Dimensional Engineering

Methods and Tools for a Dimensional Engineering Process at Scania

Master of Science Thesis in the Mechanical Engineering Programme

NADINA OMBASIC
DANESH ZARE

Supervisor: Rikard Söderberg
Examiner: Göran Brännare

Chalmers University of Technology
Mechanical Engineering
Department of Product and Production Development
Gothenburg, Sweden 2013
Report No XXX OOOO

Preface

This Master of Science thesis was conducted during the spring of 2013 on behalf of Scania at the R&D department of Scania in Södertälje, Sweden. The study was a collaboration between the master programs Product Development at Chalmers University of Technology and Production Engineering and Management at the Royal Institute of Technology.

The outcome of this work will hopefully provide enlightenment for everyone who takes the time to study it. Our aspirations are that the results of this project will serve as guidelines for Scania for future implementation of the area under subject in this thesis.

We would like to thank our supervisors at Scania - Bertil Tamm and Kent R. Johansson. They have supplied us with invaluable data and continuous inspiration. We would also like to thank Almir Smajic for giving us constant feedback on our thoughts. Our steering group members Carl-Johan Halvordsson, Peter Hermansson, Daniel Johansson, Emil Bojvall, Janne Lehto-Piironen have also been a big help for us by providing guidance throughout the project. A special thanks to Anders Ingemarsson for his pedagogical layouts.

This study couldn’t have been conducted without the support of many external parties, including people at Scania, external companies and consultancy firms. We are grateful to everyone who has been involved in this work.

Södertälje, May 2013

Nadina Ombasic & Danesh Zare

Abstract

This work proposes an implementation of a Dimensional Engineering process that is interlaced in the product development process at Scania and becomes a deeply rooted philosophy.

Dimensional Engineering is a discipline that minimizes problems in function and quality all through a product's life cycle – from cradle to grave. It is a growing field globally and Scania AB has now decided to give this area greater attention.

In order to attain a more in depth look in to Dimensional Engineering, a literature analysis was performed in the beginning of this project. Four external case studies were performed where the goal was to comprehend how other companies have implemented Dimensional Engineering in their product development process. Three internal case studies were also performed where the goal was to identify how the lack of Dimensional Engineering can cause problems in design, production and usage.

The findings of this work show that Dimensional Engineering is a profitable activity since many other companies have integrated this process in their work and the Dimensional Engineering field is expanding rapidly. It is an activity that has shown to decrease time to market, enhance product functionality and decrease product development costs. In addition, it stimulates the mindset of employees to think proactively and it boosts organizational awareness. A suggestion for the future is a full study of a detailed implementation of Dimensional Engineering at Scania aswell as the continuous development of the process and a detailed analysis of all the included elements in the Dimensional Engineering area at Scania.

Sammanfattning

Slutsatsen av den här studien består av en föreslagen implementering av en Dimensional Engineering process på Scania. Processen skall vara integrerad i produktutvecklingen och ingå som ett naturligt sätt att tänka hos de anställda. Det föreslås även att man i framtiden gör en detaljerad analys och en fortsatt utveckling av alla ingående moment i Dimensional Engineering på Scania.

Dimensional Engineering är en metod för att minimera geometrirelaterade kvalitets- och funktionsproblem genom en produkts hela livscykel – från vagga till grav. Ursprungligen är Dimensional Engineering en disciplin som härstammar ur området kvalitetsförbättringar och det finns ett stort behov av Dimensional Engineering i alla produktutvecklingsprocesser. Detta är ett växande område globalt och Scania har nu valt att undersöka och uppmärksamma det har området.

I början av det här projektet genomfördes det en litteraturstudie med syftet att få en djupare inblick i de olika områden som ingår i Dimensional Engineering. Vidare genomfördes fyra externa fallstudier med målet att kartlägga hur andra företag har implementerat Dimensional Engineering i deras produktutvecklingsprocess. En nulägesbeskrivning av Scania och tre interna fallstudier inom området för Dimensional Engineering har också genomförts. Fallstudierna har påvisat att frånvaro av Dimensional Engineering orsakar onödiga problem i konstruktion, produktion och produktanvändning.

Resultatet av detta projekt visar att implementeringen av Dimensional Engineering är lönsamt då flera andra företag har anammat det i sitt arbete och att området fortsätter att expandera. Detta är en aktivitet som minskar tiden till marknad, förbättrar funktionaliteten i produkterna och minskar kostnader i produktutvecklingsprocessen. Dessutom frammanar det ett proaktivt tankesätt hos de anställda samtidigt som det stimulerar organisatorisk kunskapsutveckling.

Abbreviations

CAD – Computer Aided Design

CAT – Computer Aided Tolerancing

GD&T – Geomteric Dimensioning & Tolerancing

DE – Dimensional Engineering/Engineer

PD – Product Development

B-rep – Boundary Represenation

CSG – Constructive Solid Geometry

CIM – Computer Integrated Manufacturing

PQ – Perceived Quality

SPP – Scania Project Planning

SOP – Start of Production

SOCOP – Start of Customer Order Production

KPI – Key Performance Indicator

LSL – Lower Specification Limit

USL – Upper Specification Limit

GPS – Geometrical Product Specification

SPC – Statistical Process Control

RSS – Root Sum Square

WC – Worst Case Analysis

MCS – Monte Carlo Simulation

FEA – Finite Element Analysis

GFA – Geometric Factor Analyzer

RD&T – Robust Design & Tolerancing

GSU – Geometry System Developer

GAE – Geaometry Assurance Engineer

PDM – Product Data Management

RCD – The Styling department at Scania

RTLX – The Truck Layout department at Scania

RCPL – The Cab Layout department at Scania

CFT – Cross Functional Team

NGS – New Generation Scania

RPS – Reference Point System

Contents

1 Introduction

This chapter covers the background of the subject Dimensional Engineering. The goals and the delimitations of this study are also included and discussed.

1.1 Background

Dimensional Engineering is a large part of the quality assurance field that companies that want to remain in the competitive field employ. It has always been an active field in the product development process, but the area is growing and getting more advanced. By establishing processes for Dimensional Engineering the lead-time for new products has shown to be shortened. In order to decrease the development costs, the goal of every company is to produce a product that is perfect every time without the need for post processing or rework. This means that each component must be made perfect every time it is manufactured.

"You cannot step twice in the same river"

- Heraclitus

The quote from Heraclitus above suggests that nothing in this world can be done twice exactly the same way. This holds true when developing products as well. There will never be a component that has the exact same dimensions as any other. Since there will always be variation from the nominal design due to the manufacturing processes, the physical products will be everything but just that – nominal and perfect. They will always have a small deviation from their nominal shape. These deviations can be discovered and controlled through methods and tools from Dimensional Engineering.

In the old days, pen and paper was enough to perform the tolerance stack-up that the dimension deviations caused. Nowadays, tolerance stack-up analyses can be performed in three dimensions with sophisticated software. This provides a more realistic outcome of the result. Tolerance variation analysis software that exist today are advanced and can in most cases predict the outcome to match the reality to almost a hundred percent. In some cases, they can also help optimize the geometrical robustness of concepts, i.e. select the best attachment points between parts in order to increase that stability of the complete assembly.

Quality problems that are geometry related are often discovered too late, normally during assembly. These problems usually occur due to unverified production processes and/or assembly processes. In addition, the geometrical robustness of parts and assemblies is not assured. An investigation regarding how a Dimensional Engineering process would affect the product development process at Scania is thus a natural consequence of the preceding problems. The establishment of a Dimensional

Engineering process at Scania with all that it implies, including organizational methods and Computer Aided Tolerancing tools, is the aftermath of that investigation.

1.2 Purpose

A need for improving the Dimensional Engineering process at Scania has taken place. An assessment of the current Dimensional Engineering process at Scania is thus performed. With the help of the theoretical framework and the case studies, the current state is analyzed and discussed. Conclusions are drawn from these discussions and an implementation of an enhanced Dimensional Engineering process is presented.

1.3 Goals

The goals of this work is divided into three research questions that are examined, answered and analyzed in the end of this report.

RQ1. *How can Dimensional Engineering improve Scania's product development process? This question will only be analyzed and no conclusions will be drawn since this* is a somewhat unpredictable matter.
RQ2. *How should Dimensional Engineering be implemented at Scania?*
RQ3. *How should the Dimensional Engineering software be used at Scania?*

1.4 Delimitations

A part of this work is about examining available Dimensional Engineering software. However, the study will be restricted to only the three most common software. There will not be an in depth examination of the structure of the software, merely a perceptible comparison of each software and how well they would serve at Scania respectively.

A series of reference visits and interviews have been conducted at various companies. Since the time frame is constrained, these visits are obviously limited and so is the retrieved information.

The analysis of the Dimensional Engineering process and the suggestion of its improvement will be restricted to the Cab and Chassis department.

Conclusions of this project will include an implementation suggestion of a Dimensional Engineering process at Scania. This implementation will serve as a goal towards which Scania should aim. No detailed description of the implementation process will be presented, such as how the Dimensional Engineering process should be compatible in the current Spectra/Enovia system.

1.5 Company Introduction

Being one of the world's leading manufacturers, Scania has business segments in more than 100 countries worldwide. A continuous and stable growth has been able to be sustained since Scania was founded in 1891. The explanation is the focus on core values and dedicated employees. Scania's objective is to be a profitable organization by putting the customer first, maintaining respect for the individual and continuously improving quality.

Scania has a strategic platform that focuses on the core processes which are producing trucks, buses and engines. The company has a unique product development process. They comprise a few components made in such a way that they have a big number of possibilities to be assembled. This module structure is an economical and engineering way of system thinking that has assured the competitive strength and uniqueness of Scania. The strategic coherence is prominent within the organization and workers on all levels are well familiarized with Scania's internal processes. An integrated control is in focus which has stimulated transparency and creativity throughout all the divisions of the company (Scania AB, 2013).

2 Method

This chapter depicts the different research methods that are used during the project work. These methods are used for the gathering of data for the literature study in the next chapter.

In this paper, a qualitative study was chosen over a quantitative study. This means that data collection and analysis occurs simultaneously and interactively. The validity of the analysis is determined by internal subjectivity and external validity. External validity refers to how well the theoretical framework links to the investigated phenomena. (Lantz, 2007)

2.1 Literature Study

A literature study on available software will be performed along with a literature study regarding Dimensional engineering, GD&T (Geometric Dimensioning & Tolerancing) and Tolerance Analysis.

2.2 Empirical Study

The objectivity, reliability and validity of both quantitative and qualitative studies are often based on viewpoints. It must also be determined whether the same results could be obtained by other authors. (Gunnarson, 2013)

2.2.1 Interviews

As mentioned above, a qualitative study was selected, where the interviews are of a semi-structured character. The semi-structured nature means that the authors set fixed questions with open answers and the opportunity for follow-up questions. (Lantz, 2007)

2.2.2 Case Studies

The requirement for the population of the case study should include is that respondents must have very good knowledge of the area being examined.

3 Literature Study

The goal of this chapter is to provide a deeper understanding for the subject at hand. A description of a general product development process followed by the product development process at Scania is the start of the literature study. Dimensional Engineering as a method is also described along with the relevant tools and research areas for this process.

3.1 Product Development Process

A product development process is always initiated by identifying customer needs. Concept generation and detail design, prototyping and testing and production ramp-up are some of the phases that a product goes through before being delivered to the customer. In order to shorten time-to-market, many companies today strive for a product development process where the different phases can be performed in parallel. This can be achieved with an integrated organization that has a common goal and efficient use of product development tools (Ulrich & Eppinger, 2012).

3.1.1 Product development tools

Product modeling technology is a way to share information and integrate technology between different departments within a company.

Data conversion is necessary when a product model is put through the different processes in a PD process. Knowledge exchange is limited between these systems and information can be lost or inaccessible in certain software. A product modeling structure that supports a coherent product modeling throughout the whole product lifecycle is important for efficiency and high quality products.

There are four different product modeling methodologies that are usually described in literature. The three relevant methodologies are solid product modeling methodology, feature-based product and STEP-based product modeling. These three metohodologies are described below (Yang et al, 2008).

Solid product modeling

Two common ways of modeling a 3D shape is through a product modeling method called "Boundary representation" (B-rep) and "Constructive Solid Geometry" (CSG). B-rep represents the solid object by edges and vertices and the data is stored directly into the same. This systems is of advantage for a fast display. CSG is a modeling method that uses primitive solids that construct a product by using operations that link the primitive solids together. The CSG modeling method thus creates complex objects but uses very little storing space. Solid modeling represents a product with rather detailed geometry, dimensioning and tolerance settings. However, it lacks the ability to evaluate a product throughout the whole PD lifecycle, such as product functionality information and manufacturing data (Yang et al., 2008).

Feature-based product modeling

The feature-based product modeling method can be seen as an extension to the solid model product modeling. It is more concerned with the computer integrated manufacturing environment (CIM) and is gaining in popularity. The features can store and integrate information throughout the whole PD lifecycle. This means that the design features easily can be integrated with the manufacturing features which is a combination of manufacturing, assembling and inspection. This system allows design improvements, connecting product geometry with functionality and focusing on the high levels geometry shapes. Product data within the areas is connected and associated, which differs from the solid product modeling method (Yang et al., 2008).

3.2 Scania's Product Development Process

Scania's product development process is generally divided into three different phases: Pre Development, Product Development and Product follow-up. These phases are also known as yellow arrow, green arrow and red arrow, respectively, see figure 1. The pre-development comprises Research, Advances Engineering and Concept Development. Small teams lead by Senior Engineers are usually working in the yellow arrow. The main goal of the green arrow is to assure market introduction at a certain point of time. This requires a lot of cross-functional work coupled with a high delivery precision from all the involved parts. The green arrow is not restricted to large projects; smaller projects are also run in the green arrow. Smaller projects include DOL, FFU and S-order projects. It is important to manage and update the current product range and this is done in the red arrow, also known as Product Follow-up (Scania CV AB, 2013).

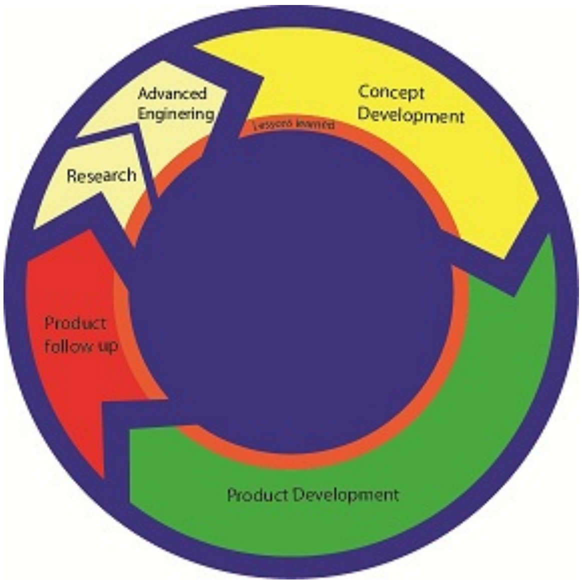


Figure 1 Scania's product development process

Scania's product development process relies on certain fundamental principles:

- Product ownership – The line organization owns the product. The projects are responsible for development and industrialization but can never own the product.
- Cross-functional and parallel – Product development at Scania is cross-functional. All cross-functions are involved at the initiation of the product and continue to be so until the product has been fully developed.
- Continuous improvements – Scania has been working with continuous improvements since 1981. This takes place on all levels in the company. If everyone focuses on the customer and their need, the efficiency of the process will be improved.
- Uncertainties – There are a lot of uncertainties in a project, especially in the early phases of the project. Iterations and rework are therefore a necessity. Uncertainties are greater in the concept development phase and there will be more iterations because of this. Small competent groups work in the yellow arrow in order to quickly produce and test new concepts. Only when a concept has been adequately verified and uncertainties have been minimized the project moves on in to the product development phase.
- Configuration – All project should have a cross-functional project team. The team needs to configure a plan with milestones that clearly show how to reach the project targets (Scania CV AB, 2013).

3.2.1 Yellow arrow – Pre Development

As mentioned earlier the pre development phase can be broken down into three sub-processes: Research, Advanced Engineering and Concept Development.

In order to be more competitive Scania always strives to gain knowledge about future technology within strategic areas, which they do by carrying out research. Scania does this together with strategic partners and academies. This knowledge is then utilized in the advanced engineering phase.

Technologies are evaluated in order to meet the customer needs and establish Scania's benefits. After this phase, Scania knows whether a technology is suitable for them or not. This information is then passed on to the next phase that is the concept development.

Behind each and every concept there must always be a demand that is clearly described. It can be a customer demand, a legal requirement or a demand from research and technology development. The demands are summarized in a demand statement after they have been analyzed with the intention of examining how well they agree with the goals set by the company's management. A decision meeting is held in order to decide which demand statements that should continue to concept development. After this a project plan is configured. The project plan contains information about deliverables that are required in order to reach the status “concept ready”.

Scania believes in using small cross-functional teams lead by a senior engineer in order to satisfy customer needs with the shortest time-to-market possible. By working iteratively uncertainties can be removed and results can be obtained quickly and efficiently (Scania CV AB, 2013).

A concept is fully approved after the following requirements are fulfilled:

1. Performance/property objectives are described
2. Profitability analysis has been performed
3. The concept is plannable
4. The concept has been modularized
5. The concept has been cross-functionally accepted

3.2.2 Green arrow – Product Development

When the project reaches the green arrow it becomes a Product Development project (PD project). Green arrow projects are characterized as being highly plannable and that the project deliveries have a high precision. Most of these projects will be offered to the customer. At this stage of the project the uncertainties are so low that 9 out of 10 project will stick to the time schedule.

PD projects are highly cross-functional and involve a lot of co-workers. In order to coordinate the development and industrialization of the product and/or the service PQ engages the project office. PQ is Scania’s decision forum for the industrialization of products and services. The role of the Project Office is to support the project manager in his cross-functional work. They do this by providing the methods and tools that the project manager needs. All delivery functions within Scania are commonly called Line Organization. The line organization is responsible for delivering at the agreed time.

By using the method called SPP, Scania Project Planning, the project is planned in order to develop the product efficiently. The project will be broken down into activities that focus on the expected benefits, the chosen concept, affected applications and demands. The configuration results in The Project Definition. When The Project Definition is approved, the project will begin the development.

The Project Definition acts as a guideline when product development continues. Adapting concepts to applications is a focus and the project manager is in control using a number of milestones. A process verification is done when the project reaches Start of Production, (SOP). Some adjustments may take place before the project moves on to Start of Customer Order Production, SOCOP (Scania CV AB, 2013).

3.2.3 Red arrow – Product Follow-Up

To be able to improve quality and/or reduce cost the product range is maintained and updated. This work is done by the Product Follow-Up organization with the support of Purchasing and Production (Scania CV AB, 2013).

3.2.4 R&D Factory

The goal of R&D is to satisfy the future needs of its customers by developing high quality heavy vehicles, engines and services. R&D Factory contains core values, principles and methods that aids Scania when they take on these challenges. The product development process is supported by the core values, principles and methods of the R&D Factory (Scania CV AB, 2010). A house is used to describe the philosophies of the R&D Factory, see figure 2.

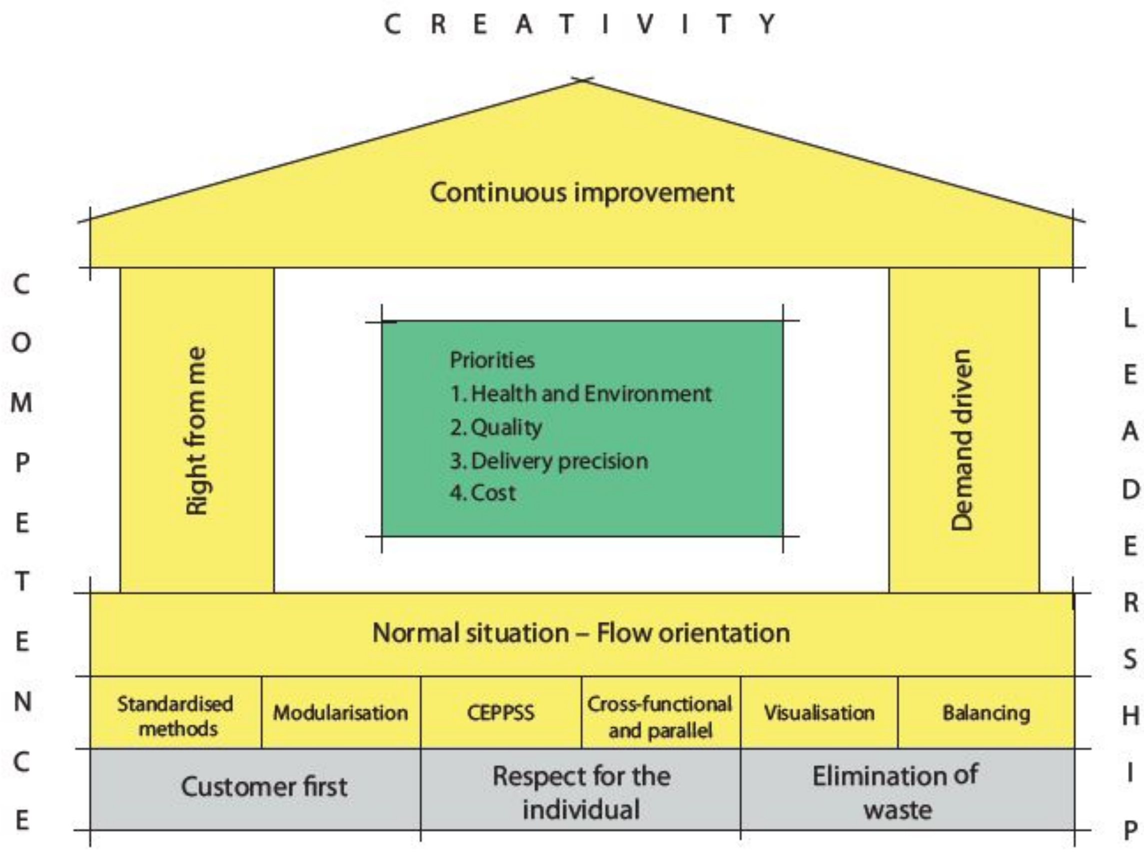


Figure 2 R&D Factory

R&D Factory enables Scania to continuously improve their competitiveness and satisfy their customers' needs by moving towards a stable and reliable product development process (Scania CV AB, 2010).

R&D Factory – Core Values

The company culture at Scania is reflected by the core values. Customer first, Respect for the individual and Elimination of waste are the core values, see figure 3 (Scania CV AB, 2010).

Customer first	Respect for the individual	Elimination of waste

Figure 3 The core values of R&D Factory

Customer first - The focus lies on the end-customer throughout Scania's whole value chain. Customers include Scania's end customer but also internal customers. Value is always defined from the customers' point of view. Knowing what is of value to the customer is critical in order to make sure that the right thing is done (Scania CV AB, 2010).

Respect for the individual - Refers to recognizing and using the employee's knowledge and experience as well as always trying to achieve continuous improvements within the operations (Scania CV AB, 2010). Individual development and delivering the right quality on time is also part of respect for the individual.

Elimination of waste - Anything that does not add value to the end-customer is seen as waste. By eliminating waste the competitiveness can be strengthened. Examples of waste are delivery delays or process disruptions (Scania CV AB, 2010).

R&D Factory – Success factors

Leadership, competence and creativity are the three success factors of R&D Factory, see figure 4.

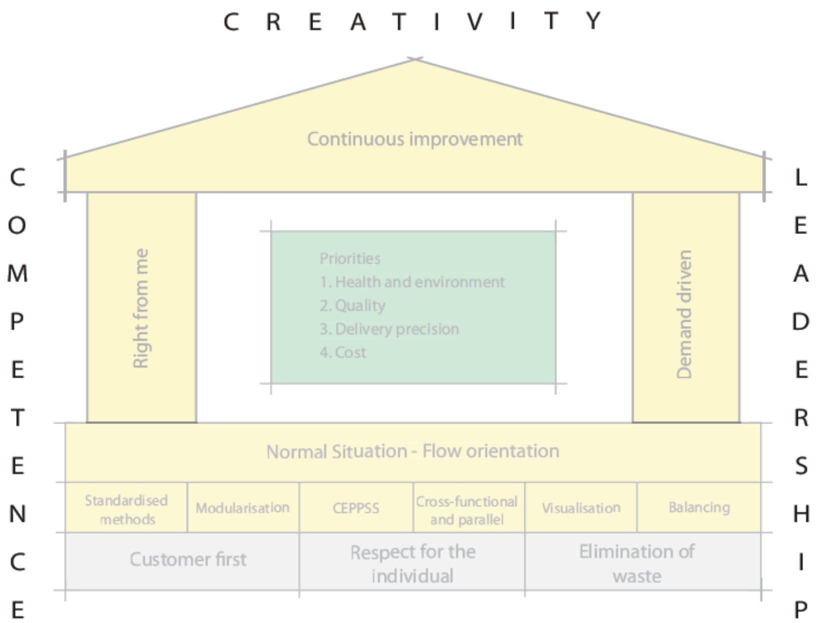


Figure 4 R&D Factory success factors

Leadership and co-workership - Scania has five leadership principles that are meant to be a way of thinking for both managers and employees. The principles are a foundation upon which leadership is made possible in every part of the organization. Scania believes that the managers should be a coach. This encompasses supporting the employees in order for them to develop to their full potential and act as good role models. It is allowed to make a mistake at Scania. Scania believe that you must learn from your mistakes and make sure that they do not reoccur. Good co-workership is required in order to achieve job-satisfaction and developing operations (Scania CV AB, 2010).

Competence - A big part of the long-term success of Scania is due to the constant development of their competence and them understanding the big picture. Competence is developed through training, experience and responsibility (Scania CV AB, 2010).

Creativity - Scania believes that creativity is a prerequisite to innovation. Important factors for creativity are freedom and a playful work environment (Scania CV AB, 2010).

R&D Factory – Principles

Everything Scania does is a part of a flow and Scania has four principles that supports them in decision making in every situation. The four principles are; Demand driven; Right from me; Continuous improvement; Normal situation – Flow orientation (Scania CV AB, 2010).

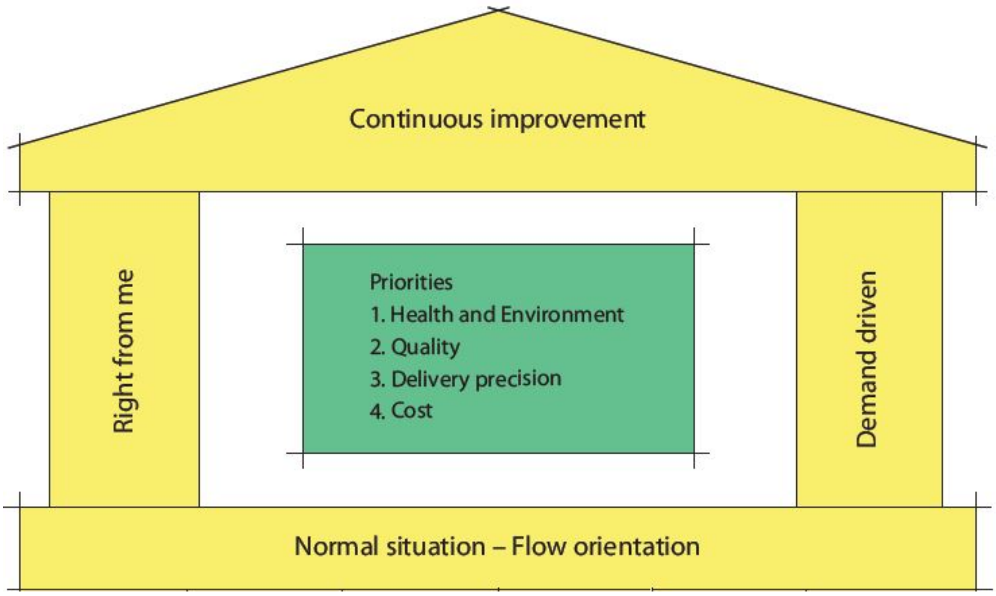


Figure 5 R&D Factory Principals

Flow orientation - The purpose of the flow orientation is to ensure satisfied customer, short lead times and eliminating waste. This requires that Scania focuses on the customer's needs. Flow orientation requires that deliveries be in constant movement. The flow at R&D primary consists of knowledge and information. Value is added in their projects by adding information to newly developed properties and by adding new knowledge to Scania's knowledge bank (Scania CV AB, 2010).

There is a difference between information flow and knowledge flow. Deliveries to projects are an information flow. If a test is run and the acceptance criterion is met, a delivery is made to the project. The test can be continued in order to gain more information and knowledge. For example, the test can be run until the component break and knowledge about the components lifecycle can be attained. Delivery is then made to the knowledge bank, see figure 6 (Scania CV AB, 2010).

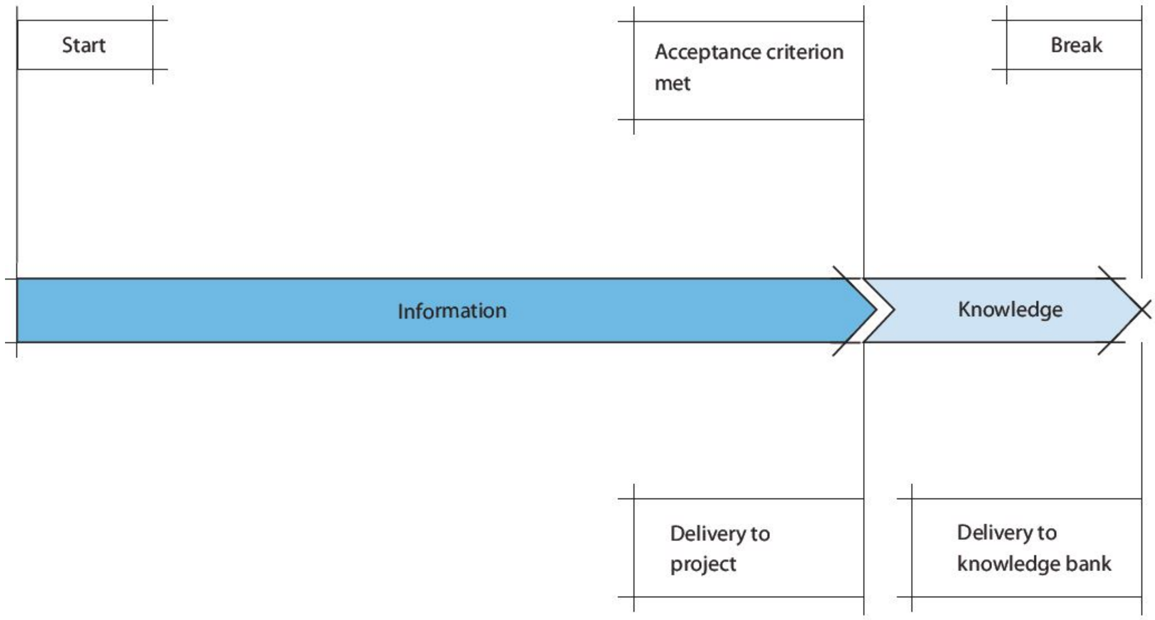


Figure 6 Information and knowledge flow

Demand driven - The flow is driven by the demand and deliveries occur when the next step in the chain demands it. This way of working reduces waste and supports Scania's planning. This principle requires knowledge of the internal customers' demands across the different sections of the flow. The idea is to create a "pull" system where deliveries only occur when it is needed. Small, well-defined deliveries with short lead times are used in order to support this (Scania CV AB, 2010).

Right from me - It is important to get things right from the start in order to keep the agreement with the previous and the next customer in the flow. This is achieved by following standardized work methods. If a standardized method is followed and the result is negative the standard has to be improved.

The next stage in the flow is the internal customer and they are responsible for evaluating the delivery and its quality. If the quality does not meet the expected quality the recipients are supposed to give feedback to the previous step. The ones who deliver are responsible for the rework (Scania CV AB, 2010).

Continuous improvement - Anything that does not add value to the next stage of the flow is considered waste, which should be eliminated. Continuous improvements enable the improvement of guidelines, procedures and processes. It is crucial to identify what value is for the upcoming stages of the flow and the end-customer. In order to identify waste one must first identify value. Everything that is not adding value is waste and should be used as input in the continuous improvement work (Scania CV AB, 2010).

R&D Factory – Priorities

Scania always puts their employees first and their top priority is therefore Health and environment, Quality, Delivery precision and cost. These priorities are monitored using Key Performance Indicators (KPI's). In abnormal situations the priorities are followed in the order that is seen in figure 7.

Figure 7 The priorities of R&D Factory

3.3 The Dimensional Engineering Process

All manufacturing processes stable or instable are affected by variation. This causes manufactured products to not always meet the requirements that are expected of them. When these variations accumulate it can result in products that do not fulfill functional, aesthetic or assembly conditions. Unfortunately these problems are normally exposed too late, normally during pre-production or right before market introduction. These problems usually occur late in the product development stage and therefore the costs are often amplified when making product changes (Söderberg, 2006).

A way to manage variation is to have permissible limits of variations called tolerances. When setting tolerances it is important to balance function and quality aspects against manufacturing constraints and cost aspects (Söderberg, 2006).

Dimensional Engineering is an important activity in the product development process. Its aim is to secure that the geometric requirements are met. A big part of dimensional engineering is understanding the origins of the variations and how the manufacturing process, the assembly process and the product concept combine and affect the final product (SWEREA, 2013).

It is important to have a holistic approach regarding the dimensional engineering processes within the organization in order to achieve higher quality and become more efficient. Concurrent engineering is essential in order to efficiently develop products and manufacturing processes. This requires that product concepts and production concepts can be verified before start of production using simulation tools. This improves the ability to “get it right from the start”. This is crucial when the goal is to fulfill set requirements from the start without the need for post processing or adjustments. Methods and tools for dimensional engineering are needed in order to make this possible (SWEREA, 2008).

Dimensional Engineering covers all activities that are aimed at achieving and improving product quality. This includes understanding the origin of variation and how it is amplified by unverified concepts that are geometrically sensitive. Tools that enable the use of robust design and simulation and visualization of variation are powerful when the goal is to increase product quality. Another important success factor is the efficient use of experience and data from previous solutions. Robust concepts result in high quality products, see section 3.4.6. Geometrical robustness is free in the sense that it does not require any investments. Robustness is achieved by placing reference points at beneficial positions. Robust concepts also result in reduced costs for adjustments, rejections and complaints (SWEREA, 2013).

Dimensional Engineering tools allow one to visualize variation and tolerance stack up. The benefits of a high-quality Dimensional Engineering process are numerous and include reduced cost due to less prototypes, shorter lead times for new products and cheaper products due to no rework or post processing (SWEREA, 2013).

The product development process can generally be divided into three different phases:

- Concept phase
- Verification and pre-production phase
- Production phase

Figure 20 depicts the Dimensional Engineering process and activities for controlling geometrical variations.

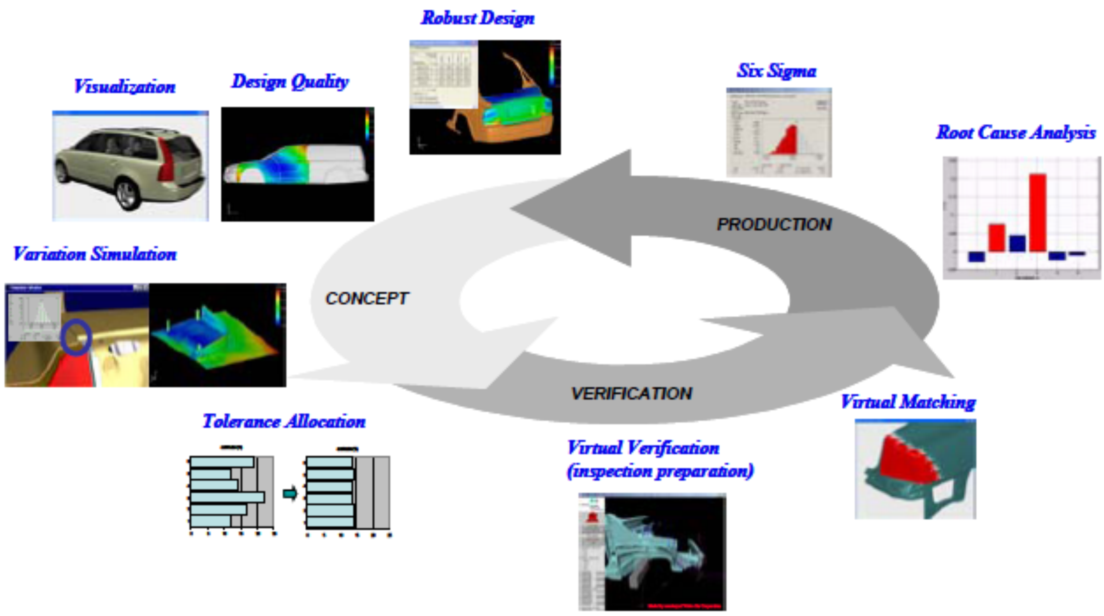


Figure 8 Dimensional Engineering process and its activities

3.3.1 Important dimensional engineering aspects

There are six important aspects to consider when working with dimensional engineering (Söderberg, 2013):

1. Which are the critical dimensions of the final products?
2. Which components contribute to the critical dimensions?
3. Create geometrically robust concepts by optimizing reference points. Optimizing tolerances on a component level in order to fulfill critical dimensions. Using statistical variation simulation does this.
4. Costing – Balance cost and tolerances.
5. Measurement planning – How should deviations on components be measured?
6. How should measurement data be analyzed and be returned to simulation?

3.3.2 Concept Phase

The product and its production concepts are developed in the concept phase. Available production data is used virtually to analyze and optimize product concepts to withstand the effect of manufacturing variation. By adjusting the reference points the robustness of the design can be optimized. Statistical tolerance analysis is used to verify the concept against assumed production system. The visual appearance of the product is also optimized. Tolerances are allocated down to part level with geometrical sensitivity, manufacturing cost and quality trade-offs taken into consideration.

Split-line analysis and optimization

The relation between hoods, doors and panels are important quality characteristics in the automotive industry. Aesthetical aspects are important and of course the functional aspects are even more important. For example, it must be possible to open the door without any interference with other parts. The quality appearance of a vehicle is often judged by the quality of the split-lines. A split-line relation can be described using requirements on flush, gap and parallelism etc. between two parts or subassemblies. The optimal split-lines in regard to gap and flush variation can be calculated once the reference concept is known.

Robust design

In the early stages of the concept phase when production data is unknown or limited, the focus should lie on developing robust concepts. A robust design is insensitive to variation and disturbance. Decreasing the sensitivity of a concept can result in a wider tolerance range on geometry features, which in turn lowers the manufacturing cost. In early concept phases the focus should be on how parts are located relative to each other. Different fixturing concepts can be considered depending on the sensitivity of the assembly (Söderberg, Lindkvist, 2002). By varying the position of the reference points on the virtual assembly model the robustness of the concept can be optimized. Critical geometry features should be placed in a robust area, either by changing the position of the locators or by changing the position of the critical feature.

Statistical variation simulation

Expected variation in critical final dimensions can be simulated and analyzed using statistical variation simulation (SWEREA, 2008). This is imperative in order to determine the quality level of a product before production starts. Statistical variation simulation can be used to analyze and improve critical assembly dimensions before the first physical prototype is built. Input in the form of part tolerances and assembly variation are applied to the virtual model and the output of the simulation is a prediction of the variation of the critical dimensions. This enables the model to be verified against the assumed production system (Söderberg, 2006).

Visualization

The possibility to use visualization as a tool enables the visual appearance of the product to be optimized. Virtual geometry verification is traditionally conducted in the early design phases with nominal models. Non-nominal verification is conducted later in the design process, during physical test series also known as prototypes. This is not ideal since post-conceptual changes are linked to higher costs. The variation simulation model can be used in conjunction with Virtual Reality tools in order to create a virtual environment for non-nominal geometry verification. Geometrical variation is introduced to the model in the form of *component variation* and *assembly variation*. The results from the variation simulation can then be visualized using the Virtual Reality tools. This enables factors that have an impact on the quality appearance of the product to be evaluated in a qualitative manner. Such factors can be gap and flush relations between doors, hoods, fenders and other parts of the vehicle.

It is important to keep in mind there is a difference in perception between virtual and physical models when making decisions based on virtual models in early phases. There are several parameters that affect the perception of distance. Such as viewing mode, texture, clear coat, color etc. The perception of the distances of gap and flush are affected by different parameters. They should therefore be evaluated using different configurations in order to minimize the error of distance. A recommendation is that gap should be evaluated in stereographic view along with texture, Clear Coat, similar colors of parts and a full model whereas flush should be evaluated with a small distance of the gap on the same split lines, same colors and with a full model.

Tolerance allocation

Tolerance allocation is an important step in the design process if the goal is to optimize the relation between quality, performance and cost. How tolerances should be allocated to parts and features must therefore be taken into consideration. Tight tolerances are normally related to high quality but also usually to high cost, this must be taken into consideration when alreference tolerances.

3.3.3 Verification and pre-production

In this phase adjustments are made to the production system and the product to correct errors and prepare for full production. The product and the production system are physically tested and verified. Inspection preparation actions are taken. This means that inspection strategies and inspection routines are decided.

Inspection preparation

Verifying the product and gathering information about the production system that can be used for correction, adjustment or compensation is enabled through inspection preparation. This is achieved by finding the optimal and minimal set of inspections points. It is common to use a large set of inspection points during pre-production in order to capture a lot of process information and make adjustments. A smaller set of inspection points are needed to be able to monitor the process during full.

Virtual trimming
Form errors on newly produced components in pre-production can cause functional or aesthetic problems during assembly. A way to manage this problem is to adjust the locators and thus reposition the component, also known as trimming production (Söderberg, 2006).

3.3.4 Production Phase

The focus in this phase is to detect and correct errors as the product is in full production as well as adjusting the production process. (Söderberg, 2006)

Monitoring the production process by inspecting the final product and gathering inspection data is a key to be able to detect and correct errors in the production system.

3.3.5 Variation

Designers work in a nominal world with perfect features and relations between dimensions. Since the world is imperfect and one feature is never the same as another, the real product will never match the perfect one made in a CAD software. Tolerances are needed in order to ensure that functional and aesthetic demands are fulfilled. The tolerances set on a drawing determine how much the dimensions are allowed to deviate from specified value. There are three different important aspects of variation – the designer point of view, the manufacturing point of view and the tolerance analysis point of view (Fischer, 2011):

Design

- On a drawing, the designer decides how much a tolerance feature is allowed to deviate from the specified value. This is variation from his point of view. It is possible that a value of a feature is right on the tolerance limit. Looking at a worst-case scenario, all the values are set on the tolerance limit and the purpose of this is to see how the product will behave if produced at the allowed extremes.

Manufacturing

- According to best practice, the limits for a functionally acceptable part when manufactured or assembled are represented by tolerances. The operations must thus be executed in a manner that will satisfy the set tolerances and this is verified through measurements.

Tolerance analysis

- A tolerance analysis is performed in order to analyze the variation of a tolerance stack-up. All deviations from the specified values of the features that contribute to the whole assembly are thus evaluated in the tolerance analysis.

Sources of variation

The precision of the manufacturing and the assembly process affect the variation of the components and the assembly. Geometrical variations in components and in the assembly process may cause unfulfilled functional, aesthetic and assembly demands. The geometrical robustness of the conceptual design can amplify or suppress the geometrical variation and this will affect the final dimensions and the geometric quality of the assembly. The picture below illustrates this (SWEREA, 2008).

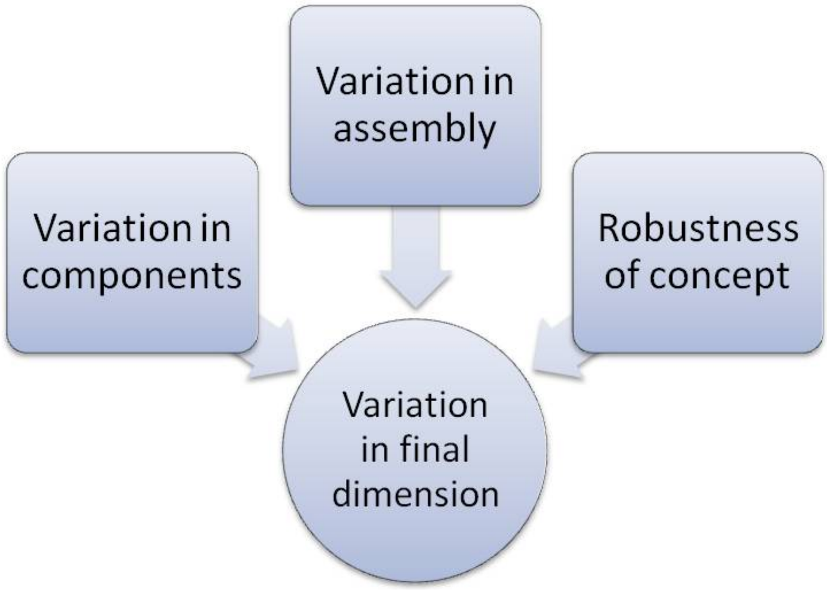


Figure 9 Sources and causes of variation in the final dimension

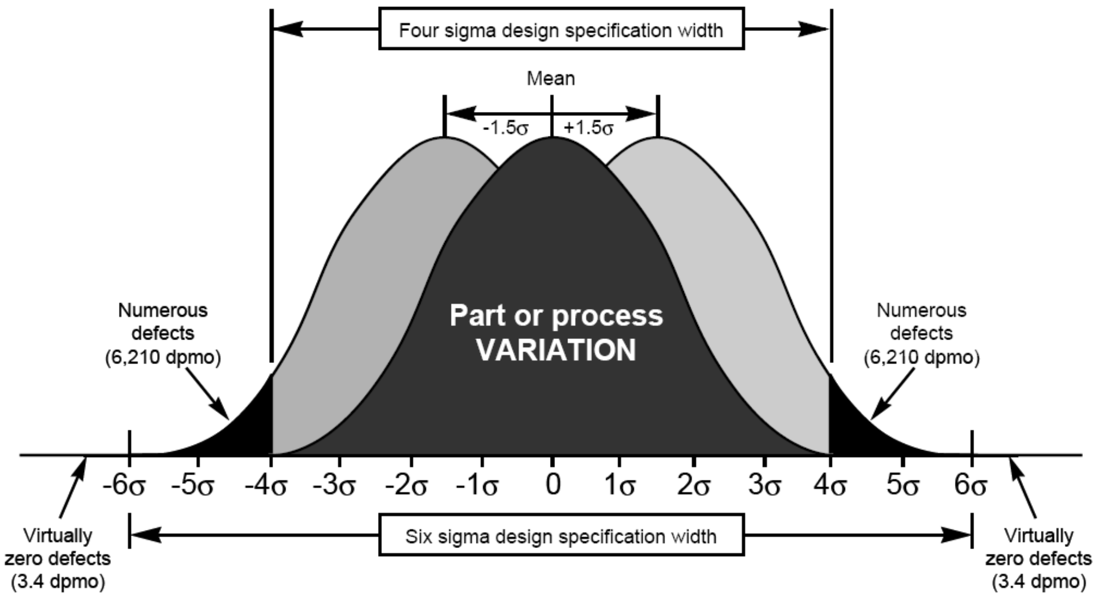
Assembly Process Variation

The variation from the assembly process is a significant contributor to the overall variation of the final product. It is imperative that the designer understands the assembly process and has it in mind during design. It can lead to serious problems if the wrong assembly process is assumed during design. The relationships between features of assembled parts are strongly dependent on the sequence of the assembly operations. It is also very important that the tolerance variation analyst understands the assembly process when performing variation simulation.

Process Capability

As previously explained, the real world can differ quite a bit from the nominal world. Geometric forms will be flawed since the manufacturing processes are imperfect and inconsistent. The aim of every company is to increase the process capability in order to get products that are as close to the nominal ones as possible. There are a number of ways to measure process capability which is a process' ability to produce components that are within the set tolerance range and close to their target values (Cano et al., 2012).

An index is usually referred to, denoted C_p, which is a measure of the range of the distribution. It assumes that the process mean is centered and the process output is normally distributed. In some cases, however, a process is not always centered around the target. It can be skewed in either direction and this needs to be taken into account. Even though a process has a good C_p, meaning that the distribution is small and the specification width is large, the data output can be far away from the target value. C_{pk} is an index that shows how well centered the process is. Figure 10 shows a common shift of 1,5σ that can cause the data output to fall outside of the tolerance limits (Cano et al., 2012).



For a product to be virtually defect free, it must be designed with both normal process variation and process drift in mind. With these things considered, a Six Sigma design specification width would produce a yield of 99.99966%–3.4 defects per million opportunities or virtually zero defects.

Figure 10 A six sigma process with a 1,5σ mean shift (Bonacorsi, 2013)

The formulas for C_p and C_{pk} are shown below.

$$C_p = \frac{ULS - LSL}{6\sigma}$$

$$C_{pk} = \min\left[\frac{USL - \hat{\mu}}{3\hat{\sigma}}, \frac{\hat{\mu} - LSL}{3\hat{\sigma}}\right]$$

Normally, C_p is enough to show the quality demands of a process. Sigma levels increase with increased C_p numbers and the number of scratched parts decrease.

C_p	Sigma	Percent	Deviations/Errors
0,33	2	68,3%	32 out of 100
0,66	4	95,5%	9 out of 100
1	6	99,73%	3 out of 1000
1.33	8	99,9935%	65 out of 1 million
1,66	10	99,999991%	9 out of 100 million
2	12	99,9999998%	2 out of 1 billion

Table 1 Process capability

Normal distribution

Unknown and real-valued random variables are distributed approximately normally. When the mean is zero, the distribution can be illustrated in a normal distribution curve which can be seen in the figure 11. The mean, μ, represents the expected value and the lower and upper specification limits depict the tolerance limits. How much a value deviates from the expected value is known as the standard deviation, σ. The span over which a process can vary is called the variance, denoted σ^2.

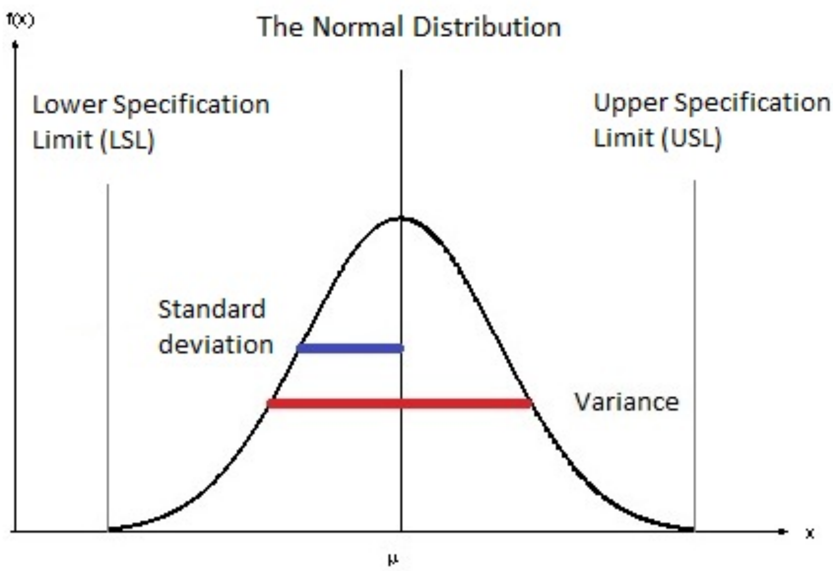


Figure 11 A normal distribution curve

Standard deviation

A small standard deviation indicates that the values are close to the mean, whereas a big standard deviation considers the possible outcomes over a bigger range. 68,26% of the values are within one standard deviation, 95,44% are within two standard deviations and 99.73% are within three standard deviations etc. A six sigma interval predicts a process that ranges in three standard deviations in each direction, see figure 12.

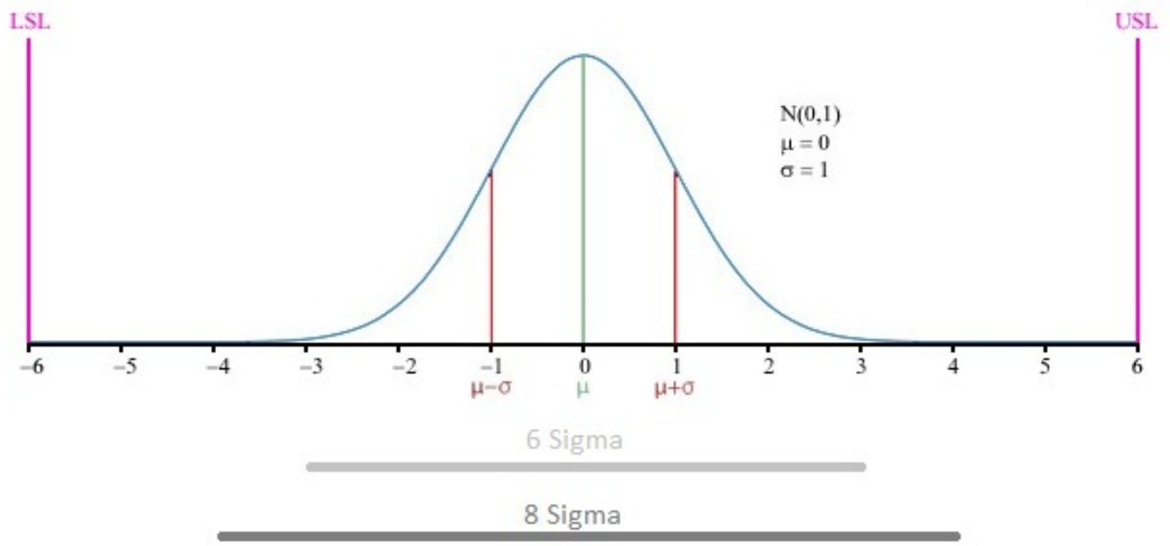


Figure 12 Standard deviation

3.3.6 Requirement Specification

The requirements of a product can be set in two ways: according to the Top Down or Bottom Up approach. In the Top Down arrangement the end product (assembly) is specified with functional requirements. This assembly is then broken down to sub-assemblies and parts that each has their own functional requirements. The parts are broken down further to features and feature elements, see figure 13. It is also possible to go the reverse way, meaning that all the smallest feature elements are given specific requirements and that the features and parts are progressively building up to the final assembly with the final requirements specification (SWEREA, 2013).

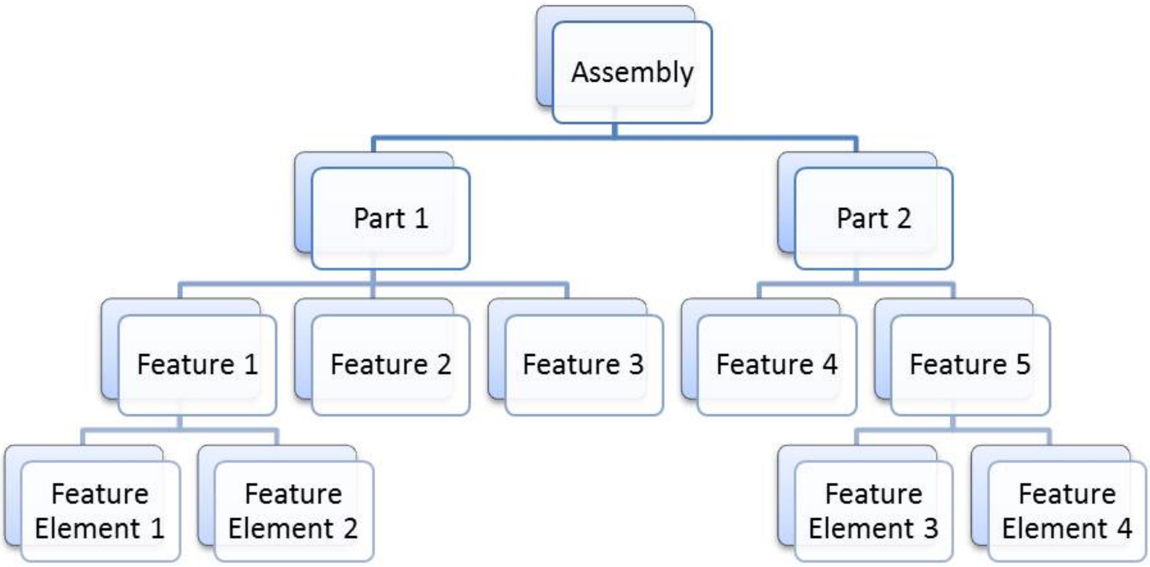


Figure 13 Example of a requirement specification breakdown

How an enterprise chooses to specify the product requirements and manufacturing methods depends on their business strategy and/or manufacturing strategy. Some companies begin with investigating and understanding market requirements followed by determining the requirements of the final product. This is synonymous with the Top Down framework. Another way is to let the manufacturing methods be the outline of the product possibilities. In this approach, the process performances determine the requirement specifications of the feature elements and subsequently the final product. An optimal requirements specification framework would be one in which it is possible to iteratively go up and down the specification tree. Flexible organizations that have the ability to appreciate the importance of the market demands as well as to adapt and improve their manufacturing processes are the ones that can accomplish this. This aligns the business strategy with the manufacturing strategy and can, if done correctly, resonate all through the organization and advance the whole product development process (Brown & Blackmon, 2005).

Critical dimensions on both components and assemblies should be identified. This helps to break down the requirements specifications into important tolerances. A tolerance on one part may affect the tolerance for another part. Different variants of tolerance chains are simulated and the task is to find the shortest tolerance chain i.e. a product that meets the functional and aesthetic demands with the minimal manufacturing cost (SWEREA, 2013). How to calculate tolerance chains is further discussed in the chapter regarding *Tolerance Analysis.*

3.3.7 Geometrical robustness

Geometrical robustness refers to how sensitive a part or an assembly is to geometrical variation. A geometrically robust part is less sensitive to variation and the variation is thus suppressed. However, a part that is not geometrically robust will amplify the variation. In the early product development phases when manufacturing data is limited the focus should lie on optimizing the geometrical robustness of the concept, this is known as robust design. By using the robust design method early in the product development process the problem of coupled tolerances can be minimized. A coupled design is more sensitive to geometrical variation due to the fact that there are several parts that contribute to the amplification of variation in the final measurement. A coupled design that is not geometrically robust will amplify the variation and small tolerances have to be assigned in order to fulfill desired requirements. However, this is expensive and can be avoided by incorporating robust design during the early stages of the product development process (Söderberg, 2006).

Geometrical robustness can be achieved by improving the position of the reference points. The placement of the reference points affects the geometrical robustness of parts and assemblies. A general rule of thumb for reference point placement is to spread the points as much as possible across the surface in order to maximize the robustness. This is explained more in depth in the section on reference systems, see section 3.4.6.1 (SWEREA, 2008).

The robustness of a concept is dependent on the relation between the input and output variation. This can be illustrated with a simple beam support example, which is seen in figure 8. The robustness is controlled by the position of the support. If the support is moved to the left the robustness will be increased and thus suppress the input, whereas moving it to the right will decrease the robustness and thus amplify the input variation. The output variation is affected by the position of the support beam and the input variation (Wickman, Söderberg, 2003).

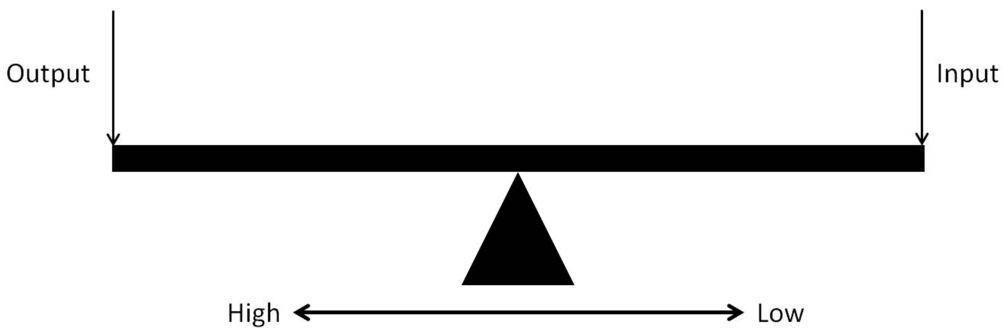


Figure 14 Beam support

Reference systems

A physical body or object has six degrees of freedom. Translation in X, Y, Z and rotation in X, Y and Z, see picture below (SWEREA, 2008).

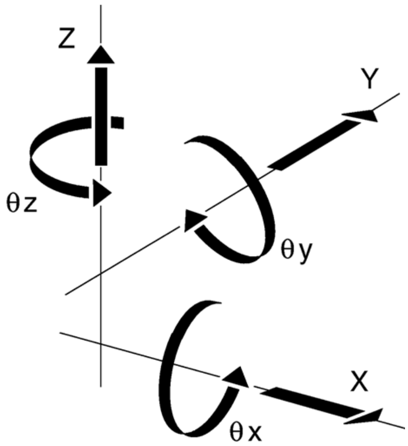


Figure 15 A physical body has six degrees of freedom, 3 translations *and 3 rotations (Wertel, 2013)*

A reference system is made up of three orthogonal planes A, B and C. The three planes represent complete surfaces and the shape of the surfaces can therefore affect the reference system. To avoid this, reference points are used. These points are tied to the orthogonal planes. The references define the part's location in space relative to other parts, see figure 10 (SWEREA, 2008).

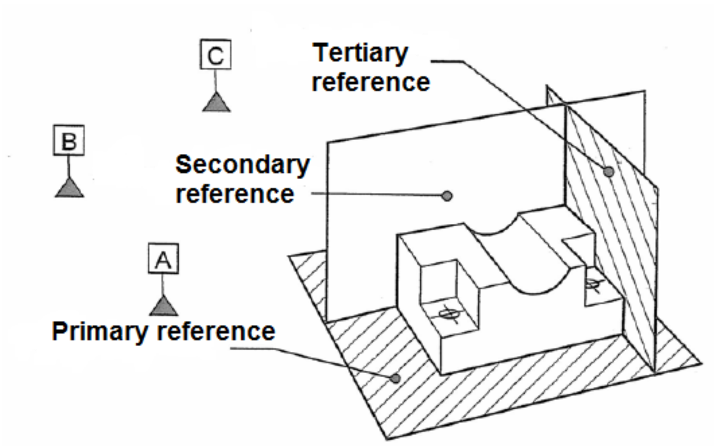


Figure 16 Reference system consisting of three orthogonal planes A, B and C (SWEREA, 2008)

References should invariably consist of the features of the article that act as the position designation in the installed position, so called mounting points. References should be chosen in such a way that they best meet the end requirements and must reflect the assembly function. These references should be used consistently throughout all the processes; design, manufacturing, measurement and assembly, In some cases, you may sometimes need to "grip" a detail, but this must be done in a systematic way. Wrongfully chosen references can overthrow function, assembly, requirement setting and fit (SWEREA, 2008).

- The references determine the method to be used in the manufacturing process.
- Geometric Dimensioning and & Tolerancing requirements are based on the references.
- Changing the references may have implications on the product hierarchy. Fixtures and installation equipment may need to be rebuilt and measurement methods changed.
- The complex product that exists today requires good documentation of the references at a early stage of the project (SWEREA, 2008).

The picture below illustrates optimal positioning of reference points.

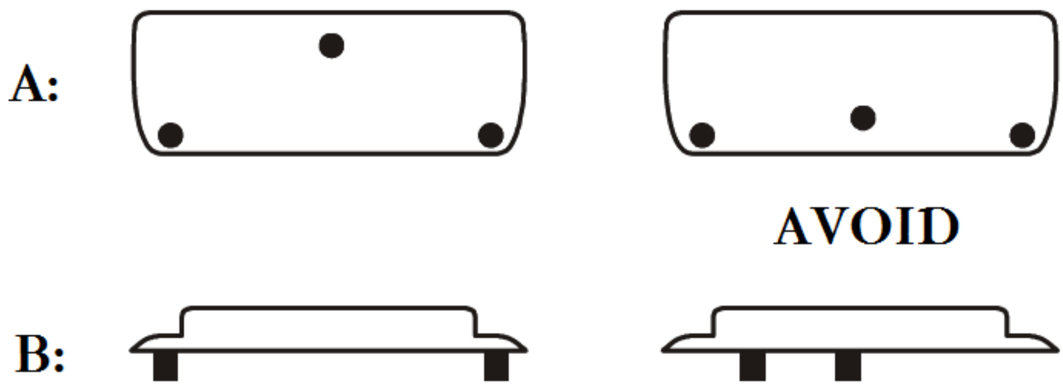


Figure 17 Optimal placement of reference points (Swerea, 2008)

In order to maximize robustness the placement of the reference points have to be chosen so that the space between the reference points is maximized. The left picture illustrates this. Here, the reference points are placed as far apart as possible for part A and B.

Support points
In some cases the support from the six reference points are not enough. This is usually the case for slim plastic details (non rigid parts) that may deform due to gravity. Support points can be used in those cases in order for the part to keep its form (SWEREA, 2008).

3-2-1 Target system

The purpose of a reference scheme is to lock a part or an assembly to its six degrees of freedom. The figure below shows an orthogonal 3-2-1 reference scheme with six reference points (Söderberg, 2006).

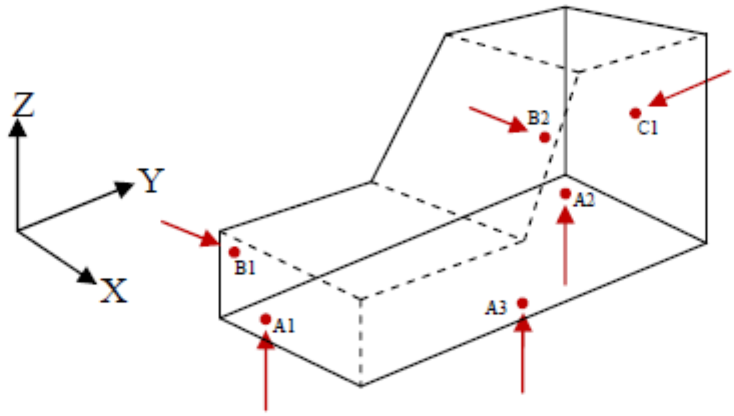


Figure 18 Orthogonal 3-2-1 reference scheme

The six reference points are A1, A2, A3, B1, B2 and C1. Points A1, A2 and A3 are the primary reference points and form the primary reference plane which controls three degrees of freedom, translation in Z (TZ), rotation around X (RX) and rotation around Y (RY). The secondary reference points, B1 and B2, forms a line on the secondary reference plane which controls two degrees of freedom, translation in X (TX) and rotation around Z (RZ). The last reference point C1, on the tertiary plane controls one degree of freedom, translation in Y (TY). (Söderberg, 2006)

Below is an example of how references can be assigned.

1. Three primary reference points, X1, X2 and X3, are distributed in a way that maximizes the distance between them. These form the primary reference plane and control 1 translation (TX) and two rotations (RY and RZ).

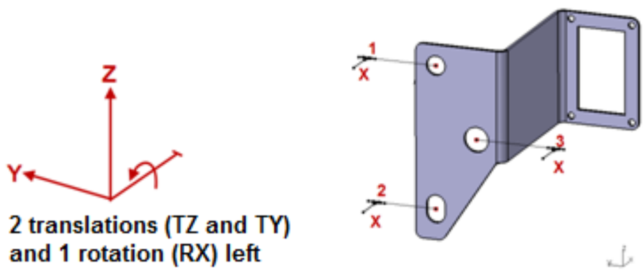


Figure 19 Primary reference points

2. The two secondary reference points, Y1 and Y2, are also distributed in a way that maximizes the distance between them. The two points form a line that controls two degrees of freedom (TY and RX).

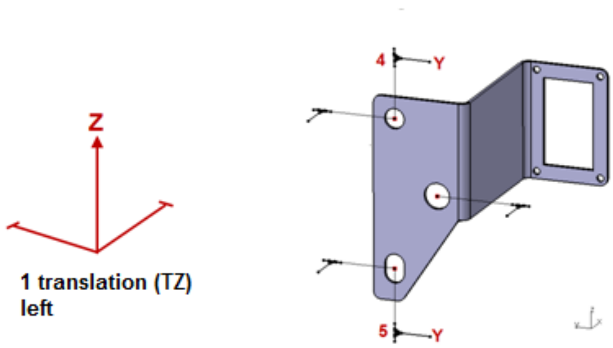


Figure 20 Secondary reference points

3. The last reference point, Z1, controls one degree of freedom (TZ) and is placed in the top left corner.

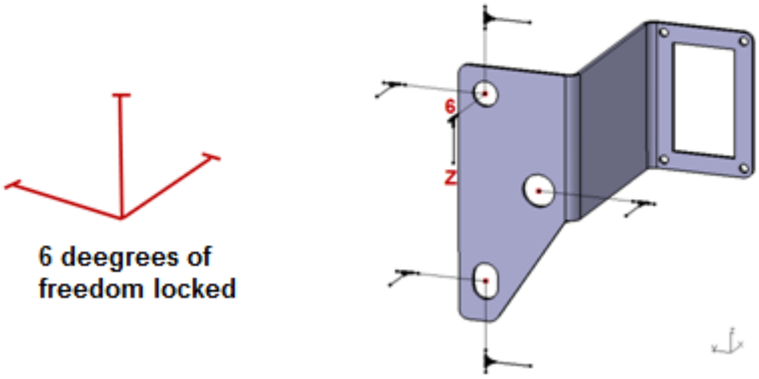


Figure 21 Tertiary reference points

The top left hole has three points distributed to it, X1, Y1 and Z1, thus this hole must have a perfect fit. The mid hole is bigger and the bottom hole is slotted along the z-axis. This procedure assures the locking of all the degrees of freedom as well as fitting during assembly (Scania CV AB, 2013).

3.3.8 Dimensioning and Tolerancing

Manufactured products are always affected by variation. In order to fulfill functional and aesthetic demands, limits have to be set to restrict variation. Tolerances are permissible limits of variation and are specified to secure function, form and assembly. Tolerances are engineering specifications of the acceptable levels of variation for each geometric aspect of a component or assembly. A tolerance is the specified amount a feature is allowed to vary from the nominal value. This may include the form, run-out, orientation or location of the feature as applicable. Traditionally tolerances are specified on engineering drawings; however it is becoming more and more common for tolerances to be set in a CAD file. There are two common tolerance types in mechanical drawings; linear tolerances and geometric dimension and tolerancing, or GD&T. The dimensioning strategy used for a drawing can greatly affect the tolerance between features on a part. GD&T has to be used in order to fully communicate functional relationships (Fischer, 2011). Scania uses the international standard SS-ISO 1101. The literature study on geometric dimensioning and tolerancing in this report is based on the standard SS-ISO 1101, Geometrical Product Specification (GPS) – Geometrical tolerancing – tolerances of form, orientation, location and run-out (Scania CV AB, 2013).

Geometric Dimensioning and Tolerancing (GD&T)

GD&T is a quality control method that is used for defining allowable variation in size, form, orientation and location using symbols. The purpose of GD&T is to precisely define part and assembly geometry. Geometric dimensioning and tolerancing can be divided into two different specifications (Fischer, 2011):

- Dimensioning specifications that define basic nominal dimensions.
- Tolerancing specifications that define permissible variation for the size and form of individual features, and permissible variation in orientation runout and location between features.

All parts are affected by variation, and consequently all features on a part are also affected by variation. The importance of setting tolerances on features is therefore high. In order to fully define a part from a geometric point of view, the geometric characteristics and the relationship of the feature to the rest of the part have to be toleranced. Feature geometry and the interrelationship between part features can be described using five geometric characteristics. Tolerances can be set for all of these characteristics (Fischer, 2011).

- Form
- Location
- Orientation
- Size
- Runout

Form

Features come in all shapes and sizes. The shape or form of the feature can be defined using the different form tolerances. Profile tolerances are included in form tolerances in the SS-ISO 1101 standard. A form tolerance must be specified for every feature of a part, be it directly or indirectly. Directly specified form tolerances include flatness, circularity, Cylindricity and straightness. An example of an indirectly specified form tolerance is to specify a profile of a surface tolerance to a basically defined surface. Profile of a surface can control form, orientation, location and size depending on the datum feature references. The indirect methods of controlling form can be overridden by form tolerances with smaller values. For example, a planar surface with a profile of a surface tolerance is overridden by a flatness tolerance, if the flatness tolerance value is lower than the profile tolerance value (Fischer, 2011).

Location

It is often important to specify where a feature lies relative to another feature. This can be specified using a location tolerance. Location is where a feature lies relative to a datum reference frame. Most features require a location tolerance. Location tolerances are not subsets of other types of tolerances and they therefore have to be directly specified (Fischer 2011).

According to the SS-ISO 1101 standard profile tolerances are included in location tolerances. All location tolerances require a datum reference except the position tolerance.

Orientation

Orientation can be described as the amount a feature may tilt relative to a datum reference frame. Every feature on a part must have an orientation tolerance. Just like form, orientation can also be controlled directly or indirectly (Fischer, 2011).

All orientation tolerances requires a datum reference frame. Profile tolerances can control orientation and are thus included in orientation tolerances.

Runout

According to the SS-ISO 1101 standard a runout tolerance limits the axial or radial deviation in relation to a datum reference frame. Consequently all runout tolerances require a datum reference frame.

Size

A size tolerance is normally specified as a plus/minus tolerance associated with a dimension. Size can be described as the straight-line distance between two points on one or two surfaces. Where the surfaces normal vectors are collinear and are pointing in opposite directions. Features without size characteristics do not require a size tolerance to be completely defined (Fischer, 2011).

Symbols

Symbols for geometrical characteristics can be seen in table 2.

Tolerances	Characteristics	Symbol	Datum needed	Subclause
Form	Straightness	—	no	18.1
	Flatness	⏥	no	18.2
	Roundness	○	no	18.3
	Cylindricity	⌭	no	18.4
	Profile any line	⌒	no	18.5
	Profile any surface	⌓	no	18.7
Orientation	Parallelism	//	yes	18.9
	Perpendicularity	⊥	yes	18.10
	Angularity	∠	yes	18.11
	Profile any line	⌒	yes	18.6
	Profile any surface	⌓	yes	18.8
Location	Position	⌖	yes or no	18.12
	Concentricity (for centre points)	◎	yes	18.13
	Coaxiality (for axes)	◎	yes	18.13
	Symmetry	⌯	yes	18.14
	Profile any line	⌒	yes	18.6
	Profile any surface	⌓	yes	18.8
Run-out	Circular run-out	↗	yes	18.15
	Total run-out	⌰	yes	18.16

Table 2 Symbols for geometrical characteristics

Additional symbols are presented in table 3.

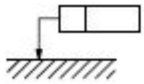
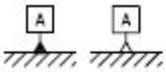
Description	Symbol	Reference
Toleranced feature indication		Clause 7
Datum feature indication		Clause 9 and ISO 5459
Datum target indication		ISO 5459
Theoretically exact dimension	[50]	Clause 11
Projected tolerance zone	Ⓟ	Clause 13 and ISO 10578
Maximum material requirement	Ⓜ	Clause 14 and ISO 2692
Least material requirement	Ⓛ	Clause 15 and ISO 2692
Free state condition (non-rigid parts)	Ⓕ	Clause 16 and ISO 10579
All around (profile)		Subclause 10.1
Envelope requirement	Ⓔ	ISO 8015
Common zone	CZ	Subclause 8.5
Minor diameter	LD	Subclause 10.2
Major diameter	MD	Subclause 10.2
Pitch diameter	PD	Subclause 10.2
Line element	LE	Subclause 18.9.4
Not convex	NC	Subclause 6.3
Any cross-section	ACS	Subclause 18.13.1

Table 3 Additional symbols

Tolerance frame

Requirements are specified in the tolerance frame. The tolerance frame Is a rectangular frame which Is divided into two or more sections. See picture below.

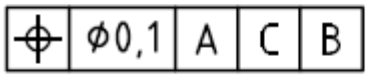


Figure 22 Tolerance frame

The requirements are set from left to right. The symbol for geometrical characteristic is in the first section from the left, in this case the position tolerance symbol. The second section from the left contains tolerance value information and possibly a symbol showing if the tolerance area is circular or spherical. The last section contains information regarding datum systems. If the requirements in the tolerance frame applies to more than one feature it is indicated on top of the rectangle as seen in figure 17.

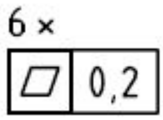


Figure 23 several features

3.3.9 Tolerance analysis

Tolerance analysis can generally be divided into two subcategories. The first subcategory is aimed at determining the individual tolerance specification. The second subcategory is the process of determining the cumulative variation between two or more features. The second subcategory is normally referred to as tolerance stackup. It is imperative to have a good understanding of GD&T in order to perform a tolerance stackup (Fischer, 2011). The purpose of a tolerance stackup is to summarize and examine a chain of tolerances to see what the cumulative effects of these are. The concept can then be analyzed to see if it fulfills final aesthetical and functional requirements (Swerea, 2006). There are two different types of tolerance stackups: worst-case (arithmetic) and statistical (Fischer, 2011).

Tolerance stackup

Variation simulation is a powerful tool that helps in decision making during product design. The information gathered from the tolerance stackup is used to determine if a change has to be made to the part and assembly geometry, to their dimensions and/or tolerances, to the dimensioning strategy in place and assembly drawings or annotated models, to the assembly process or to the manufacturing process. There are several ways to reduce the variation that is predicted by the tolerance stackup. Parts can be redesigned in regards to geometrical robustness, elimination of clearance that lead to misalignment at final assembly, eliminating parts by modifying mating parts and finally eliminating contributing tolerance from the tolerance stackup (Fischer, 2011).

According to Fischer, a tolerance stackup allows the analyst to:

- Optimize the tolerances of parts and assemblies in a new design.
- Balance accuracy, precision and cost with manufacturing process capability.
- Determine the part tolerances required to satisfy a final assembly condition.
- Determine the allowable part tolerances if the assembly tolerance is known.
- Determine if the parts will work at their worst-case condition or with the maximal statistical variation.
- Determine if the specified part tolerances yield an acceptable amount of variation between assembled components.
- Troubleshoot malfunctioning existing parts or assemblies.
- Determine if problems with existing parts or assemblies is a function of the design or a function of a manufacturing process problem.
- Determine the effect changing a tolerance value will have on assembly function.
- Explore design alternatives using different or modified parts.
- Determine how changes to the assembly process will affect variation between features on mating parts.

Worst-case analysis

Worst-case analysis is the traditional type of tolerance stackup. Worst-case analysis determines the largest possible variation by letting all the features assume their largest or smallest values. This method doesn't take into account the laws of probability. The result from the worst-case analysis makes sure that all the parts will be able to be assembled and function properly; however the margin of safety is unnecessarily big. Most of the manufacturing processes have a spread that is normally distributed. When performing a worst-case analysis the whole spread of the process is considered. This requires tighter tolerances for individual parts which results in a higher cost due to a higher manufacturing cost, higher scrap rate and a more expensive inspection process (Fischer, 2011).

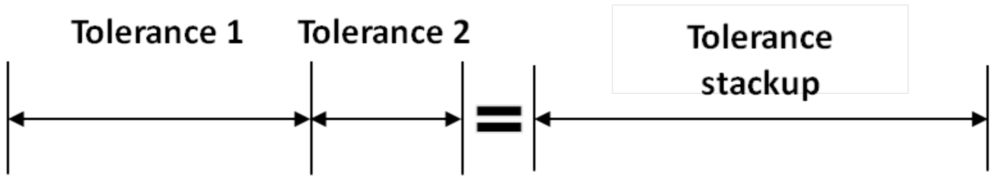


Figure 24 Worst-case tolerance stack up

Statistical tolerance analysis

A worst-case scenario is assuming that all the dimensions of the features are at their maximum or minimum level. The statistical tolerance analysis however evaluates a number of more likely dimension outcomes in between the tolerance limits to obtain the total variation. Statistical tolerance analysis is very similar to worst-case analysis, the big difference is that statistical analysis determines the maximum *probable* variation, whereas worst-case analysis examines the maximum *possible* variation. The probability of all the dimensions being extremely close to their tolerance limits is quite small which is why statistical tolerance analysis is a more realistic tool for variation simulation. Since statistical analysis predicts less variation than a worst-case scenario does, the designer has more freedom in fitting the parts tighter which will cause smaller gaps and increase the perceived quality. It can also result in being able to widen the tolerance interval, making the product cheaper to manufacture. Statistical methods include Root Sum Square (RSS) and Monte Carlo Simulation (MCS), among others (Fischer, 2011).

Computer aided tolerancing

Computer-aided tolerancing (CAT) tools use MCS to statistically distribute values within the tolerance limits. Computer-aided tolerancing enables 3D-effects of tolerance stackups to be analyzed. The tools also provides information on how much each part contributes to the total variation. Given the information above, tolerances can be optimized for each part or feature (SWEREA, 2006).

Monte Carlo Simulation

Monte Carlo Simulation is very popular when working with tolerance analysis because of its unlimited potential in regards to precision. For a long time MCS has been used as a tool for examining complex systems. Monte Carlo Simulation is based on random number generation and is a statistical technique that uses probability distributions in order to represent the variable nature of a complex system (Rydén and Lindgren, 2013). MCS assigns a random value, that is within the range, to all the variables that are present in a tolerance stackup. The result is then derived and saved and this process is iterated thousands of times. The results from the iteration are averaged and the predicted statistical distributions is presented (Fischer, 2011).

The MCS estimates the variation in the assembly due to the dimensional variations within the assembly. As mentioned earlier, the variations are represented by statistical probability distribution. The principle of the Monte Carlo simulation is explained in the picture below. The output distribution is a function of the distrubutions of the input variables and the assembly function. In order to get a reliable measure of the output distribution, thousands of input variables are combined (Cvetko et al. 2013).

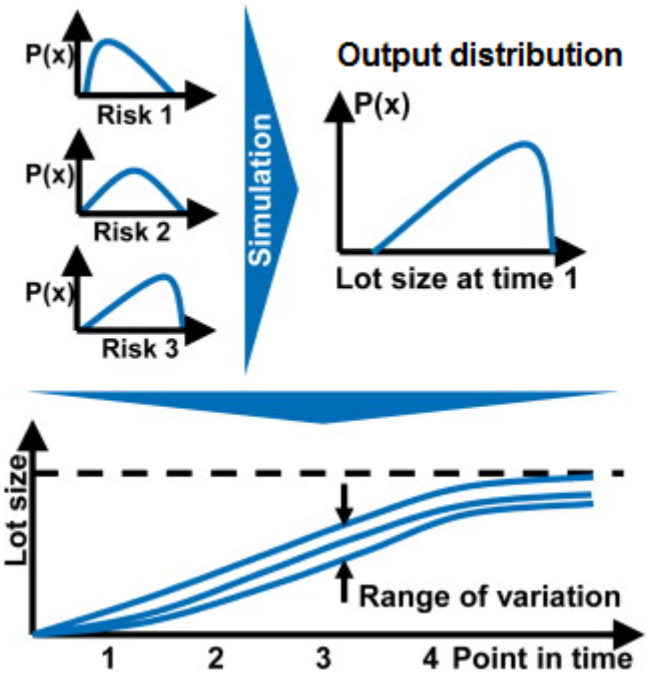


Figure 25 Monte Carlo simulation

The output distribution which is derived is a representation of the assembly dimension. MCS assigns random values of variations to all the parts that are a component of the assembly and then calculates the resultant assembly variation. The random value assigned is based on probability distribution and the value has to be within the respective parts range. This process is iterative and after thousands of iterations the result is then predicted (Cvetko et al. 2013).

Standards and conformity assessment

In an ideal world, measuring procedures are mandatory all throughout the product development process. They are usually performed in such a way that it is hard to uphold a conform and coherent measurement system, i.e. being comparable. There are standards for a sustainable measuring system that serve as guidelines for companies. ISO-standards for a GPS (Geometrical Product Specification) can also help an enterprise to separate the possible inaccuracy in measurement system and an inaccuracy in a part. However, this difference is not always understood in an organization. The effect that a measuring process may have on the measuring result itself is usually underestimated (SWEREA, 2013).

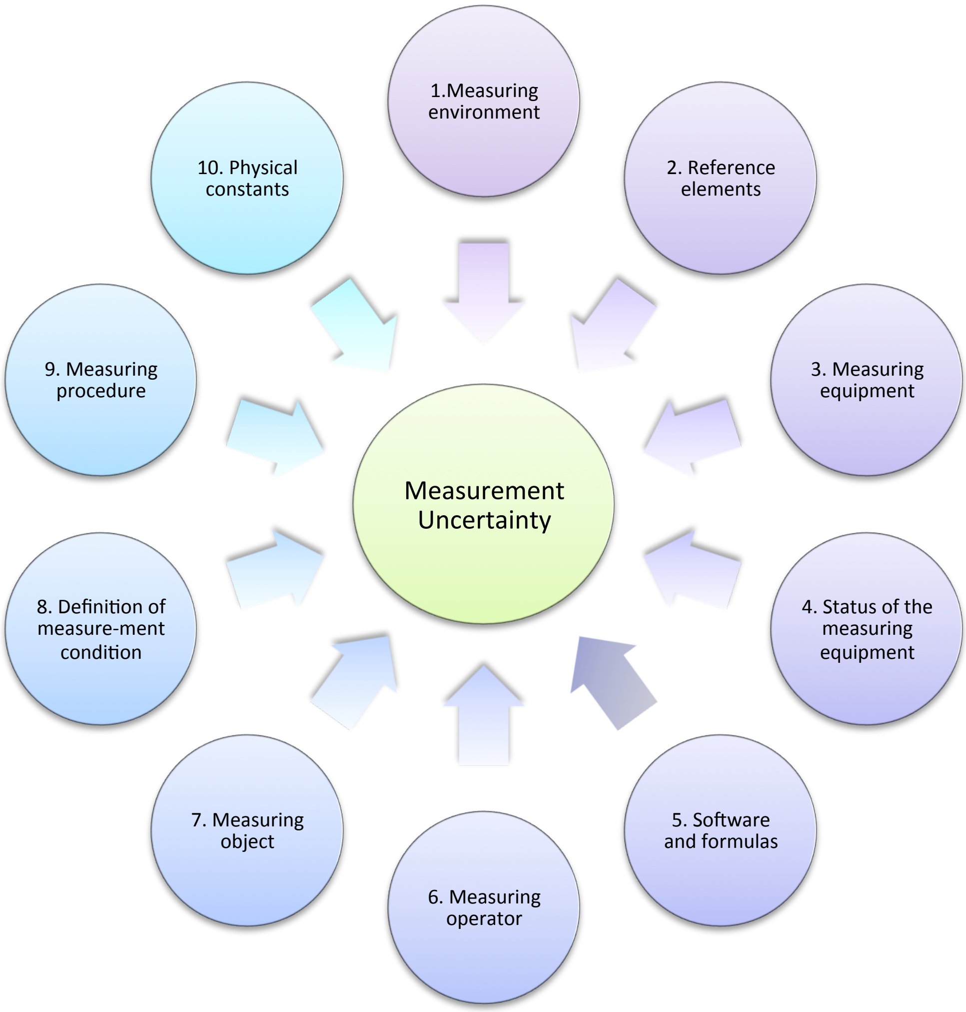


Figure 26 There are usually ten different factors that influence the measurement uncertainty.

The input parameter, for instance a scanning machine, needs to be properly assessed with all the disturbance factors that would affect the outcome, i.e. the quantified measurement. These ten factors mentioned above are all elements that could serve as a disturbance consideration. However, some are more likely than other to cause the measurement procedure to be more or less sensitive to the input depending on the situation (JCGM, 2008).

3.4 Dimensional engineering software

3.4.1 3DCS

3DCS CAA V5 is a variation simulation software that has the possibility to use both feature based and point based geometry. This means that the 3DCS can be used directly in Catia V5 but also independently (3DCS Software Manual, 2012). Some of the most important features of 3DCS are as follows.

Assembly sequence

Assembly sequences are defined using moves in 3DCS. Points and features can be used in all moves. The moves are used to build the simulation model in the 3DCS software. Moves must be added to the model to define each part's position in the assembly. The moves can be defined as either point based or feature based. Point based moves uses target systems, for example the 3-2-1 target system, to define the assembly sequence whereas feature based uses constraints to define the assembly sequence (3DCS Software Manual, 2012).

Statistical Variation Simulation

After the simulation models has been built using moves the variation simulation can be performed. The statistical simulation tool in 3DCS is based on Monte Carlo Simulation. 3DCS allows for simulation of both non rigid and rigid parts. This is possible due to FEA (Finite Element Analysis). Tolerances can be defined using GD&T or actual part capability (inspection data). The tolerances are defined as either feature or point based. Statistical distribution-types such as Normal, Weibull, Uniform or User-Defined can be defined for part tolerances to emulate manufacturing capability (3DCS Software Manual, 2012).

Sensitivity Analysis

The sensitivity analysis is used to examine which tolerances within an assembly that are the largest contributors for a particular measurement (3DCS Software Manual, 2012).

Geometric Factor Analyzer

3DCS geometric factor analyzer (GFA) is an add-on module that allows the analysis of how inter-relating part features and the placement of tooling locators impact the overall assembly quality. Only analyzing tolerances are not enough in order to ensure assembly quality. Critical dimensions are affected by the geometrical robustness of parts and how much the part geometry amplifies the variation. GFA also allows worst-case tolerance analysis to be performed (3DCS, 2013).

Visualization

3DCS allows manufacturing and assembly variation to be animated to show how they affect the assembly. The assembly sequence and features that vary within their tolerance zones can be animated (3DCS Software Manual, 2012).

Documentation

3DCS has a automatic report generation feature. The tool automatically generates a report containing model and analysis information. The generated report is exported in either .html or .xls file formats. The report includes model information and pictures and details of input/output (3DCS Software Manual, 2012).

3.4.2 RD&T

RD&T stands for Robust Design and Tolerancing and is a standalone software for statistical variation simulation. Allowing manufacturing and assembly deformations of the product to be simulated and visualized long before physical prototypes are being made. Different concepts can therefore be analyzed and compared and thus improving the quality of decisions (RDTTECH, 2013) (RD&T Software Manual, 2011).

The RD&T software package supports the Dimensional Engineering process in all of its phases. From early design and styling to pre-production and production. Making the product concepts robust to manufacturing variation and to be able to predict final variation in the products' critical dimensions is important (RDTTECH, 2013). The main modules in RD&T will be explained below.

Positioning Systems

The assembly sequence is described using points in RD&T. The positioning system or target system, e.g. 3-2-1 target system, for each part is defined as a positioning frame (P-frame) on the part itself and a target P-frame where the part is being assembled. The model is built in RD&T using these positioning systems.

Stability analysis

Stability analysis is a tool within the RD&T software. Determining the optimal reference point's placement for a complex shape and especially assemblies is often very difficult and that is why a stability analysis is required (Söderberg, 2006).

To illustrate how variation will propagate from the locators to significant areas of the part or assembly, a color-coding system is in effect. Where stable areas are represented by a blue area and unstable areas are represented by a red area. Blue areas have less variation amplification and red areas have more variation amplification (Söderberg, 2006).

The picture below illustrates a stability analysis. The picture on the left shows the initial reference points. The red area in the left picture results in an amplification factor of roughly 50 times. The picture on the right shows the optimal reference points, calculated through the stability analysis, the amplification factor is reduced to ca 2 times in the red area (Söderberg, 2006).

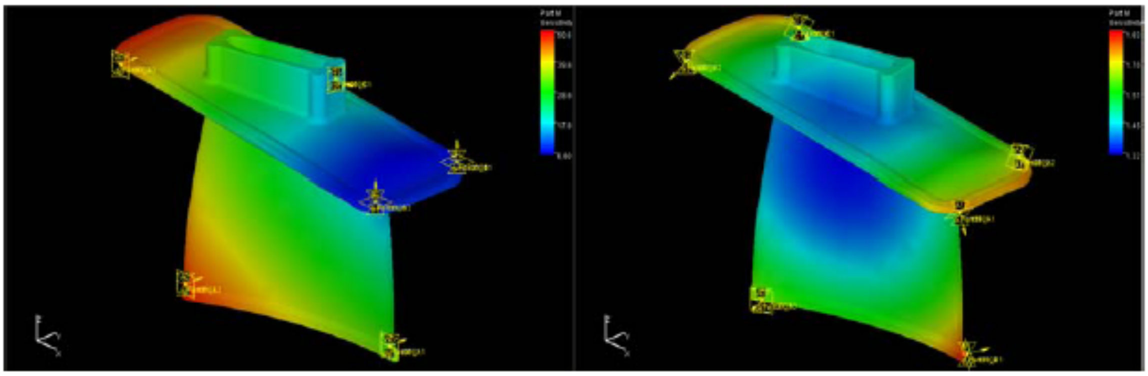


Figure 27 Optimization of reference points

Statistical variation simulation

RD&T's statistical variation simulation is based on Monte Carlo Simulation. This enables capturing of 3D effects and interactions for complex assemblies. It can be used for non-rigid analysis thanks to the integrated FEA (Finite Element Analysis) solver. Sheet metal or plastic parts that bend or deform during assembly can thus be examined. Assembly, welding and clamping order can also be analyzed and optimized to minimize variation using this module (RDTTECH, 2013). Part tolerances can be defined using GD&T or actual part capability (inspection data). The tolerances can be defined globally on the model level and be used by several points or individually for each point. Worst-case tolerance analysis is also available in RD&T.

Visualization

RD&T showroom is a visualization tool that allows the variation effects to be visualized with a high degree of realism by adding lightning, shadows, textures and material properties. Using the visualization tools allows the visual sensitivity of the product to be analyzed with respect to geometrical variation long before production takes place and thus avoid late changes.

Documentation

Documents containing requirements, master and subsystem layouts and drawings can be generated in RD&T. Important aspects such as tolerances, reference point systems and measuring points can be illustrated in the generated document. Reports including information from contribution analysis and the variation analysis can also be generated. The documents can be printed or saved as PDF-documents.

File format

RD&T supports many file formats such as IGES, VRML 1.0/2.0, STL or JT format. These files are neutral and are imported from a CAD system. Using points, arcs, lines and primitives, may also create part geometry.

Add-ons in RD&T

Some modules in RD&T are not standard in the original version of RD&T but have to be purchased separately. These add-ons are explained further in this section.

Virtual matching
Virtual matching allows for adjustments of locators to compensate for form errors.

Calculation of envelope
Calculation of envelope allows calculation of variation or motion envelope for packaging analysis.

Inspection point reduction
Inspection point reduction based on statistical cluster analysis is used to reduce the number of inspection points in pre-production to a small number of representative inspection points for full production.

Inspection point preparation
This module allows for generation of inspection drawings, definition of inspection points and PKI documents (company specific).

Root cause analysis
Inspection data on a product level is used to identify errors in individual fixtures/locators.

3.4.3 Cetol

Cetol is a feature based tolerance analysis software that is fully integrated with CAD software such as Catia V5, Pro/ENGINEER, Creo and SolidWorks. Cetol is integrated as a workbench in Catia V5. This means that a CAD model is required in order to build a Cetol model. Cetol can be used to solve both single-dimensional tolerance problems and multi-dimensional tolerance problems. The statistical variation simulation in Cetol is based on the Method of System Moments. The method is based on Taylor series functions. The three main components of Cetol is modeling, analysis and reporting (Sigmetrix, 2013).

Modeling
Designers and engineers can quickly build models for analysis by utilizing the model component of Cetol. Since the software uses the necessary geometry features directly from the CAD system models the analysis stage can be reached fast (Sigmetrix, 2013).

Kinematic Joints
Most products consist of several parts that are fit together into an assembly. When performing a tolerance analysis on an assembly the relationship between the parts have to be defined. This is achieved by using assembly constraints. Assembly constraints can consist of a simple mating contact or a more complex fastener interface. It is imperative to correctly define these constraints in order for the results from the tolerance analysis to be accurate. These assembly constraints are described using kinematic joints in Cetol. This is true for both kinematic constraints and to rigid constraints, such as fasteners and welds. The kinematic joints are defined from surfaces in contact. Cetol determines the appropriate kinematic joints based on type of surfaces and their relative orientation (Cetol Software Manual, 2008).

Analysis

The analyzer window in Cetol provides the user with important information such as top contributors to quality and how tolerances affect the assemble quality, this window is not integrated in the CAD environment. The tolerances can be adjusted in this window (Sigmetrix, 2013).

Fast and easy interpretation and interrogation of results with data sorting and organization. Multiple measurements can be viewed at the same time when using cross-table view, values can be changed and the results can be seen immediately (Sigmetrix, 2013).

Embedded Sensitivity Animation shows how a single variable is affected throughout the tolerance range on both assembly position and measurements. This can be shown for both statistical and worst-case (Sigmetrix, 2013).

Tolerances and measurements can be seen and adjusted using the key contributor analysis for a truly robust design (Sigmetrix, 2013).

Reporting

Reports are a great tool for communicating with manufacturing and management. The reports are customizable but standard templates for reports are available (Sigmetrix, 2013).

3.5 Research to Design to Industrialization – A Continuous Loop

Activities in the research stage have to be aligned with the ones in the design and development stage as well as the manufacturing process. Any design specification has an impact on the robustness, the quality and aesthetics as well as the functional outcome of the product. These factors need to be established early and kept under supervision and control throughout the product development process. Activities and processes need to be monitored and the measuring data collected. This information should then be passed on back to the research stage. This way, the knowledge is connected back to the source who can evaluate what factors influenced the outcome, what was done well, what was done poorly and what lessons there are to be learned. Continuous improvements are thus enabled (Quality Digest, 2013).

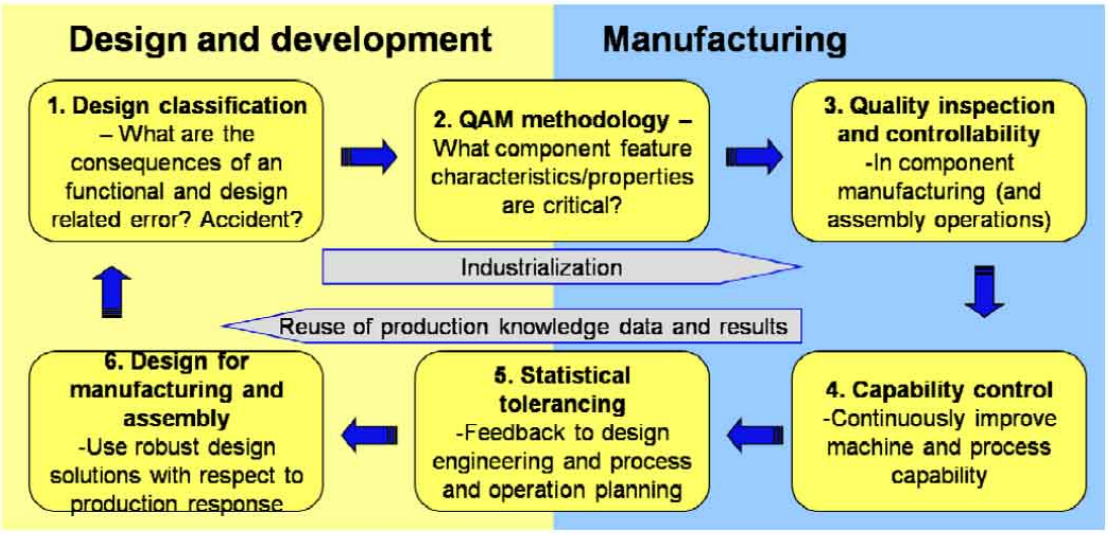


Figure 28 The continuous loop of research to design to industrialization (Quality Digest, 2013)

As the industry continuously changes areas of focus depending on what the customers want, the research sector has to be flexible and follow these changes. The research results also need to be technologically validated before a system implementation of the new research ideas. As a new opportunity in the market is identified, new tools and methods might be needed. Research is often performed within the areas of advance after which these results are implemented in the industrial system. However, efficient industrialization requires the validation of the results from the research. So, all these three dimensions should be in focus (Chalmers, 2013).

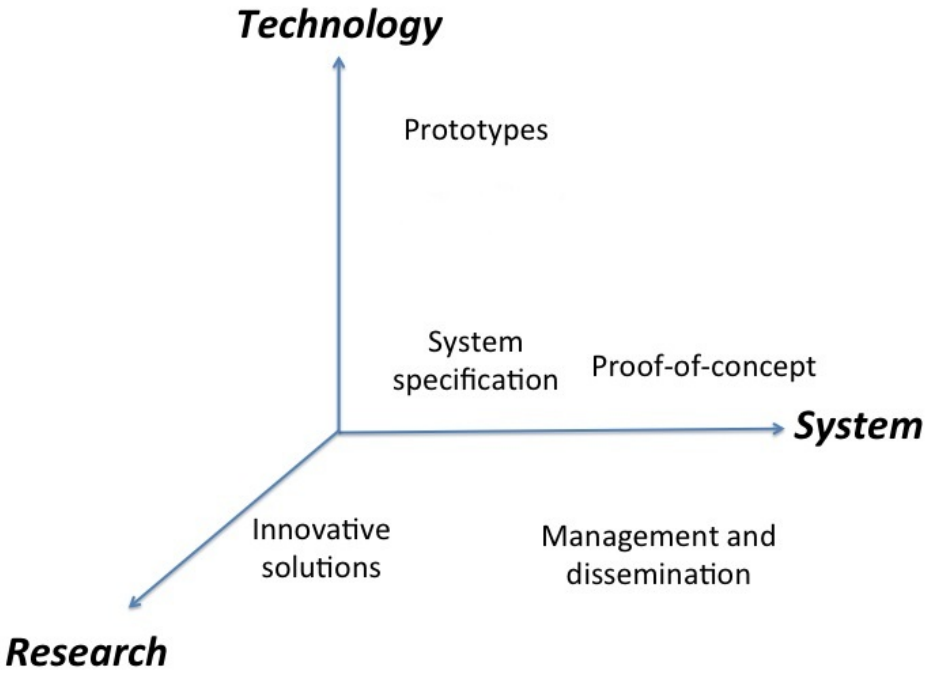


Figure 29 There are three dimensions of product quality improvements

3.5.1 Proactive Risk Management

Risk management options are subject to an extra cost to companies. These costs need to be compared to the benefits these risk management activities would provide. Many companies have recognized the payback that risk elimination has for the long-term perspective. It is widely known that the cost of change is greater the later it is performed (Smith et al., 1998).

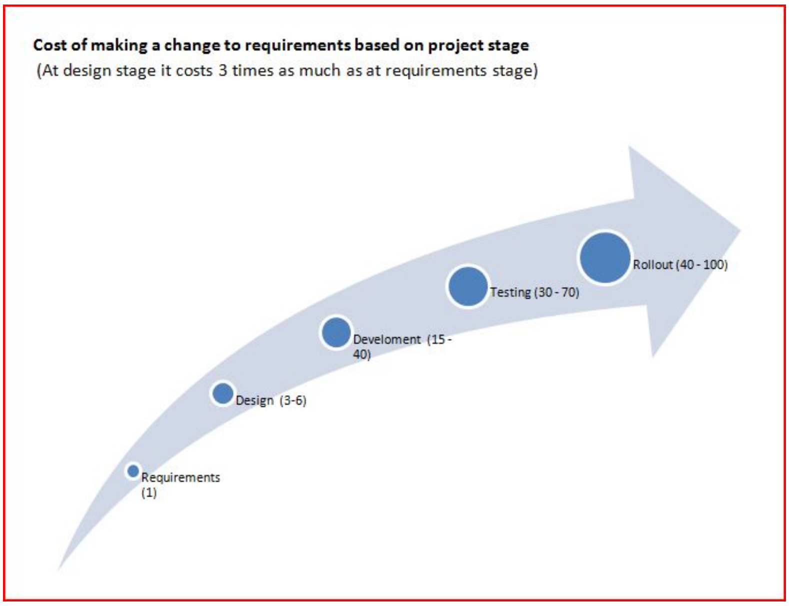


Figure 30 The figure depicts how the cost of change increases as the time of a project elapses (The Bridger, 2013)

The uncertainty and the risk are the highest in the beginning of a project. But so is the stakeholders' influence. They can affect the outcome of a project the most in the beginning of the process, since the big decisions are hopefully made at that time. These decisions can be right or wrong, but they cost the least to change in the early stages. Most companies have chosen to focus on test-driven and virtual designs as opposed to the rapid but untested development process (Ulrich & Eppinger, 2012).

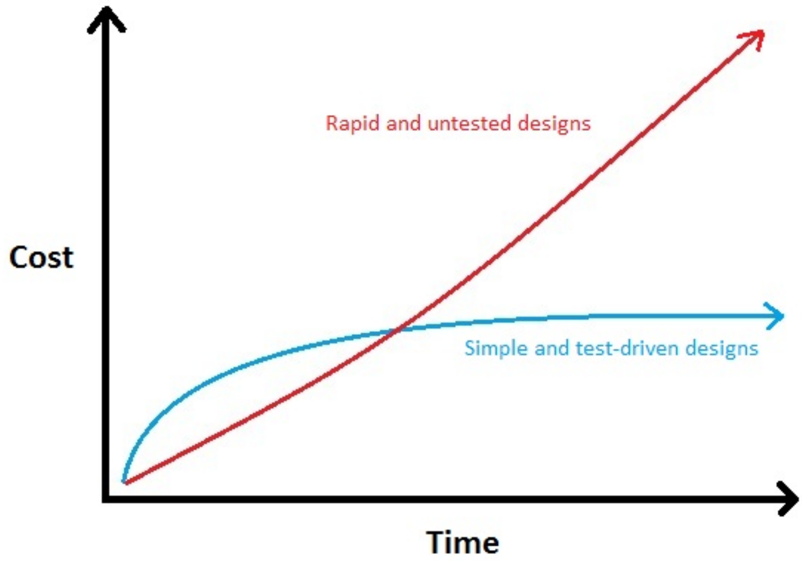


Figure 31 The picture above shows the difference in cost between test-driven design and the untested design

4 Results from case studies

This chapter presents the results of this study. The first part of the chapter consists of the four external case studies form four different companies. It is followed by the results from the case study at Scania along with three specific case studies at Scania that are related to the subject of this thesis.

4.1 Volvo Cars Corporation

Dimensional Engineering at Volvo Cars was in the beginning a part of the Quality Assurance process. Since Dimensional Engineering was dominant in the meetings, it was decided to be lifted out as an individual and specialized activity. They have an executive board that has quality questions as one of their top priorities.

The Dimensional Engineering ownership roles at Volvo Cars are subdivided in the concept development, the verification phase and the production ramp up. Each of these three stages has a particular Dimensional Engineering role appointed to them.

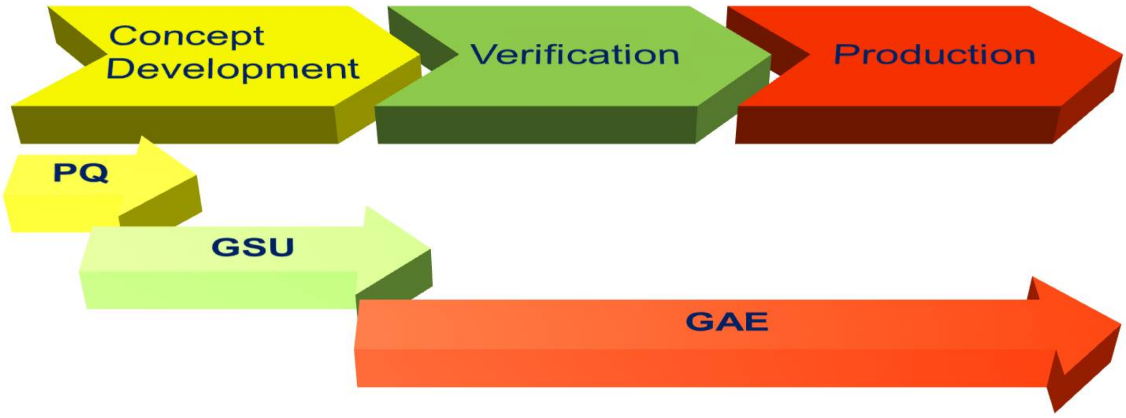


Figure 32 The picture shows how the three different Dimensional Engineering roles are compartmentalized through the concept development, the verification and the production phase

- PQ stands for Perceived Quality and they are responsible for defining the split lines of the vehicle, the fit & finish and the requirements specification. They do this together with designers, styling and production.
- GSU stands for Geometry System Developer and they break down the specification requirements from PQ according to the Top Down approach. Reference systems and tolerances are determined and together with the broken down requirements specification they form the *design preconditions.* These preconditions are respected by the designers and are upheld and refined all through the product development process through variation simulations and cross-functional meetings.
- GAE stands for Geometry Assurance Engineer that is the one who verifies the final demands and tolerances. The measurement procedures are determined by this role and they are responsible for measurement programming and the specification

of how the parts are to be measured manually. The GAE group surveys the processes for deviations and they are responsible for the measurements of the final product.

4.1.1 Ownership

A distinctive trait that Volvo Cars has is their Total Vehicle Geometry & Quality. It is part of Manufacturing and they *own* the demands for function, packaging and fit & finish. They begin by determining the final specifications from the eyes of the customer and they break it down to specifications on component level – the Top Down approach. Manufacturing owns these demands and follows them from the concept development all the way until the end of the product's life. This is unique in the car industry. Geometrical robustness is assured in the earliest phases of the concept development – sometimes even before an actual sketch or drawing has been made. This is done with the RD&T software.

4.1.2 Standardization

There are many standardized tools and interfaces being used at Volvo Cars. Standardization is applied as a way to smooth all the processes and to facilitate and stimulate continuous improvements. A measuring operator in a measuring room at Volvo Cars can be put in any of their other measuring rooms in the world and be able to recognize everything. Developing standards and communality is part of the work with cost of poor quality where quality costs are revised.

4.1.3 Measurement

Volvo Cars realized in the 1980s that in order to do an efficient quality assurance, something needed to be changed. In 1994, they developed a standard for the name of a measurement point. This standard would contain the cuts and sections of the parts and all the levels of the tolerance chains. A red thread needed to be visible throughout the whole product development process. Also, in order to avoid having to buy many different tools, a stable base needed to be created. This was solved with their database where all the information can be handled and analyzed. Volvo Cars constructs a drawing of the measurement points of the complete delivery unit when it is assembled. The drawing contains the piece in its surroundings with cuts and sections and all the demands. The supplier's job is to make sure that all the demands are fulfilled when he manufactures his piece to the customer.

4.1.4 Supplier

It is clearly stated where the supplier takes his measurements. The suppliers thus have a format to stick to when they report their measurements of the parts. They have a duty to report live to Volvo Cars' PDM system. Any process deviation from the target needs to be quickly discovered and adjusted accordingly. The suppliers make sure that their processes are connected to the parts that they are making. Since the suppliers still work reactively, Volvo Cars' next step is to improve their supplier structure. The suppliers will be encouraged to work proactively by performing their own dimensional engineering process. This to make sure they deliver fast, with a high quality and at a low cost.

4.1.5 Mindset

A big part of the dimensional engineering thinking is the Lean concept of doing the right thing from the start. According to Volvo Cars, the whole point of dimensional engineering is to know early on that your design most surely will be possible to manufacture, assemble and function. If you choose to accept the fact that you know too little in the beginning or that you will get surprises later on anyway, you will always work reactively. But if you choose to have the mindset that you today know enough, you will start thinking proactively. Volvo Cars choose the mindset of not accepting to wait and see what will happen and to avoid taking risks.

4.2 SAAB

The dimensional engineering process at SAAB was similar to the one at Volvo Cars. In the beginning of a product development process benchmarking, lessons learned and a management overview is performed.

Figure 33 The picture above depicts the nine steps in the Dimensional Engineering process at Saab (Saab, 2008)

4.2.1 Ownership

The product is broken down according to the Top Down principle. In order for the designers to start their work, the dimensional engineers need to have created a design condition. Here, all the demands are visualized with cuts and sections. The reference systems are clearly appointed and given to the designers.

4.2.2 Measurement and Suppliers

The designers can access all the information in the database. The drawings are also sent to the suppliers where it has been assured that the measurement points are clearly stated. After the measuring, the suppliers report the PDM database. Production is closely linked to the database. Inline measurements from production are reported to the database frequently.

4.2.3 Mindset

As for Volvo Cars, the mindset at SAAB is to work proactively. It also included finding all the relevant information early on in the concept development. The designers' work depended upon the work of the dimensional engineers. Assuring high quality and maintaining a holistic perspective of the end product was a top priority. The ambition was to keep the final goal in focus within all the departments.

4.3 Volvo Trucks

The Dimensional Engineering process at Volvo Trucks is very similar to the dimensional engineering process at Volvo Cars, see chapter 4.1. This is not surprising considering that Volvo Trucks adopted the process from Volvo Cars. One distinctive difference is that Volvo Trucks only have one Dimensional Engineering role whereas Volvo Cars have three different roles. But the process is the same and all of the dimensional engineering activities that are performed at Volvo cars are also performed at Volvo Trucks. Aspects that are relevant to the truck industry and the differences between the processes of Volvo Trucks and Volvo Cars will be highlighted in this section.

4.3.1 Final geometrical requirements

Volvo Trucks establishes final geometrical requirements very early in their projects. This includes functional geometrical requirements and aesthetic requirements such as gap & flush. They breakdown the requirements using the Top Down approach but they use the Bottom Up approach iteratively as the project progresses.

4.3.2 Inspection database

Volvo Cars initiate projects much more frequently than Volvo trucks so the importance of an inspection database is more important for Volvo Cars than it is for Volvo Trucks. An experience form earlier project is still used frequently at Volvo Trucks. They try to reuse as much of the old concept as possible in order to minimize unnecessary rework.

Volvo Trucks have an inline measurement station where they measure the final product in order to gather statistical data on critical dimensions. Measurement data from suppliers is also documented and entered into the PDM system. The suppliers measure their components based on the inspection preparation that the dimensional engineers have established.

4.4 VW

Volkswagen Group is a multinational automotive company in which Scania is part of. Volkswagen has been employing Dimensional Engineering for a considerably longer time than Scania. They are using several software in their Dimensional Engineering work, but they have a standardized Dimensional Engineering process.

4.4.1 Tolerance Analysis Process Standard

Volkswagen employs a Tolerance Analysis Process Standard in their Dimensional Engineering work and is described below.

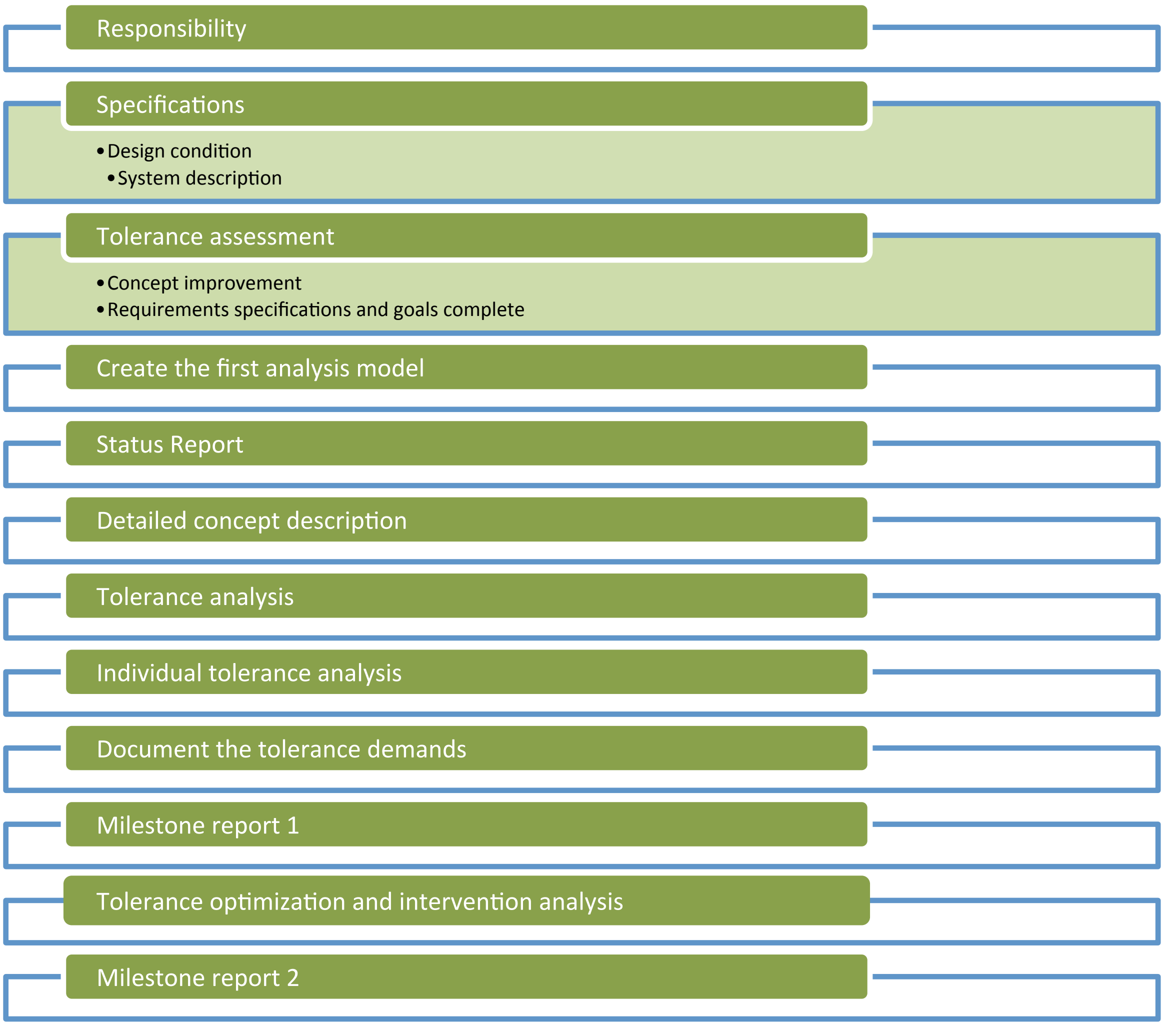


Figure 34 The image above shows the steps that are included in the Tolerance Analysis Process Standard at Volkswagen, starting from the top and descending in the depicted order (Volkswagen AG Prozessstandard, 2013).

The standard for the tolerance analysis at Volkswagen that is portrayed above is explained in more detail below.

1. *Responsibility:* Throughout the whole product development process, there are clear descriptions of which department is responsible for the concept/product at the time. As the concept/product moves to another stage, the responsibility shifts.
2. S*pecifications*: The final requirements specifications are established through “quality, development and planning”.
   - Design condition
     - System description
3. *Tolerance assessment*
   - Concept improvement
   - Requirements specifications and goals complete
4. *Create the first analysis model:* The establishment and creation of a Gap & Flush plan is made.
5. *Status report:* A report of the outcome is sent out.
6. *Detailed concept description:* According to the Top Down approach, the demands are broken down to detailed level.
7. *Tolerance analysis: Acceptance (demanded) tolerances are compared to the calculated ones.*
8. *Individual tolerance analysis:* Individual improvement assessment.
9. *Document the tolerance demands in the design condition description:* Documentation is an important step in the Dimensional Engineering work at VW. A great deal of knowledge is gathered through this step and this helps save time and money.
10. *Milestone report 1*
11. *Tolerance optimization and intervention analysis:* Tolerance refinement is balanced to cost and contingent mediation tactics.
12. *Milestone report 2*

4.4.2 Ownership

The Dimensional Engineering process at Volkswagen is well implemented in the product development process. A concept goes through a series of phases in the product development process in which there are departments that *own* and are responsible for the Dimensional Engineering aspects of the concept. Before the concept development is initiated, market positioning and concept attributes are determined. At Volkswagen, t is widely understood that setting the final product goals *as early as possible* is key to maximizing the quality and minimizing the costs.

4.4.3 Standardization

In order to be able to set these goal early, Volkswagen has developed at standardized process for Dimensional Engineering. This process helps integrate the statistical analysis tool, all the planning, the quality assurance and the cross-functional participation in the product development process.

4.5 Scania

A qualitative study has been performed at Scania in order to establish how Scania works with dimensional engineering. The study consists of interviews with key people working in relevant functions within the R&D department. The respondents consist of people with different roles and functions within the company, such as dimensional engineers, designers and managers. A list of the respondents can be found in Appendix A and the questions can be found in Appendix B. See table 4 for a complete distribution between respondents.

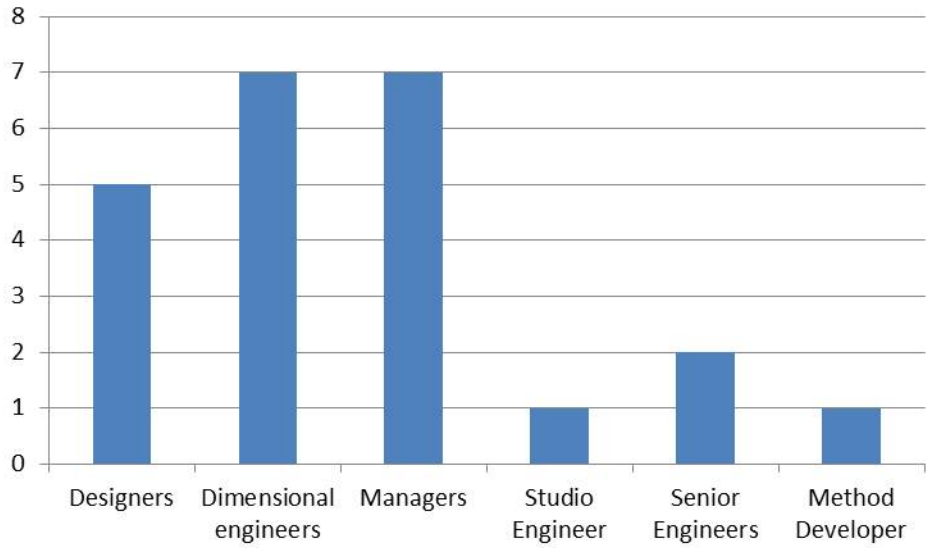


Table 4 Distribution between respondents

4.5.1 Dimensional Engineering at Scania

There are currently six people working with dimensional engineering at Scania. Only two departments employ dimensional engineers, these are RCPL and RTLX. RCPL has the responsibility for cab and RTLX has the overall responsibility for the whole truck. There is no process or standardized work method for Dimensional Engineering at Scania. Dimensional Engineers usually get involved when a need arises. The need can come from a designer that wants to analyze a part or an assembly or it can come from a manager who feels one specific area should be looked in to. Since the designer has the full responsibility of its components it is up to the designer to decide if a simulation has to be performed or not.

Scania have not been working with Dimensional Engineering for long and because of this barely any work has been done during the concept phase by the Dimensional Engineers. Most of the work has been done late in the projects when physical testing already has begun or when the drawing is set and only small changes are allowed.

The interviewed dimensional engineers agree that they should be involved much earlier when working in projects. They feel that they are doing a lot of reactive work and fixing a lot of problems instead of doing what a dimensional engineer should be doing: preventing problems. This is mainly the cause of not having a process for dimensional engineering. All of the dimensional engineers stress the importance of working iteratively at the beginning stages of a project, when the cost of change is relatively low. The optimal way to work is to have a lot of loops in the concept phase, and as little loops as possible during the verification and production phase. Making changes to prototypes costs a lot of money. The cost of change is higher the further the project progresses. One of the respondents highlights that another benefit of working this way is that the production phase can start a lot earlier, and this is what generates money.

Ownership

The styling department, RCD, at Scania is responsible for setting split-lines. They do this with feedback from the suppliers in mind. They take geometrical robustness into consideration when setting split-lines, but they could think about it even more.

As mentioned earlier the designers have full responsibility of their components. This means that they are responsible for setting reference points and tolerances.

Robust design

Many of the concepts generated in the concept phase are not very geometrically robust. This is due to the reference point systems being poorly chosen. Many designers choose reference points that do not coincide with the reference points. Some designers are influenced by the suppliers who wants' reference points that match their production system and enables them to measure their components more easily. Reference Point Systems that are set in this way are seldom the best regarding geometrical robustness. Designers have a designer's checklist which contains steps and activities that are supposed to aid the designer with his work. There are no activities in the designers' checklist that helps the designer in making geometrically robust concepts.

The dimensional engineers emphasize the need for getting involved early so that they can set the reference points in order for the design to be as geometrically robust as possible. Reference systems and tolerances can either be set by the dimensional engineer or by working iteratively with the designer. As it is today, designers set the reference system and hopefully the dimensional engineers can affect them by having a discussion with the designer. Unfortunately some designers' don't have the knowledge to make geometrically robust designs. Reference systems can be set very early in the concept phase on styling surfaces or drawings, the goal is to get involved as early as possible. Some of them argue that they can get involved as early as when styling is determining split lines. The idea is to have a discussion with styling in order for the concept to be as geometrically robust as possible.

Requirement Specification

Historically there have been no clear final geometrical demands when working in a project. A technical specification is available but the technical specification only contains functional demands. Scania does not decide on final geometrical demands early in their projects but instead use more of a bottom-up approach. And as a result there is no real requirement specification. This means that the individual designers allocate tolerances based on what they think is optimal or what they think is possible from a supplier's point of view. They later assemble all the parts and verify if the end result is acceptable. And if the end result is not satisfying a lot of changes have to be made in the late stages of a project. They only recently started to work with final geometrical demands. This is done in the verification phase and they work with verification and demands in parallel. Dimensional engineers work in Cross Functional Teams (CFT's) with designers and people from the styling department, and they decide on the demands together.

Requirement specification is an important part of dimensional engineering and many of the respondents agree that there is a need for clearly stated final geometric demands. This is needed in order to have a common goal. It is incredibly hard to work without having a goal. Final geometric demands are needed in order to set product requirements according to the top down approach. They are working a lot in CFT:s, Cross Functional Teams, in order to agree on final geometric demands. The CFT:s usually include the following roles: designers, styling, dimensional engineers and a senior engineer. Styling has a lot of opinions regarding gap and flush. One of the dimensional engineers thinks that the optimal way to work is to start with the final geometric requirements and determine what tolerances that are needed on in order fulfill them. This way of working is according to the top down approach. Many of the respondents agree that it would be good to work according to the top down approach, or maybe a combination of top down and bottom up.

Tolerance analysis

Tolerance analysis is traditionally done in Microsoft Excel using the RSS and the WC methods. A designer and not a dimensional engineer conducts the analysis. This is not something that is done routinely. The designers working with engines and transmission are typically much more aware of tolerance chains. As mentioned earlier Scania recently started to work with Dimensional Engineering and they are now performing statistical variation simulation.

Suppliers

Suppliers are often contacted too late at Scania. A lot of assumptions are made and sometimes the suppliers cannot live up to the expectations. Engines prototype suppliers often deliver components that are outside their specification. This makes it hard for engine to verify their product.

Measurement

Scania does not have a standardized method for gathering and handling measurement data. Often suppliers do not even deliver measurement data. No inspection preparation takes place in the verification phase since Scania do not measure their final product. Dimensional Engineers at RCPL has recently started to measure final critical dimensions such as gap and flush on the final product.

There is a lack of data from earlier projects. Important data include reference systems and tolerances for previous concepts and process capability of both suppliers' processes and in-house processes. A measurement database containing the aforementioned information is crucial in order to reuse what worked in the last project and improve what didn't work. The measurement database has two important functions: Monitoring and detecting deviations and collecting information for future projects. It is important to measure your own processes and to get measurement data from the suppliers in order to know the normal mode. It is easy to detect whenever a process starts to deviate from the normal mode if the processes are continuously measured and monitored. Actions can be taken if the process starts to deviate before disaster strikes. There may be several reasons to why a process may deviate, is it a worn out tool that has to be replaced? Does the machine have to be recalibrated?

4.5.2 Scania Case 1 - HD Front

Many reoccurring problems in the assembly line can be traced back to the development process where no tolerance variation analyses were performed. One problem that occurred a few years ago at Scania is the famous HD front problem. Since no part is ever nominal it will vary from the CAD model, and in this case, where there were quite a few components linked to each other, it gave rise to a big tolerance stack-up. One issue was that the six holes in the figure below couldn't match the attaching points of the sub ordinate reference system.

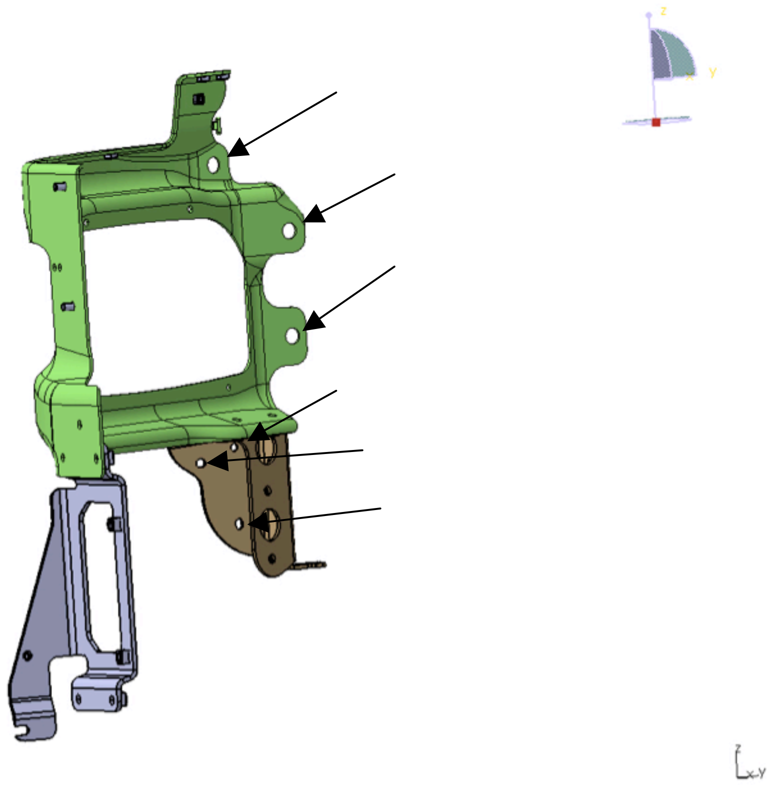


Figure 35 The HD Front at Scania

In order to make the holes fit the attachment points, the holes needed to be enlarged. This problem was solved with extra tooling operations and a fixture. The consequent problem was that the enlarged holes weren't meeting the esthetic demands – it didn't look good enough.

The initial plan was to launch the HD front in the fall of 2011 in order to meet the season of 2012. However, due to the tolerance issue the big launch had to be delayed. Instead, a minor launch was done in Germany in September with a following press launch in Barcelona in October of 2011. The extra costs for these launches were significantly higher than the original would have been. Four months behind schedule, it was clear that a substantial amount of sales weren't possible to occur. It is also possible that some customers were lost during this time.

The HD front consists of a number of components. Many of which are linked together causing tolerance stack-ups. The following components were found to have tolerance and reference system issues.

Article number	Component	Original order	Cost of change
[redacted]	Bumper attachment assy LH	[redacted]	[redacted]
[redacted]	Bumper attachment assy RH	[redacted]	[redacted]
[redacted]	Bumper attachment assy	[redacted]	[redacted]
[redacted]	Lamp frame LH	[redacted]	[redacted]
[redacted]	Lamp frame RH	[redacted]	[redacted]
[redacted]	Lamp frame attachment RH	[redacted]	[redacted]
[redacted]	Lamp frame attachment LH	[redacted]	[redacted]
[redacted]	Step well reinforcement	[redacted]	[redacted]
[redacted]	Step well reinforcement	[redacted]	[redacted]
Total Sum:		[redacted]	[redacted]

Table 5 The cost and the cost of changes for some of the articles of the HD Front

The main problem with the HD front issue was that the tolerance chains were not known. They were also very long and complicated. The coupling components were not visible and very little time and attention were put into understanding how these components were linked together. As the project was approved for the green arrow, there were still many unknowns and the project was virtually started in the dark. Not enough simulations performed in the early product development phase consequently caused problems with the physical part later in the product development process. Since the HD front was unable to be assembled, the launch was postponed and many new tools had to be ordered. It is evident that these costs and time losses would have been avoided with *early* virtual simulations and tolerance variation analyses of the components.

To sum up, the following problems were a consequence of the lack of tolerance variation analysis:

- Four months delayed time-to-market
- Extra tooling costs of [redacted]
- Extra human resources in both R&D and production
- Quality issues in the HD front (forced tension in components)
- Possible loss of customers

4.5.3 Scania Case 2 – Boarding step

One of Scania's trucks that currently is in production is the NGS. Production has encountered problems during assembly of the boarding step on the NGS. A case study was therefore performed in order to show where this problem has arisen. A dimensional engineer working as a consultant at Scania using the RD&T software performed the study. A variation simulation and a contribution analysis on the boarding step and its underlying parts were performed.

In order to perform the case study a few assumptions had to be made. There is no standardized work method for assembling the boarding step so the assembly order may vary. The assembly order was assumed based on watching the assembly of the boarding step during production. The tolerances were taken from drawings and probable tolerances were assumed for parts where drawing tolerances were not available.

The boarding step is assembled to an APS bracket. The APS bracket is behind the boarding step on the right side of figure 17. In order for the screw to align with the hole without bending the APS bracket the dimension can only vary 4 mm in the direction of X and Z. This can be seen in the picture below.

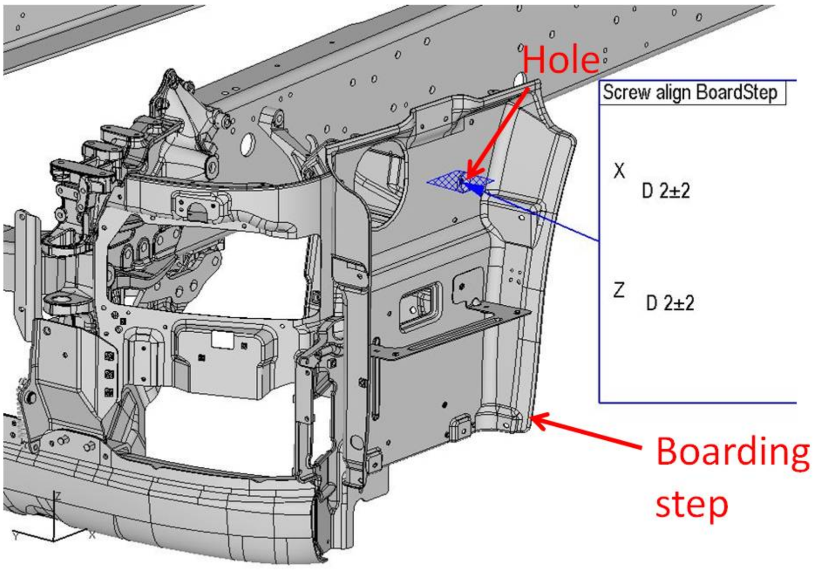


Figure 36 Boarding step

Variation simulation and contribution analysis

A simulation was performed using the assumed tolerances and assembly order mentioned earlier. The calculation revealed that in order to align the screw with the hole the system demands a minimum gap of 11.9 mm in the X direction. This is illustrated in the picture of the cross-section below.

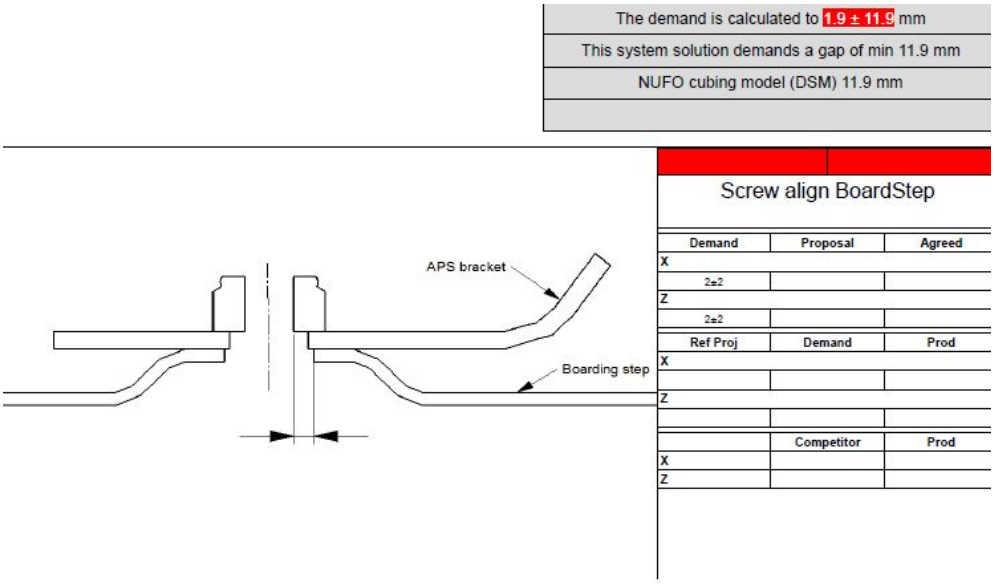


Figure 37 Cross-section of boarding step, X direction

The demanded gap in the Z direction was a minimum of 9.9 mm. This means that in order to align the screw with the hole the APS bracket has to be moved 11.9 mm in X direction and 9.9 mm in Z direction. This is the reason why production are experiencing problems assembling the boarding step.

The purpose of the case study was only to illustrate why production are experiencing problems and also to show how big the issue really is. There was no time spent trying to solve this problem. However a contribution analysis was performed which gives some clues on what is causing the problem. The results from the contribution analysis are shown in picture 23.

Screw align BoardStep: X						
Static Variation	Tolerance Name		Comments	Contr. %	Tol.	6s
1	APSBracket Surface to BracketAPS in X		2105660	27.9%	2.00	1.50
2	BumperBeam Hole pos to BracketAssy in X		1787347	12.9%	1.60	1.20
3	SideMember flatness to BracketAPS in Y		1520558	11.9%	0.50	0.38
4	SideMember flatness to BracketAPS in Y		1520558	11.1%	0.50	0.38
5	BumperBeam Hole pos to BracketAssy in X		1787347	7.0%	1.60	1.20
6	BracketAPS Surface to APSBracket in X		1333733	4.7%	0.50	0.38
7	BracketAssy Hole pos to BracketLampHousing in X		1915256	4.2%	1.00	0.75
8	BumperBeam Surface to HingeAssy in X		Estimated	4.1%	0.50	0.38
9	BumperBeam Surface to HingeAssy in X		Estimated	3.3%	0.50	0.38
10	BumperBracket Surface to HingeAssy in X		1802160	2.9%	2.00	1.50
11	BracketAPS Surface to APSBracket in X		1333733	1.7%	0.50	0.38
12	play BracketAssy to screw XZ		Hole Ø8.2 +0.2/0; M8	1.2%		0.15
13	BumperBeam Hole pos to BracketAssy in X		1787347	0.7%	3.00	2.26
14	play BracketAssy to screw XZ		Hole Ø8.2 +0.2/0; M8	0.7%		0.15
15	play BumperBrkt screw to BaseBrkt XZ		Hole Ø20.5 ±0.2; M20	0.4%		0.30
			RD&T SIMULATION (Range)		23.8	(51.44% Out)

Table 6 Results from the contribution analysis of cross-section X

The contributors are sorted from the biggest contributor to the smallest contributor in the table. The largest contributor was the APSBracket Surface to BracketAPS in X direction, with 28%. It would be wisest to start looking at the biggest contibutors first and trying to improve those areas first. The tolerances can be lowered or maybe the concept can be redesigned in regards to geometrical robustness.

The contribution analysis for the cross-section in Z direction is seen in picture 24.

Screw align BoardStep: Z					
Static Variation	Tolerance Name	Comments	Contr. %	Tol.	6s
1	BumperBeam Surface to HingeAssy in X	Estimated	10.8%	0.50	0.38
2	SideMember Angularity flange to Crossmember	Perpend. +0.3/-0.7 ;1520558	10.6%	1.00	0.75
3	BumperBeam Surface to HingeAssy in X	Estimated	10.2%	0.50	0.38
4	BumperBracket Surface to HingeAssy in X	1802160	8.8%	2.00	1.50
5	BumperBracket Surface to Bumper in X	1802160	8.7%	2.00	1.50
6	BumperBeam Hole pos to BracketAssy in X	1787347	8.2%	1.60	1.20
7	BumperBeam Hole pos to BracketAssy in X	1787347	8.2%	1.60	1.20
8	BracketAssy Hole pos to BracketLampHousing in X	1915256	5.4%	1.00	0.75
9	BumperBracket Pin pos to Bumper in Z	1802160	4.4%	3.00	2.26
10	BumperBeam Hole pos BracketAssy in Z	1787347	2.3%	3.00	2.26
11	play APS Bracket to screw YZ	Hole Ø14.5 ±0.3; M14	2.1%		0.45
12	play APS Bracket to screw YZ	Hole Ø14.5 ±0.3; M14	1.8%		0.45
13	FrontSpringBrkt Surface to BumperBrkt in Y	Estimated	1.7%	1.00	0.75
14	APSBracket Surface to BracketAPS in X	2105660	1.7%	2.00	1.50
15	SideMember flatness to BracketAPS in Y	1520558	1.4%	0.50	0.38
		RD&T SIMULATION (Range)		19.8	(50.57% Out)

Table 7 Contribution analysis for boarding step in Z direction

The difference in the contributions between X and Z directions are quite big. There are three big contributors in the picture above but none of them really stands out like the one in the X direction. The biggest contributor is 11% followed by 11% and 10%.

4.5.4 Scania Case 3 – Reference Point System

A case study was conducted in order to show how important the correct placement of reference points is. The study was carried out using the RD&T software and specifically the stability analysis tool. The purpose of the case study was to compare the geometrical robustness of different reference point systems (RPS). The basis of the study was the original reference point system according to the drawing, which is shown in figure 28. The reference system consists of 3Y, 2Z and 1X and a support point +Y. The lower left corner's reference points are XYZ. The upper left corner's reference points are ZY and the upper right corners reference point is Y.

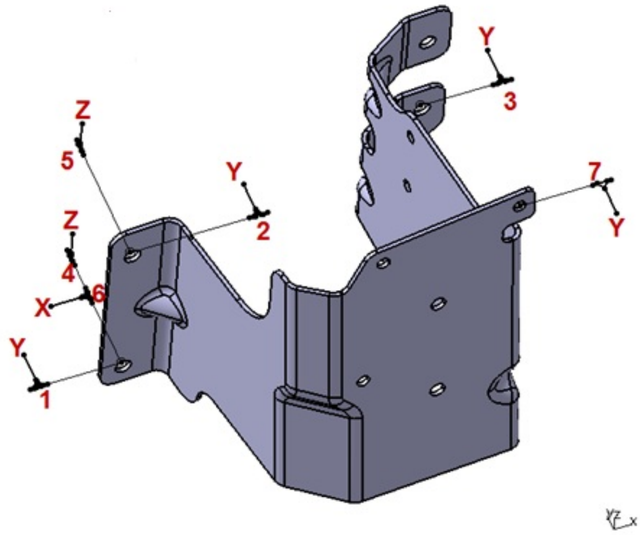


Figure 38 Original RPS

A stability analysis was performed on the part using the original RPS. The result is seen in figure 29.

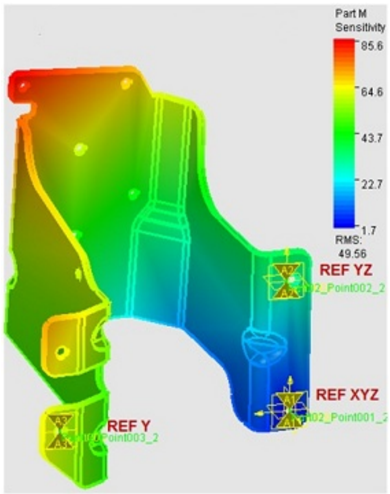


Figure 39 Results from the stability analysis original RPS

The results show that the original RPS is very sensitive to variation. The red area in the figure is the most sensitive area of the part and amplifies the variation with a factor of roughly 85. The system is not geometrically robust.

The RPS should be changed so that the part becomes more geometrically robust. Another RPS was considered which is seen in figure 30.

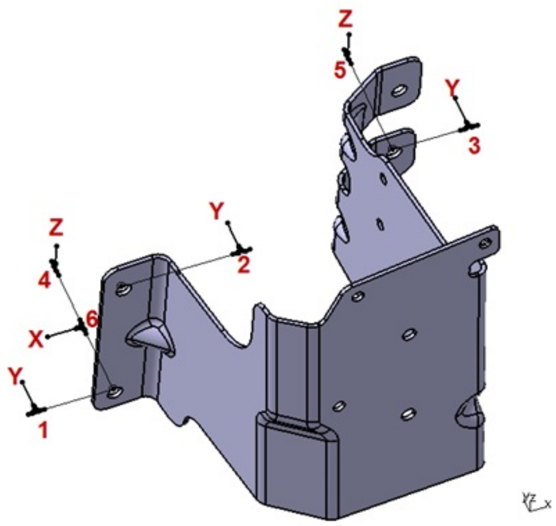


Figure 40 Revised RPS

Another stability analysis was carried out using the new RPS and this resulted in a system that was much more geometrically robust than the previous system. The new RPS was much less sensitive to variation and only amplified variation with a factor of 5 in the most critical area. The difference in geometrical robustness is staggering and all that was changed was the RPS. The results from the stability analysis using the new RPS can be seen in figure 31.

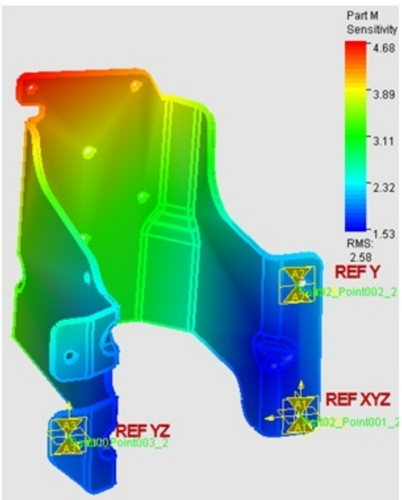


Figure 41 Result from stability analysis with the new RPS

Measurements were carried out in order to verify the results from the stability analysis. The measurement data supports the findings of the stability analysis. The original RPS amplified the variation roughly with a factor of 70, whereas the stability analysis predicted an amplification factor of 85.

5 Analysis and Discussion

This chapter analyses the results from the literature study and the case studies. The focus of this chapter is to analyze the three research questions that are presented in the first chapter of this thesis.

5.1 Analysis – Dimensional Engineering

This section is aimed at analyzing the question "How would Dimensional Engineering impact the product development process at Scania?"

5.1.1 Requirements Specification

As we have seen in the theoretical framework, the requirements specification can be broken down or built up by either the Top Down or Bottom Up approach, respectively. Since the technological trends aim towards a more customer oriented product development, more and more companies have chosen the Top Down approach. And rightly so – the increased competition demands that companies deliver products that exceed the customers' demands. Brown and Blackmon (2005) point out that the Bottom Up approach can be a supplement to the Top Down approach. This would allow the product development to balanced according to the customers' needs and the company's abilities. However, the Top Down approach seems to be harder to perform since it in the beginning of the product development process is difficult to know what the end product should be.

Both the literature and the case studies suggest that in order to avoid assembly difficulties, the requirements need to be set very early in the product development process. It is evident that if the requirements at Scania were set earlier, there would be less problems in the assembly. Less tools and maybe even less fixtures would be needed. Time to market would decrease, as would most costs, except for the investment of doing the tolerance analysis. Functionality would be improved and the aesthetic appearance would be enhanced.

5.1.2 Robustness

Geometrical robustness is an important issue that has shown to be of the outmost importance when performing Dimensional Engineering activities. Since geometrical robustness will affect the geometrical outcome and performance of a product regardless of how well the tolerances are, it is the issue that needs to be addressed first. In all of the external case studies, where the companies described their Dimensional Engineering process, geometrical robustness was a key subject. In most cases, geometrical robustness is assured even before the initial concept development phase.

5.1.3 Holistic View

The way of doing Dimensional Engineering where the geometrical robustness is prioritized over the detailed concept requirements and descriptions is becoming more common and it makes sense. By letting geometrical robustness “rule” over the component design, the risk of sub-optimization is eliminated. Since the reference system constitutes the attachment points of an assembly, the reference systems need to be optimized from a geometrical robustness point of view. This evocates a holistic perspective in which the final product is more important than the sub-components.

5.1.4 Ownership

The idea of the requirements being set early in the product development process would be just that – an idea – if there is no one who takes the responsibility for the requirements. There seems to be an urgent need for a dedicated group of people who are in charge of the Dimensional Engineering aspects at Scania and who resonate these aspects all through the organization. It is apparent that the organizational knowledge about the effect that Dimensional Engineering can have the final product is lacking. Reference systems and tolerances are often set without any grounds, only because the drawings should include tolerances. Since the knowledge about what the reference systems and tolerances ought to be, it would make more sense if there were no reference systems and tolerances on the drawings at all.

5.1.5 Measuring and Suppliers

The literature suggests that the measuring techniques greatly affect the final assembly process. A supplier doesn’t necessarily measure in the same way that a designer does and this can cause problems in the final product, either in assembly or the perceived quality of the product. Having measuring procedures clearly stated where there is no risk of design, supplier and production to misunderstand each other appears to be of the outmost importance.

Frequent measuring has been shown to be important at the companies in the case studies. This data should be collected in a form of database where it should be open and accessible for the employees. There are three main positive aspects of a database:

- It would allow the knowledge to be transferred between projects (lessons learned). The organization can ask itself what was done well and what was done poorly.
- It would boost the organizational awareness of the Dimensional Engineering issues. The knowledge would be spread across the departments.
- The suppliers would be forced to use the format in which the data is collected. This might both influence them both to give the information in a specific and understandable format and to give the information in the first place.

5.1.6 Standardization

Standardized processes are in the studied companies used in order to facilitate the continuous improvement work. A standardized Dimensional Engineering process at Scania would enable the creation of technical standards. Such technical standards would permit all parties in a company to consensually agree upon an engineering matter. This standardized process could help validate and repeat the set goals and also to strive for higher quality and continuous improvements.

5.2 Analysis of Software

This chapter is aimed at analyzing the question "How should the Dimensional Engineering software be used at Scania?"

In order to be able to determine the best requirements in the early phases of a product development process, a Computer Aided Tolerancing tool is required. Three different software were discussed in chapter 3.11. These were 3DCS, RD&T and Cetol. The characteristics of each software is described below with regard to some relevant criteria for a Dimensional Engineering implementation. Other different aspects are discussed further.

Criteria	CETOL	RD&T	3DCS
Fileformat	CatPart, CatProduct	IGES, VRML, STL, JT	CatPart, CatProduct, V4, IGES, STEP
Customizable	No	Yes	No
License cost	High	Low	High
Simulation with measurement data	Yes	Yes	Yes
Catia integrated	Yes	No	Yes (optional)
Visualization	Nej	Internal and External	Internal
Contribution analysis	Yes	Yes	Yes
Stability analysis	No	Yes	Yes
Optimization of Reference Points	No	Yes	No
Documentation	Good	Excellent	Good
Associative	Yes	No	Yes and no

Table 8 Showing the how well the software fulfill the critical criteria.

5.2.1 Statistical Variation Simulation

All three software have the ability to perform a statistical variation simulation. Both 3DCS and RD&T adopt the Monte Carlo Simulation that allows for the analysis of complex assemblies. Cetol uses the Method of System moments which is more accurate than the Monte Carlo Simulation. However, the relationship between parts needs to have the functions described before performing a stability analysis. This would seem to be better suited for mechanical joints such as in the engine assembly, while RD&T and 3DCS would fit better in the Chassi and Cab parts.

5.2.2 Stability Analysis

When it comes to determining the robustness of a concept, the software RD&T seems to have an advantage over the others. The point-based system allows for an easy-to-use robustness analysis. 3DCS can also evaluate the robustness of a concept, but it takes a longer time.

5.2.3 Integration in Catia

Cetol needs a complete CAD model before running a tolerance variation analysis. This means that a model needs to have a rather detailed requirements description before robustness and other important aspects are analyzed. RD&T uses a shadow model of the CAD model, for instance VRML that is imported from the CAD system. This takes less computational data and time to perform the analysis, which has an advantage over Cetol. It also implies that analyses of robustness, contributions and critical dimensions can be performed earlier than with Cetol. 3DCS has the ablity to run the tolerance variation analysis in both Catia and outside of Catia. This is a very flexible trait that 3DCS has and it could be an important aspect when determining which software Scania should use.

5.2.4 Visualization

The visualization tool is very powerful when demand requirements need to be set and there are several departments with different goals involved. A good visualization tool can help reach a decision faster and support the decision of a common goal. Among the three investigated software, 3DCS is the one that has the most advanced visualization opportunities. It can render images in a very realistic way. RD&T is improving their visualization tool as well and it is approaching the same standard as 3DCS. This shouldn't be the characteristic that fights out all the other software, but the visualization tool is very important and can help answer a yes- or no question.

5.2.5 Documentation

Documentation is an important activity in the Dimensional Engineering process that is needed in order to pass on knowledge to the coming projects. It also serves as an automatic requirements demands conformation that can be used by suppliers and other departments in a company. Whether the documentation should be in .html, .xls or PDF format depends on what is more appropriate for Scania. There is also the issue of what has been used before and what format people are used to engage. One department at Scania that has used .xls format might insist on continuing with that format, while another thinks that PDF is the best way to go.

5.2.6 Other aspects

There are various add-on modules that these three different software offer. Inspection preparation and measuring planning can be performed in these software. They can also be used as a help to reach the various goals in each and every one of the product development phases. These goals can be to determine the assembly attachment points, to find the best measuring plan and procedure or to find the best welding sequence. RD&T seems to have been adapted to fit all of these phases and can be seen a bit more superior to the other software from this point of view. Another positive aspect regarding RD&T is that it is very adaptable and close to the customer. The user can get a unique and tailored solution of the software. This is not possible with either 3DCS or Cetol.

6 Conclusion

This chapter concludes the results from the literature study and the case studies after the analysis of the consequences of an realization of the subject of this thesis.

6.1 Dimensional Engineering Process at Scania

Scania should strive to implement a Dimensional Engineering process that supports the product development process in all of its phases. The final product should be completely verified digitally before any physical prototypes are built. Scania is an organization that takes small steps when developing new areas. They only work with proven methods and the suggested process is something that they can strive towards and maybe implement in the future, see figure 32.

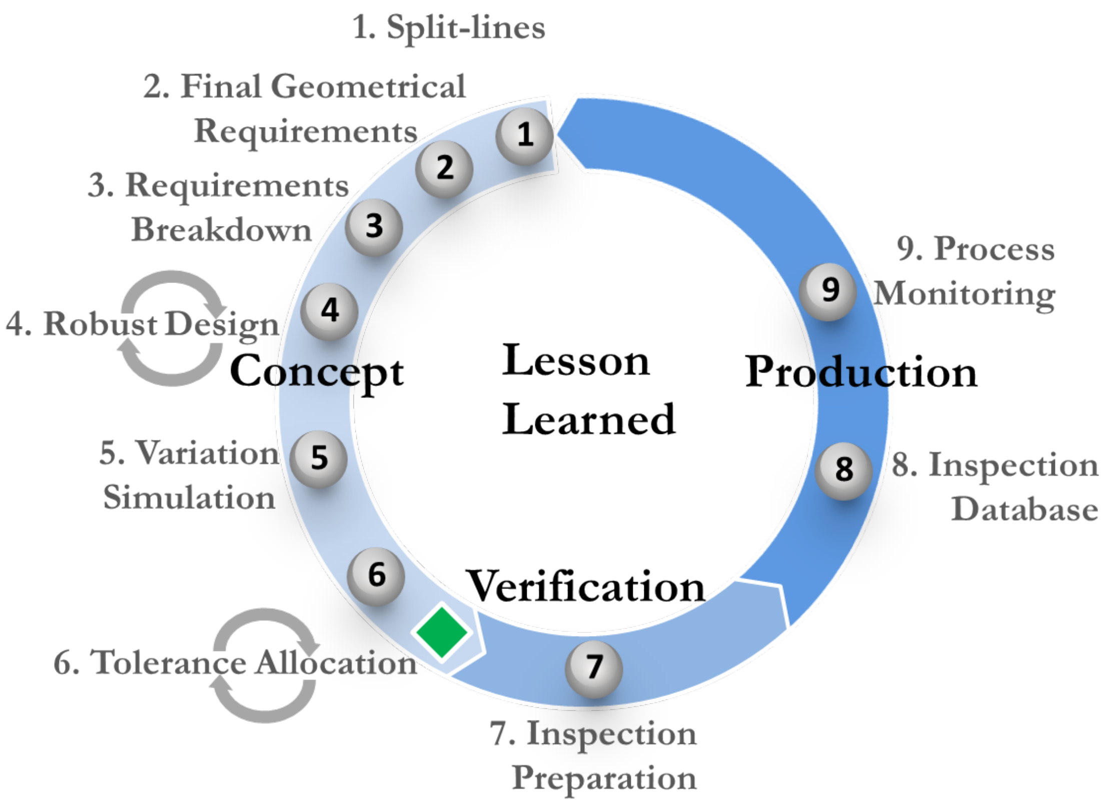


Figure 42 Future Dimensional Engineering Process at Scania

The concept phase is longer than the verification phase because late changes cost a lot of money. There is a lot of iterative work done in the concept phase because of this fact and the fact that there is a lot more freedom of change in the beginning stages of a project. The goal of a project is to reach Start of Production (SOP) as fast as possible. SOP is what generates money and that is the main goal of every producing company. The cheapest and fastest way to reach SOP is by having a long concept phase and not making many physical prototypes.

6.1.1 Concept phase

Split-line optimization

The styling department, RCD, at Scania is responsible for setting the split-lines of the truck. Dimensional Engineers are involved when setting the split-lines in order to balance visual appearance and geometrical robustness.

Final Geometrical Requirements

When entering in to a new project the first thing to consider is breaking down the requirements of the product. It is optimal to break down the requirements using the Top Down approach at the beginning stages of a project. This requires that final geometric requirements are specified early in the concept phase. Final geometric requirements should consist of *aesthetic requirements* and *functional requirements.*

Aesthetic requirements - *Aesthetic requirements* are critical dimensions of the final product such as gap and flush. RCPL and RTLX are the two groups at Scania who should be responsible for *aesthetic requirements.* RCPL is responsible for the *aesthetic requirements* of the cab and RTLX is responsible for the rest of the a*esthetic requirements.* The *requirements* should be owned by these departments but they should be set by the Dimensional Engineers working at the respective departments and engineers working at RCD. See figure 40 for an example of how an *aesthetic requirements* document can look like.

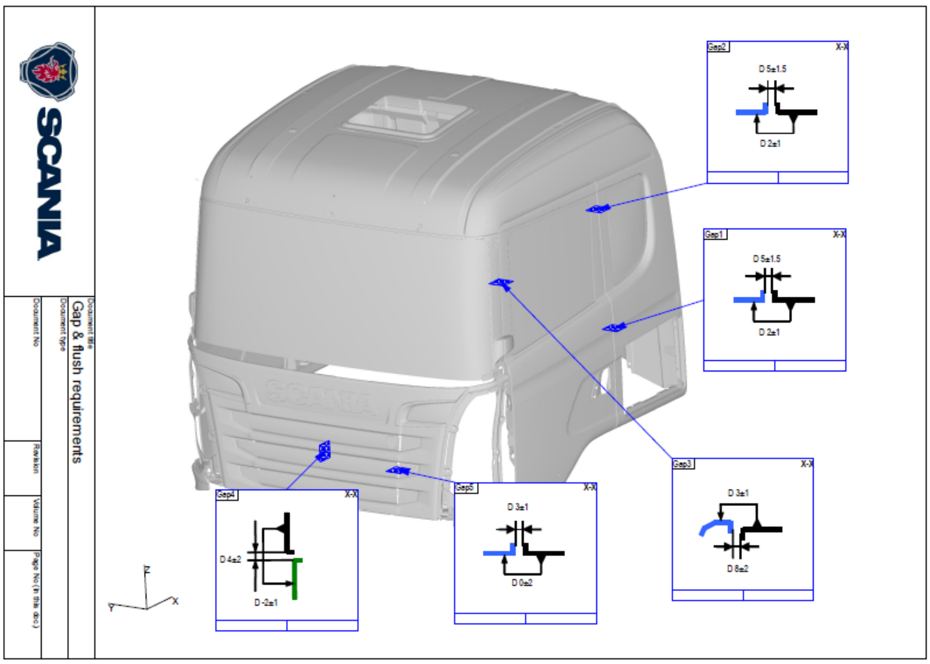


Figure 43 Example of an aesthetic requirements document

The status of every critical dimension can be tracked using the document in figure 40. Every critical dimension that is fulfilled is marked with a green box at the bottom of each cross-section.

The *Aesthetic Requirements* should be set based on experiences from previous projects, benchmarking and demands from upper management. This requires that Scania measure critical dimensions in their final product in order to gather data that can be used in the next project. It also requires that they gather data on their competitors' critical dimensions. The *aesthetic requirements* may change as the project proceeds and more information is gathered. Using visualization tools as a basis for aesthetic decisions is important during the *concept phase*.

Functional Geometrical Requirements - Examples of *functional geometric requirements* are truck width, space between the cab floor and the engine etc. These requirements should be handled by RTLX since they have the overall responsibility for the whole truck. RTLX should therefore own the requirements but the requirements should be set by RTLX, RTLI and the affected design groups. RTLI are responsible for making sure that there is no collision between components and subsystems. See figure 41 for an example of a *functional geometrical requirements* document. The document in the picture contains truck height dimensions and truck width dimensions. The status of these dimensions are handled in the same way as the critical dimension of the *aesthetic requirements.*

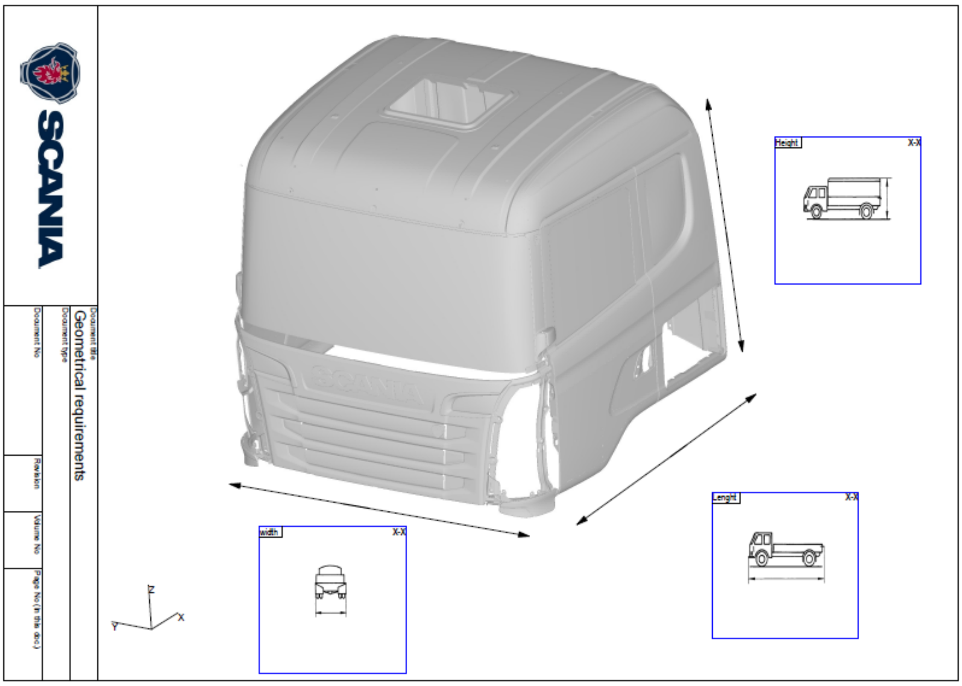


Figure 44 Example of a functional geometrical requirements document

The *Final Geometric Requirements* should be a document that consists of *functional geometric requirements* and *aesthetic requirements.* The status of the Final Geometrical Requirements should be revised periodically. Below is a summary of how the *final geometric requirements* should be handled.

Final geometrical requirements

Aesthetic requirements

- *Aesthetic demands* of RCPL: These requirements should be set by Dimensional Engineers working at RCPL together with RCD
- *Aesthetic demands* of RTLX: These requirements should be set by Dimensional Engineers working at RTLX together with RCD

Functional geometrical requirements

- *Functional geometrical requirements:* These requirements should be set by Dimensional Engineers working at RTLX, engineers working at RTLI and the affected design groups

Requirements Breakdown

When the critical dimensions are identified and the *final geometric requirements* are set the product can be broken down to a component level using the Top Down approach. The components of the product that affect the critical dimensions are thus identified. RTLX should be responsible for breaking down the requirements. The *Requirements Breakdown* of the final requirements results in an Requirement Specification. The Requirement Specification is a document containing *Final Geometrical* Requirements and requirements on a component level. This is a living document where the tolerances, reference point systems and the Final Geometrical Requirements are refined as the project proceeds. Requirements that are set using the Top Down approach are sometimes unrealistic. It is important to balance the requirements against the resources and that is why the Bottom Up approach should be used iteratively later on in the project.

Robust Design

Early in the concept phase when there is no available manufacturing data the focus should lay on developing robust concepts. This can be done very early in the concept phase, on styling shapes or old concepts. It would be best if the Dimensional Engineers own and set the Reference Point Systems (RPS). The designer would then have to use the RPS appointed by the Dimensional Engineer (DE). The DE provides the designer with a system description where the component/part and its RPS is described, this is called the master system. A description of where and how the component/part should be assembled is a part of the system description, this is called the subsystem description. The subsystem description also includes its RPS. This is an iterative process between the designer and the DE until the concept is geometrically robust.

Variation Simulation
As soon as 3D computer models are available, a variation simulation model should be built by the Dimensional Engineers. This model can be updated when more data is available. The variation of the critical dimensions can be simulated using different inputs of part tolerances and assembly variation. The results from Variation Simulation can be visualized using Virtual Reality tools. The model can be verified against the assumed production system.

Tolerance allocation
Using the 3D model the part tolerances should be optimized in regards to cost, quality and performance. The Dimensional Engineers should be responsible for alreference part tolerances. The tolerances should be set so that the critical dimensions are within the allowed limits. A measurement database containing measurement data is important in order to keep track of what suppliers can deliver. If no measurement data is available the suppliers should be contacted. This is important in order for the Dimensional Engineers not to just use best guess in order to allocate tolerances.

The DE are responsible for setting tolerances. The optimization of tolerances is done iteratively between the Dimensional Engineers, design groups and suppliers.

Milestone
Before the project moves on to the verification phase and any prototypes are built the final product should be completely verified virtually. The *final geometrical requirements* should be completely fulfilled. If the final product is not verified virtually there is no point in trying to verify it physically. Suppliers should be contacted before entering the verification phase so that they can start planning their manufacturing processes and start to manufacture tools. This is important to do early on so that suppliers can give feedback and that there are no surprises later on.

6.1.2 Verification and pre-production
The product and the production system are physically tested and verified in this stage.

Inspection preparation
The purpose of inspection preparation is to determine how tolerances on components should be measured. Defining inspection points on components is important so that the suppliers measure their components in the right way. Inspection points should also be defined for all of the in-house components.

6.1.3 Production

Monitoring the production in order to detect and correct errors is imperative. Measuring the final product is critical as it has numerous important functions. By inspecting the final product: gathering inspection data, monitoring the production process and quality assurance.

Inspection database

Inspection data on critical dimensions can be gathered and stored in an inspection database. This information can and should be used by designers when working with tolerances and by dimensional engineers working with tolerance stack-ups. The database should contain information on suppliers' capability and Scania's capability. This requires that the suppliers deliver capability data. The suppliers need to measure their components based on the inspection points determined in the verification phase. The data from the suppliers need to be stored in the database.

Process monitoring

The production process can be monitored. It is easy to know when the production process deviates if the normal mode is known. Adjustments can be made to the production process before the process deviates outside of the UCL and LCL. The process can be evaluated by having an inline measurement station. There is no need to measure every single truck. A significant amount of trucks need to be measured in order to gather statistical data.

Lesson Learned

It is important to measure the final product and compare it to the simulation data. This should be documented so that people that are entering into a new project can learn from previous experiences. How did the final product differ from the simulation results and why did it differ? This should be documented in a report so that people working on the next project can learn from previous experiences.

6.2 Continuous improvements – Dimensional Engineering

6.2.1 Robust Design

Various design groups are responsible for their components and consequently their components Reference Point Systems and tolerances. It is recommended that Scania develops a standard on how designer should set Reference Point Systems. This standard should be a part of the designers' checklist. Early contact with suppliers and tooling manufacturers is important in order for it to be no surprises later on in the project. The Reference Point System should be set by the design groups and then be delivered to Dimensional Engineers that evaluate the RPS. This work should be done iteratively until the RPS is geometrically robust and is achievable.

6.3 Conclusion – Software

All three software are built up differently and they all have positive and negative aspects as discussed in the previous chapter. However, they all have one common goal, which is to serve as a sophisticated tool in the Dimensional Engineering process. Since Scania is yet to have a fully functional Dimensional Engineering method, there will in the near future be a handful of people working with the software. The development and the future standardization of a Dimensional Engineering process is thus of higher importance than the selection of a tolerance variation analysis tool. There is nevertheless the very important aspect of the fact that since the implementation of a new process can be difficult to realize, this progression should be facilitated. This means that a software that can adapt to the process would be a better choice rather than having to develop a process that has to be adapted to the software. Though, it still holds true that some software are better than others depending on what types of components that are being examined, and this mustn't be forgotten.

7 Further Studies

The next step for Scania is to develop a detailed work method for the Dimensional Engineering process. This should include the people that should be involved in the different phases of a product development process. A standardized method should be developed that includes the following aspects:

- What role and decisive power of a matter that a Dimensional Engineer has in each phase of the product development process
- When the Dimensional Engineer's work starts in each project
- A process description of the tasks of a Dimensional Engineer
- Which other roles that are included in the Dimensional Engineering process

Scania works with the interface system where there are descriptions of how for instance the cab is related to the engine. These interfaces need to be described in more detail where it will be possible to perform a Dimensional Engineering simulation. A set out department that has the responsibility for these interfaces should be appointed and they should focus on the final product by maintaining a holistic perspective of the product development process.

Another important aspect is how the engine department should handle their Dimensional Engineering process. There is now Dimensional Engineering work performed on the engine today. The reason for this is that the construction of the engine is controlled by the engine performance. This way, the tolerances are kept within tight limits and the Dimensional Engineering work is not prioritized. However, a Dimensional Engineering process in the engine department might simulate a result that shows that functionality and performance of the engine would be maintained with bigger tolerances. This would decrease the product development costs for the engine considerably. The matter of the suitable Dimensional Engineering software for the engine would also need to be investigated further.

As we have seen in the analysis, documentation is promoted in the Dimensional Engineering process. How this documentation is supposed to be used should be studied in more detail. A standardized format for all the suppliers should also be described in order for the documented data to be clear and usable.

References

Lantz, A. 2007. *"Intervjumetodik".*

Doc. Gunnarsson, R. 2002. "*Validitet och reliabilitet".*
http://www.infovoice.se/fou/bok/10000035.shtml [2013-01-18]

Ulrich, K.& Eppinger, S. 2011. "Product Design and Development, fifth edition".

Yang,K. & El-Haik, B. 2008. "Design for Six Sigma: A Roadmap for Product Development".

Söderberg, R. & Lindkvist, L, Carlson, J. 2006. "*Virtual dimensional engineering for effective product realization".*

Scania CV AB, 2011, "Product Development Process".

Scania CV AB, 2010, "R&D Factory".

Wahlborg, P. 2013. "*Geometry Assurance*".
http://www.swerea.se/en/Start2/Testing-and-analysis/Geometry-Assurance/
[2013-02-05]

Swerea, *2008, "Introduktionskurs Geometrisäkring".*

Fischer, B. 2011. "*Mechanical Tolerance Stackup and Analysis*".

Cano, E. Moguerza, J. & Redchuk, A. 2012. "Six Sigma with R".

Brown, S. & Blackmon, K. 2005. *"Linking manufacturing strategy to the strategy mainstream".*

Wickman, C. & Söderberg, R. 2003. "Increased concurrency between industrial and Engineering design Using CAT Technology Combined with Virtual Reality".
http://www.udec.edu.mx/BibliotecaInvestigacion/Documentos/2009/Marzo/Ing%20Increased%20Concurrency%20between%20Industrial%20and%20Engineering%20Design%20Using%20CAT%20Technology%20Combined%20with%20Virtual%20Reality.pdf [2013-02-11]

Six degrees of freedom . 2013. http://wertel.blogspot.se/2009/11/designing-for-degrees-of-freedom.html [2013-02-02]

Cvetko, R. Chase, K. & Magleby, S. 2013. *"New metrics for evaluating monte carlo tolerance analysis of assemblies".*

3DCS Software Manual. 2013.

3DCS, Geometric Factor Analyzer. 2013. http://www.3dcs.com/3dcs-add-on-geometric-factor-analyzer.html [2013-05-22]

RD&T Software Manual. 2013.

RD&T, Tools. 2013. http://www.rdttech.se/tool.html [2013-05-22]

Sigmetrix, Cetol Software Manual. 2010.

Sigmetrix, Tolerance analysis software cetol. http://www.sigmetrix.com/tolerance-analysis-software-cetol.htm [2013-05-22]

Appendices

Appendix 1: Interview questions Scania

1. Bakgrund
2. Hur ser ditt arbete ut?
3. Vilka typer av monteringssproblem stöter ni mest på?
4. Hur åtgärdas dem?
5. Hur är medvetenheten om toleranskedjors påverkan på monteringsbarhet i fabriken?
6. Hur kan man sprida den kunskapen?
7. Tror du på att man kan ha olika arbetssätt för monteringssäkring (ex programvaror) på olika avdelningar?
8. När bör monteringssäkring komma in?
9. Vad kan exempelvis chassi lära av motor när det gäller monteringssäkring?
10. Bör slutkraven bestämmas i början av ett projekt?
11. Vilka bör äga dem?
12. Vilka bör driva dem?
13. Kan monteringssäkring vara en stödjande funktion till både konceptframtagning och produktutveckling?
14. Hur ser ditt arbete ut idag?
15. Har ni något standardiserat arbetssätt för monteringssäkring?
16. Beskriv ett exempel på hur monteringssäkring har löst ett problem.
17. Beskriv ett exempel på hur monteringssäkring har undvikit ett problem.
18. Vem bestämmer de geometriska (slut)kraven?
19. Vilka borde bestämma de geometriska (slut)kraven?
20. Hur samlar du in nödvändig information för att kunna utföra monteringssäkring?
21. Hur jobbar ni med gränssnitt?
22. Hur många konsulter jobbar med monteringssäkring?
23. Hur många anser du behövs?
24. Hur tidigt bör monteringssäkring komma in i PD-processen?

Appendix 2: Interview questions Volvo

1. Förklara eran produktutvecklingsprocess ur geometrisäkringsperspektiv?
2. Top Down och/eller Bottom Up?
3. Hur länge har ni jobbat med GEO?
4. Kopplat med CATIA och andra system?
5. Vilka fördelar har ni sett med GEO?
6. Hur jobbar ni med att utveckla GEO?
7. Anser du GEO vara väl implementerat i eran produktutvecklingsprocess?
8. Hur jobbar ni med geometrisäkring?

9. Hur ser rollerna ut?
10. Finns specifika geometrisäkrare på heltid?
11. Vilka avdelningar?
12. CFT?
13. Hur väl införstådda är konstruktörer och andra med GEO? Motstånd mot användning?
14. Vilka är involverade i geometrisäkrarnas arbete?
15. Hur hanteras krav och toleranser? Specifika kravhanterare?
16. Standardiserat arbetssätt?
17. Geometrisäkringssprocess?
18. Programvara?
19. Vilka använder programvaran (konstruktör/geometrisäkrare)?
20. Vilka möjligheter och begränsningar med programvarorna?
21. Vilka möjligheter och begränsningar med formaten i programvarorna?
22. Länkar och associativitet?
23. Vilka måste ha tillgång till resultatet av en stabilitets-/variationsanalys?
24. Hur viktigt är det med bra visualiseringsverktyg (e.g. ledning)?
25. Hur tar man vara på kunskapen från tidigare projekt?
26. Har ni dynamisk GEO