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Procedia CIRP 43 (2016) 3 – 12

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14th CIRP Conference on Computer Aided Tolerancing (CAT)

Virtual Geometry Assurance Process and Toolbox

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Abstract

Geometrical variation in individual manufacturing and assembly processes often propagates and accumulates, resulting in products that do not fulfil functional, esthetical or assembly conditions. Geometrical quality problems are often discovered late with huge cost for changes and delays as a consequence. The ability to simulate and foresee geometry problems early, allows robust concepts to be developed, tolerances and assembly sequences to be optimized and key inspection features to be selected. This paper presents a comprehensive geometry assurance process with an efficient set of tools that supports the geometry assurance process from early concept phases, through verification and pre-production and finally during production.

Peer-review under responsibility of the organizing committee of the 14th CIRP Conference on Computer Aided Tolerancing

Keywords: geometry assurance; robust design; tolerance managment

1. Introduction

Tolerance analysis and variation control is an area that has been addressed quite extensive over the years. Historically, the area started with mass production in early 20th century, where interchangeability among parts resulted in the need for tolerances to be specified. After the Second World War, Japanese quality began to improve a lot, followed by a quality improvement in the west in the 1980´s. In total, this quality development has been supported by persons like Shewart [1], Deming [2], Juran [3] and Taguchi [4].

A *robust design* is a design insensitive to variation. The ideas of robust design and quality improvement, however, were originally introduced by Taguchi [4]. The factors affecting a concept are divided into control factors, easy to control, and noise factors, which are hard to control. Transfer functions, relating inputs (control factors) to outputs determine whether variation will be amplified (sensitive concept) or supressed (robust concept). Taguchi also introduced the “quality loss function” as a concept for assessing the monetary loss as a function of deviation from a target, see Figure 1.

Figure 1: Robust Design [4]

In the theory of *axiomatic design*, see Suh [5], the design activity is described as a mapping between functional requirements (FR:s) and design parameters (DP:s) and the proper selection of DP:s that satisfy FR:s. According to Suh, a good, *uncoupled* design, is characterized by the fact that each output (FR) is controlled by only one input (DP). A *decoupled* design is an acceptable design that has to be tuned in a certain order, whereas a coupled design is very difficult to tune and control (Figure 2). Generally, minimizing the number of parameters controlling an output parameter is an effective way to increase design robustness.

Peer-review under responsibility of the organizing committee of the 14th CIRP Conference on Computer Aided Tolerancing
doi:10.1016/j.procir.2016.02.043

$$\begin{pmatrix} FR_1 \\ FR_2 \\ FR_3 \end{pmatrix} = \begin{bmatrix} X & O & O \\ O & X & O \\ O & O & X \end{bmatrix} \begin{pmatrix} DP_1 \\ DP_2 \\ DP_3 \end{pmatrix} \quad \begin{pmatrix} FR_1 \\ FR_2 \\ FR_3 \end{pmatrix} = \begin{bmatrix} X & O & O \\ X & X & O \\ X & X & X \end{bmatrix} \begin{pmatrix} DP_1 \\ DP_2 \\ DP_3 \end{pmatrix} \quad \begin{pmatrix} FR_1 \\ FR_2 \\ FR_3 \end{pmatrix} = \begin{bmatrix} X & X & O \\ X & X & X \\ X & O & X \end{bmatrix} \begin{pmatrix} DP_1 \\ DP_2 \\ DP_3 \end{pmatrix}$$

Uncoupled Design *Decoupled Design* *Coupled Design*

Figure 2: Axiomatic Design [5]

Tolerance analysis has in the literature often been treated somewhat separated from robust design which may be reflected by the fact that it in industry often is performed quite late, when the design is frozen and there is no way to change the embodiment design in order to increase robustness. Ideally, tolerance allocation should be performed top down (Figure 3), i.e. product requirement should be broken down to part tolerance based on sensitivities, cost etc. Summaries of tolerance analysis methods and issues can be found in [6]. In Figure 3, the sensitivity coeffients between part tolerances and product tolerance (the transfer function) is 1 which means that a change in one of the part tolerances t_1, t_2 or t_3 will have equal effect of the product tolerance t. However, in most real applications, 3D effects related to the six degrees of freedom for each part and how the locators are positioneed will result in sensitivity coefficients that may be difficult to calculate manually, and also to quite complex tranfer functions. Computer aided tolerancing (CAT) tools like RD&T, VSA, 3DCS, CETOL can then provide a good support [7-10]. Söderberg [11], proposes how CAT tools can be used to support the product development process and bridge the gap between tolerancing and product development.

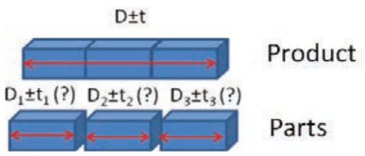

Figure 3: Tolerance allocation

According to Ebro [12], typically 60 % of all late changes in the development of a new product are related to sensitive or unclear concepts or tolerances. The company costs for late changes can be quite extensive and the potential to shift late changes to early prevention of failure, with focus on more robust concepts, has therefore a great potential.

1.1. The scope of the paper

The areas of quality, robustness and tolerancing have in the literature been addressed, to a large extent, separately and on different abstraction levels. The relation to the product development process is, in the literature, sometimes not obvious. This has also been pointed out in [13]. Therefore, this paper aims at bringing these areas more close together by describing a working procedure and a set of tools for managing variation from early design phases through the whole product realization loop. The paper builds on the geometry assurance process developed by the authors since 1997, partly reported in [11]. The main motivation for this paper is to describe new research results in specific fields, specifically within non-rigid analysis, and to give an outlook on some future needs and challenges. The research results, and the working procedure described, have been implemented at a large number of companies, which can be seen as verification of its usefulness. Some general conclusions, based on the industrial implementation of the results, are also reported.

The structure of the paper is that Section 2 presents the geometry assurance process and the importance of locating schemes. Section 3 presents the geometry assurance toolbox with support in concept phase, verification phase and production phase. Section 4 presents an outlook for the area and Section 5 concludes the paper.

2. Geometry assurance and locating schemes

In this section, the geometry assurance process and the importance of locating schemes is described.

2.1. Geometry assurance

Geometry assurance can be described as a number of activities, all contributing to minimizing the effect of geometrical variation in the final product. Activities can be found in all the different phases of the product realization loop (see Figure 4):

In the *concept phase* the product and the production concepts are developed. Different concepts (sub-solutions) are analysed and optimized to withstand the effect of manufacturing variation and tested virtually based on available production data. In this phase, the concepts are optimized with respect to robustness and verified against an assumed production system by statistical tolerance analysis. The visual appearance of the product is optimized and product tolerances are allocated down to part level. See Section 3.1.

In the *verification* (pre-production) *phase* the product and the production system are physically tested and verified. Adjustments are made to both product and production system to correct errors and prepare for full production. In this phase inspection preparation and off-line programming of coordinate measurement machines and scanning equipment takes place. Here, all inspection strategies and inspection routines are decided. See Section 3.2.

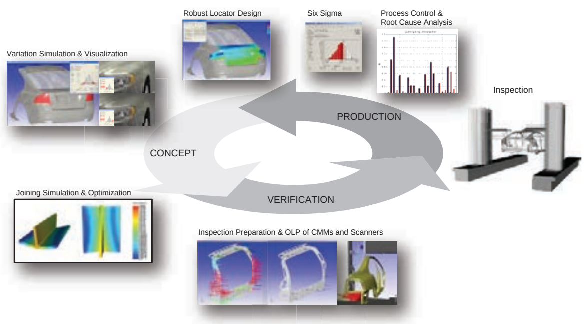

Figure 4: Geometry assurance activities

In the *production phase* all production process adjustments are completed and the product is in full production. Focus in this phase is on inspection data to control production and to detect and correct errors. See Section 3.3.

Figure 4 shows typical activities that aim at minimizing the effect of variation in the final product. In Chapter 3, tools for supporting all these activities are presented and discussed.

2.2. Locating schemes and "the main rule"

Variation propagates through the physical contacts (locating schemes) between the different parts and/or fixtures in an assembly. Properly done, these contacts are chosen to prevent over-constrained or geometrically sensitive solutions. The locating schemes can be seen as the transfer function between input and output variation and are the most important "control factors" for creating a robust mechanical assembly. The purpose of a locating scheme is to lock the position of a part or a sub-assembly in space. A number of different locating schemes exist and are used in various industrial situations, see [14]. Figure 5 (left) shows an orthogonal 3-2-1 locating scheme with six locating points, used for rigid analysis. The three primary locating points, A1, A2 and A3, control three degrees of freedom, translation in Z (TZ), rotation around X (RX) and rotation around Y (RY). The two secondary locating points, B1 and B2, control two degrees of freedom, translation in X (TX) and rotation around Z (RZ). The last, tertiary locating point controls one degree of freedom, translation in Y (TY). For non-rigid parts, over-constrained locating schemes with additional support points, are used. Figure 5 (right) shows a 17-7-1 non-rigid locating scheme for a body side of a car.

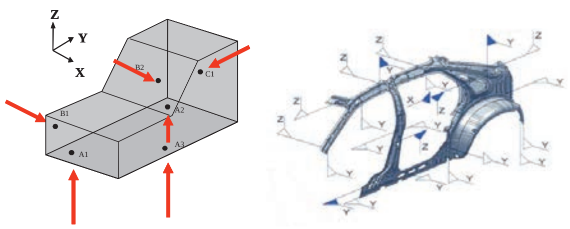

Figure 5: Rigid and non-rigid locating schemes

The main rule in geometry assurance

To prevent unnecessary introduction of variation it is recommended to use (as far as possible) the same locating scheme during part manufacturing, inspection and assembly. This is often referred to as "the main rule in geometry assurance". To not introduce new variation sources, it is also recommended (when possible) to reuse locators from previous assembly steps instead of introducing new ones [15].

3. Geometry Assurance Toolbox

This chapter describes a set of integrated geometry assurance tools that supports the geometry assurance process from early design concept phases, through verification and pre-production and finally during production. The analysis tools presented use a virtual assembly model (variation simulation model) where all parts and sub-assemblies in the product or assembly, the mating conditions (locating schemes), the product requirements (outputs) and the expected part variations (inputs) can be defined. Three dimensional rigid body transformations, describing the kinematical relations of the assembly, relate the inputs to the output and capture all sensitivities. Based on mating conditions and top-level constraints, assembly structures and coupling matrices are automatically generated. All functionality presented in the paper has been implemented and industrially tested in the software RD&T (Robust Design & Tolerancing) [16]. The software also contains a document suite with a number of drawings and simulation result documents that support the geometry assurance process. Most of the document are semi-automatically generated and fully associated with the actual geometries.

3.1. Concept Phase

In the concept phase the product and the production concept are developed. Product concepts are analysed and optimized to withstand the effect of manufacturing variation on part level and tested virtually using available production data. In this phase, basically the following interrelated tasks are performed, often iteratively:

1. Definition of split-lines (i.e. how to divide the product into components)
2. Definition of top level requirements (defining product tolerances)
3. Definition of locator positions to optimize geometrical robustness
4. Tolerance allocation (defining part tolerances)

In the concept phase, the virtual assembly model (the variation simulation model) and a set of tools are used to support the three activities of defining split-lines, locators and tolerances.

Robust locator design

In most situations in this phase, the position of the split lines are defined by styling or industrial design and the focus is therefore on finding robust locating schemes that minimize the effect of the manufacturing variation in the individual parts. The *stability analysis*, see [2], evaluates the geometrical robustness of a concept, i.e. how variation, introduced to the components by the locators, propagates and affects critical features and dimensions. By varying each locating point with a small increment, Δinput, one at a time, Δoutput/Δinput may be determined in the X, Y and Z directions separately for a number of output points, representing the geometry. The RSS values for all points, representing the sum of variation in each point caused by variation in the six locating points, are determined and shown in color-coding, where red means high amplification of input variation (a sensitive concept) and blue means low amplification (a robust concept). Figure 6 shows an example of a door-to-body case. By summarizing the sensitivities from all individual locating points, the locating scheme sensitivity for a part or a subassembly can be calculated and visualized. The stability matrix shows the part position sensitivities with respect to locating scheme variation and also indicates the unwanted couplings in red. By changing the position of the locators for the parts, the sensitivity can be reduced. By changing the assembly sequence or strategy, the number of unwanted couplings and controlling parameters can be reduced [9-10], and it can also resulting in reduced amplification of variation and increased robustness.

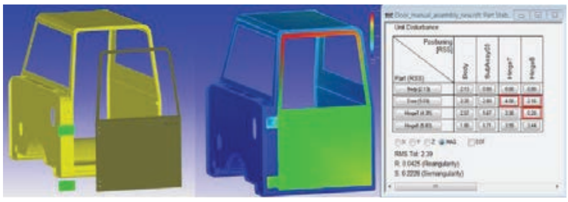

Figure 6: Stability Analysis

Locating scheme optimization

The general design rule for selecting locating points is to spread the points as much as possible over the geometry in order to maximize robustness. In many design situations it is not obvious how to do that in the best way. The six degrees of freedom for a part can be controlled by the locators in many ways. Optimization of locator positions has been presented in [17]. Figure 7 shows an example with an aero component. The locating scheme to the left is the initial proposition, resulting in an amplification factor of 50.6 times in the red area. The locating scheme to the right is the one calculated by the optimization algorithm, resulting in 1.8 times variation amplification in the red area. The locators are illustrated with red arrows.

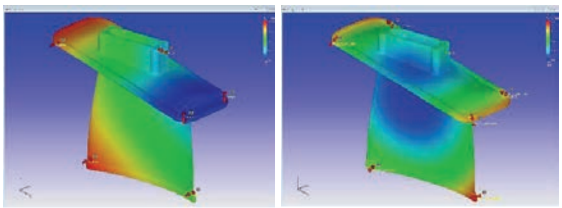

Figure 7: Initial locator positions (left) optimal locator positions (right)

In Figure 7, the robustness was optimized with respect to the whole geometry of the part. Figure 8 shows the same type of optimization but for a set of critical measures, in this case a number of gap/flush measures between a pipe and a cylinder. Here, the pipe is to be welded on the cylinder, why the relation between the parts is important.

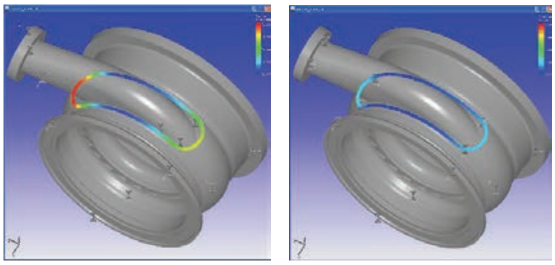

Figure 8: Initial locator positions (left) optimal locator positions (right)

Statistical variation simulation

Variation simulation (Figure 9) is extensively used in automotive industry in early phases of the product realization loop to compare different designs and to analyze different tolerancing strategies. There are two main approaches to statistical tolerance analysis: the MC simulation-based approach and the deterministic methods, often based on Taylor's series expansion [18]. The MC simulation-based approaches can be done using direct Monte Carlo (DMC) simulation or by a linearization. For a DMC-based variation simulation, distributions for all input parameters are defined. In each DMC iteration, values of the input parameters are randomly sampled from the defined distributions. For analysis of non-rigid parts, finite element analysis (FEA) is used to calculate the response in the output parameters. Usually, thousands of iterations need to be run to get a good accuracy in this kind of simulation, which will be very time consuming, since a FEA must be run in each iteration. Therefore, the method of influence coefficient (MIC) [19] is used in most MC based variation simulation approaches. The main idea of MIC is to find a linear relationship between part deviations and assembly deviations after spring-back. A sensitivity matrix, calculated using FEA, describes that linear relationship. The sensitivity matrix is then used to calculate the response in each MC iteration. The method was used by Camelio et al. [20], who applied it to a multi-station system. Dahlström and Lindkvist [21] investigated how to combine MIC with contact modeling. Contact modeling was also further developed by Wärmefjord et al. [22] and [23]. Variation simulation for non-rigid sheet metal parts and assemblies is described in [24, 25]. Variation simulation for composites is treated in [26], [8] and geometrical induced variation simulation of stress in composites is treated in [27], see Figure 9 (right). The problem of model growth in variation simulation is discussed and treated in [25].

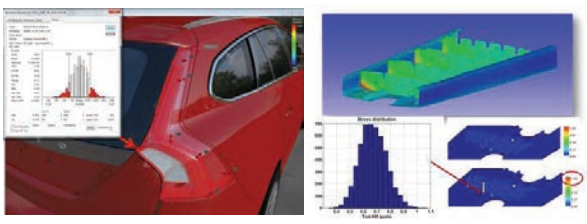

Figure 9: Variation simulation

Part variation estimation and modelling

To be able to perform assembly variation analysis that correlates with reality, the description of part variation is crucial. Often in early concept phases, before any physical parts are manufactured, the exact variation behaviour of the parts is not known. Methods to model part variation by superposing different variation modes had been proposed by [28-33]. To capture and model part variation, DOE in combination with manufacturing simulation (stamping, moulding, forging) and principle component analysis (PCA) has been proposed in [34] and [35]. Methods based on morphing technologies and inspection data from similar projects has been proposed in [36]. The description of part variation is used together with MC simulation in the assembly variation simulation.

Split-line evaluation

The spatial relations, the split-lines, between parts in assembled products are often critical. In the automotive industry, the relations between the doors, hoods and panels are important perceived quality (PQ) characteristics (see Figure 10). Today, the quality appearance of a vehicle is judged by the quality of the split-lines between the body panels, i.e. doors, hoods, fenders and panels. A split-line relation on the product level is described by a number of requirements on flush, gap, parallelism etc between two subassemblies or parts. A framework for evaluation of the visual robustness of car body exteriors, based on split-line types (Figure 10a) and degrees of freedom (Figure 10b) are proposed in [37] and the parameters influencing the perception of geometrical deviations are discussed in [38], see Figure 10c.

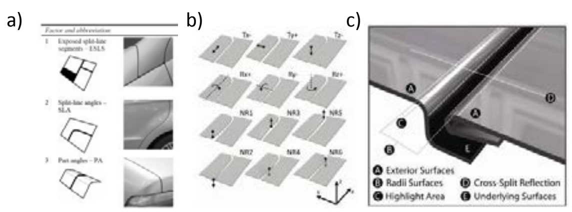

Figure 10: Split-line evaluation

To evaluate the total split-line concept for a product with respect to robustness and variation the *seam variation analysis* was proposed in [39]. In the simulation model the seams (split-line measures) can be generated more or less automatically as a large number of critical dimensions by tracing technique. Variation is predicted using the variation simulation model with Monte Carlo simulation and can be presented as distributions or by a colour coding in each direction, see Figure 11. The *quality appearance index*, rates the total variation in all seams of the body. The latter is calculated as the mean variation in all defined seams of a body and allows for evaluating the final appearance of the body, with one measure, already in the early concept phase. The seam variation analysis differs from the stability analysis and locator optimization shown in Figure 8 by using Monte Carlo simulation and real part variation data as input.

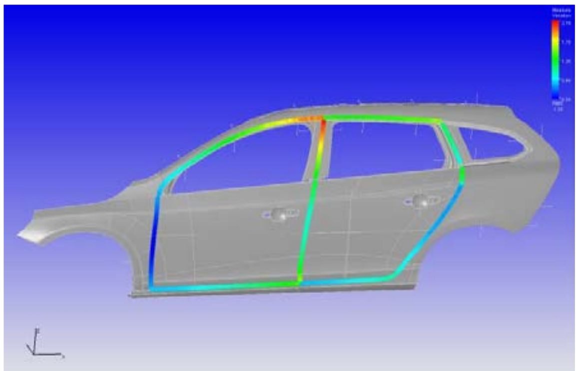

Figure 11: Split line (seam) variation analysis.

Split-line optimization

Normally, split-lines are defined before locators are optimized. In platform-based design of product and assembly platforms the opposite could also be of interest. When the locating concept, i.e. how to hold and assemble the parts, is pre-defined, the optimal split-line position can be calculated with respect to gap and flush variation. This situation becomes more and more common when the plant, the production line and the assembly equipment is a constraint for the design, see [40] and [41]. In Figure 12, the position of the locators (the fixture) is predefined and the question is where to put the split lines, in this case weld-lines, in order to achieve as high geometrical quality as possible.

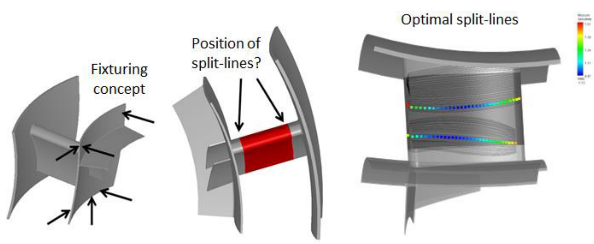

Figure 12: Optimal split lines

Visualization of variation

To enhance the understanding of the effect of variation and to support the definition of requirements, realistic visualization of variation can be very powerful. The use of colours, textures, illumination, reflections, shadows and environments, in combination with variation simulation support visual evaluation of variation and robustness in early product development stages. Different split-line positions, locating concepts and variation sources can be visualized and better understood by people outside the dimensional control area. The usefulness of variation visualization was highlighted in

[42] and a framework for non-nominal visualization and perceived quality evaluation was proposed in [43]. Figure 13 shows variation visualization in RD&T. Here, the statistical min/max of the simulated distribution is visualized to support the definition of split-line requirements.

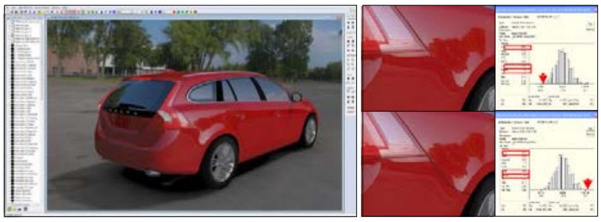

Figure 13: Variation visualization in RD&T

Tolerance Allocation

Optimizing quality, performance and cost often requires tolerance allocation considerations, see [44]. The question is how to allocate the available product tolerances down to parts and features. For a complex product, due to different geometrical sensitivities, variation in individual part dimensions contributes differently to fulfilment of the product characteristics. Since tight tolerances are related to high quality but also in many cases to high cost, allocation of tolerance must be done with respect to the present situation. Basically three strategies can be used [11].

1. When cost is of little importance or when all included parameters have about the same cost, one strategy could be to strive for equal contribution, i.e. all part tolerances contribute equally to the product tolerances with respect to their individual sensitivities. This way of spreading the risks may however lead to an unnecessarily coupled concept.
2. When parts are of different types with different tolerance/cost relations, the overall strategy is to fulfil the product tolerance requirement with tight tolerances on parts where it is less expensive and where the sensitivities are high. This can be formulated and optimized using both continuous and discrete optimization routines [44].
3. In many situations a holistic approach, including both manufacturing cost and "quality loss" can be strategic. Since bad quality not only generates loss for the customers but also for the company in the end, the sum of the manufacturing cost and the "quality loss" should be minimized. This strategy can be optimized using both continuous and discrete optimization routines but requires some data about cost and expected loss [44].

Joining sequence optimization

For non-rigid parts, the joining sequence is crucial for how variation in the individual parts, fixtures and welding equipment will affect the final assembly. Figure 14 shows an example where the same two parts, with the same fixture, are joined together using two different sequences. As can be seen, one sequence results in quite large deviation while the other does not. In a sense, the latter can therefore be seen as the more robust one. Joining sequence optimization is a non-linear problem, and requires contact modelling [22]. Therefore, genetic algorithms are often used to find the optimal sequence [45], [46]. Furthermore, in [47] the cycle time is simultaneously optimized and in [48] the assembly feasibility of non-nominal parts is considered. An important aspect is also the position variation of the welding gun [49].

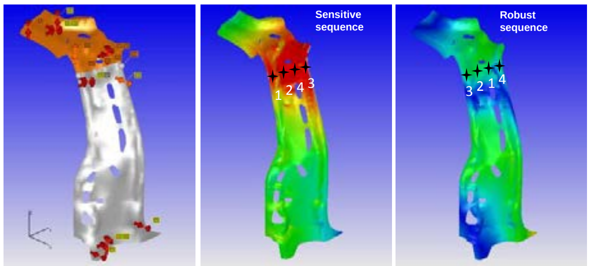

Figure 14: The effect of joining sequence

For many non-rigid assemblies the force needed to close the gap between the parts is quite critical. For sheet metal assemblies, this may affect the size of welding gun that may be used and for assemblies with plastic parts it affects the size and type of clips that may be used to join the parts [50]. For joining of dissimilar material, the effect of temperature is also quite important to consider [51].

3.2. Verification (pre-production) phase

In the verification (pre-production) phase the product and the production system are physically tested and verified. Adjustments are made to both product and production system to adjust errors and prepare for full production. In this phase the *inspection plans* are defined. Here, the virtual assembly model (variation simulation model) is also used for *virtual trimming* to compensate for form errors by adjusting locators and to support inspection preparation.

Inspection preparation and OLP of CMM and scanners

The activities of inspection preparation aim at finding the minimum and optimal set of inspection points that verifies the product and also captures information about the production process that may be used for correction, adjustment or compensation. Here, tolerance analysis and robustness analysis gives important inputs to where to measure, along with information about specific requirements. Since a number of actors and activities use inspection data as input, the number of inspection points sometimes becomes quite large. Often, a large set of inspection points are used during pre-production to be able to capture a lot of process information and make adjustments. During full production a smaller set of inspection points are used to monitor the process. To reduce the number of inspection point from an initial large set of points, cluster analysis can be used [52]. Here, statistical correlations between points are used to find groups (clusters) that are then represented by one inspection point. With this method an initial full inspection plan can be reduced by 80-90% and still capture most of the information [53]. Figure 15 shows an example where the number of points was reduced to 7% of the original number.

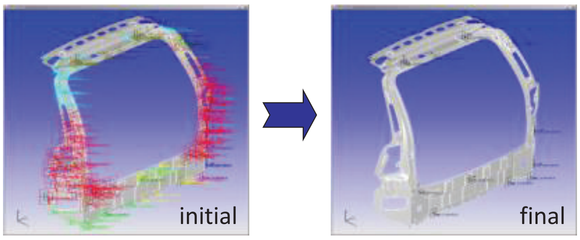

Figure 15: Cluster based reduction

Based on the geometries and the defined set of inspection points, inspection features and time optimized collision free DMIS programs are generated. This is done by combining RD&T functionality with automatic collision free path planning in the IPS software. Tests at automotive OEMs have shown up to 90% reduced programming time and approximately 25% more time efficient programs [54]. The same type of algorithms has also been adapted to scanners in combination with robots for in-line scanning (Figure 16).

Figure 16: Automatic collision free path planning

Virtual trimming

In pre-production, during assembly of newly produced components form errors are discovered that can cause either functional or esthetical problems. Often this is compensated for by adjusting the locators, also known as trimming. Traditionally this is done by manually assembling a number of components, measuring the deviations to surrounding parts and adjusting the locator points. This is repeated until the result is satisfactory which is quite time consuming. In [55], a method for virtual trimming was proposed. Based on inspection data from the initial components and the variation simulation model, all trimming activities are performed in the computer tool presented. After the locators are adjusted, the result is presented directly, which eliminates the need for physical inspection in order to verify the result of the trimming. The tool also includes optimization of the trimming.

3.3. Production phase

In the production phase all production process adjustments are completed and the product is in full production. In this phase, the virtual assembly model (variation simulation model) is used together with inspection data to control production and to detect and correct errors.

Root Cause Analysis (RCA)

The assembly process for a complex product such as an automotive body is carried out in both serial and parallel sub-processes. Parts within a subassembly are typically assembled serially, whereas independent subassemblies on the same hierarchical level may be assembled in parallel.
Fixture related geometrical errors, may in a complex assembly be difficult to identify. A number of fixture errors may occur that leads to similar deviations in the final assembly. The state space approach for fault diagnosis of multistage manufacturing processes was proposed in [56]. A general approach and a tool for RCA that allows individual station, fixture and locator errors to be identified were proposed in [57]. The tool translates variation and deviation in geometry data to actions for adjustable process parameters. During production, the virtual assembly model is fed with inspection data from the final product. This is used to analyse if product error originate from assembly fixtures and decide what fixture and what locators that has generated the error [58]. The tool has been tested at two automotive OEMs.

Six Sigma

Six Sigma is a five-step improvement methodology (DMAIC) [59] that starts with a *define* phase where the need for improvement is identified. In the *measure* phase one or more outputs (Y's) of the product or process that is to be improved, as well as their inputs (X´s), are selected. In the *analyze* phase, data gathered for the inputs and outputs are assessed. Typically calculations are made on the mean value and dispersion values. The performance of the outputs in terms of sigma values is calculated. In the *improvement* phase the focus is to find the inputs which have high influence on the outputs and improve these by shifting their mean, reducing their variation or their influence. After the improvement has been carried out, the *control* phase is launched to verify that the planned improvement has been achieved.
During the analyze phase and the improvement phase, the variation simulation model is used to simulate mean value and variation in the outputs (Y´s) based on inspection data from the inputs (X´s). The virtual assembly model is used together with real inspection data to calculate the relative importance of each input on the outputs (contribution analysis). This contribution considers both geometrical sensitivity as well as variation amplitude. In [11] a door example from a Six Sigma case at Volvo Cars is presented.

4 Discussion and outlook

The proposed toolbox has been implemented at a number of OEMs in the automotive and aerospace industry. Specifically, at one Swedish car manufacturer, the following savings were reached [11].

- Approximately 80% time save in the documentation of Gap and Flush requirements.
- Approximately 30% time save for definition of locators and requirements breakdown.
- Approximately 80% time saved compared to making the drawings in CAD.
- Drastically reduced launch costs and less adjustments in production.

Even since the proposed geometry assurance process and toolbox is quite powerful, there are still a number of future challenges in different areas. In the area of digitalization and Industry 4.0 one challenge is to gather and link customer data and preferences and to better understand how geometrical variation affect the area of perceived quality. Another challenge is to link inspection and material data to variation simulation, root cause analysis and joining sequence optimization in order to allow self-adjusting production lines and personalized production. This may also affect the inspection preparation, the storage of inspection data and the meta-data needed to allow for effective usage of inspection data. To allow variation simulation of new and mixed material, new material models need to be developed and integrated in the simulation tools. This may open up for variation simulation outside the traditional manufacturing business segment. Geometry assurance of additively manufactured parts is another area that will require more knowledge in the future. Also, even if computers are getting more and more powerful, the need for different types of meta-models will increase as the variation simulation models grow with increased functionality and complexity.

5 Conclusions

Research within quality, robustness and tolerancing has in the literature been addressed, to a large extent, separately and on different abstraction levels. Since research results are often presented as small pieces of knowledge or new functionality, the relation to the product development process is, sometimes not obvious. Therefore, this paper presents a geometry assurance process with set of tools that supports the geometry assurance process from early concept phases, through verification and pre-production and finally during production. The paper summarizes many years of research and positions it in the product development process. The research results, and the working procedure described, have since 1998 been taken into use by a large number of industrial users which can be seen as a verification of its usefulness.

Based on experience from implementing the results in industry over this period of time, the following conclusions can be made:

- *The geometry assurance process is a central process for companies producing physical products.* However, many companies today do not have a clear geometry assurance process. Since geometry assurance relates to a number of activities and departments such as CAD, styling, design, assembly, quality, manufacturing, inspection this is often a problem, in the end leading to increased costs and/or decreased quality.
- *An effective geometry assurance process is necessary in platform-based design.* Since the geometrical interfaces between parts and subassemblies control the robustness, combinatorial effects must be handled in a structured way when producing complex products with many variants. An effective geometry assurance process, where requirements are decomposed in a structured way, and geometrical couplings and sensitivities are known, supports flexibility and reuse of solutions.
- *An effective geometry assurance process reduces costs and adjustments in production.* Most companies today are fully aware of the fact that a change is more costly in production that in the design phase. Since development time and time on the market are continuously shrinking, the need for “first time right” becomes more and more important.

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