.

Cantamessa (2003) highlights the fact that it is difficult to define the content, the research approach or the community behind research in engineering design. And for results to have validity in generic, practical and theoretical science, design research must be scientific, a point made by Blessing and Chakrabarti (2009). Due to this fact, the authors argue that a design research methodology is required. Other authors highlighting the need for a clear work practice are Finger & Dixon (1989) and Cross et al. (1991). Blessing and Chakrabarti define design research methodology as:

"an approach and a set of supporting methods and guidelines to be used as a framework for doing design research"

Further, the same authors define the objective of design research as:

"the formulation and validation of models and theories about the phenomena of design, as well as the development and validation of support founded on these models and theories, in order to improve design practice, that is, to improve the chances of producing a successful product"

2.3 DRM – A DESIGN RESEARCH METHODOLOGY

The Design Research Methodology (DRM) defined by Blessing and Chakrabarti (2009) (see Figure 8) is a collection of research methods that aim to assure the quality of the result. It was proposed to support the systematic development and validation of knowledge within design research. It focuses not only on understanding design, but also on using this understanding in order to change an existing situation into a new one.

This methodology is well-suited to computer-based engineering design projects, and it has been widely used on related research projects. The decision was made to apply this methodology to this research project.

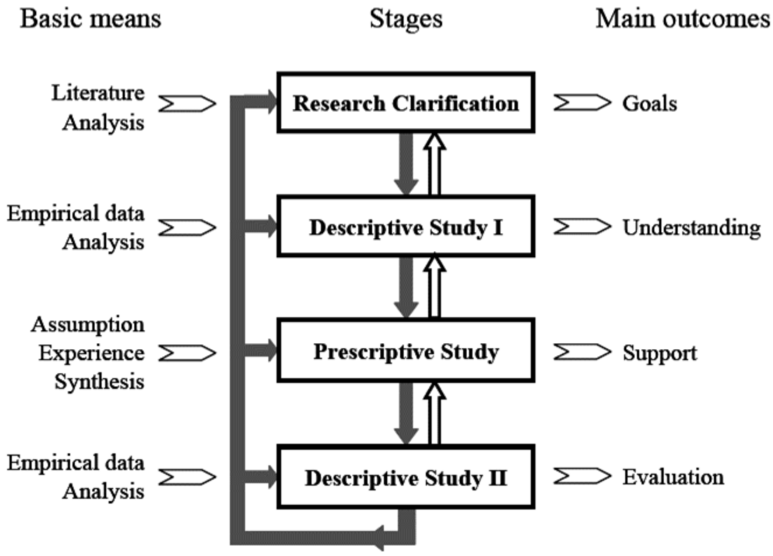


Figure 8. Framework of DRM (Blessing and Chakrabarti, 2009).

The methodology proposed by Blessing and Chakrabarti is divided into four areas. When conducting the research, these areas do not have to be executed in a rigid and linear way. Naturally, as the Descriptive Study II described below is seen as an evaluation step, it will have to be preceded by some kind of application supporting the product development process.

- *Research Clarification:* Based on the researcher's assumption, this stage aims at finding indications that support this. It includes an initial description of the desired situation and the definition of criteria that later on will be used to judge the success of the research.
- *Descriptive Study I (DS I):* This step involves an objective analysis of the existing design process including its tools and methods. Focus lies not only on understanding the process, but also on finding areas where improvements can be made.
- *Prescriptive Study (PS):* In this step, the goal is to influence the current design process by generating a relevant prescription, solution or method that responds to the research clarification.
- *Descriptive Study II (DS II):* In this final step, the effects of the proposed solution are evaluated further, applying observations and analyses of the new situation as the solution is being implemented in the design process.

2.3.1 Research clarification

The research project is partly based on earlier research done in the area (Wickman, 2005). Here, it was indicated that there is a need to consider non-rigid contributions when evaluating perceived quality in early phase. During the Research Clarification phase, the goals were clarified further, partly based on literature-studies and other influencing factors that have also led to project delimitation. Moreover, the research questions presented in Section 1.6 were initially defined during the first phase of this project. One of the objectives of the Research Clarification stage is to identify the criteria that the research is expected to realize during the time of research. According to DRM, success criteria should be clearly defined in the initial phase of the project, and latter serve as the ground for measuring the success of the research. By judging of the introduction of this thesis it is clearly the case that the focus on perceived quality evaluations, robust design and tolerance management and finally virtual prototypes, has the aim to "increase quality", "minimize cost", and "shorten project time", which could be used as main criteria. However, these criteria are not easy to measure during the relatively short time of a Ph.D. project (Blessing and Chakrabarti, 2009). Also, Eckert et al. (2003) states that the real issues in a research project may be missed if the fixation of measurable criteria is too large in the initial phase. They instead see criteria for the success of tools and methods as desired results of a study, rather than a starting point. The following criteria have however been selected to be able to discuss the success of this research project:

- Manage virtual evaluation of perceived quality with realistic component behavior in early phases even though data maturity is low.
- Provide support showing the importance of visualizing realistic component behavior when evaluating perceived quality of split-lines.

2.3.2 Position of research in DRM framework

This section describes how the different stages in the DRM framework have been approached. The relationship between the research questions, the appended papers and the four DRM stages, is visualized in Figure 9.

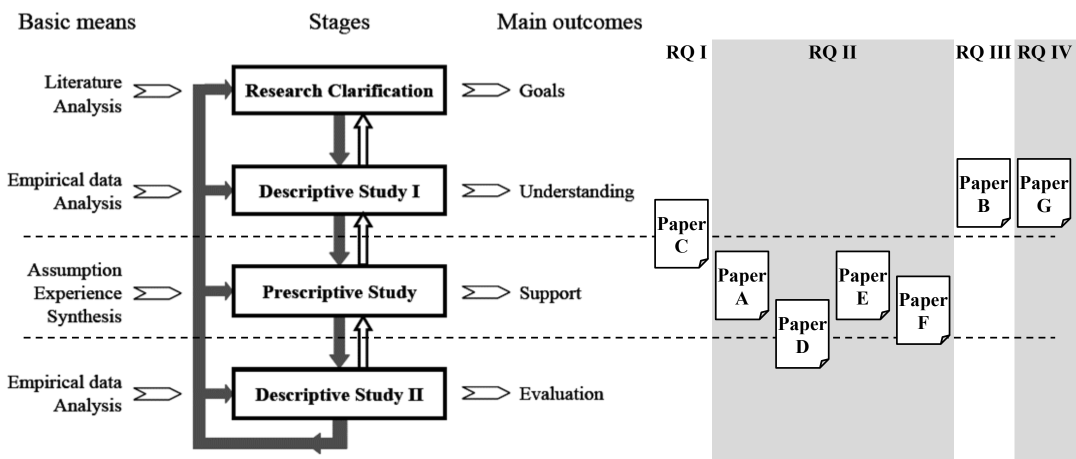


Figure 9. Positioning of appended papers in the DRM framework.

Research question I, with focus on the proposal of a process, has partly been answered in Paper C. The study includes focus both in the DS I and PS phase, as the work with developing the framework proposed in the paper was preceded by observations of the current working principles in the industry and identification of important knowledge. It includes currently used methods and tools in the industry. It also includes the methods proposed and presented in Papers A, D, E and F. Furthermore, methods and tools available or under development, closely related to the research presented in this thesis but not yet implemented in the current working procedure, are included.

Research question II is covered in Papers A, D, E and F. These studies propose support in the form of methods for how to manage simulations and visualization of non-rigid components in early phases. The method in Paper A is described as a workflow, including an analysis phase and a synthesis phase. In parallel, a plan for verification, also included as a deliverable in the PS stage, was described. In Paper D and Paper F, a so called non-FEA-based method is presented. Paper D contributes as a PS and also as a DS II. It is prescriptive in the sense that it presents a method that is based on an existing approach for mesh morphing. It can also be defined as prescriptive since it proposes a workflow in the CAT-tool in which the method has been implemented. The descriptive part is the evaluation of the applicability of the approximate deformation method. However, the method was not evaluated in the actual product development process at the involved companies, and thus not a full DS II. Paper F has a similar approach, as it proposes a workflow for the same method based on paper D as one part of the study. The other part of the study presents cases of how the proposed workflow can be applied, representing actual cases in a currently ongoing vehicle project. However, a comprehensive DS II was not included here. Finally, Paper E presents a prescriptive method with similar approaches as applied in the methods presented in Paper A and Papers D and F.

Research question III has been addressed in Paper B. An investigation of critical areas where non-rigid behavior in components has an impact on perceived quality was investigated, thus being a DS. The paper also extracted knowledge about the current situation in terms of how simulation activities are performed at the company. It also identifies a number of factors important to address in order to improve the simulation activities on non-rigid components in early phases.

Research question IV has its focus on the visualization aspects that separate results from non-rigid variation simulations and rigid variation simulations when evaluating perceived quality. The initiation of the study that tries to answer this question, presented in Paper G, was based on previous work within this research project (Forslund et al. 2011). In that study, indications that there is a difference in how non-rigid vs. rigid simulation is perceived during evaluation of split-lines, were discovered. The study presented here is of a descriptive type, and was realized by an experiment where eye-tracking data collection was used to register how the subjects viewed and evaluated rigid and non-rigid visualization models.

2.3.3 Research types in the DRM framework.

In addition to the framework described above, Blessing and Chakrabarti also discuss different types of research projects. Figure 10 below shows the seven types of research projects that the founders of DRM see as possible.

The research project's first important contribution was a comprehensive PS, presented in Paper A. As described in the Research Clarification section, the study was preceded by a research project, literature studies and observations in the industry of the current situation. Therefore, the initial form of the research project was Type 3. As seen in Figure 9, this first study was not followed by a DS II, even if this was proposed as one of the next steps to be taken. The project took another direction due to other findings in this study. These findings proposed that critical areas from a non-rigid perspective should be identified (Paper B). Thus, the project jumped back to a DS I. In this phase of the project, it felt important to get a more holistic view of the overall process, and thus be able to answer research question I. The framework proposed in Paper C became the subsequent step. This was also important to better understand the need of the methods that latter would be prescriptively studied to answer research question II, presented in Papers D, E and F. The final paper in the project was Paper G. As discussed earlier, this study was derived from the results obtained in Forslund et al. (2011), where indication that would lead to answering research question IV was identified. This, and the awareness that this study was initiated in the middle of the project, helps in understanding the late position of this DS.

Thus, comprehensive studies were conducted and looped both in the DS I step, and the PS step. It also needs to be emphasized that the order of the studies were somewhat related to the opportunities that were given during this project, something that is encouraged by Eckert et al. (2003). Due to these aspects, the project was more or less transformed into a Type 7 project. As the founders of DRM state, Type 7

	RC	DS I	PS	DS II
1.	Review-based	Comprehensive		
2.	Review-based	Comprehensive	Initial	
3.	Review-based	Review-based	Comprehensive	Initial
4.	Review-based	Review-based	Review-based Initial / Comprehensive	Comprehensive
5.	Review-based	Comprehensive	Comprehensive	Initial
6.	Review-based	Review-based	Comprehensive	Comprehensive
7.	Review-based	Comprehensive	Comprehensive	Comprehensive

Figure 10. Types of research projects in DRM (Blessing and Chakrabarti, 2009).

projects are often introduced when a problem with a very specific scope is addressed, such as the project presented in this thesis.

2.4 Research methods

The research presented in this thesis is wide and includes several disciplines of science. It includes people, processes, products and tools, interplaying in one large organization. Therefore, several different methods are necessary when conducting the research. The following methods have been applied during the project.

2.4.1 Literature studies

It is important to conduct literature studies to assure that current knowledge, theoretical and methodological contributions and other substantive findings within the studied research field are considered. Thus, literature studies have been conducted related to all studies in this project.

2.4.2 Interviews

Semi-structured interviews that are closer to unstructured in-depth interviews, compared to the structured form, were used in the qualitative studies. The respondents' perspectives on a situation under study can be observed and captured using a more in-depth approach, (Mellon, 1990). This approach was used during the study presented in Paper B and D. Subject areas were introduced to the respondents using open questions. Main questions were complemented by more specific questions within the subject area. This approach would help capture the respondents' spontaneous and unbiased views on the subject. The gathered information was then analyzed and compiled to form a basis for the result. This was followed by the transcription and coding of the material.

2.4.3 Analysis of qualitative data

In Paper B and D, the framework for analysis of qualitative data proposed by Miles and Huberman (1994) has been applied. Their approach is especially useful when analyzing case studies. It consists of three main activities; data reduction, data display and conclusion drawing/verification. The first step was to *reduce data* by extracting statements from the raw data and to take documented observations into consideration. In the subsequent *data display* step, statements were structured and categorized through coding. Repetitive phrases, expression and ideas were identified by coding for patterns. Manual coding was applied in both studies, providing good overview of the data. Moreover, this step involved securing the traceability to the raw data and to the respondents and to combine statements and display them according to the selected coding mark. The final activity involved *drawing conclusions*, which was carried out by establishing similarities and differences. In both studies, this was complemented with a counting activity, counting the number of times comments and patterns emerged.

2.4.4 Eye-tracking

In paper G, eye-tracking was used in order to record where the subjects actually look when evaluating the visualisation model. The method is based on the assumption that there is a relationship between where people focus their attention and where they look (Bokjo, 2005). The eye-tracking data was recorded with the equipment X120 from Tobii Technology. Visit count and visit duration time was then analysed in the software Tobii Studio 2.1.12 with gaze-plots and heat-maps. Calibration was required for all subjects to guarantee continuous recording of data.

3 FRAME OF REFERENCE

This chapter presents the theoretical background and the frame of reference that forms the foundation for the research presented in this thesis.

There are several disciplines involved in this research project. The research explores areas such as Tolerance Management, Engineering Design, Industrial Design and Cognitive Psychology. Handling variation that stems from the manufacturing process through Robust Design and Tolerance Management is an important factor in the development process to achieve high perceived quality. These areas will be introduced in this section. Furthermore, work on perceived quality and assessing the level of perceived quality if split-lines in a virtual environment through linking CAT softwares with virtual reality tools is discussed. A short summary of research on the product development process will begin this chapter.

3.1 PRODUCT DEVELOPMENT PROCESS

There have been several suggestions of how to describe a generic development process by renowned researchers in the area, such as Ullman (2003), Pahl and Beitz (2007), and Ulrich and Eppinger (2004). In this thesis, we examine a product development process applied to industry. The process description by Ulrich and Eppinger (2004) has been selected to give an understanding of the main activities that in many development projects are included. Their process consists of a sequence of steps or activities to conceive design and commercialize a product (see Figure 11). The process starts with the creation of a wide set of alternative product concepts, subsequently narrowing the alternatives and increasing the specification of the product until the reliability of the product and production system is satisfactory. The generic development process described by Ulrich and Eppinger (2004) consists of six steps:

- *Planning*. A corporate strategy that consists of the assessment of technology developments and market objectives. The output of this step specifies target markets, business goals, key assumptions and constraints.
- *Conceptual development.* The needs of the target market are identified and alternative product concepts are generated, evaluated and analyzed. The ambition is to select one or more concept for further development and testing.
- *System level design.* Includes the definition of the product architecture and, further, the decomposition of the product into sub-systems and components. The output usually consists of a geometric layout of the product and functional specifications of sub-assemblies.
- *Detail design.* A complete specification of the geometry, materials and tolerances for components and sub-assemblies. Tooling is designed for

fabricated components and assemblies. Output is documents such as drawings and specifications on purchased components and assemblies.

- *Testing and refinement.* Construction and evaluation of multiple pre-production versions of the product. Early prototypes, models or mock-ups are built with pre-produced components to simulate the final product.
- *Production ramp-up.* The production is made using the intended production system with the purpose of training the workforce and working out remaining problems in the production process.

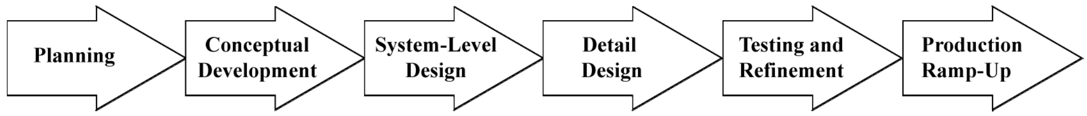


Figure 11. Product development process (Ulrich and Eppinger, 2004).

Not included in the figure are the necessary iterations and concurrent activities that inherently occur in an industrial development process.

3.2 ROBUST DESIGN

Genichi Taguchi was one of the pioneers of developing methods to improve product quality. From the mid 1960´s and forward, he introduced numerous methods, included in what he defined as quality engineering (or the Taguchi Method in the western countries) to support the work with quality (Taguchi et al., 2005). Taguchi's philosophy is based on the fact that any decrease in the quality of a system leads to customer dissatisfaction. This may in turn create a long-time loss for the manufacturer. Further, Taguchi defines quality as "the loss imparted by the product to the society from the time the product is shipped." This might be illustrated by the quality loss function in Figure 12, whose objective is a quantitative evaluation of loss caused by the variation of a product's quality characteristics within a field.

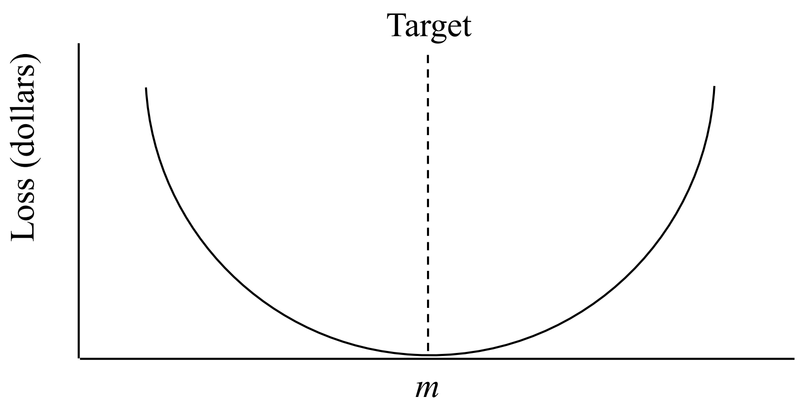


Figure 12. Quality loss function (Taguchi et al., 2005).

The function states that any deviation from the target value m leads to a quadratic loss in quality or customer satisfaction. The quality characteristics may vary within functional limits, represented by the horizontal axis in the figure. Examples of quality characteristics include length, width, concentration and flatness. Söderberg (1993, 1994 and 1995) further developed the loss function to include all aspects regarding manufacturing and customer value into it.

The causes that make the characteristics vary are defined as noise factors (Phadke, 1989), and can be generally classified as follows:

- *External.* This includes variation caused by the environment in which a product is used and also load-related noise.
- *Unit-to-unit variation.* Variation that stems from the manufacturing process when mass-producing components.
- *Deterioration.* As the product is being used, the values of individual components may change. This could lead to the deterioration of elements or material in the product.

When a product's quality characteristics are not sensible to variation caused by the noise factors, the design is said to be robust. Hence, it follows that Robust Design is the term for designing a product that may function properly, under various conditions of use (Taguchi et al., 2005). The more common statement, defined by Phadke (1989), reads as follows:

"The key idea behind Robust Design is to improve the quality of a product by minimizing the effects of the cause of variation without eliminating the causes."

Further, Phadke (1989) defines a strategy for an engineering design problem based on Taguchi´s work. The strategy considers the relationships between parameters, which in turn influences the quality characteristics or response of the product. It also handles the difficulty of not knowing the precise magnitude of noise factors or the cost of various grades of materials, components or tolerances. There are three design activities in this strategy:

- *Concept Design.* This is a creative and innovative stage where the designer examines architecture and technologies that might be possible to implement to reach product requirements and customer needs. Sensitivity to noise factors and manufacturing cost may be efficiently reduced in this activity.
- *Parameter Design.* In this stage, the designer determines the settings for the control factors that minimize quality loss. These are the factors that the engineer may vary without affecting the manufacturing cost.
- *Tolerance Design.* When parameter design is accomplished and the understanding of how different factors affect the product performance is achieved, focus may be placed on reducing and controlling variation in critical areas.

Phadke (1989) highlights the facts that relying on concept design will result in longer development time and too much focus on tolerance design makes components more expensive to manufacture. He further states that it is in the parameter design activities that the engineer may be efficient from a robust point of view. Robust Design and its methodology therefore have their focus in this area, according to Phadke. Mørup (1993), however, identifies obvious weaknesses in this approach to Robust Design. He argues that perhaps 80% of the robustness has already been fixed during the conceptual design, and therefore the Taguchi approach has its focus too late in the development process. Mørup and Matthiassen therefore have provided a wider framework to support robustness in the design process (Mørup, 1993; Matthiassen, 1997).

Hasenkamp et al. (2009) speak about the overall methodology of robust design (RDM) and state that the traditional techniques for identifying robust design solutions all have more or less been statistically based. Arvidsson and Gremyr (2008), therefore, have elaborated on the basic framework of DRM and provided the following overall definition:

"Robust Design Methodology means systematic efforts to achieve insensitivity to noise factors. These efforts are based on an awareness of variation and are applicable in all stages of product design".

Hasenkamp et al. (2009) have further tried to clarify the concept of "systematic efforts" and the practical simplification of their definition. They characterize RDM by means of principles, practices and tool. With principles, the question of "why work with DRM" is answered. Practices answer "what activities need to be done to fulfill the principles" of DRM, and the tools provide instructions for "how to actually put the practices into action". The idea is illustrated as a pyramid in Figure 13.

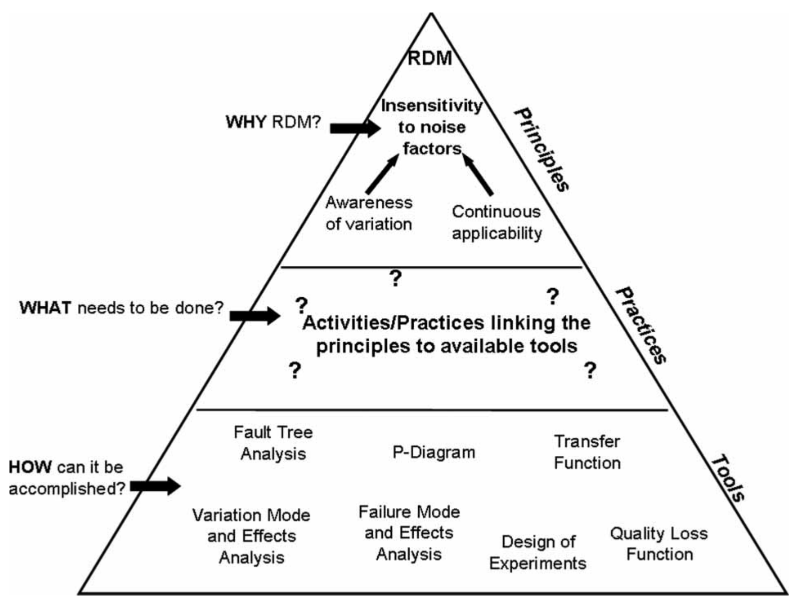


Figure 13. Principles, practices and tools of RDM (Hasenkamp et al., 2009).

3.3 TOLERANCE MANAGEMENT

Tolerance limits are implemented on drawings to define the allowable manufacturing variation and thus make sure that functional or/and aesthetical requirements are fulfilled. Tolerance management has been an important part of a designer's work in product development, and it was in the early 20th century that tolerances were first used on drawings. Furthermore, cost is a crucial factor in tolerance management, as decreased tolerances mean increased manufacturing cost. It is therefore important to find the right tolerances to achieve a good balance between quality and cost of the product. Dahlström (2005) has divided the tolerancing research area into three main groups (depicted in Figure 14): *Tolerance Definition*, *Tolerance Application* and *Tolerance in Production*. Further, these main groups have been divided into a number of areas. Innumerable publications in the area of tolerancing have been released through the years, some of them summarizing different disciplines within the area. Worth mentioning are Hong and Chang (2002), Bjørke (1989), Singh et al. (2009a, 2009b), Zhang and Huq (1992), Shen et al. (2005) and Shah et al. (2007).

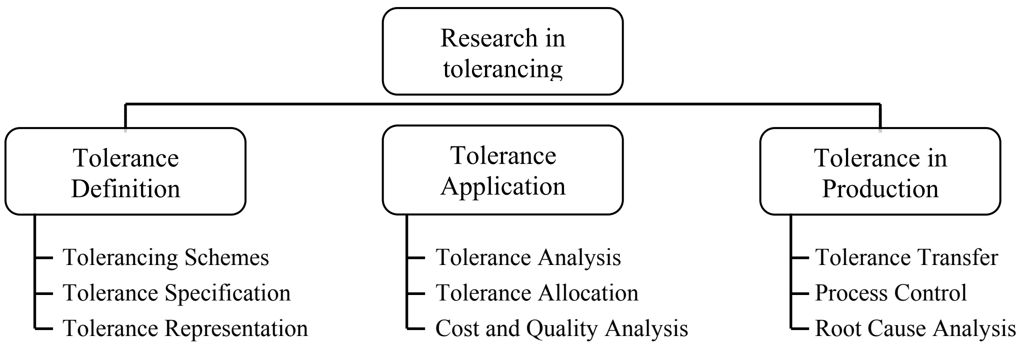


Figure 14. Above: branches of tolerancing research (Dahlström, 2005).

The following chapters will discuss Tolerancing Schemes, Tolerance Analysis and Tolerance Allocation since these areas apply to the research in this thesis. Tolerance Analysis and Tolerance Allocation for non-rigid assemblies will be given a separate chapter. However, the first chapter will present research on geometrical robustness and locating schemes, linking robust design with tolerance management. This is an important base for the research presented in this thesis.

3.3.1 Geometrical robustness and locating schemes

Applying the robust design concept when focusing on geometrical variation in engineering design has been discussed by Söderberg and Lindkvist (1999). The approach presented is addressed on both the component and the assembly level in the design process, and the fundamental idea is depicted in Figure 15. It shows how the design concept (support) may be selected to suppress or, preferably not, amplify the output variation propagated from the input variation on the component and assembly level.

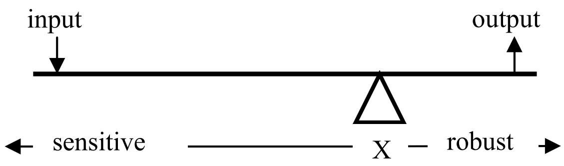


Figure 15. Geometrical robustness of a chosen design concept X.

To support the work with robust design, locating schemes are introduced. A locating scheme defines the fixing points for a component in an assembly. The position of the locating points impacts the output variation of the assembly and, accordingly they affect the geometrical robustness of the design. It is important to mention that the same locating points may well be used for different activities throughout the whole development process, and not only for mounting one component onto another. The repeated use of locating points in larger assemblies is advantageous since it may shorten the tolerance chain. Also, the locating points will be used when placing components and assemblies in inspection fixtures. There are several variants of locating schemes. For rigid objects, being a component or an assembly, the overall objective is to lock all six dof (degrees of freedom) in a way that supports defined requirements. The locating schemes are either orthogonal or non-orthogonal schemes. A more circumstantial study of locating scheme configuration can be found in Söderberg et al. (2006a). The physical locators that correspond to the locating points are small planes, holes and slots. One variant of a locating scheme, and the most common one in the automotive industry, is the 3-2-1 scheme, (Söderberg and Lindkvist 1999). The concept may be described as follows, and is presented in Figure 16:

- **3**-2-1 indicates that three dof are locked in a plane defined by these points and this prevents the rotation in 2 dof and translation in 1 dof. A1-A3 in Figure 16.

- 3-**2**-1 indicates that the object is locked in the third rotational dof and the second translational dof. B1-A2 in Figure 16.

- 3-2-**1** indicates that the last dof, being a translation, is finally locked and the object is fully constrained to the locating scheme. C1 in Figure 16.

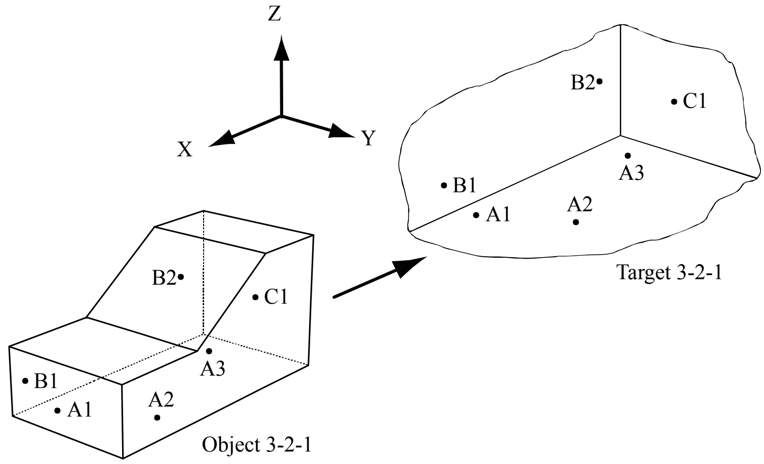
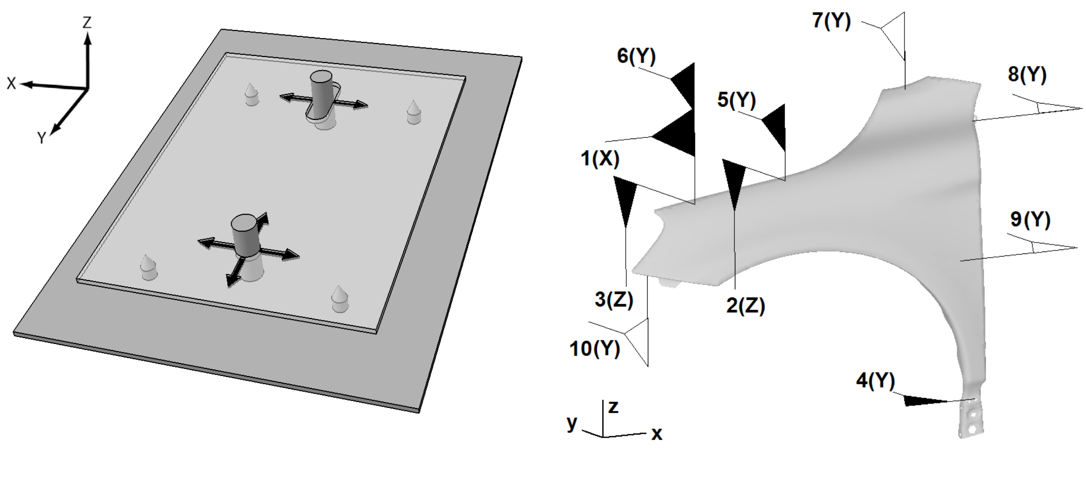


Figure 16. An orthogonal 3-2-1 locating scheme (Söderberg and Lindkvist, 1999).

For non-rigid components and assemblies, the locking of six dof is generally not enough to fully constrain the object. Therefore, the 3-2-1 locating scheme has to be expanded, and the size of the scheme depends on factors such as the size, shape and elasticity of the object. To get an acceptable constraint of the non-rigid object, the number of dof may therefore be chosen based on these influencing factors. Generally, the locating scheme for non-rigid components requires N (≥ 3) locators/supports on its primary datum plane. The N-2-1 locating principle was therefore proposed by Cai et al. (1996). Figure 17(a) shows a sheet metal part with a N-2-1 locating scheme, where N=4. The locators here consist of a 4-way pin/hole and a two-way pin/slot combination to constrain the transformation and rotation in the XY plane. Four pins are used to locate and support the component in the Z direction. In engineering terms, the locating scheme for a component is often referred to as a Master Location System. On drawings of a non-rigid component, the MLS is complemented with support points and, in some cases, inspection points used for measurements, for example, in a



(a) (b)

Figure 17. The N-2-1 locating scheme.

fixture. Figure 17(b) shows a virtual model of a front fender with filled flags marking the MLS and empty flags marking the support points.

Söderberg and Lindkvist also apply the theory of axiomatic design (Suh, 1990) to geometry related issues. In axiomatic design, the design activity is described as the mapping between functional requirements and design parameters. It further describes how the input design parameters may be selected to satisfy the functionality. Figure 18 shows the difference between an uncoupled and a coupled design in the theory of axiomatic design. This corresponds to an uncoupled and a coupled assembly solution. In the uncoupled assembly, each component is only dependent on its own locating scheme and defined as a good design by Suh. A coupled assembly is dependent on the locating scheme for each component. This is defined as an acceptable design solution by Suh but may, depending on its structure, also be regarded as a good design.

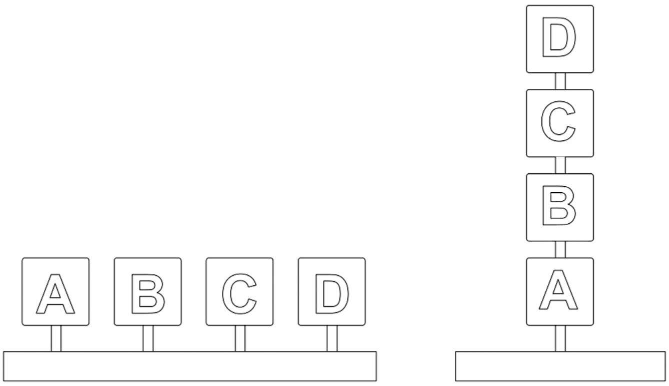


Figure 18. Uncoupled and coupled design respectively (Söderberg and Lindkvist, 1999).

3.3.2 Tolerancing schemes

The two most common types of tolerance schemes are parametric and geometric. Parametric tolerances consist of parameters limited by a range of values, such as the typical plus/minus tolerancing and the more novel vectorial tolerancing. Geometrical tolerancing, instead, is directed at the attribute of a feature on the specific geometry. In the ASME Y14.5 standard, the features are divided into five categories: form, profile, orientation, runout and location (Meadows, 2009).

3.3.3 Tolerance analysis

Tolerance analysis, also defined as tolerance control, is widely used in engineering design to verify the functionality, manufacturability and, as discussed in this thesis, the perceived quality of a product. In tolerance analysis, individual dimensions on the component level with its own distribution give rise to a propagated assembly distribution as numerous components are assembled together. This is visualized in Figure 19.

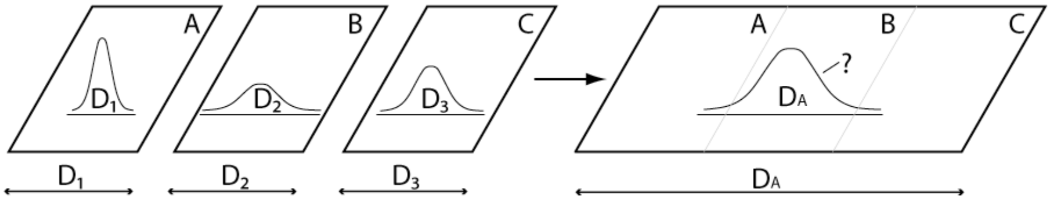


Figure 19. Tolerance analysis.

Through the years, an abundance of methods have been developed for performing tolerance analysis on rigid components. Many of them are described in Singh et al. (2009a). The worst-case model and a number of statistical models, presented in Table 1, form the basis for these models. The worst-case model is based on the arithmetic law and was first described by Fortini (1967). It assumes all tolerances in a chain to be at the extreme simultaneously and, hence, describes a worst possible assembly. The worst-case model may be applied in cases where the production volume is low and the tolerance chain is very short.

Fortini (1967) also highlighted the use of statistical models for the purpose of performing tolerance stack-up activities. The Root Sum Square (RSS) is the most simple of the statistical models. The RSS model assumes a normal distribution of component tolerances in an assembly. The model is very optimistic, and the approach is applicable in high volume production and when the tolerance chain is sufficiently long. To obtain better results, Bender (1962 and 1968) and Gladman (1980) have introduced an approach where a correction factor Cf is multiplied to the standard RSS model. However, this approach has substantial limitation as described by Greenwood and Chase (1987).

A combination of the worst-case model and the RSS model was presented by Spotts (1978). Spotts' modified approach is based on practical observation, and the result from the model is the average of a worst-case and an RSS-based analysis. This approach is assumed to be more realistic since it reflects a mean between one very optimistic and one very pessimistic model.

Greenwood and Chase (1987) pointed out the problem of shifted mean due to setup errors or drifts due to tool wear. They proposed a unified approach based on the estimated mean shift (EMS). In this model, the mean shift factors for different dimensions may be controlled during tolerance accumulation. This results in a model where everything in between the worst-case and the RSS model may be simulated.

Table 1. Basic tolerance stack–up methods (Singh et al., 2009a).

	Analysis Model	Method	Comment
1	$\Delta Y = \sum_{i=1}^{n} t_i$	Worst Case	
2	$\Delta Y = \sqrt{\sum_{i=1}^{n} t_i^2}$	Root Sum Square (RSS)	
3	$\Delta Y = \frac{1}{2}\left[\sum_{i=1}^{n} t_i + \sqrt{\sum_{i=1}^{n} t_i^2}\right]$	Spotts' Modified RSS	
4	$\Delta Y = \sum_{i=1}^{n} \alpha_i t_i + \frac{Z}{3}\sqrt{\sum_{i=1}^{n} (1-\alpha_i)^2 t_i^2}$	Estimated Mean Shift	*α_i = mean shift factor associated with the manufacturing process* *Z = 3.00, corresponding to 99.73 per cent yield, most commonly used*
t_i = ΔY = n =	Tolerances of individual component dimensions Total assembly variation Number of components in assembly		

A Monte Carlo simulation is a non-linear variation simulation approach. In contrast to the models described above, it handles the individual distribution of components more effectively. This method relies on random sampling to calculate natural phenomena, and the approach is therefore quite useful when performing statistical analysis. Knappe (1963) was one of the first to use a Monte Carlo simulation for tolerance analysis. Shan et al. (1999) shows how a Monte Carlo approach may be applied when performing 3D statistical tolerance analysis. Furthermore, the Monte Carlo model is the basis for the majority of today's CAT systems (Prisco and Giorleo, 2002). This approach is more suited for tolerance analysis, compared to tolerance allocation, since it is not easy to get the derivatives or gradients of the design function. Solutions to this have been described by Skowronski and Turner (1996) and (1998). Chen and Zhao (2010) have performed a review of the application of the Monte Carlo method in statistical tolerance analysis.

In addition to the Monte Carlo simulation technique, which is by far the most employed method today in engineering design, several other methods have been developed through the years. Important to mention is the vector loop based model, Tolerance maps. The vector loop (or kinematic) based method, developed by Chase et al. (1996), is a kinematic approach to tolerance analysis. The method uses vectors to represent the dimensions in an assembly. The vectors are then arranged in chains or loops to perform tolerance stack-up. Using the Tolerance-Map® model for tolerance analysis has been described in Davidson et al. (2002) and Mujezinovic′ et al. (2004). The tolerance map consists of a point cloud that describes possible surfaces through deviations of size, form and orientation within tolerance limits. Component T-Maps are accumulated using the Minkowski sum to represent the T-Map for the final assembly.

3.3.4 Tolerance allocation

Tolerance allocation is described as the opposite of tolerance analysis. The purpose of tolerance allocation is to break down the requirement on the assembly level to the individual component. Tolerance allocation is also defined as tolerance synthesis, tolerance assignment and tolerance design in practice and literature. Figure 20 represents the practice of tolerance allocation.

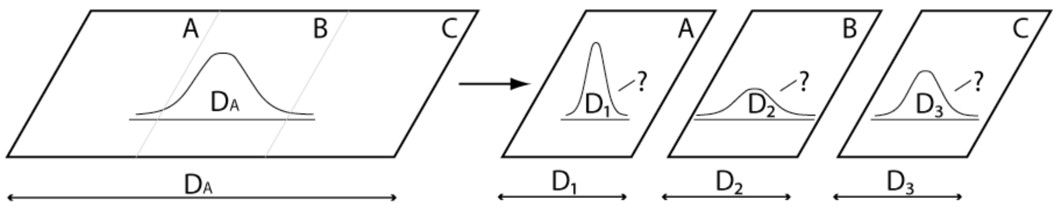


Figure 20. Tolerance allocation.

Tolerance allocation is often associated with manufacturing costs, as an optimal distribution of tolerances over components needs to take this into consideration when focus is put on minimizing costs. Chase et al. (1990) proposed a procedure for tolerance specification based on quantitative estimates of the cost of tolerance for the minimum cost of production. For an optimal tolerance allocation, knowledge about manufacturing cost/tolerance relationship is of high importance. However, cost/tolerance data is difficult to obtain since only few companies gather such data. Generally speaking, the data is proprietary information (Singh et al., 2009b).

3.3.5 Non-rigid variation simulation and related work

The tolerance analysis methods described above are developed for the analysis of rigid components. However, the vast majority of the components that form the visible split-lines on a vehicle are non-rigid sheet metal or plastic components. Furthermore, the underlying structure, being the BIW (body in white), is an assembly of several sheet metal components. Dahlström and Söderberg (Dahlström, 2005) have identified a set of influencing parameters that need to be defined or checked during the analysis of sheet metal assembly (see Figure 21). The large amount of parameters in the diagram depicts the complexity of simulating variation in non-rigid assemblies. The same authors also identified how the parameters correlate with each other.

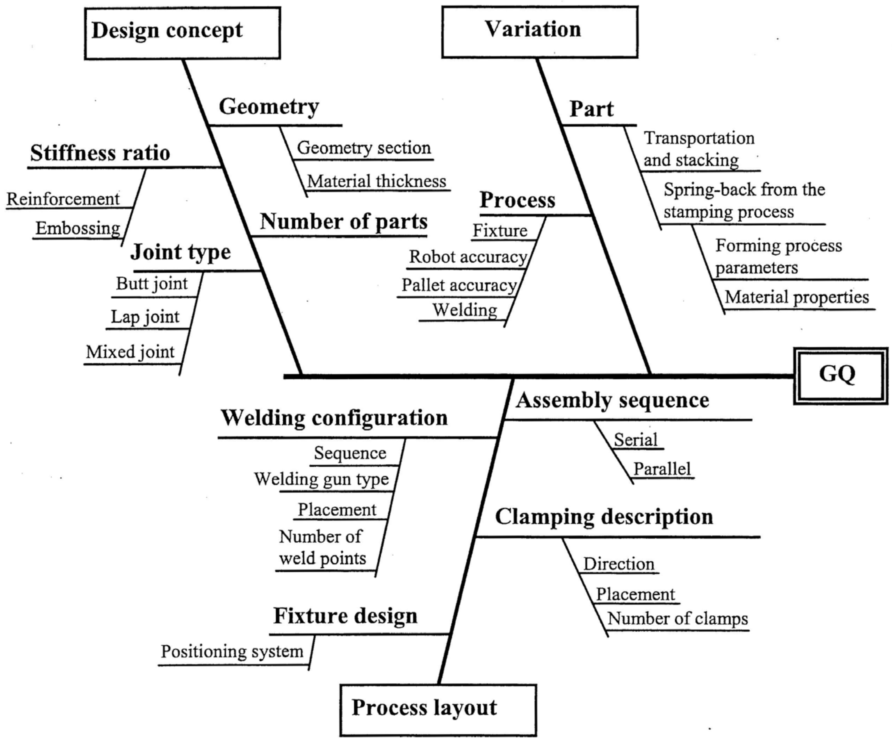


Figure 21. Key factors identified by Dahlström (2005).

To perform variation simulation on non-rigid assemblies, component behavior in terms of material elasticity has to be taken into consideration. This is because the forces applied as components are assembled together through welding or by using fasteners such as screws and clips. In most cases, this is solved by using FEA as a base to handle deformation during variation analysis. FEA, however, puts great demand on simulation models and increases calculation complexity. Several methods have been proposed to overcome this.

Research on variation analysis on non-rigid assemblies has expanded extensively during the last decade. The majority of the work focuses on sheet metal assemblies. One of the earliest, most acknowledged in the discipline is the work of Liu and Hu (1997). They proposed a method to predict the effects of component variation and assembly spring-back on assembly variation by applying linear mechanics and statistics. The method is a combination of FEA and Monte Carlo simulation, and is defined as the method of influencing coefficients (MIC). This combination reduces the computational cost, and MIC forms the basis for the component stiffness matrix. The proposed method divides the assembly process into four steps, and it handles both variations in the incoming components and from tooling.

The steps, depicted in Figure 22, are executed in the following order:

1. Components are located by the fixture.
2. Clamps push the components against the locators.
3. Weld guns join the components.
4. Weld guns and clamps are released, and the components experience springback.

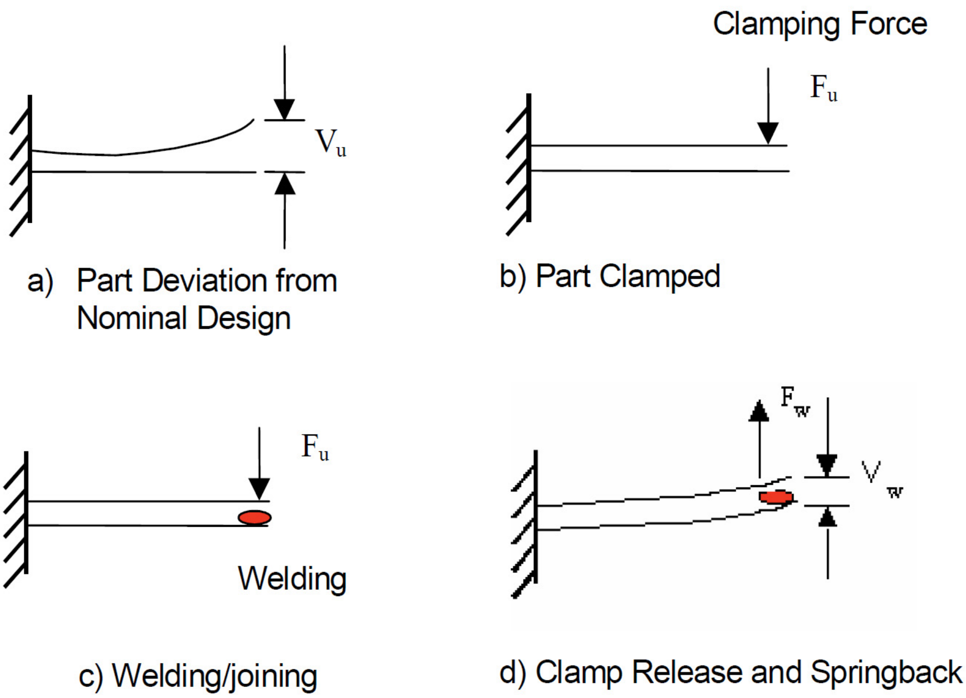


Figure 22. Four step assembly process (Liu and Hu, 1997).

This method has been further extended in Camelio et al. (2003), where the propagation of variation in multi-station assembly systems is analyzed. Parallel and serial assemblies were discussed in Hu (1997). There it was shown that parallel assemblies, such as an inner and outer hood where the assembly stiffness has greater stiffness than the individual components, have a tendency to suppress variation. If the assembly instead is of a serial type and the stiffness is lesser than the individual components, the variation will be amplified. Hu et al. (2001) proposed a method for simulating assembly processes involving compliant parts and dimensional variations using FEM. This method considers the interaction and interference between compliant parts due to component variation, assembly tooling variation, welding distortion, and spring back effects. Xing et al. (2010) later proposed an improved sensitivity matrix between the incoming component variation and the assembly variation for the assembly. In it, thickness variation has been taken into consideration. Another important contribution concerning methods for non-rigid sheet metal assemblies has been proposed by a research team in the ADCATS consortium at Brigham Young University in the US. The method is based on the work by Merkley (1998), and is called Flexible Assembly Spectral Tolerance Analysis (FASTA). Sellem and Riviere (1998) proposed another method that also uses the MIC as a basis but does not involve the Monte Carlo model. Liao and Wang (2005) developed and investigated a method based on wavelet analysis and FEM.

Lustig et al. (2005) have also contributed to the research on non-rigid variation simulation, focusing on sheet-metal assemblies. In Lustig et al. (2004), the same authors describe a method suitable for the simulation of elastic deformations and tolerance zones, including an example of surface waviness with a two-dimensional approach.

In recent years, traditional non-rigid sheet metal assembly analysis has been extended by incorporating contact modeling. Dahlström and Lindkvist (2004) proposed a model for contact modeling in MIC. Later, Wärmefjord et al. (2008) proposed a simplified method for automatic contact detection performed in the Monte Carlo simulations, keeping the simulation time down. Ungemach and Mantwill (2009) extended and coupled the model proposed by Liu et al. (1995) with numerical contact mechanics methods. This was done in order to realistically portray the problem with a minimum of additional effort.

Additionally, spot welding sequences with respect to geometrical variation have been covered by Wärmefjord (2011) and Segeborn (2009). Tolerance allocation for non-rigid assemblies has also been discussed by Li et al. (2004) and by Manarvi and Juster (2004). Franciosa et al. (2010) proposed the use of a morphing mesh approach to simulate shape errors as an addition to the method proposed by Liu and Hu (1997). Lindau et al. (2012) have performed a study showing how forming simulation results can be used in virtual assembly analysis to study the effects of component variation.

Simulation of geometrical variation in injection-molded plastic components has been discussed in Lorin et al. (2010) and Lorin et al. (2012a). In Lorin et al. (2012b), the authors propose a method for analyzing thermal expansion in combination with geometrical variation.

With the use of PCA (Principal Component Analysis) it is possible to reduce the dimensionality of a dataset containing a large number of correlated variables, still keeping the most of the present variation. PCA-analysis is described more in detail in Jolliffe (2002). PCA has also been applied in studies on non-rigid components and assemblies. A short overview of the scientific contributions is presented by Lindau et al. (2013).

3.3.6 Visual sensitivity and visual robustness

The first use of the term visual sensitivity can be found in Wickman and Söderberg (2001). It describes how sensitive a product's form and shape is to geometrical variation with focus on split-line areas. Just as the geometrical robustness can suppress unwanted effects by controlling the locators, visual robustness works in the same manner. However, it is steered by the structure, form, colors and materials of visible components. Wickman (2005) has defined visual robustness, being the opposite, as "the ability of a design concept to suppress a, by customer or user, visually perceived lacking quality appearance caused by part or assembly variation." Forslund has later defined Visual Robustness as "the ability of a product's visual appearance to stimulate the same visual product experience as the nominal product despite small variety in its visual design properties" (Forslund, 2011). Forslund and Söderberg (2009) have provided an extended model of the levels of visual robustness. The four levels are: visual reference level, optical level, perceptual level and response level. Furthermore, a method for how to evaluate visual robustness on the visual reference level was proposed. Here, split-line segments are analyzed by identifying where translations, rotations and the scaling of parts have no visual references. Finally, Forslund et al. (2006) identified the factors that control visual sensitivity by modeling design as a process of communication between producer and consumer.

3.3.7 Form division

Based on the theory presented by Tjalve (1989), split-lines are the result of a concept defined as form division. Initially, form division describes how a product or a machine may be divided into elements by functional, physical and visual division. In the work by Dagman (2007), the concept has been narrowed down from dividing a whole product to dividing only the surfaces visible to the customers. Dagman presented an approach for how to reduce the effects of geometrical variation by creating robust form division concepts (in other words, robust positions of the split-lines). By combining computer-aided tolerance analysis with computer-aided industrial design, aesthetical aspects and robustness can be considered simultaneously.

3.3.8 Computer-Aided Tolerancing

While the draftsman community uses tolerance charts for tolerance analysis, the engineering community in general uses commercial software for computer-aided tolerancing (Shah et al., 2007). Many of the CAT software use the same parametric setup as in CAD systems, and Monte Carlo simulation is the most common analysis method used. Overviews of different commercial CAT softwares can be found in Söderberg et al. (2006b), Shah et al. (2007), Shen et al. (2005) and Prisco and Giorleo (2002). Examples are VisVSA®, RD&T®, Mechanical Advantage®, 3DCS® and CETOL®. The majority of the software is capable of 2D and 3D dimensional and geometrical tolerance analysis. However, tolerance allocation and tolerance specification (how to specify tolerance 'types' and 'values') is still limited in this group. Some of the tools mentioned above now offer a visualization interface, sometimes referred to as a showroom. In Section 3.8, a more thorough description of the research on high-end visualization software interacting with CAT software for the purpose of evaluating perceived quality is presented.

3.4 INDUSTRIAL DESIGN AND ENGINEERING DESIGN

As the industrial era took off in the late 1800´s, an increased awareness of crafting and aesthetical values in combination with mass-production techniques was gradually developed. This focus later gave birth to a discipline defined as industrial design. However, about 50 years later, Ashford (1969) identified that engineers needed to broaden their view and include the aspects that he meant were lumped together under the designation of industrial design and were natural aspects of engineering design. Looking at the current situation, the significance of aesthetics versus functional requirements has never been as important as it is today (Pahl and Beitz, 2007). It is therefore of great importance to integrate the discipline of industrial design into the product development process.

There are several definitions and interpretations of industrial design in literature. De Noblet (1993) states that the industrial design process includes creating and executing design solutions towards problems of form, usability, physical ergonomics, marketing, brand development and sales. As Ashby and Johnson (2002) state, successful products depend on a balanced mix of technical and industrial design. Here, technical design includes the aspects of design related to the "technical functioning of the product," such as mechanical performance, cost and durability. This is also defined as the technical attributes of the product. Industrial design includes aspects that bear on the "satisfaction afforded by the product." This could be tactile attributes, associations and perceptions, so-called personal and characteristic attributes.

Persson and Wickman (2004) have studied the interplay between industrial design and engineering design within tolerance management and the work with perceived quality in the automotive industry. Generally, the relationship was described as open, and the cooperation was described as a “healthy fight” or a “love-hate” relationship. However, the study identified a number of issues that affected the interdepartmental work. To start with, there were pre-conceptions that the interplay actually was a problem. Lack of understanding of each other’s work and its goals and the lack of trust between the disciplines was also found to be evident. Another problem identified was that perceived quality evaluation activities were given low priority by management.

3.5 PERCEIVED QUALITY AND CRAFTSMANSHIP

Another discipline that has strong relations to both industrial design and product experience is perceived quality, which earlier more commonly was defined as craftsmanship in research. Forslund (2011) has summarized the research on craftsmanship and perceived quality towards the automotive industry. However, the first definition of perceived quality originates from the marketing domain. Here, Garvin (1987) brought forward the definition perceived quality, which was the customer's view of quality, based on indirect measures such as images, brands and reputation.

Many researchers have made the attempt to define this discipline throughout the years, such as Wang and Holden (2000), Williams et al. (2005) and Ersal et al. (2011). Maxfield et al. (2000b) write about cosmetic quality and have a very vague definition as the "'look' of the product." Further, they involve size and shape of gaps and the flushness between mating surfaces as areas that need to be checked to reach high cosmetic quality.

Hence, an important criterion, especially when it comes to premium brands, is to fulfill the customer's perception of high quality. Ersal et al. (2011) describe craftsmanship, i.e. perceived quality, in automotive design as "a property that gives the product the appeal of being well-made and well-functioning at its very early interactions with the customer." Wang and Holden (2000) divide the concept of craftsmanship into four main areas: attention to detail, material selection, careful workmanship and innovative product design. Wickman and Söderberg (2009) discuss perceived quality in the automotive context and refer to "product attributes that determine the impression of imaginary quality of a product, experienced through senses by a customer." Material quality, sound quality and solidity, fit and finish, detail execution, paint and finish, and glossiness are some examples of attributes included in this definition.

3.6 VIRTUAL PROTOTYPING, VIRTUAL ENVIRONMENT AND VIRTUAL REALITY

Virtual prototyping (VP), virtual environment (VE) and virtual reality (VR) are terms that are used frequently in both literature and industry. These terms may also be interpreted in different ways, which makes it even more confusing. Wang (2002) identifies that there is a need to clarify the definition of virtual prototyping, stating that:

"Virtual prototype, or digital mock-up, is a computer simulation of a physical product that can be presented, analyzed, and tested from concerned product life-cycle aspects such as design/engineering, manufacturing, service, and recycling as if on a real physical model. The construction and testing of a virtual prototype is called virtual prototyping (VP).

Regarding virtual reality, it is defined by the Academic Press Dictionary of Science and Technology (Morris, 1992) as:

"a computer simulation of a system, either real or metaphorical, that allows a user to perform operations on a simulated system and shows the effects in real time; e.g., a system for architects might allow the user to "walk" through a proposed building design, displaying how the building would look to someone actually inside it."

Furthermore, Wang (2002) does not distinguish between VE and VR. The difference between VE and VP is however stated to be firstly that VP is the construction and testing process of a virtual prototype while a VE is an environment. Secondly, a VP system does not necessarily incorporate a virtual environment, i.e., the immersion is not absolutely required. This is also the approach that has been adopted in this thesis. Jasnoch et al. (1994), on the other hand, suggests that VR is one of three VP domains, the others being simulation and manufacturing process design. Pratt (1995), however, states that basically all computer models may serve for some purpose as a virtual prototype and thus, as Zorriassatine et al. (2003) states, that VP terminology should not be restricted to the domain of VR.

Virtual prototyping is nowadays well incorporated in the development process, i.e. covering support for styling, engineering, manufacturing, service and maintenance (Zorriassatine et al., 2003). Furthermore, combining virtual reality tools and virtual prototypes for product reviews is a common procedure in the product development process (Zwolinski et al. (2007), Di Gironimo et al. (2006) and Gomes de Sá and Zachmann (1999)). Zimmermann (2008) presents a survey of how this specifically can be applied in the automotive industry. Moreover, the combination is also particularly supportive when performing virtual assessment of perceived quality of split-lines, as many related issues are subjectively evaluated through visual inspection (Wickman et al. 2003 and Söderberg et al. 2006b). The virtual prototypes used for such inspections are tessellated geometrical models, converted from the product-defining digital CAD models. These models need a sufficient level of detail and geometry quality level to facilitate realistic high-end visualizations that will support the decision making.

3.7 MESH MORPHING

3D morphing is a shape deformation technique that has been widely used in both geometric modeling and computer animation for several years. By using 3D morphing, faces of a source object are transformed to those of the target object. Mesh morphing is one of several approaches for geometry morphing (Alexa, 2002). Chalipat et al. (2008) present a study where mesh morphing is applied in the automotive industry. Here, the mesh is modified by reshaping the elements at the nodal coordinate level in order to achieve the required geometry change, instead of the traditional way of updating a geometry model by using CAD. By moving user defined control points the reshaping of the mesh may be managed in a controlled way. Another study related to the automotive industry is presented by Van der Auweraer et al. (2007) with the focus on early concept phases. As previously mentioned, Franciosa et al. (2010) have proposed the use of mesh morphing when simulating shape errors. This method is based on the approach by Borell and Rappoport (1994) defined as *Scodef*, simple constrained deformation. It is a simplified variant of geometric covariance, where a displacement or force of one node on a surface will make points in the vicinity to follow.

3.8 VISUALIZATION OF SIMULATED RESULT FOR PERCEIVED QUALITY EVALUATION

As analysis tools in CAT software are getting more sophisticated and at the same time may be applied directly to the geometry models used in the design process, visual aspects of the effects stemming from geometrical variation can be analyzed. With this step, results presented in a qualitative form may be transformed into quantitative information that can support the work with perceived quality related issues. Furthermore, this highly supports the increased focus on virtual development in the automotive industry, as fewer physical series are needed.

In Maxfield et al. (2000a), the authors proposed the use of virtual environments to support the work with perceived quality, or cosmetic quality as the authors defined it, in early design phases. The work was part of a project at the University of Leeds in England called VITAL (Visualization of the Impact of Tolerance Allocation in Automotive Design), and had the aim to visualize effects from manufacturing tolerance and assembly sequences. A software architecture defined as the VITAL system was proposed. The architecture consists of a number of examples of simulation software developed by VITAL, interacting with third party tools. This software handles the interaction between interfaces, tolerance analysis, assembly sequence, deformation and visualization. Additional work derived from the VITAL project, further discussing the proposed system and its content, has been documented by Fitchie and Juster (2004), Juster et al. (2001a and 2001b), and Maxfield et al. (2000b).

Wickman et al. (2003) presented a similar method for how to add realism into analysis activities described above by connecting CAT software to high-end visualization software. The method enables the evaluation of different tolerance levels and how it affects the final perceived quality in split-lines. Existing simulation and visualization models are used and results are transferred from the CAT software, via virtual ports, to the visualization environment. The setup is depicted in Figure 23. Currently, however, high-end visualization interfaces are more and more common as plug-ins to the CAT-tools, and are often referred to as showrooms. With these interfaces inside the simulation software, evaluation activities may be performed even more efficient.

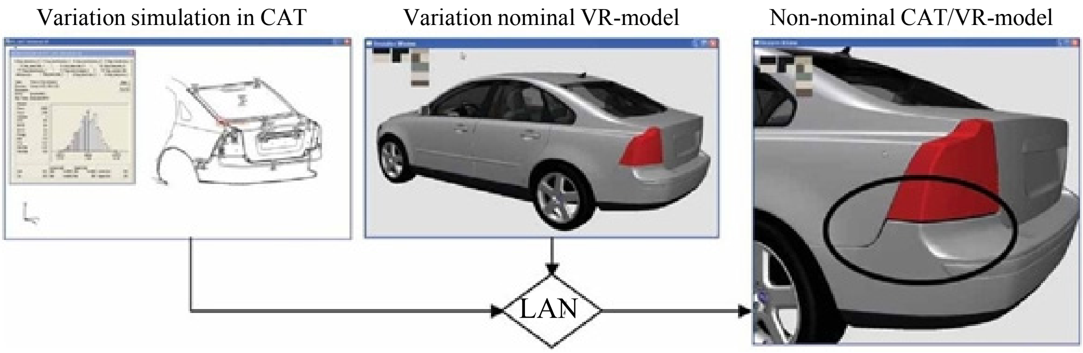


Figure 23. Virtual evaluation setup (Wickman and Söderberg, 2007).

Further, Wickman and Söderberg (2004) extended their research by investigating how the perception of distance in a virtual environment differs from a corresponding physical environment. The investigation showed that the estimation of distance was harder on virtual representation compared to physical. It was concluded that there is a higher degree of uncertainty when estimating virtual representations in general.

Söderberg et al. (2008) extended the method proposed in Wickman et al. (2003) to include non-rigid components and assemblies for visualization activities. The tool presented allows manufacturing and assembly deformations to be visualized with a high level of realism.

In Maxfield et al. (2002), the VITAL system was extended with an approach for the simulation and visualization of non-rigid components. To facilitate geometrical deformation at interactive rates, the commonly used FEA approach was excluded to provide for a method involving Free From Deformation (FFD) and Force Density Method (FDM) (see also Sederberg and Parry (1986) for FFD and Scheck (1974) for FDM). However, with the rapid development of performance in workstations, this approach may not compete with FEA in the same manner today.

At the Friedrich-Alexander-University of Erlangen-Nuremberg in Germany, a group of researchers has published several papers in the area of the simulation and visualization of non-nominal components and shape deviations. The group has developed and implemented a workbench to support the design engineer (Wartzack, 2001). This workbench is based on a hybrid data model used for storing and providing product attributes concerning geometry and semantic information. Information regarding tolerances may be stored in the data model facilitating the visualization of shape variation from shape and position tolerances. This procedure is described by Koch and Meerkamm (2005), and the application is called TolVis. The random simulation of shape variation is performed through the manipulation of the *IndexedFaceSet* in the VRML file, describing the geometry. In TolVis, VRML scenes are generated where different geometrical, coloring and texturing options for the visualization scene exists.

In Stoll et al. (2011) and Stoll and Paetzold (2008), members from the same research group have also presented an approach for generating shape deviation of an assembly split-line. By defining gap and flush measurements in different points, perceived quality of split-lines may be evaluated for different non-nominal scenarios in a quick way. The method is divided into three main steps: mesh generation, deformation of the geometry and finally, visualization. The method is based on the same principles, and is a further development of the method presented by Koch and Meerkamm (2005).

In a collaboration between Helmut-Schmidt University in Hamburg, Germany, Dimensional Control Systems Inc. (DCS) and Volkswagen AG, further methods have been presented for the visualization of component deformation and component shape deviation (Ungemach et al., 2008). Superelement stiffness matrixes are used to deform components, and applying the Response Surface Method (RSM) performs the visualization of deformation on the graphical object. For shape deviations, a method called "Influence Sphere Method" is proposed, similar to the one presented by Stoll and Paetzold (2008). Like previously discussed approaches, the visualization of simulated and generated results is presented in a virtual environment that is either integrated in the simulation tool or externally connected.

4 RESULTS

This chapter will provide a short summary of the results that were gained from the work that formed the basis for the appended papers in this thesis.

4.1 SUMMARY OF APPENDED PAPERS

In this section the papers are summarized in chronological order. Only short summaries are provided. For further details, please refer to the appended papers in the appendix.

4.1.1 Paper A – Behavior prediction on styling data

To be able to answer the main research question, and in particular research question II, it is important to understand how non-rigid variation simulation may be performed when engineering CAD data is unavailable. The difficulty here lies in the fact that styling data, that is released prior to the engineering CAD data, lacks important detail information needed when running variation simulation on non-rigid components, such as flanges, radii and reinforcements. Therefore, this styling data has to be supplemented with other information.

Documented in Paper A, an initial method that enables styling data to be used for non-rigid variation simulation has been developed and proposed. The method is carefully described in the paper with a comprehensive workflow, covering all aspects from initial models to final variation analysis. In this method, styling and engineering CAD data from so-called reference projects, preferably based on the same vehicle platform, is used to predict the behavior of a similar component in a new project. The level of detail on the styling data models is then increased until a lowest possible level is found where the bending behavior matches the behavior of their corresponding engineering CAD models in critical areas (see Figure 24). Here, deviations in sizes and areas corresponding to existing tolerances and locating schemes of components and assemblies are of interest. Behavior simulations are performed in FEA-software using these magnitudes. When a similar behavior pattern has been identified for all reference projects, it can be assumed that the same behavior will be applicable for the current project that is to be evaluated. The same level of detail is then applied to the

Figure 24. Stepwise analysis of boundary behavior on reference projects.

new styling model. Finally, non-rigid variation simulation may be performed in the CAT-software. The paper also includes a case study performed with a positive outcome, which indicates that this approximate method to support behavior prediction could be used during the concept phase in order to evaluate effects of variation.

Looking at it from a broader context, a method such as this would of course benefit from being possible to apply on several different types of components with different complexity and material properties. However, at this particular stage, only a single surface component has been selected for a case study compared to more complex geometries such as a hood complete, which consists of a visible outer hood and a structural inner hood.

4.1.2 Paper B – Identifying critical areas

In Paper A, it was identified that different vehicle areas need different focus due to the complexity of the design in components. Paper B was a result of this. Here, the aim was to identify areas where perceived quality is most frequently evaluated with non-rigid behavior in components and assemblies as a contributing factor. This will help indicating where non-rigid variation simulation is most critical for a more reliable prediction of the final perceived quality of split-lines.

The study included an explorative, qualitative study with semi-structured interviews carried out at an automotive manufacturer. Eleven respondents were selected from two different roles at the company, both having good knowledge and experience in working with aesthetical geometrical requirements and appearance quality. They have experienced issues that the study tried to identify, and thus the ones that could best give a qualitative basis to analyze upon. The purpose was to investigate the individual's own view within the area of the impact of non-rigid behavior of components on the perceived quality. The interviewees were asked to point out areas where non-rigid behavior has a contributing factor to the final perceived quality, possible problems that have been identified in these areas, and in such cases how these problems were solved. A secondary interview was performed where the respondents were only to define the 5 most critical areas from a non-rigid perspective. To achieve a complete triangulation of data sources, the result was then compared with the issues brought up in perceived quality evaluation activities for an ongoing project at the company.

Several split-lines were identified, which are documented in Paper B (see Figure 25 for an overview). Also, a number of factors made it difficult to point out specific components or areas that are more critical than others. The result covers relations on both the exterior and the interior. It was clear that it was easier to identify specific relations on the exterior compared to the interior. The explanation for this could be that in comparison to exterior components, interior panels have to be evaluated in every specific project, since system solutions differ more between projects.

One aspect that constituted a large challenge to identify critical areas depends on the fact that the manufacturing process gets more stable as a project evolves. Deviations

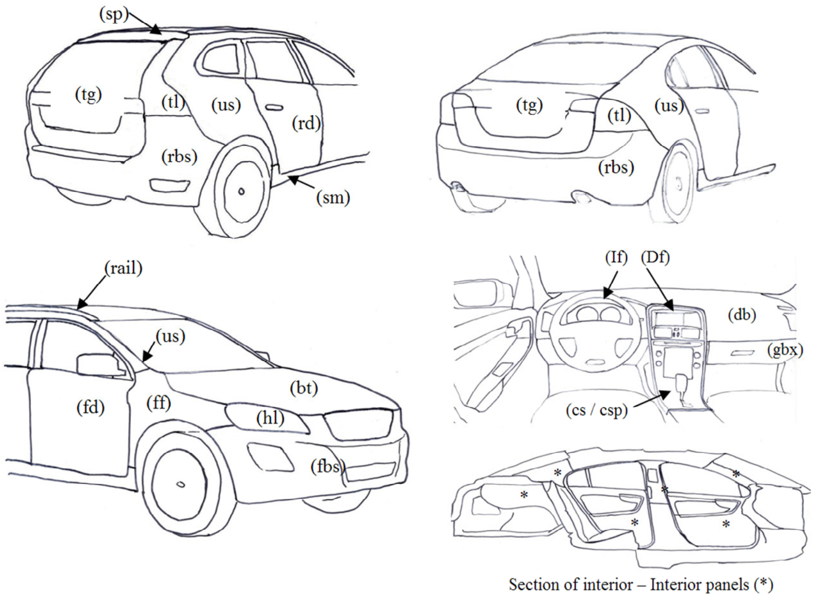


Figure 25. Overview of identified areas and components (Paper B).

that could appear critical in early stages are thus minimized along the road to finally meet the geometrical requirements that were initially defined.

Another interesting aspect that came out during this study was the identification of external affecting factors that make it even more difficult to perform early predictions of component behavior in several of the identified areas. According to involved interviewees, these factors become evident first in the pre-assembly activity. Examples of such factors were; sealing and insulation designed to be in conflict, forces in spring and gas struts and the property and behavior of different fasteners. When performing non-rigid variation simulation these aspects should be taken into account if the engineer finds it relevant for the specific case.

4.1.3 Paper C – Framework for activities supporting perceived quality evaluation

In this paper, a comprehensive framework for managing and supporting the evaluation of perceived quality aspects in a product development process is presented. The framework is depicted in Figure 31 and it will discussed more in detail in Section 4.2. The framework is based on an industrial process in combination with recent research within the field. The framework focuses on activities that can be performed at different stages in the developing process based on the maturity of the CAD or styling data i.e. styling model. The visualization is the primary tool in this framework for the evaluation activities generating new project knowledge. Generally, the main target here is to perform visualizations where there is an evident need. Quantitative knowledge, as a combination of either styling data or engineering data and available project knowledge is translated into new qualitative knowledge through these visualization and evaluation activities. Consequently, it puts certain demands on the engineers evaluating the result, as decisions generally are based on subjective judgments.

There are four main blocks that constitute the frame of the proposed framework. These blocks are also roughly positioned in relation to the generic development process from Ulrich and Eppinger (2004). Only Planning, Conceptual development, System-level design and Detail design have been applied as these are the phases most interesting from the perspective of this framework. The main blocks in turn consist of activities supporting perceived quality, supported by tools and methods. The majority of these have previously been both verified and validated, demonstrating that the framework rests on a solid foundation. Input to these four main activity blocks are of two different types. Firstly, we have the styling status which represents the geometrical styling data, or styling concepts, an output product from the stylist or a styling department. This styling data is the basis for performing the activities in the framework. As earlier discussed, the maturity of this data is continuously increasing and eventually becoming engineering CAD data. Consequently, the choice of applied method is based on data maturity, regardless of the phase in the developing process. The second source of input to the activities is knowledge derived from experience stemming from previous projects. This is visualized by the top bar in the figure. Finally, new information is generated as output from the activities and fed back to the project as new project knowledge, visualized in the lower bar.

It is important to mention that the framework shall be seen as a suggested way of working and describes where in the process the different activities are adequately executed. Therefore, it is not always significant to strictly follow the flow-chart in one single procedure.

4.1.4 Paper D – Non-FEA-based approach for perceived quality evaluation

As previously described, FEA-based methods for non-rigid variation simulation demand meshed models which detail level almost correspond to the final engineering design, for a correct calculation of the stiffness matrix. This paper reflects the approach to consider approximate methods as an option to better deal with this restriction in early development phases. The main goal was to evaluate the applicability of an approximate non-FEA-based method for CAD geometry deformation. The method was first proposed by Borrell and Rappoport (1994), and selected for this study since it previously have been applied in a similar context

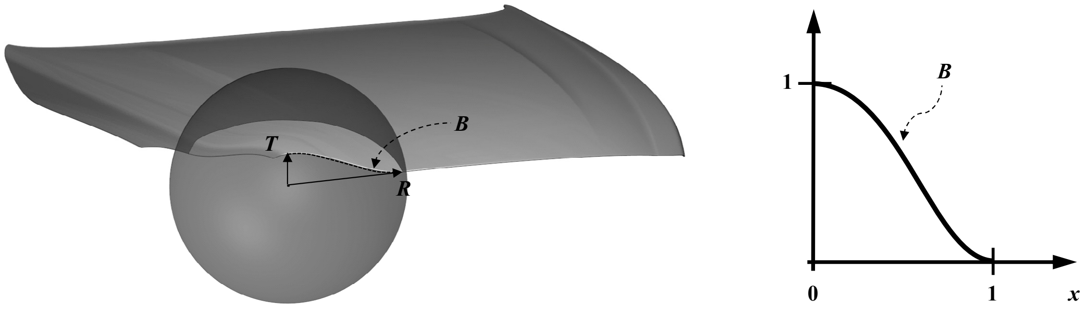


Figure 26. Simplified overview of evaluated deformation method.

(Franciosa et al. 2010). It is based on a mesh morphing approach where the deformation is controlled by a basis function (*B*), the radius of the deformation sphere (*R*) and the size of the deviation (*T*) in the analyzed area (see Figure 26). The method first needed to be implemented in a CAT-tool to enable demonstration. For purposes of gathering empirical data for the evaluation, a case study with a qualitative approach was conducted. It included a focus group study involving eleven engineers that work daily with perceived quality issues. It also included interviews five with top level managers from both ongoing and previous vehicle programs. Two vehicle manufacturing companies were involved in the study. The method was explained in detail and demonstrated prior to the focus group and the interviews. The study provided reflections on this type of approximate method by experienced engineers. Moreover, it helped identify its applicability, strengths and risks.

The study shows that providing the possibility to perform visualization activities in the early phases is highly sought after, both on an engineering level and on a management level. As an example, despite the approximate nature of the method, the project managers had no issue with taking decisions based on simulated results. They instead emphasized the strength of having the possibility to visualize possible scenarios early on in the development process. By applying the presented method, the problem of low level of detail in CAD models in early phases may be reduced. This is important as focus on virtual prototypes is increasing. Moreover, as vehicle projects become shorter with an increased front-loading mindset, the wish for quick and simple alternative analysis methods increases. One obvious benefit of the method is the simplicity with which one could visualize expected scenarios. Therefore, this tool could be a suitable complement to more time-consuming FEA simulations later in the development process.

As a result of the study, a number of purposes and application scenarios for this type of approximate method were proposed (see Figure 27). The study also identified

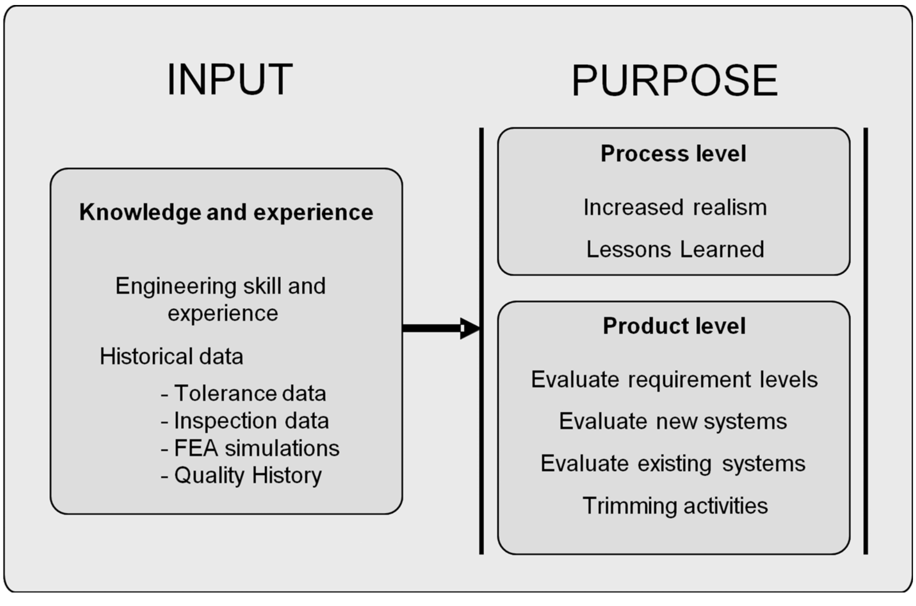


Figure 27. Overview of results from focus group study (Paper D).

strengths and risks of visualizing the effects of geometrical variation in this way. Concerns were raised regarding how the input to the method should be controlled. The potential input identified in this study (see Figure 27) needs to be converted to facilitate selection of the right radius and the right basis function. If the method should be used for the purposes described above it needs to be reliable and reproduce the desired variation visualization for the specific analysis.

4.1.5 Paper E –Morphing techniques in variation analysis

In this study, a method for early evaluation of the impact of geometrical variation on perceived quality of split-lines is proposed. Starting from a new exterior styling model, mesh morphing techniques have been used to distort an exterior model according to available measurement data acquired in running production. In this way, the component variation can be predicted. Morphing techniques have also been used to adapt previous structural design solutions to the new styling, in order to make an early assumption of the assembly stiffness. The aim of this study was to show the potentials using morphing techniques in combination with CAT-tools in perceived quality evaluations performed in early concept phases. Since little is known about the final design and the specifications of components and assemblies, input to the proposed approach was instead gathered from previous projects. This is depicted in Figure 28, giving an overview of how inspection data and information regarding detailed design in previous projects are reused to predict the behavior of a new styling model.

To predict the component variation, mesh morphing was applied to reshape a number of geometrical models representing the styling of a new vehicle hood, based on the same number of measured hoods from an existing vehicle program in running production. The morphing was controlled by the position of the inspection points and the deviation in each point. By applying PCA, the large dataset was compressed to create a statistical representation of the component deviation, represented in this sequential dataset. The next thing was to predict the behavior of the structural

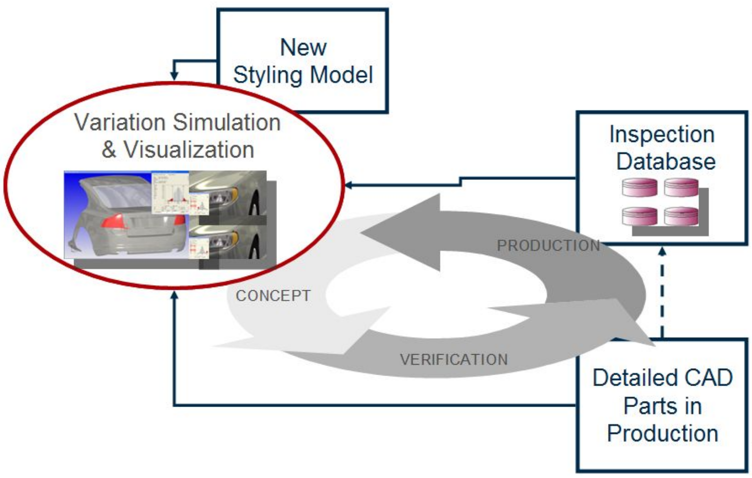


Figure 28. Available data for early judgment, (Paper E).

component model. The morphing was carried out here using a different approach. The edge domains of the new styling model were used as a morph constraint when morphing the existing inner structural model to fit the new outer contour.

Simulated results for component variation were verified by comparing it with inspection data from the production. It showed that range in edge deviation was mainly underestimated, whereas surface deviation was both under and overestimated. Regarding the stiffness estimation, the unit disturbance response was compared between results from the proposed method and a final engineering model. The maximum response of the unit displacement was in the same magnitude, but how it is distributed over the surfaces differed.

With this approach it is now possible to generate a more trustworthy analysis model from a visualization perspective, compared to simulations where the components are treated as rigid. These models can be used for perceived quality assessment of split-lines, taking into account correlated component deviations and their non-rigid behavior. The effects of component variation, locating schemes etc. can now be analyzed and visualized separately or combined. Questions were raised about the amount of production measurement to be included in the modeling, and also how this data should be selected. Sampling sizes and distributions of the data also need to be addressed further, as well as the morphing procedure and the applied distortion algorithms.

4.1.6 Paper F – Knowledge reuse in early perceived quality predictions

This paper may be seen as a continuous study of the one in paper D. In that paper a number of different benefits of using the presented method were identified, one being lessons learned. In this paper, the case study is showing how the non-FEA-based method may be applied in an industrial context to support knowledge transfer between projects, as a lessons learned activity. The model of transferring the knowledge is

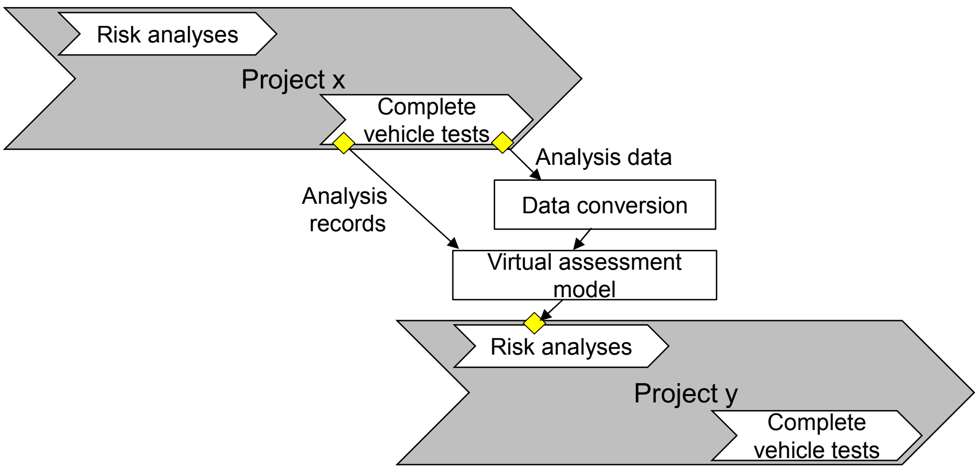


Figure 29. Overview of knowledge transfer procedure (Uffmann and Sihn (2006), modified in Paper F).

inspired by Uffman and Sihn (2006), illustrated in Figure 29. This is also in line with the fact that due to the circumstance that the amount and quality of information in early phases is low, it is of high value to optimize the knowledge transfer from former project outcomes to subsequent projects, highlighted by Jahn and Binz (2007).

In the presented model a two-step procedure is carried out. Firstly, in the analysis record step, potential issues that could form a relevant scenario are identified. In the case study presented in the paper, a number of actual identified scenarios from an ongoing vehicle project at a collaborating company were selected. Due to confidentiality, the scenarios in the paper are merely examples but selected to represent the main issues in a similar way. When these were identified, the next step was to gather feasible data that would serve as input to the non-FEA-based method. In the case study, this input was selected from inspection data and from scanning data that was gathered when analyzing the previously identified issues. Finally, this data had to be converted to suitable input values for the applied method. It was identified that this step is an iterative process which requires just as good product knowledge as production systems knowledge and of course also skill in using the applied method.

This case study demonstrates a good way of taking care of and transferring knowledge between projects for a visualization purpose, information that otherwise could have been harder to grasp by only looking at the analysis data from the presented cases. It has been shown how an approximate non-FEA-based deformation technique can be used to analyze risks in a project, based on knowledge derived from a previous vehicle project. This also supports the aim towards increased decision making based on virtual models and a decreased number of physical prototypes.

4.1.7 Paper G – Rigid vs. non-rigid perceived quality evaluation

To guarantee that the right decisions are taken during a perceived quality evaluation activity an important thing to understand is the difference between a non-rigid and a rigid visualization model, in terms of how the evaluator perceives it. In a previously presented study by Forslund et al. (2011), also included in Wagersten (2011), the authors investigate the influence of different split-line geometries, types of deviations and visualization settings on the human ability to detect deviations. One of the results that the study showed was that there is a significant difference in how certain relevant deviations (here meaning deviations normal to the surface extent) on non-rigid components are perceived, compared to how the corresponding deviations are perceived when performing rigid simulation. Results indicated that non-rigid behavior is important to include when evaluating split-lines. These indications made the basis for this continuous study with the aim of, in a more comprehensive manner, investigating whether there is a difference in perception of the visualized simulated result when using non-rigid versus rigid simulation. Thus, it will indicate if there is any risk in using rigid-simulation in combination with visualization when assessing perceived quality.

Figure 30. Eye-tracking gaze plot for visit duration time, view 1.
Left frame, rigid. Right frame, non-rigid (excerpts from Paper G).

This paper presents a comparative study in which eye-tracking equipment has been used in order to explore whether interpretation of variation differs between rigid and non-rigid based variation simulation during evaluation of visualized models. Subjects from the automotive industry were asked to evaluate two virtual models where the same amount of variation was represented by rigid and non-rigid models. The rigid simulation model was built using the traditional way of working, using so called alternative assemblies. The non-rigid model was built using meshed geometries and FEA and MIC for variation simulation. Eye tracking was used to record how the subjects performed the assessment. Analysis of both visit duration time (see example in Figure 30) and visit count for the eye-tracking data showed that subjects look more at the area where variation is unrealistically larger if rigid simulation is used compared to non-rigid simulation. This indicates that they were distracted by areas other than the one that should actually be evaluated. Furthermore, analysis of assessment data shows that subjects judge split-lines represented with variation based on rigid simulation as significantly worse looking compared to split-lines represented with variation based on non-rigid simulation, although both simulation cases represent the same amount of displacement.

These results conclude that there is a risk in showing non-nominal visualization models for non-rigid components based on rigid simulation when evaluating perceived quality on a vehicle. The study indicates that in those cases where the phenomenon with unrealistic variation occurs in split-lines other than the actual evaluated split-line, non-rigid simulation should be used. This is also in line with the previously performed study on the same topic (Forslund et al. 2011). It is thus highly motivated for companies having compliant components and the need to evaluate perceived quality of split-lines to apply non-rigid simulation and visualization in critical cases.

4.2 INTERCONNECTION OF ACHIEVED RESULTS

The very first styling models released from the industrial designers are plain surface models, describing the interior and exterior styling of the vehicle. And as the project evolves, the models available for simulation, visualization and evaluation will gradually become more detailed. This influences the work with perceived quality in split-lines in two important ways.

First, model maturity affects the level of detail of the visualization models built for evaluation. This applies especially to areas in and around the split-lines. Examples of such shortcomings could be information about radii size, flange size and position, sealing types, all of which are valuable pieces of information that are important when visually observing and evaluating customer perception of the split-lines.

Second, the detailed structure of a component (in other words, the detailed design) has an important impact when simulating the effects of variation on non-rigid components and assemblies. This also includes information about radii size, flange position, and reinforcements, factors that influence the behavior of the object. However, these are not necessarily details that are visible for the customer or user, observing and evaluating the vehicle. Rigid components do not face the same problem, and, as earlier mentioned, non-rigid components are considered rigid in most variation simulations.

The proposed framework presented in Paper C and depicted in Figure 31 shows that there are other means available in these early phases in addition to the styling models. It is therefore desirable to achieve interplay between these means, being styling

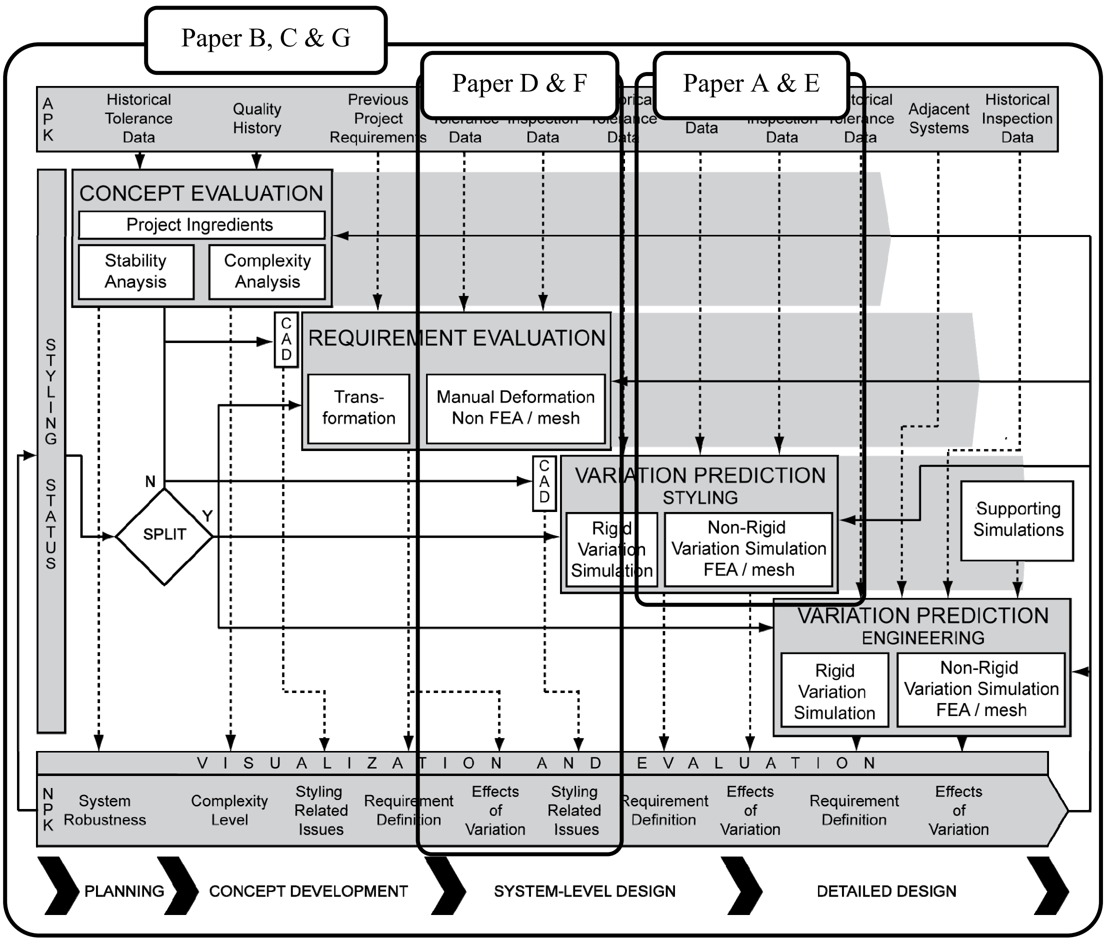


Figure 31. Position of contributions in the proposed framework (Paper C).

models, project knowledge, tools and visualization techniques, to support the perceived quality work. The framework is described more deeply in detail in Paper C. It shows where it is most adequate in the process to execute a perceived quality-supporting activity during the development process. It should be emphasized that the development phases depicted in the lower bar are only there for references and should not be considered as fixed to the overall framework. Furthermore, the grey extended arrows illustrate that the activities may also be executed later in the process.

The four main blocks are placed in a downstream order following the maturity of the styling data. Further, these blocks represent four different foci in the framework: *Concept Evaluation, Requirement Evaluation, Variation Prediction Styling and Variation Prediction Engineering*. The relevant knowledge available is presented in the top bar of the framework. The lower bar shows the new knowledge generated through visualization activities in general, but also the evaluation of more of a quantitative kind. This new knowledge is fed back to the project to act as new input.

The first styling models released in a vehicle project have not been divided into separate components, being one complete vehicle model. Therefore, additional CAD-work has to be performed to facilitate further analysis. However, what characterizes the *Concept Evaluation* block is that it manages undivided styling models.

In Figure 31, the position of the remaining six papers has been marked out. In Paper A, a method is proposed for how to simulate variation on non-rigid components in early phases when the detail level is low. It is therefore placed as an activity under *Non-Rigid Variation Simulation* in the *Variation Prediction Styling* block. It is a more comprehensive analysis then *Manual Deformation*, since it includes FEA-based non-rigid variation analysis in a CAT tool. However, it lacks the input that allows an equivalent analysis in the *Variation Prediction Engineering* block. The study also concluded that different approaches were needed for different components depending on the level of detail complexity. For instance, it is difficult to predict the design of an inner reinforcing component not visible or presented in the styling concepts.

The result from Paper A formed the basis to Paper B, where focus was put on identifying areas where compliancy in components has a fundamental impact on the perceived quality. Further, it tries to identify the areas on a vehicle where non-rigid variation simulation might be required for a thorough investigation or where rigid analysis is considered to be sufficient. As rigid variation simulation is the most common analysis procedure today, this result can support the decision of where and when the step to non-rigid simulation needs to be taken. It will also support the methods presented in Paper A, D and E, as the range of possible cases may be limited. This will further save important time and increase efficiency in the daily work.

Included in the same boundary as Paper A is Paper E, which proposes a method based on morphing techniques to predict component variation and structural behavior in early perceived quality evaluations. The position of the paper in the framework is determined by the fact that the method is not in any way dependent on the final engineering data, as it only requires the new styling surface in terms of geometrical models. Instead, *Available Project Knowledge* constitutes the input to the method, here being inspection data and previous design solutions. Of course, since the method only relies on the new styling surface and on a feasible reference project, the method could be applied in very early development phases.

Paper D discusses the importance of using alternative methods to FEA-based methods as means for simulation and visualization of non-rigid components. Such alternative methods are mainly applied in the *manual Deformation Non FEA / mesh*, which is an activity positioned in the *Requirement Evaluation* block in the framework (see Figure 31). The method presented in Paper D has shown to be beneficial, partly due to the strength of having the possibility to visualize possible scenarios early on in the development process and the simplicity with which one could visualize expected scenarios. These are properties that are well suited to the process of performing requirement evaluations. Moreover, Paper D covers aspect on visualization and how the actual input to the presented method should be selected, which explains the larger boundary in Figure 31. It should be emphasized here that the use of this method is not fixed to this specific point in the framework. Certainly, non-FEA-based methods may be applied at several stages in the development process for several different purposes. A more thoroughly analyze of these aspects can be found in the paper (Paper D).

In Paper A, C, D and E the issue of transferring knowledge between projects is discussed. The study in Paper F is a continuous elaboration on this specific topic with the basis of the method being the same non-FEA-based simulation method as presented in Paper D. It covers a specific purpose of knowledge transfer, being lessons learned, and therefore covers the top bar of *Available Knowledge*, as seen in Figure 31. The study in Paper F also covers some aspects of how the result from such study is actually used in a specific project, and thus the impact of this paper also includes *Visualization and Evaluation* and *New Project Knowledge*, as seen by the boundary in the same figure.

Finally, Paper G is positioned on the very outer boundary of the framework since it highlights the risk of not taking into account the non-rigid behavior of components when performing virtual evaluations of perceived quality. As seen in the framework, the *Requirement Evaluation* block and the two *Variation Prediction* blocks all include aspects of rigid and non-rigid behavior and thus need to be part of the overall mindset. The *Conceptual Evaluation* block will also in some sense be affected even if the results from a *Stability Analyses* or *Complexity Analyses* are interpreted through color coding and numerical values. If a result in some way needs to be visualized for a more deep-dive analysis that for some reason is performed using visualization based on rigid components, it is of high importance that the engineers performing the analysis is well aware of the difference in behavior.

5 DISCUSSION

In this chapter, the research questions will be discussed and the results achieved will be evaluated in terms of validation and verification.

5.1 ANSWERING THE RESEARCH QUESTIONS

RQ I - Process

How can a process for simulation and visualization be defined, in order to support early perceived quality evaluations based on immature data?

In Paper C, this specific research question has been treated. The paper presents a framework, or a process, for handling immature styling data in different phases of the development process. The framework was developed in close relation with industry. Therefore, it includes aspects from the industrial discipline as well as tools, methods and other supporting knowledge that are products from modern research on tools and methods supporting the work with perceived quality during a development process. Furthermore, the framework was developed with a strong focus on the front-loading concept. By following the proposed framework, many of the activities supporting the work with perceived quality may be executed early and with low data matureness as input. All studies performed in this research project can also be positioned in this framework.

With this work as a base, one approach to answer the research question has been explored and presented in this thesis. As this framework has not yet been fully implemented and tested (by performing a Descriptive Study II in DRM, for example) all conclusions cannot be drawn at this stage.

RQ II - Tools/methods

What tools and methods are needed to predict geometrical variation and component behavior to support early perceived quality evaluations based on immature data?

This question has partly been answered by the methods presented in Papers A, D, E and F. When predicting the effect from geometrical variation on perceived quality, these could be divided into two categories. The first category covers methods that can be applied using FEA-based simulation, and covers Paper A and Paper E. In both methods, FEA in combination with MIC can be used to calculate the variation. The second category for predicting effects from geometrical variation covers non-FEA-based simulation methods, where one is presented in Papers D and F. Here, mesh morphing is instead applied, controlled by the user, to simulate and visualize these effects. Regarding the effects stemming from component variation, both Papers D and F, and Paper E, show how this could be simulated and visualized using mesh morphing but with different approaches.

The one thing that these methods have in common is that they all rely on knowledge that is derived from previous projects. Thus, it has also been shown how experience, knowledge, information and data, can support work in early development phases to facilitate the work with perceived quality.

RQ III- Focus

What vehicle areas should be focused on when performing early non-rigid perceived quality evaluations with respect to geometrical variation?

This is addressed in Paper B, trying to answers the question what areas might be important to simulate from a non-rigid perspective when evaluating perceived quality of split-lines. Results from the study show that there are a lot of areas that are critical from this point of view, and that it was easier to identify specific relations on the exterior compared to the interior. The answer of this research question can support work in very early phases, as engineers and other stakeholders may take preventive measures to avoid undesirable perceived quality in these areas. However, it is important to understand that these effects are related by several factors such as system solutions, material properties and structural design. But, as many automotive manufacturers seldom make radical changes when it comes to these factors, the research question is of high interest. In summary, the question has been answered although generalization of the results is somewhat limited.

RQ IV - Visualization

What is the difference in how non-rigid and rigid components are perceived when evaluating perceived quality through visualization?

Answers to this research question have been presented in Paper G. Firstly, the results from the study showed that there actually is a significant difference in how deviations on non-rigid components are perceived, compared to how the corresponding deviations are perceived when performing rigid simulation. Moreover, it has been shown that subjects look more outside the area of focus where variation is unrealistically larger if rigid simulation is used, compared to if non-rigid simulation is used. Also, split-lines represented with variation based on rigid simulation are perceived as significantly worse looking compared to split-lines represented with variation based on non-rigid simulation. In summary, this study has helped to answer the research question stated. Even here it is hard to debate that the results may be generalized in a broader sense. However, the answer to the question has been presented according to the circumstances in which this type of evaluation is performed.

Main research question

How can variation simulation and visualization of split-lines be performed, to support early perceived quality evaluation, when complete engineering CAD data is not available?

It has been shown how effects of variation on perceived quality may be predicted in early phases with a number of suggested methods. However, to apply a more holistic view on answering this question, it has also been shown how such tools and methods fit in a proposed framework that supports engineers working with perceived quality issues in a development process. Furthermore, this framework clearly distinguishes between non-rigid and rigid simulation and visualization. It is therefore important to understand that there is a difference between these two from an evaluation perspective, and also what this difference might be. Finally, since it has been shown that rigid visualization using so called alternative assemblies can disturb the evaluator, a non-rigid behavior of components is preferable to assure that correct decisions be taken. It is thus important to understand what areas to prioritize and to focus on, not least as industry becomes leaner with increased focus on value adding activities.

In summary, this thesis has presented an answer to the main research question. Aside from the new knowledge in the field, it consists of the proposal of a framework that includes novel methods proposed for early perceived quality evaluation, areas where to focus on with a non-rigid perspective, and answers to differences between non-rigid and rigid visualization models.

5.2 Discussing the success criteria

In section 2.3, the following research success criteria were presented. These will be the grounds for discussing the success of this research project.

- Manage virtual evaluation of perceived quality with realistic component behavior in early phases even though data maturity is low.
- Provide support showing the importance of visualizing realistic component behavior when evaluating perceived quality of split-lines.

The methods presented in Papers A, D, E and F all support the first criterion. They show how immature data can be used for virtually evaluating effects of geometrical variation on perceived quality in early phases. With the basis of literature identifying the need of virtual prototypes in early phases (see Introduction), in combination with the result in Paper D, showing that virtual evaluation is sought for by both managers and engineers in a vehicle development project, the success lies within the fact that the method supports this. Even if the method for geometry deformation in Papers D and F has previously been presented in scientific publications and thus not novel per se, the acceptance of this kind of approximate deformation method has been identified. Success can also be motivated due to the fact that this method has now been implemented in industry and applied in a project. It has been used based on results derived from these studies. Furthermore, no similar methods for supporting perceived quality evaluations as the ones in Papers A and E, using existing knowledge as input, have been found in literature. The framework in Paper C answers the criterion in a broader sense, since it supports engineers working with perceived quality issues in different stages of the development process. It has also been discussed in this thesis how the presented methods from this project fit in this framework. Results from Paper B further support and guide the engineers to manage virtual evaluation of perceived quality.

Moreover, to secure that the right decisions are taken, the models used for evaluation needs to be as realistic and trustworthy as possible. This has been proven in Paper G, where results show that non-rigid visualization models are judged differently compared to rigid visualization models, which supports the second success criterion. Non-rigid behavior is a red line throughout all the methods presented in this project.

5.3 INDUSTRIAL RELEVANCE

An important aid to strengthening the attractiveness of a product is to focus on the overall quality. This, in turn, increases the customer's impression of product quality. Further, this especially applies to the automotive industry, where more and more brands strive to reach near-premium or premium class. The customer's perception of perceived quality has always been a criterion for premium products and, thus, a motivation for the producer to increase their margins. And, as previously mentioned, increased focus on front-loading in today's development projects demands new methods to support a new way of working. As a result, the work contributed in this thesis will support the focus on increased perceived quality in an industrial setting by proposing, for example, tools, methods and knowledge for use specifically in the early phases of the development process. This will in turn facilitate simulation- and evaluation activities at an earlier stage than is currently possible. As an example, work presented in this thesis has highlighted the importance of early virtual evaluations for decision making regarding perceived quality. Also, the presented method in Paper D and F have been implemented in a CAT-tool and applied in ongoing projects in industry during this thesis work, and it have been well received. This will support earlier identification of faults and issues, meaning minimizing the number of severe problems in late phases. In the end, this can save the company both time and cost.

5.4 SCIENTIFIC RELEVANCE

The research in this thesis explores areas such as Tolerance Management, Engineering Design, Industrial Design and Cognitive Psychology. In addition, it involves the area of Concurrent Engineering (CE), whose objectives include improving quality, reducing costs, compressing cycle times, increasing flexibility, raising productivity and efficiency, and improving the social image (Huang, 1996).

The results from the research conducted in this project can be positioned in the area of design science (Hubka and Eder, 1996). Through its definition, design science has an opportunity to gain and organize knowledge concerning and surrounding designing. A substantial amount of the work in the area of design research focuses on describing methods and tools to support design and the design process in early phases. Results from the research presented in this thesis have an aim that meshes well with this perspective. It includes a framework to support the product development process in an environment where perceived quality is of importance. Three methods supporting this framework have also been presented. Similar methods to the ones proposed by the authors have not been found in literature and this may therefore be seen as a novel contribution to the research area. Further, obtained results give an understanding of what is feasible in early phases and what is needed in terms of knowledge. Further, the need for non-rigid variation simulation has been qualitatively.

The position of this research related to Figure 7 by Hubka and Eder (1996) can also be discussed. Papers A, C, D, E and F all end up in the first quadrant as they prescribe methods of working in the design process. Paper B, D and G clearly have descriptive contributions. Paper B describes the current situation and identifies requirements for a method of working. Paper D describes the reflections and thoughts about a method aimed at simulation and visualization in a virtual environment, and thus, this paper will also have its contribution in the lower half of the circle. Finally, the work in Paper G tries to identify the difference between rigid and non-rigid evaluation of perceived quality (from a visualization perspective) to support the evaluation process. G is therefore positioned in the lower half of the circle.

5.5 EVALUATING THE QUALITY OF THE RESEARCH RESULTS

To evaluate the quality of research conducted and presented in this thesis, it will be discussed in the terms of *verification* and *validation*. Pedersen et al. (2000) defines validation of new methods as "a process of building confidence in its usefulness with respect to a purpose". Maxwell (1996) states that validity within qualitative research refers to "the correctness, or credibility of a description, conclusion, explanation, interpretation or other sort of account". Verification on the other hand is a question of how well a model corresponds to its specification. To summarize, verification as defined by Boehm (1981) refers to the question "Are you building it right?", whereas validation can be expressed by the query "Are you building the right thing?" In this thesis, this will be discussed according to the type of study that has been conducted. The papers are in this evaluation divided into three groups; (1) descriptive studies covering Paper G, (2) case studies, covering Paper B and D, and (3) prescriptive results, covering Paper A,C, D, E and F.

5.5.1 Descriptive studies with quantitative approach – Paper G

In Paper G the study was conducted using a quantitative approach. The quality of statistical studies is often discussed in terms of reliability and validity (Filed, 2005). Reliability refers to the ability to produce the same results under the same condition. To speak in the terms of verification and validation, here we equate reliability with having a verified setup in the study that is reliable. To secure valid results from the study, a number of actions were taken. Firstly, it was secured that the setup of the experiment agreed well with corresponding evaluations in actual projects, in terms of using the same power-wall, setup in the room, procedure of evaluation split-lines etc. Secondly, the cases that were used in the experiment were taken from realistic issues in previous vehicle projects, where the models were built by experienced engineers within the area. Also, the respondents in the study were selected since they were well aware of the concept of perceived quality of split-lines, and thus represented a homogeneous group of participants.

To secure a verified setup and thus reliable results, strict instruction of how to setup the eye-tracking device was followed. Also, calibration was performed for each individual to secure acceptable sampling rate. Each individual experiment was performed with identical instruction where three researchers were involved to supervise on every occasion.

5.5.2 Case study research involving interviews – Paper B and D.

As recommended by Yin (2003), four approaches commonly used to estimate the quality of any empirical social research have been selected for the qualitative studies presented in Paper B and Paper D. They are *construct validity*, *internal validity*, *external validity* and *reliability*. These tests are common to all social science methods and have been summarized in numerous textbooks.

Construct validity: establishing correct operational measures for the concepts being studied. Two recommended tactics have been used as approaches to secure the construct validity, using multiple sources of evidence and establishing a chain of evidence. In both studies, several stakeholders from different parts of the companies and of the development chain, were selected as interviewees to achieve multiple sources of information. In Paper B, the results from the interviews were compared with issues that had been identified in an ongoing vehicle project to achieve increased validity. In Paper D, the number of sources further increased when complementing the focus group with short interviews on a management level. A chain of evidence was established in the studies through clear research questions, questionnaires that were established with researchers experienced with similar studies, tape recordings and observer notes from the sessions, transcriptions from the sessions, and finally, conclusions drawn from this material.

Internal validity: ensuring that the practitioners communicate their perspectives in an unbiased way to the researcher. There were no signs that people were disturbed by having a recording device in the room. In the study in Paper D, the moderator made sure that the opinions of all the respondents were considered. Although some voices were heard more than others, this did not jeopardize the case study generally. Independent feedback from an observer further supported the internal validity in this study. However, as these studies were of a more explorative nature, internal validity was not as significant a threat as in the case of explanatory case studies (Yin 2003).

External validity: establishing to what extent the case study's findings can be generalized and the domain in which the findings can be of interest to other people outside the investigated case (Yin 2003). These studies, are investigating issues that are delimited to the automotive industry and are not assumed to be generalized in a broader sense. In Paper D, however, a multiple case-study design involving two automotive companies enhanced the possibility of generalizing the results. The companies selected for the study also had slightly different product ranges. Furthermore, related research presenting similar approaches as the one demonstrated in this study have been carried out, published by Stoll et al. (2011) and Franciosa et al. (2010).

Reliability: demonstrating that the operations of a study can be repeated with the same results. Case-study research demands that certain procedures are followed so as to identify a documentation trail (Yin, 2003). Yin recommends two tactics to enhance reliability which have been applied in both studies: a detailed case-study protocol and a structured case-study data base with all the relevant data such as recordings, transcripts, interview guides and observations.

5.5.3 Prescriptive results – Paper A, C, D, E and F

To verify and validate the prescriptive studies, the results are discussed using the approach by Buur (1990) as it applies well to research related to product development. It includes *Logical verification* and *Verification by acceptance*.

Logical verification

Buur includes four levels in the logical verification step:

- *Consistency*. There is no internal conflict between individual elements of the research.
- *Coherence*. Well-established and successful methods agree with the results from the research.
- *Completeness*. All relevant phenomena can be explained by the findings.
- *Ability to explain phenomena.* Case studies and design problems can be explained by the means of the results.
- Claims made by the theory are verified by experienced designers
- Models and methods elaborated from the theory are accepted by experienced designers

The results summarized in this thesis are very much based on existing theories and prior well-known research within the involved areas. Further, to support logical verification, an important part of the research is the literature studies. The proposed framework in Paper C and the methods generated through the prescriptive studies in Paper A, D, E and F consist of several individual theories and methods that are linked together. Many are common in product design and widely used in the industry today and may therefore be considered as valid. Some are under evaluation or currently under development. However, they are all based on research, either from within the area or from closely related areas. Regarding the papers presenting methods, they in turn include theories and methods that are covered by broad research, such as FEA, PCA and Morphing. These have been validated scientifically through numerous studies and also accepted in industry as they are widely used in product design today.

Verification by acceptance

This means that proposed methods and models should be verified by the acceptance from experienced users within the application area to secure validity. It is thus a question about verifying the validity of the methods presented in the research.

The research conducted may be validated by acceptance both internally and externally. Within the research project, a validation process has been implemented for guarantee acceptance from both internal and external stakeholders. This involves an annual conference at the company where the latest results are presented (annual VIPP conference at Volvo Cars for industrial PhD students). As part of the conference, external evaluators from academia are evaluating the research through an annual report from the PhD student, covering the overall research so far. Annual result days within the specific research project and within the Wingquist Laboratory are also part of this process. The latter have continuous seminars where PhD students present their research for colleges and industrial stakeholders. In addition, all appended papers in this thesis have gone through peer-review processes for acceptance to the different journals and conferences. Two of the included papers in this thesis are accepted journal papers which have gone through extensive reviewing from at least three reviewers per paper. One more paper has gone through a first journal reviewing step. These review process have in some cases resulted in improvements and additional information.

At the same time, the close collaboration with the industry externally supports the verification by acceptance. The research project was initiated since both academia and industry identified a need to explore this area, much due to previous research within the field. The method presented in paper D and F has been implemented in a collaborating company. Furthermore, a lot of the results from the research have given increased insight to the phenomena around non-rigid variation simulation in early development phases. It has also given a better understanding to the strength of being able to visualize issues in early phases, not least as the industry is becoming more and more dependent on virtual prototypes and virtual environments as support to secure validity in the projects.

6 CONCLUSIONS AND FUTURE WORK

This chapter contains conclusions of the results achieved and discusses proposals for future work.

6.1 CONCLUSIONS

The results presented in this thesis aim to support the work with perceived quality, with specific attention to early phases of the development process. The main focus lies on visualizing the effects of geometrical variation on perceived quality of split-lines in a trustworthy way, despite low data immaturity of geometrical models in early phases. Not only is it important to investigate issues in a realistic manner, many vehicle projects are today minimizing the number of physical test series, and thus, more knowledge is needed for how to perform virtual evaluations.

All research questions have been treated and debated and answers have been presented in this thesis, as well as in the appended papers. Industrial and scientific relevance of the results is discussed, are well as the verification and the validity of the conducted studies, and their results. Implementation of results in industry has been conducted. Some results are still not mature enough to fulfill this step. Furthermore, this project has resulted in new knowledge within this research area. General concluding remarks from this project are summarized below.

- Non-rigid variation simulation is motivated by the fact that there is a risk in showing non-nominal visualization models for non-rigid components based on rigid simulation when evaluating perceived quality on a vehicle.
- The strength of having the possibility to visualize possible scenarios early on in the development process has been identified.
- Knowledge reuse can be of great support when predicting effects of geometrical variation on perceived quality of split-lines in early phases of the development.
- With reference projects as support, immature styling data may be used to visualize component behavior in a trustworthy manner on selected components within the magnitude of expected variation.
- There are areas on the vehicle where non-rigid variation simulation is preferable to rigid simulation in terms of what is gained from the simulation.
- Morphing technique can be used in early project phases in order to create simulation models to assume the future component variation for the assessment of perceived quality of split-lines.
- Morphing techniques can be used to make an assumption of the sub-assembly stiffness by using design input from previous projects.

- An approximate non-FEA-based deformation method for visualization provides significant support in early phases of the development process to manage non-rigid components when investigating and evaluating the effects of geometrical variation on the perceived quality of split-lines.
- It is acceptable from a management perspective to take decisions based on simulated results from approximate non-FEA-based deformation methods, despite the approximate nature of such methods.

6.2 Future work

This thesis has presented tools, methods and support to manage virtual evaluation of perceived quality of split-lines in early concept phases. Based on the results and conclusions, future research can address the following points:

- One of the presented methods in this thesis has been implemented in industry (Paper D and F). A proposed way of applying the method has also been presented. However, more work is needed to fully understand the potential of the method.
- The proposed framework in paper C needs to be studied through a Descriptive Study II. However, as some of the methods included in the framework are long-term projects and others are under current evaluation, certain activities in the framework might be excluded from this study.
- The approach of using mesh morphing technique to predict and visualize effects of geometrical variation on perceived quality, presented in Paper E, needs to be explored more. Focus should be put on how to select the inspection data and on how to select the morphing algorithms.

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