CHALMERS

Robust Tolerance Design at Volvo Aero Corporation

Master of Science Thesis in the Master's program Product Development

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CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

Volvo Aero Corporation develops and produces advanced components for aircraft engines. To fulfil the demands for lighter engines, their new product development is based on Volvo Aero's capability for light weight design, through fabrication. Fabrication, as opposed to traditional production methods of a one-piece casting, consists of smaller cast, forged and sheet metal worked parts, which are welded together. Simultaneously with this new design follows problems that need to be solved in order to stay competitive and to be able to produce their products. By working with robust tolerance design and geometry assurance, variation related problems can be avoided and thereby improve the quality of produced products. Robust tolerance design is also required in order to, avoid manual adjustments in production and thereby make it possible to increase the level of automation.

In the thesis work, several case studies have been conducted in order to investigate Volvo Aero's potential to adapt to robust tolerance design methods. These studies show improvement potential for the parts tested and have been used in order to describe important work procedures and tasks. A "geometry system developer" role has been tested in a project in concept phase, were the robust tolerance design tasks and questions have been handled.

Key words: Robust tolerance design, Fabrication, Variation, Geometry assurance.

Robust Tolerans Konstruktion på Volvo Aero Corporation
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SAMMANFATTNING

Volvo Aero Corporation utvecklar och tillverkar avancerade komponenter till flygmotorer. För att uppfylla kraven för lättare motorer, är deras utveckling av nya produkter baserade på Volvo Aeros lättvikts konstruktion, genom fabrikation. Fabrikation, i jämförelse med traditionella framställningsmetoder genom ett gjutet stycke, består av mindre gjutna eller smidda delar samt plåtar, som svetsas samman. Tillsammans med denna nya design följer problem som måste lösas för att förbli konkurrenskraftiga och för att kunna producera sina produkter. Genom att arbeta med geometrisk robust konstruktion och geometrisäkring kan variationsrelaterade problem undvikas och därigenom förbättra kvaliteten på producerade produkter. Geometrisk robust konstruktion är också nödvändigt för att undvika manuella justeringar i produktionen och därmed göra det möjligt att öka graden av automatisering.

I examensarbetet har flera fallstudier genomförts för att undersöka Volvo Aeros potential att anpassa sina metoder till geometrisk robust konstruktion. Dessa studier visar förbättringspotential för de testade komponenterna och har använts för att beskriva viktiga arbetssätt och arbetsuppgifter. En "Geometri System Utvecklar" roll har testats i konceptfasen av ett projekt, genom att ta hand om arbetsuppgifter och frågor relaterade till geometrisk robust konstruktion.

Nyckelord: Robust konstruktion, Fabrikation, Variation, Geometrisäkring.

CONTENTS

Preface

This Master of Science, thesis report, describes a study about how Volvo Aero Corporation can implement robust tolerance design into their Global Development Process (GDP). The research has been carried out between March 2010 and November 2010, at Volvo Aero Trollhättan, Sweden. The thesis work is the final part of the master's program Product Development at Chalmers University of Technology. It comprises 30 units of credits.

The work has been carried out by Andreas Stenlund and the progress has been supervised by Prof. Rikard Söderberg at Product development, Chalmers University of Technology. At Volvo Aero Corporation, mentoring and supervising have been performed by PhD Johan Lööf.

I would like to thank Rikard for being my mentor and Volvo Aero Corporation for being able to perform this thesis. Special thanks to Johan who has been the company supervisor. I want to thank him for all his mentoring and support during the whole process. I am also thankful to Alejandro Vega Galvez, Tor Wendel, Jesper Larsson, and all other persons who have helped me at Volvo Aero Trollhättan.

Because of company secrecy policy, all important figures, manufacturing methods and delicate information have been moved to classified appendixes and can be viewed in Volvo Aero Corporation's internal system. With these appendixes available the reader is advised to ignore Section 4.1 and instead read the appendixes.

Göteborg, Mars 2011

Andreas Stenlund

1 Introduction

1.1 Background

Volvo Aero Corporation (VAC) a part of Volvo Group (2010), develops and produces advanced components for aircraft engines. A part of their vision is to develop lightweight products to lower the fuel consumption of aerospace industry and thereby reducing costs and emissions (Volvo Aero Corporation, 2007).

To fulfil their vision new product development is based on VAC's capability for light weight design through fabrication. Fabrication, as opposed to traditional production methods of a one-piece casting consists of smaller cast, forged and sheet metal worked parts, which are welded together (Volvo Aero Corporation, 2007).

One of the major challenges in VAC's projects is to without any manual adjustments, assure optimal geometrical conditions before welding. Assuring optimal conditions will have a great impact on the quality outcome of their production process which constantly is adapted towards automation. Therefore there is a need to develop geometry assurance and robust tolerance design techniques applied to aircraft engine manufacturing.

1.2 Purpose

The purpose is to improve Volvo Aero Corporation's work with robust tolerance design and geometry assurance, in line with their Global Development Process (GDP).

1.3 Objective

The thesis work consists of three main objectives.

- To perform case studies on projects from different stages in the GDP to gain knowledge about what work can and needs to be done in each stage.
- To perform a method study about how VAC is working with geometric robust design and geometry assurance today, and produce a guide for how that work can be improved.
- Conduct studies about what skills are needed for a person with a geometry system developer role (GSU, Geometri System Utvecklare in Swedish) and how this role should function in the company.

1.4 Research questions

To guide the work and verify the results afterwards a set of research questions have been stated. The importance and use of these questions is further described in Section 3.1.

How well adapted are VAC's products and processes for implementation of a robust tolerance design process? RQ 1

This question is stated with the aim to investigate how well implemented the work with robust tolerance design can become at VAC. It is interesting to test how well the analyse process work with the products geometry and manufacturing processes.

How should the everyday work with robust tolerance design, function within VAC? RQ 2

This question relates to the GSU role which is explained in Section 2.5, if VAC should implement a similar role there is a need to conduct research about how the role should function.

Is there any problems related to robust tolerance design with VAC's products today? *RQ 3*

This question is stated to find out if VAC could gain anything, if the company starts to work with robust tolerance design.

1.5 Scope

The case study analyses in this thesis are performed using the software Robust Design & Tolerancing (RD&T) and the recommendations about how to perform similar studies is based on the software. No other software has in this thesis been evaluated or tested but the limitation is based on the results from Mia Westins thesis work (Westin, 2010), performed at VAC, where she gathered information about different analysis software, for robust design.

A limitation for the analyses conducted is that only rigid parts have been analysed. However a section about the use of non rigid parts can be found in Section 5.1.

2 Frame of Reference

This chapter shortly explains the basic theory used throughout the thesis, regarding robust tolerance design, geometric robust design and geometry assurance.

2.1 Tolerances

A tolerance is an engineering tool to handle manufacture variation, to make sure that the functional, assembly and aesthetic demands on the product are met. Tolerances are often defined in intervals which give the upper and lower limits for how much a certain measure can vary (Volvo Group, 2006).

To anticipate the final size of a product, when manufactured, tolerances for each part need to be taken into consideration as well as the locating scheme for each part, see Section 2.2. With information about both these things the anticipated maximum and minimum size of the product can be calculated according to different theories. Worst case and statistical tolerancing are two common used calculation methods which will be explained in the following sections, Section 2.1.1 and Section 2.1.2.

2.1.1 Worst case tolerancing

When tolerances are calculated according to worst case scenario, it is implied that all measures included in the analysis is at it maximum or minimum value. The total measurement for the whole product is then calculated as the sum of all part measurements. Figure 1 illustrates the relation. The chance for that the worst case will occur is very small and therefore is statistical calculations more realistic and useful.

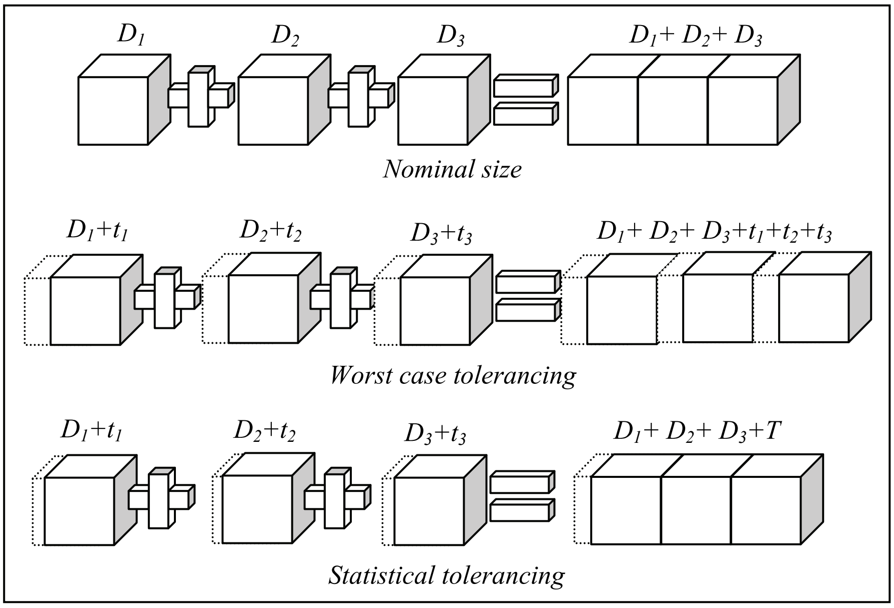

Figure 1 Illustrates two different tolerance calculation methods

2.1.2 Statistical tolerancing

If statistical tolerancing is used when calculating a measurement of the total product, tolerances for parts can in some cases provide the advantage of cancellation because one part is smaller and one is bigger than nominal size (Srinivasan, 1999). A calculation method in statistical tolerancing is Rot Sum Square (RSS). In this method the total tolerance (T) for a set of parts is a function of all part's tolerances and their amplification factor (Chase & Parkinson, 1991).

$$T = \sqrt{\sum_{i=1}^{n} (a_i t_i)^2} \qquad (1)$$

Where $a_{\mathrm{i}} = \frac{\partial f}{\partial x_i}(\mu_i)$, is the sensitivity coefficient (amplification factor), n is is the amount of parts and the mean value μ_i is the expected value. The difference of worst case tolerancing and statistical tolerancing is illustrated in Figure 1.

2.1.3 Process capability indices

The interval specified by tolerances does not describe how the measurement within the interval is distributed, to specify the behaviour of the measurement standard deviation and process capability indices are used.

If the variation in a process is measured and documented it can be illustrated in a histogram where the distribution curve will have a spread around a mean value. This spread is defined as the standard deviation which is calculated as (Montgomery & Runger, 2007):

$$\sigma = \sqrt{Variance(X)} \qquad (2)$$

$$X = value\ of\ measurement$$

The variance is a measure of the dispersion in the distribution. The standard deviation implies how well a measurement can be realised, a low value shows that the measurement size often is close to nominal. The actual spread of a measure (process performance) can be related to the allowed tolerance interval with a capability index, C_p, when the data follows a normal distribution. This capability index relates with which confidence a measure will fit in between an upper and lower distribution limit (UDL, LDL) (Forrest, 2003). It is calculated as:

$$C_p = \frac{UDL - LDL}{6\sigma} \qquad (3)$$

One limitation when calculating with C_p is that the mean value is assumed to be correct according to the desired value. In normal processes this is hardly ever the case; therefore several alternative indices to C_p have been developed. C_{pk} is one of them which are taking variation into account as well as a mean shift from the target value. The C_{pk} value is calculated as:

$$C_{pk} = min\left(\frac{UDL - \mu}{3\sigma}, \frac{\mu - LDL}{3\sigma}\right) \qquad (4)$$

$$\mu = mean$$

A normal minimal C_{pk} value in industry is 1.33 which refers to four standard deviations and a confidence level of 99.99%. This is 66 parts per million outside the specified distribution limits (Pearn & Kotz, 2006).

2.2 Locating scheme

A locating scheme for a part is the collection of defined points that locks the part in all six degrees of freedom. A locating scheme usually consist of three points (A1, A2, A3) that form a plane and lock the part in one translation and two rotations, two point (B1, B2) that locks one translation and one rotation and one point (C1) that locks the last translation. For a better understanding see Figure 2 below.

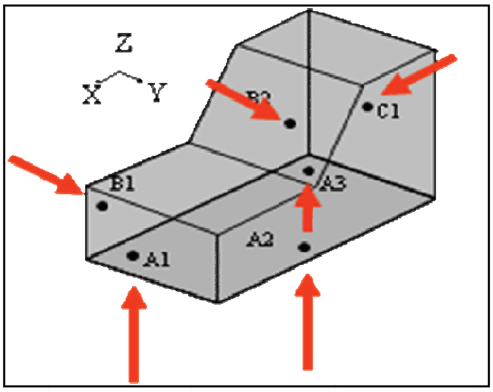

Figure 2 Illustration that shows the six points necessary to lock all degrees of freedom in a locating scheme.*(Söderberg et al., 2006, p.76)*

The name that describes the collection of points that locks a parts position can differ between different users. The collection and the points themselves may be called locating scheme and locators, datum planes and datum points or reference system and reference points. However, in this thesis the collection is referred to as locating scheme and the points as locators.

2.3 Geometrical robust design

Two produced products are never identical; there will always be geometrical variation due to variation during manufacturing. This variation may lead to poor quality and high manufacturing costs. A geometrical robust design is less sensitive to variation which means that the product will be satisfying regardless of ingoing variation, see Figure 3 (Söderberg & Lindkvist, 1999). The work with increasing the robustness of a part is closely linked with improving the parts locating scheme which was described earlier in Section 2.2.

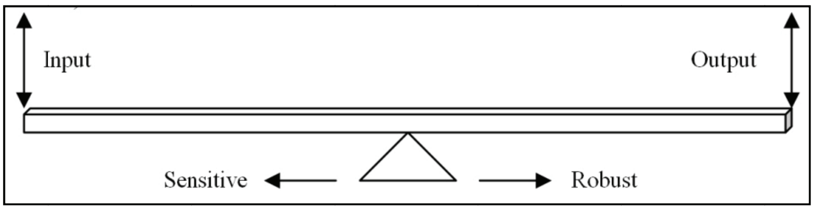

Figure 3 Illustrates the relation between input and output when the robustness is varying *(Söderberg & Lindkvist, 2002, p.175)*.

Robust design was developed in Japan during the 1950's by Genichi Taguchi (The American Supplier Institute, 2000). By using the method early in the development process, the locating schemes can be improved and coupled tolerances be avoided. In a coupled tolerance chain, the geometrical variation is not only affected by the part itself but also by other parts. A coupled design is therefore more sensitive to variation because it is amplified further out in the chain which results in a higher risk of causing problems. One way to solve problems caused by a coupled design is to assign more narrow tolerances to the parts. This solution is however expensive. Small tolerances can instead be avoided by implementing robust design early in the product development process which consequently leads to cost savings. (Söderberg & Lindkvist, 1999).

Improving the locating schemes to archive a more robust design is enabled by allocating the locators to more suitable positions. The main idea is to spread out the locators in a way that minimizes the effect of variation in the points. Figure 4 shows two separate sets of locators with different robustness. The three locators that form a plane have in the right figure been moved away from each other. A variation in one point would not affect the part as much as it would in the left figure. The right figure therefore shows a more robust behaviour and is less sensitive to variation. A locating scheme's sensitivity to variation can therefore be analysed by affecting one locator at a time and measuring the resulting movement of the part. This procedure has to be made for each locator and the movement tracked for each surface of the part, which is time-consuming and hard. However there are computer software tools too quickly and effortless do this analysis virtually. One such software is RD&T (Robust Design & Tolerancing) developed by Wingquist Laboratory at Chalmers University of Technology (RD&T Technology AB, 2010).

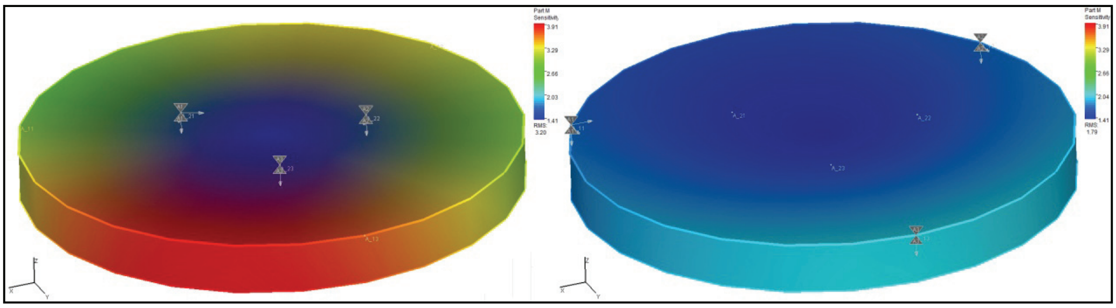

Figure 4 Illustrates the difference in robustness between two locating schemes. The right is more robust as indicated by the legend.

2.3.1 Wingquist Laboratory and RD&T

Wingquist laboratory is an internationally competitive competence centre for multidisciplinary research in the field of product and production development. Their four main research areas is System Engineering and PLM, Geometry Assurance & Robust Design, Geometry and Motion Planning lastly Flexible Automation. The research area that is related to this thesis is Geometry Assurance & Robust Design which focuses on how to handle geometrical variation throughout the whole product realization process. With distinct activities during each phase of the Virtual Geometry Assurance loop, the variation can be controlled throughout the whole process see Figure 5. The research group working in this area is lead by Professor Rikard Söderberg and includes ten additional senior researchers and 9 PhD students (Silow, 2010).

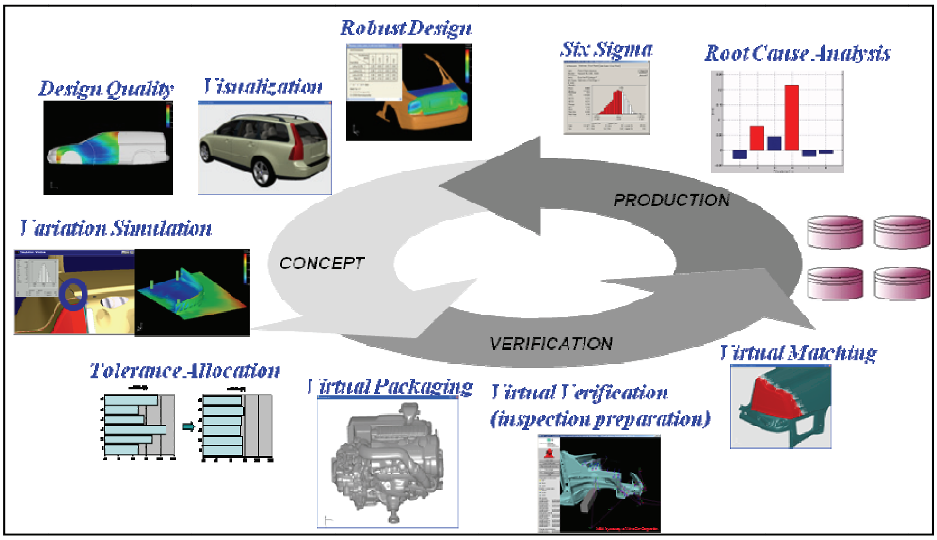

Figure 5 *Geometry assurance activities illustated by the "Virtual Geometry Assurance Process" loop (Söderberg et al., 2006)*

In 1998 Rikard Söderberg and Lars Lindqvist introduced the Computer Aided Tolerancing (CAT) software RD&T (RD&T Technology AB, 2010) to assist the work in the Virtual Geometry Assurance Process. CAT software such as RD&T could be used to simulate variation and calculate standard deviation. At first, the software requires Computer Aided Design (CAD) models of all parts, to represent the design and shape of the product. The next important step in the process is to evaluate what geometries that actually lock the parts together and in what directions they act. Then locators and locating scheme can be assigned and positioning the parts to each other (Söderberg & Lindkvist, 2007).

In the software RD&T it is possible to perform analyses like stability analysis, variation analysis and contribution analysis. In a stability analysis every locator is allowed a unit sized distortion. Then the amount of units that this variation affects the entire structure is visualised by colour coding. The variation analysis uses the so called, Monte-Carlo method to generate random variables for variation of each point in line with their assigned tolerance. The variation of all assigned measures is then documented for each assembled product, which is repeated for a chosen number of iterations. Contribution analysis uses the documented values from the variation analysis and calculates in which amount (percentage) the different points contribute to the variation in the different measures (Söderberg et al., 2006).

2.4 Measurements

For a better understanding some measurements that are used in the thesis are here described and Figure 6 illustrates them further.

Gap is the perpendicular distance between two opposing surfaces or edges

Mismatch, also called flush is the height difference between two neighbouring surfaces.

Parallelism between two parts is also measured by calculating the variation in two gap or mismatch measures.

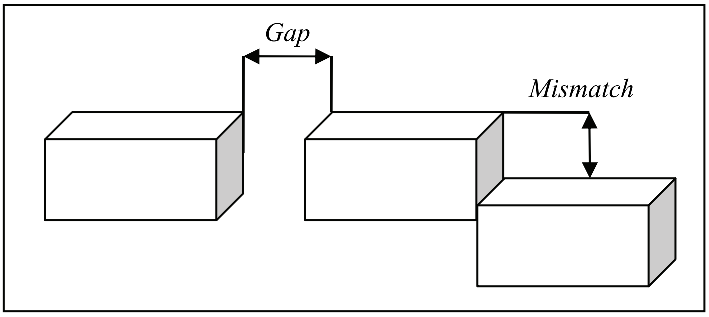

Figure 6 Illustrates how mismatch and gap measurements are defined

2.5 Geometry System Developer role

Geometry System Developer (GSU, Geometri System Utvecklare, in Swedish) is a common name for the people at Volvo Cars Corporation and Volvo 3P (Volvo Group, 2010) that work with geometric robust design. Information about his (hers) work tasks, processes and role are more described in research findings, Section 4.2.

3 Research Approach

The research mainly consists of testing if the Virtual Geometry Assurance Process developed by Wingquist Laboratories is possible to apply into VAC's development process. Geometry assurance and geometric robust design are new work methods at VAC. The analysis, about how the work should be implemented and which work methods are suitable are therefore hard to structure beforehand. According to Yin (2003), highly unstructured analyses and problems can benefit from using a case study research design, which also have been chosen for this thesis. Yin (2003) also explains that the aim for a case study is to verify the feasibility of the chosen research procedure which mainly is the case at VAC. A more fixed and pre-decided research method would become hard to manage due to the nature of the project. Other research approaches lack the flexibility that exploratory case study possesses.

To get more deep knowledge in the area qualitative semi structured interviews was planned. However due to lack of response from interviewees, only one interview could be performed. The interview where held at VAC face to face with prepared subject matters to discuss but otherwise unstructured.

3.1 Case study research

With the use of a case study, it is possible to look into an organisation and keep the holistic and real characteristics of important events, such as relations and processes (Yin, 2003). Case studies are in other words used to catch the dynamics present and to increase the understanding of an area in interest (Eisenhardt, 1989). The studies often use data collection from many sources, combined together to give a true holistic representation of the real life case (Tellis, 1997).

Yin (2003) has divided the case study research into three different types, explanatory, descriptive or exploratory. An explanatory case study should be performed when a situation is known and there is a need to explain why the situation is present or occurred. A descriptive case study mostly aims at describing social and personal issues such as performance, group structure and social relations of neighbourhoods. An exploratory study is used when not much about the structure and process is known. The study aims at answering questions of the type "How?" and "Why?", which fits well with the stated research questions. Stuart *et al*. (2002) states similar questions of type "What is there?", "What are the key issues?" and "What is happening?" when the case study is meant to explore a territory, which is the case in this thesis.

3.2 Research process

Three case studies are conducted to capture the different stages of Volvo Aero's GDP. The individual case studies have been tailored to fit into Wingquist Laboratory's "Virtual Geometry Assurance Process" that was mentioned in Section 2.3.1. By implementing this process the case studies aim at describing how well the process can be adapted and connected to VAC's development process. According to Yin (2003) there is a need for a plan or design how to get from the initial research questions to their answers when conducting a case study. In this thesis the plan or design is simply as mentioned, to apply Wingquist Laboratory's process and for each case follow enough of that path to be able to answer the stated research questions

4 Research Findings

This chapter describes the different findings gained during the case studies and interviews.

4.1 Case studies

The case studies were conducted in order to provide information about what type of work that is possible and viable to perform during a product development process. The three projects that were chosen for the case studies are in different development phases according to VAC's GDP and could therefore provide information from a wider spectrum. The GDP which is based on the Volvo Corporate's, is a development logic, formed to compose a generic and common ground for product development with the flexibility to adapt to different assignments.

The three case studies performed are described, regarding analyse and result in the following Sections. Figure 7 explains where in the GDP the projects currently are.

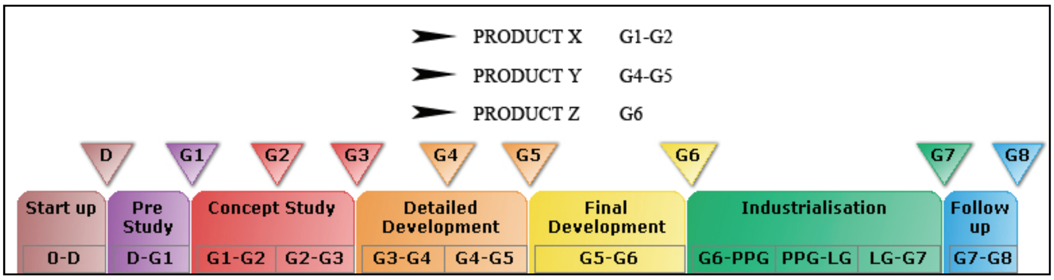

Figure 7 Describes the case studies and in which phase of the development the product are.

Common for all the case studies is that they provided interesting information and understanding about how to gather useful data and how to perform the analysis effective.

It was found that for products in late developments stages a study of the drawings where necessary in order to get a complete view of the product. After this initial analyse of the geometry and drawings the already defined locating scheme could be analysed with respect to geometric stability. The overall stability (RMS-value) can be insightful and guiding but more interesting is the stability in a certain direction. Which direction that is most important, have to be figured out by experience and is not always clear. This shows that theoretical knowledge is not enough, practical experience from working with robust design and analyses like this case are truly important.

The next analyse step with these matured products is to identify problem areas that could be related to variation, either from the initial study or from persons familiar with the product. However it is more likely to come from the latter. It is necessary that for each problem area identify some critical dimensions and define these in RD&T. With the critical dimensions at hand it is possible to define tolerances according to drawings or process capability and perform a focused analyse. The results from the analysis are documented with the help of standardised report supplied by RD&T. The documentation and acceptance/approval of results and are according to Peter Edholm (2010) a key to be able to make changes in a developments process. He states that clear deliverables in form of reports that can be signed, are important in order to keep leverage in upcoming discussions and decisions.

4.1.1 Product X

Because of company confidentiality some of the information regarding the analysis can not be included into this report. The complete version of this analysis is therefore explained in Appendix A. Case Study of Product X, available internally at VAC.

The work needed to be performed in the Product X project was about building up a good ground for the continuing development and to increase the interference between different organisational functions. The work was conducted together with the design team at VAC. At first the work was focused on aiding the project team regarding robust tolerance design and tolerance chains, during concept selection for the product. The two concepts were called ”Forged” and “Sector” and as the names imply one is made mostly by forging and the other assembled from smaller sectors, by welding them together.

Stability analyses were performed and assembly sequences were discussed for each concept. During that work, questions were raised regarding level of control that would be needed for the different concepts to assure that variation could be kept within limits. To answer these questions more investigations needed to be performed regarding manufacturing methods and fixture design. The two concepts Sector and Forged were very different, but when regarding robustness, quite similar. Hence, for the upcoming stage gate, a comparison between them, was delivered, see Table 1**Fel! Hittar inte referenskälla.**. The main difference between the two, are the lack of process control, that concept Sector suffers from. Since the structure is composed of several parts welded together it is hard to ensure good position for each of them. Because of anticipated weld distortions there would be necessary to weld prepare several connection surfaces between the parts. This extra operation is expensive but good from a robust design, point of view, because it in this case, avoids an unwanted tolerance chain.

During the manufacturing it is favourable to weld all or some parts together in an even distribution and in the same fixture (Aronsson, 2010). Hence, the fixture that is to hold the parts during welding for the concept Sector would become extremely complex. The fixture complexity would not only come from the number of parts but because of the parts locating schemes, if they were to be geometrically robust.

Table 1 Important aspects to consider during concept selection, regarding robust design.

	Forged	**Sector**
Fixtures	*One fixture*	*Two fixtures (one complex)*
Level of certainty and control	*Good control*	*Hard to predict weld distortions*
Tolerances	*Defined by milling operations*	*Hard to control due to weld distortions*
Tolerance chain	*Good*	*Good*

The locating schemes for the other concept, Forged, was instead optimised to use easy accessed surfaces and consist of three locators. The process control for Forged would also be improved because the tolerances for the parts would be well defined by process capability. Because of more integration of parts as opposed to concept Sector, there is no need for extra weld preparations. However the forging of the part is time-consuming and difficult, but that is not considered in this analysis.

The development of the locating scheme for the two concepts involved so much more than optimising regarding geometric robustness which was the initial objective. Several aspects proved to affect the choice of design for the locating scheme and sometimes these were hard to discover and understand, some of them are gathered in Table 2.

Table 2 Important aspects regarding the choice of locating scheme

It should be strived for, to use only one locating scheme for a part
Areas near weld seam could be deformed and the position of locators/fixture may hinder the weld tool
Areas that is to be machined, should not be used, othervise the locating scheme for that part need to be varied during production
Locators should be positioned so that there is possible to clamp the part directly towards the locator
It is favourable if the locating scheme provide an easy fixturing of the part, partly because of fixture design but also because of assembly time during production
Flexible areas could increase input variation and should be avoided

The resulting proposed locating schemes for both concepts are developed with these guidelines in mind, trough several iterations to become optimal in every aspect. Parallel as the concepts were to be reviewed for further development a design work was presented that resulted in a change of the concept Forged. This altered the geometry but not the locating schemes for the parts. With input regarding robustness, concept Forged were later selected for further development which for the case study work, resulted in that robust locating schemes were developed for each part. These locating schemes are described in Appendix A.

An analysis was performed to gain knowledge about what tolerances and processes that would be needed to control variation. To perform this variation analysis, information about the manufacturing method was required and then mainly what tolerances that method results in. The capability for those methods was acquired thru discussion with production engineers, which enabled the analysis to be performed. During this more extended analysis required size of tolerances was calculated. The result was elicited with variation analysis in RD&T, which is explained in Section 2.3.1. The variation analysis calculated anticipated process capabilities and found areas more sensitive to variation than others. It was also found that the initial stated value for tolerances, given by the project team could be increased and the assembly would still work. A more complete description about the analysis can be found in Appendix A.

4.1.2 Product Y

Because of company confidentiality some of the information regarding the analysis can not be included into this report. The complete version of this analysis is therefore explained in Appendix B. Case Study of Product Y, available internally at VAC.

The Product Y design is developed according to VAC's concept lightweight through fabrication. Since the development of Product Y is in phase G5-G6 according to Volvo Aero's GDP, all interfaces and locating schemes have already been set. The analysis in this phase need to be more verification than an input to design, and are therefore limited to one small but critical part of the production. The part selected in this case study is a specific welding sequence. This operation will affect all the following operations because of the tolerance chain built into the design and it is therefore extra important that it is performed correctly. The main question is if the fixture that holds the parts during welding and the parts themselves are adequate geometrically robust for this operation.

The first step in the analysis was to, from drawings, locate the defined locating schemes for all parts and apply these in RD&T. To fully understand what actually happens during the welding sequence, in order to not leave any important aspects out, a more comprehensive study was required for some parts. In the analysis of the drawings and models of the fixture and the parts it was found that VAC had applied some geometrically robust design in this project. For the included parts there were well defined locating schemes realised mostly with the use of discrete bosses. However, theses locating schemes proved not to be especially geometrically stable.

The idea from the start was to use the locating schemes to fixture the parts together and perform weld preparations on several surfaces at the same time before welding. This proved, during prototyping, impossible to perform due to weld distortions and the weld preparations for all other surfaces than the first one were removed. Hence, the locating scheme is as a result, located far from the actual weld seam to avoid interference with operations that is not performed anymore. Therefore it is not optimised regarding geometrical robustness, in relation to the weld seam which results in unnecessary big amplification of the variations.

The next step was then to define critical measurements on the assembly and add these to the analysis in RD&T. The critical area in this analysis was defined to be the weld seam and the measurements selected were therefore gap and mismatch measurements between the interfering parts. With the gap measurement analysed on four locations the distance between the two parts can be checked together with the angle between the parts. Mismatch measurements gave information about the size of the misalignment between the two parts. When the measurements had been defined in RD&T the tolerances for all surfaces, pins and holes that are used by the locating schemes or the measurements needed to be inserted from drawings. However for the fixture no tolerances were specified since this part was defined as rigid without any possibility to move. As mentioned, variation analysis provided results about gap, mismatch and parallelism for the relations in the seam. The size of these variations was however hard to relate to, since there were few products produced and no requirements stated, for the condition of the seam. The only demand on the weld seam was standardised values about largest allowed mismatch between two parts. In this process a major lack in communication and coupling between functions was identified. All weld simulations done by engineers at VAC are performed on nominal geometries. However in design and production tolerances and variation are defined and conditions that are not nominal are frequently identified. There is therefore no control and simulation performed for what impact geometric variation has on e.g. weld distortions.

From discussions with weld engineers and operators, it emerged that if a gap between parts is present before attachment welding this gap will shrink during the more extensive welding that will follow. If the parts, in the weld seam, are not parallel in relation to each other, they would therefore tend to become more parallel. Mismatch between parts would however still be present after all welding is performed. What this really denotes and what complications this might result in are discussed in Appendix B.

To easier understand and to display the results from the different analyses a RD&T analyse document was created during the case study and is available internally at VAC.

4.1.3 Product Z

Because of company confidentiality some of the information regarding the analysis can not be included into this report. The complete version of the analysis is therefore explained in Appendix C. Case Study of Product Z, available internally at VAC.

The phases of the process that are analysed are the manufacturing, measurement and assembly of a part of the product. The analysis is conducted because VAC wishes to improve the control and reduce the variation of this manufacturing process. The case study of Product Z was supposed to be a study of the possibility to verify results from analyses against measured values. It was known that the product had some problems possibly related to geometric robust design but the source was not known. Soon into the analyse it was clear that the product had big problems related to repeatability and robustness.

At first the drawings and the model were achieved to be able to understand the geometry and locating scheme of the product. The part analysed have all locators positioned against non machined surfaces and the positions for the locators is not well defined. Therefore it is hard to position the part in the exact same way repeatedly. Furthermore, the geometric stability of the locating scheme is far from robust which amplifies this variation even further. The total variation in an area or point is a combination between input variation in the locators, variation in the measured area and the geometric robustness of the locating scheme. Hence, the total variation of Product Z is in some areas to big. Exact values of the analysed variations are described in Appendix C. However these results were hard to verify due to much bigger problems. One problem is that the geometry seems to be deformed when it comes from the supplier. This deformation makes the hardware measurements performed on the part somewhat unusable since they do not reflect the same geometry as in the analysis. Another problem is that the bad repeatability affects the conducted measurements and there is no way to determine in what extent. The hardware measurements are conducted on more than 50 parts with respect to the same locating scheme. However, no measurements are conducted to determine with which precision one particular part could be fixtured over and over again, i.e. the fixture's repeatability.

Even if the improvements would be hard to verify, a set of new locating schemes was designed, see Appendix C. The three new locating schemes are designed so that their implementation would need different amount of change to the process. Table 3 shows a comparison between the different locating schemes. Even if all of the new locating schemes suggested would be an improvement in relation to the current one, it is not clear that they all will provide adequate improvement, for a change to be implemented.

Table 3 Comparison between the different alternative locating schemes suggested. Robustness with Rot Mean Square (RMS)-value implies how well the locating scheme can handle variation. The changes to geometry and fixtures rows, implies how much change that need to be performed in order to use the suggested locating scheme. Repeatability shows with which precision the part can be inserted into the fixture repeatedly.

Robustness	Original	Alternative 1	Alternative 4	Alternative 5
RMS-value	3.30	2.28	2.27	1.64
Changes to geometry	None	None	Significant	Significant
Changes to fixtures	None	Significant	Significant	Significant
Repeatability	Bad	Bad	Improved	Good

A more complete description about the analysis can be seen in Appendix C.

4.2 GSU role

The GSU should be a central role inside the corporation that actively works to increase knowledge about robust design and improve the geometrical robustness products by e.g. optimising locating schemes. To optimise a new product regarding robust design it is important to include the GSU from pre study until production starts. The most important should be to set the locating schemes for each part in a really early stage to give each other function in the company a common ground for each part. The locating schemes provide a ground for e.g. quality measurement, requirement specification that will help to guide and control the process. On the further development these locating schemes will also be developed to fit with the changing product. When questions about tolerances, fixturing and packing studies arise, the GSU is present and well-grounded to answer these questions with proper analyses and writes a report. Much of this knowledge has been acquired during an interview with Peter Edholm (2010) which can be read about in Appendix D.

It is important that the GSU is a part of the development team and that (s)he have clear stated deliveries for each stage. If the GSU provide a result and get it accepted by project leader or design leader it is easy to go back to that decision later, if pressure of time affects the priority of robust design.

5 Discussion

5.1 Discussion about research questions

The stated research questions in the introducing chapter (1.4) are here discussed and answered based on result in this thesis.

How well adapted are VAC's products and processes for implementation of a geometry assurance process? RQ 1

VAC's products are often hard to model in an analysis due to the rotational symmetry. When there are no well defined geometries like bosses or such that specify where the locators should be placed but instead only a flat surface, it is hard to position e.g. only three points. What could happen if the surface is deformed is that the three points on the surface is located on one side and thereby tilt the whole part. To adapt VAC's process to a more robust design, well defined locating schemes are required. The locators in this scheme could be realised by geometries on the parts themselves, or by geometries on their fixtures.

VAC's parts are mostly welded together into products, these welds are somewhat hard to analyse. Welding in e.g. automotive industry could partly be seen as a glue process, were the geometry mostly stays in the position that it is fixtured. However, in VAC's case the welding often require more extensive use of heat which makes the geometries deform and then shrink during cooling. This process deforms the geometries in such extent that several assemblies cannot be analysed in one simulation model. Often in VAC's case there are demands that the variations should be really small, weld operations are therefore often followed by machining due to the deformations. Hence, it is mostly interesting to analyse the state before welding because after the operation the structure will be machined to desired geometry anyway. To correctly analyse the weld operation a more advanced non-rigid analyse would need to be performed, incorporated with weld simulation, to anticipate deformations. A non-rigid analyse allows for more than 6 locators to hold a part, it permits extra support points that can define the weld seam. A non-rigid module for e.g. sheet metal analyses is available in RD&T but for VAC's complex geometries, there is a need to analyse solid models.

How should the everyday work with geometry assurance function within VAC? RQ 2

Like explained in Section 4.2 the work with geometry assurance should be handled by a person with a GSU role since the area is too complex to be handled at every single department separately. The important connections made between department will also be lost if there is no central role. If a single person in one project gets the responsibility for geometric robust design instead of a central GSU, this person will not have time to fully learn and utilise the techniques. The person responsible should therefore do this work consistently to become better but also have a central function within projects and be inserted into the projects from start.

As described earlier the work should consist of defining geometric robust locating schemes for all parts and during the development process continue to optimise and develop them further. The work will consist of joining different functions in the organisation together and in unity decide where it is possible to place locators. Functions or persons that the GSU need to have contact with are e.g.:

- Leaders; Design and Project
- Mechanical engineers
- Weld engineers
- Aero engineers
- Fixture developers
- Production
- Suppliers

During many of the steps in the case studies it was clear that knowledge and experience about geometrically robust design, tolerances and locating schemes are truly important. If the person who performs the analyses and interpreted the result from them should be able to do this in a efficient and correct way (s)he needs experience.

The GSU also need to inform and slowly train affected employees about robust design and what they together with VAC can gain from working with it. Only if the benefits with robust design are widely known they can properly be utilised.

Is there any problems related to geometric robust design with VAC's products today? *RQ 3*

VAC need to design products with locating schemes that are better defined in order to gain control of the process variation throughout the entire product lifecycle. One example is the lack of ability to control and review the variation in the Product Z project. A better defined locating scheme would solve the repeatability problem as well as the control problems.

Throughout all the case studies it has been found that VAC could gain a lot from increasing the geometric robustness of all their products. Some problems might have been avoided and some narrow tolerances could be increased to lower expenses. Although it seems like many things can be improved, it is hard to beforehand give a indication about how much.

5.2 Discussion about research approach

The use of case studies as research approach during the thesis work has encouraged testing and exploration of new way to solve problems. Since the research method is less controlled during its implementation than other methods, it allows changes to be performed that are needed to reach conclusions. During the case study of Product Z changes was performed from the initial plan since the verification of the product was found to be harder than expected. This change provided a chance to investigate the product for improvements instead of ending the research with only the results about the verification problems.

The common work method for dealing with geometric robust design, during product development, proved to work for most cases. However, the different steps were sometimes hard to apply due to the fact that necessary information about the product or process sometimes was missing. This was the case for e.g. the Product Y case study where necessary information about the requirements for a weld seam was missing. In the future, these problems have to be identified and work methods may have to be changed to manage them.

5.3 Discussion about case studies

The case studies resulted in several new ideas and work methods of how to implement geometric robust design into VAC's GDP. However, there are a big difference in providing ideas and getting them implemented. The projects are as explained, in different developments stages and are naturally therefore more or less easy to guide in the right direction. Early changes like those in Product X project, does not affect that many other areas, however, the effect from them are huge. In a later stage like with Product Z necessary changes are easy to find but hard to realize. It is often hard to put a figure on the improvement potential and therefore even harder to get the change approved. Since the main reason for implementing geometrically robust design, is to avoid problems in manufacturing instead of having to solve them, it is more interesting to look into new products and projects. However, as already stated, a lot can be learned from analysing already developed products to identify company specific problem areas and avoid these problems in the future.

Welding at VAC creates another problem since it deforms the part in such extent that assemblies cannot be analysed in sequence. The welding deforms of the parts between two following assemblies which makes today's software unable to simulate them. Today there are no analyse method to simulate the connection between variation and deformation from welding at VAC but it would be needed.

One problem that needs a change in behaviour and definitions are the fact that VAC uses the engine's centreline when making drawings. The centerline is in theory, a good point to define tolerances, in relation to, but not in practice. The centerline cannot be found anywhere and this affects for example the measurement of the part. Since this position is not a physical location but a point in the middle of the part, it needs to be measured every time it should be found. This measurement increases the tolerance chain for the part or process with another tolerance which is unwanted. Furthermore, many of VAC's products are rotational symmetric and therefore quite hard to analyse. The analysis tool demands that all degrees of freedom are locked and need discrete locator positions. A solution about how to solve these problems needs to be discussed further, internally at VAC.

6 Conclusion

If VAC should be competitive on the market and produce product according their vision, “Best Partner”, they need to implement new work methods to control variation. The difficulties and problems related to variation, which will come from working with fabrication instead of single cast parts, needs to be taken care of. With an implementation of robust tolerance design and a GSU role, several benefits will be obtained. New products developed will become more geometrical robust and from a early start in the projects there will be a common ground defining the product, spreading from design to fixture manufacturing, drawings and production.

The implementation of a new work method, a new role within the company and a new way of thinking might take time. It will probably take several years until the process is well adapted to the project work at VAC. Even if there is an interest and somewhat understanding in the company it will become a hard process. However, as seen in the cases studies every little step makes a huge difference.

This new work method needs to get proper support from the top management otherwise it will be hard to gain full advantage of robust tolerance design and geometry assurance. The benefits from working with robust tolerance design are hard to translate into numbers and sometimes even hard to see, since the main factor is to avoid problems instead of solving them. Therefore is support for the area even more important.

6.1 Recommendations

The recommendations to VAC are to implement robust tolerance design into the company and later when more knowledge is gathered, customize the process to fit their own processes. Some areas can be looked into further, like how to avoid a tolerance chain when working with the engines centerline and how to analyse the connection between variations and weld deformations. A study regarding deformations could be initiated as a master’s thesis work to gain some knowledge before a complete study is conducted. VAC will gain a lot if they can predict weld distortions originated from geometric variations and thereby be able to define more accurate demands on weld seam conditions before welding.

Even if VAC introduces new work methods with robust tolerance design and implements a GSU role, some kind of 3D simulation software need to be acquired. The simulations and calculations that need to be performed are impossible to perform by head. Therefore is there a need for some kind of software that can calculate geometrical variation outcomes, related to robust tolerance design.

7 References

Aronsson, E., 2010. *Interview about welding techniques at Volvo Aero*. Trollhättan, Sweden.

Chase, K.W. & Parkinson, A.R., 1991. A Survey of Research in the Application of Tolerance Analysis to the Design of Mechanical Assemblies. *Research in Engineering Design*, 3, pp.23-37.

Edholm, P., 2010. *Interview about Robust Design and GSU Role*. Translated by A. Stenlund. Trollhättan, Sweden.

Eisenhardt, K.M., 1989. Building Theories From Case Study Research. *The Academy of Management Review*, 14(4), pp.532-50.

Forrest, W.B., 2003. *Implementing Six Sigma: Smarter Solutions Using Statistical Methods, Second Edition*. John Wiley & Sons.

Montgomery, D.C. & Runger, G.C., 2007. *Applied Statistics and Probability for Engineers, fourth edition*. Hoboken, New Jersey: John Wiley and Sons Inc.

Pearn, W.L. & Kotz, S., 2006. *Encyclopedia and Handbook of Process Capability Indices: A Comprehensive Exposition of Quality Control Measures*. World Scientific Publishing Co.

RD&T Technology AB, 2010. *RD&T Technology - The Tool RD&T*. [Online] Available at: http://www.rdttech.se/tool.html [Accessed 26 October 2010].

Silow, N., 2010. *Produkt- och produktionsutveckling. Research Areas*. [Online] Available at: http://www.chalmers.se/ppd/wingquist-en/research/research-areas7743 [Accessed 12 October 2010].

Srinivasan, V., 1999. Statistical Tolerancing. In Drake, P.J. *Dimensioning and Tolerancing Handbook*. McGraw-Hill. p.Ch. 8.

Stuart, I. et al., 2002. Effective case research in operations management: A process perspective. *Journal of Operations Management*, 20(5), pp.419-33.

Söderberg, R. & Lindkvist, L., 1999. Computer aided assembly robustness evaluation. *Journal of Engineering Design, 10(2)*..

Söderberg, R. & Lindkvist, L., 2002. Stability and seam variation analysis for automotive body design. *Journal of Engineering Design 13(2)*.

Söderberg, R. & Lindkvist, L., 2007. Robustness evaluation and tolerance analysis, Software manual Robust Design & Tolerancing.

Söderberg, R., Lindkvist, L. & Carlson, J., 2006. Virtual Geometry Assurance For Effective Product Realization. In *1st Nordic Conference on Product Lifecycle Management - NordPLM'06*. Göteborg, 2006.

Tellis, W., 1997. Application of a Case Study Methodology. *The Qualitative Reports*, 3(3).

The American Supplier Institute, 2000. *Dr. Genishi Tagushi*. [Online] Available at: http://www.amsup.com/taguchi_methods/dr_taguchi.htm [Accessed 26 October 2010].

Westin, M., 2010. *Tolerance Design and Processes for Fabricated Jet Engine Components*. Master's Thesis. Luleå, Sweden: Luleå University of Technology Industrial Design Engineering.

Volvo Aero Corporation, 2007. *Technology - Make It Light*. [Online] Available at: http://www.volvoaero.com/volvoaero/global/en-gb/aboutus/Technology/Pages/Technology.aspx [Accessed 23 Augustus 2010].

Volvo Aero Corporation, 2010. *Weld modelling & automation*. [Online] Available at: http://www.volvoaero.com/volvoaero/global/en-gb/aboutus/Technology/weld_modeling_automation/Pages/weld_modeling_tech.aspx [Accessed 23 Augustus 2010].

Volvo Group, 2006. *STD 112-00, Geometrical tolerances*. Standars. Volvo Group.

Volvo Group, 2010. *Volvo 3P*. [Online] Available at: http://www.volvogroup.com/group/global/en-gb/volvo%20group/our%20companies/volvo3p/Pages/Volvo3P.aspx [Accessed 15 November 2010].

Volvo Group, 2010. *Volvo Group: Home*. [Online] Available at: http://www.volvo.com/group/volvosplash-global/en-gb/volvo_splash.htm [Accessed 23 Augustus 2010].

Yin, R.K., 2003. *Case study research - Design and methods*. 3rd ed. Thousand Oaks: Sage.

8 Appendix A. Case Study of Product X

This part of the report is removed due to confidentiality. Refer to Volvo Aero Corporation’s intern servers for a full version of the report.

9 Appendix B. Case Study of Product Y

This part of the report is removed due to confidentiality. Refer to Volvo Aero Corporation's intern servers for a full version of the report.

10 Appendix C. Case Study of Product Z

This part of the report is removed due to confidentiality. Refer to Volvo Aero Corporation's intern servers for a full version of the report.

11 Appendix D. Interview

This is a summary of an unstructured interview with Peter Edholm about robust design and GSU role. Summarised and translated by Andreas Stenlund.

Peter Edholm works with a consultant firm, PE Geometry Development AB, to implement robust design into businesses in the area. He has been involved with implementing robust design into Volvo Trucks and Volvo Cars Corporation among others.

Team design

Usually geometry assurance activities is performed by consulting businesses but in larger companies as with the automotive industry it is usually performed internal by about 10 people. In a single project, it may be up to 6 people (GAE, Geometry Assurance Engineer), each divided into a structural component in the project. These GEA can either sit together or be placed in design teams. They converse with each other about the entire design solution in the project and put up a common strategy, but deliver and discuss individually against design department.

GSU role

A GSU should be involved in a project from pre-study, to the production start of the part. Most important in a project is to establish and optimize the locating schemes early, this can be implemented at low cost and it will have positive repercussions in design as well as production. Locating schemes thereby creates a basis for setting standards, monitoring measurements etc. on the product, that makes it possible to guide and control the process. Is work done on a new detail, the process is simple and rather theoretical because the GSU can decide what (s)he wants but if it is an existing product or production system, a lot of cooperation with production is needed.

It is important to include design and be active as GSU to get as much cooperation as possible. It is also important with fixed deliverables lashed to the project plan and get them approved in order to highlight the decisions taken later in the project phase. It is hard to put requirements on design as GSU but with active discussions the GSU can get ideas through and thereby get the solution implemented in the design.

Later when the part takes shape the GSU can set up a specification of requirements on the product, such as critical functional requirements, split lines, packing studies etc. However, these requirements are often found because someone seeing a potential problem and wonder if that is the case. The GSU then does an analysis of requirements and delivers a report of the results, possibly with an alternative solution to the problem.

Robust design within a company

It is difficult to both in forehand and afterwards, point out in figures what robust design can give a company. What you do if you in an efficient way work with robust design is to avoid problems and therefore produce a better product instead of solving the problems once they arise. Often it can be difficult to be understood within the company and many do not realize how important it is to work effectively with robust design. To ensure this does not occur, which might reduce the positive effects of the process, active support from the management of the company is required.