Proceedings of the First International Symposium on Robust Design 2014

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Link to article, DOI:
10.11581/DTU:00000006

Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

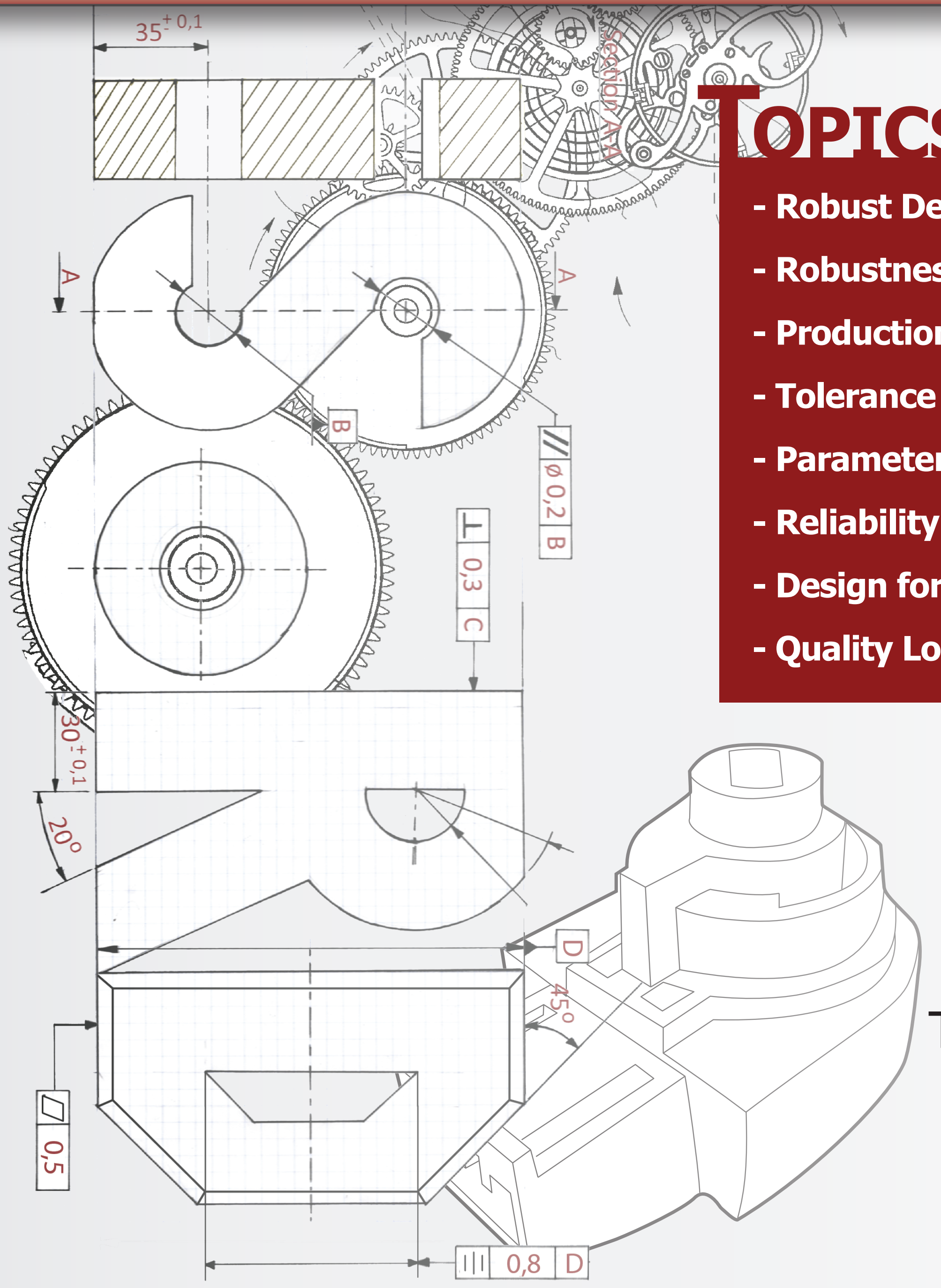
Citation (APA):
Howard, T. J., & Eifler, T. (Eds.) (2014). Proceedings of the First International Symposium on Robust Design 2014. Copenhagen: Technical University of Denmark (DTU). DOI: 10.11581/DTU:00000006

ISoRD 2014 CPH

FIRST INTERNATIONAL SYMPOSIUM ON ROBUST DESIGN

PROCEEDINGS

14TH-15TH AUGUST, 2014 - KØBENHAVN, DK



TOPICS

- Robust Design Methodology
- Robustness Indicators
- Production Process Capability
- Tolerance Analysis
- Parameter sensitivity analysis
- Reliability engineering
- Design for Six Sigma
- Quality Loss Functions

Edited By
Thomas J. Howard
Tobias Eifler

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2014 CPH

ISoRD14 Proceedings

14th-15th August 2014
Copenhagen, Denmark

Organised by
The Robust Design group,
Section Engineering Design & Product Development
Department of Mechanical Engineering, DTU

Edited by
Thomas J. Howard
Tobias Eifler

ISoRD is the official series of the Robust Design Special Interest Group (SIG) and official SIG of the Design Society (charitable body)
ISoRD14 was supported by and hosted at the Technical University of Denmark

ISBN: 978-87-7475-381-0

DOI:10.11581/DTU:00000006

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Preface by conference chairs

Welcome to the ISoRD14 Proceedings!

The International Symposium on Robust Design is a dedicated meeting where academics and industry delegates meet to discuss the challenges and advances in robust design and related topics.

The principle benefits of robust design are widely accepted. Robustly designed products are less sensitive to variation and are therefore easier to produce, more reliable during operation with a more consistent quality. However, there is still a large gap between robust design in theory and robust design in practice during product development. Many of the current approaches are slow and difficult to use and often are only applicable at later stages when design change is less feasible.

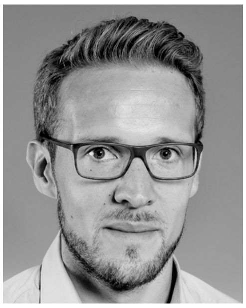
The symposium has greater focus on applied robust design, focusing on operationalising robust design research for use in product development. The symposium has therefore been constructed as more hands on and dialogue based, with workshop exercises and software demonstrations as well as the usual podium and poster presentations.

We aim for the ISoRD symposium to support discussion and knowledge exchange as much as possible. In order to achieve this, we designed the reviewing process with 2 reviews for each paper, which were "Double Open", meaning, both the reviewers and authors are known to each other. This meant that authors and reviewers were able to contact each other during the review process to discuss and improve the contributions. If you look closely, the reviewers are named on each paper and the reviews performed have been made available to view. The ISoRD14 proceedings are also open access to maximize the outreach.

ISoRD14 is hosted by the Robust Design Group at DTU Mekanik and is the official symposium of the Design Society affiliated Robust Design Special Interest Group – see www.robustdesign.org for more details. This year, ISoRD is proud to be sponsored by Novo Nordisk the world's leading provider of diabetes care and champions of Robust Design, and Valcon Design, the consultancy group pioneering the Six Theta® Robust Design methodology.

We hope that you enjoy the symposium and look forward to interesting discussions and a fruitful exchange of experiences as well as new ideas.

Thomas J. Howard
Conference Chair



Tobias Eifler
Conference Co-Chair

Foreworded by

Novo Nordisk is a Danish owned pharmaceutical company having more than 40.000 employees. Novo Nordisk is perhaps best known as the provider of medicines, especially insulin to diabetics but also medicines to treat growth hormone deficiency and haemophilia.

Insulin is a hormone that controls the blood sugar and it needs to be injected in the skin at least once a day, but some treatment regimens requires up to 6 injections a day. As blood sugar needs to be controlled in very narrow span (not too high to avoid serious late complications and not too low to avoid acute unconsciousness and even death.) insulin injections needs to be very precise (typically within ± 5% of 100 – 400 µL).

Novo Nordisk has for more than 25 years provided injection devices mainly insulin pens to people with diabetes for making the frequent injections precise and more convenient to perform. Using Insulin pens is today the state-of-the art treatment.

Unfortunately the number of insulin using diabetics has increased dramatically over the last decade, and keeps increasing all over the world.

The challenge for Novo Nordisk in these and the coming years is to continue to produce and supply high quality insulin pens from different production sites over the world in very high and increasing numbers (several hundred million pieces/year) to the customers.

It is important for Novo Nordisk to design devices that fulfil real customer needs. Equally important is it to make device designs robust so they can be produced in very high numbers, at a very high quality level and with a very high level of predictability both during the project phase and during the subsequent production. Novo Nordisk Device R&D started focusing on robust design in 2011 and now implements robust design principles already when drafting a device design in the very early project phases. Novo Nordisk is proud to support the ISoRD14 symposium which will help to bring state of the art knowledge on Robust Design into practice.

Niels Hansen,
Chief Engineer
Novo Nordisk Device R&D

Foreworded by

It is a great pleasure to see the creation of a symposium dedicated to the subject of Robust Design.

Robust Design is an extremely important and valuable paradigm for production companies. In a globalised market, companies must compete on price, quality and being first on the market with new products. As a consequence, most companies have well-described product development and quality assurance processes to ensure that the products are developed fast have a desired quality level prior to launch.

However, many companies still struggle with their production ramp-up, i.e. going from a finished design to a full-speed production. During this phase, the companies are faced – for the first time – with the true variation of their production and assembly setup, leading to delayed product launches, high internal scrap rates, and extensive quality control procedures – all of which leads to a loss to both the company and to society.

Robust Design is an important paradigm for smoothing the way from design to production as it provides methods and processes to forecast and mitigate the consequences of variation. Unfortunately, surveys have shown that Robust Design Methods are not adopted by industry, primarily because the methods have been too complex and focused on statistics for the development engineers to use them.

I believe that ISoRD14 can help bridge this gap. With delegates from both industry and academia and combination of presentations, discussions and workshops, the framework is provided for a fruitful exchange of ideas, methods and knowledge.

Janus Juul Rasmussen
CEO
Valcon Design

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Robust Design Impact Metrics: Measuring the effect of implementing and using Robust Design

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Robust Design, Effects Measurement, Design Process, Design Metrics

Abstract

Measuring the performance of an organisation's product development process can be challenging due to the limited use of metrics in R&D. An organisation considering whether to use Robust Design as an integrated part of their development process may find it difficult to define whether it is relevant, and afterwards measure the effect of having implemented it. This publication identifies and evaluates Robust Design-related metrics and finds that 2 metrics are especially useful: 1) Relative amount of R&D Resources spent after Design Verification and 2) Number of 'change notes' after Design Verification. The metrics have been applied in a case company to test the assumptions made during the evaluation. It is concluded that the metrics are useful and relevant, but further work is necessary to make a proper overview and categorisation of different types of robustness related metrics.

1. Introduction & Delimitation

Organisations constantly strive to optimise their operations in general, including their product development process. To do this, metrics are used to monitor and benchmark performance over time, against competitors, between projects, etc. Production companies typically consist of a number of different departments with different responsibilities such as *production, product development, quality assurance, sales,* etc. It is the impression of the authors, that there is a notable difference in the use of performance metrics between departments. For example, in *production*, performance is measured using metrics such as *production yield*, *process capability,* and *customer complaint rate*, whereas in product development the equivalent metrics either do not exist or are not used. This makes it challenging to measure the performance of a product development department in general.

This contribution is delimited to focus on the measurement of performance related to the implementation and use of Robust Design. Robust Design is a paradigm focused on designing products with a functional performance that is insensitive to variation and noise. As a further delimitation, a distinction is made between *design metrics* and *management metrics*. The former refers to the embedded metrics of the individual Robust Design Methods, such as the Risk Priority Number (Failure Mode and Effects Analysis) and Signal-to-noise Ratio, whereas the latter refers to the overall metrics related to the use of the paradigm. In other words, the pur-

DOI:10.4122/dtu:2082

Cited as: Ebro, M., Olesen, J., Howard, T. J., 2014. Robust Design Impacts Metrics: Measuring the effect of implementing and using Robust Design. In: Howard, T. J. and Eifler, T., ed. 2014. *Proceedings of the International Symposium on Robust Design - ISoRD14*. Copenhagen, Denmark. pp. 1-10.

pose of a design metric is to measure the impact of a change to the design (within a project), where a management metric is to measure the impact of a change to a processes/procedures (across projects). This contribution focuses on the management metrics. More specifically, it would be valuable to have metrics to measure:

1. **The relevance of Robust Design**. Before applying Robust Design, it is beneficial to know the current level of performance in order to evaluate whether Robust Design is a relevant methodology to implement.
2. **The effect of Robust Design**. Implementation of Robust Design (or any other methods), requires resources such as training, change management, documentation etc. Ideally, a positive effect should be seen after the change has been introduced, such as depicted in Figure 1. This data can be used to evaluate the benefits of the implementation.

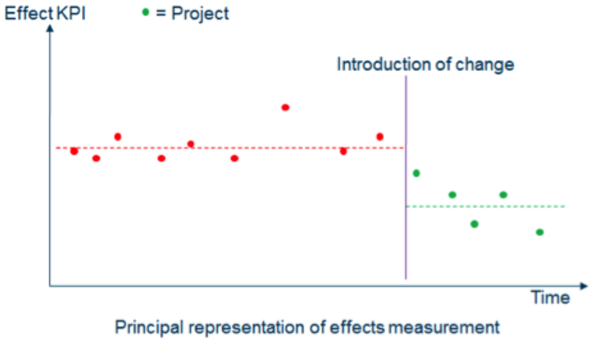

Figure 1 – A principal example illustrating how a performance metric can be used to visualise the effects of implementing a change in the development process.

Summing up, there is need to measure performance of product development in general and of the use and implementation of Robust Design in particular.

The next section introduces some requirements for selecting suitable impact metrics for robust design. The following section then lists, evaluates and selects suitable metrics. Before the concluding section, the results of five case studies are described using the selected metrics (four cases before and one after robust design implementation).

2. Requirements for Robust Design Impact metrics

A simple method, depicted in Figure 2, was used to identify and evaluate the metrics. Based on experience and case descriptions from literature, a list was made of parameters that are typically affected by using Robust Design, such as scrap, lead time etc. For each parameter, the corresponding metric was identified, e.g. scrap being measured by the metric *First Time Yield*. The metrics were passed through a filter of requirements (see below for a detailed description) that had to be fulfilled. The remaining metrics were then evaluated against a list of criteria that would be valuable for the metrics to fulfil. In the end, a shortlist of relevant Robust Design metrics was created. To test the validity of the results, 4 historical case projects were selected and the metrics were applied to these.

2.1 Description of the requirements and criteria

There are certain requirements and criteria that the design metrics ideally fulfil in order to be useful as performance metrics.

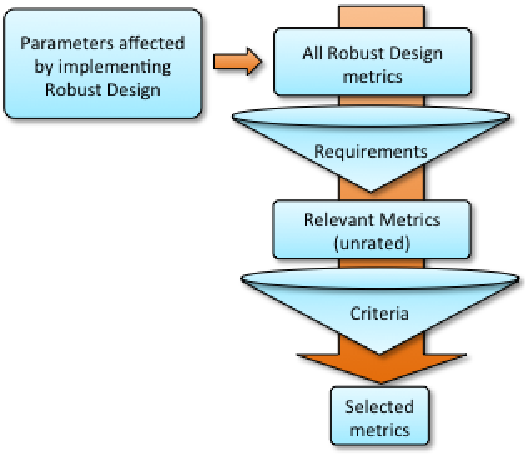

Figure 2 - A visual representation of the method applied for identifying and evaluating Robust Design Metrics

Requirements (Must-haves)

1. **Accuracy**. The quality and accuracy of the data must be trustworthy. Inaccurate data can lead to wrong conclusions. It should be noted that the act of measuring itself, can affect accuracy, either by attracting focus to a certain problem area (Hawthorne Effect) or by inducing a certain behaviour, e.g. including multiple design changes on the same Change Note, to minimise the number of Change Notes being registered.
2. **Relevance**. Data should be of relevance to what we are trying to measure – in this case Robust Design. Irrelevant data can mislead users. An obvious example is using the number of new product introductions as a metric, since this is not closely related to Robust Design (it has stronger correlation to other factors than robust design).
3. **Objectivity.** Metrics should be based on objective data only, as opposed to personal impressions and gut-feeling.
4. **Correct incentives**. Certain metrics can create unwanted incentives, which should be avoided. An actual example of this, from the case company described later, is the measurement of production drawings being ‘submitted on time’. This created a strong incentive to register drawings as ‘completed’, although the quality of the drawings was questionable, which led to many subsequent drawing revisions. As a rule of thumb, any of the so-called *activity based metrics*, which simply measure whether a certain activity has been carried out, is prone to create unwanted incentives. Instead, the metrics should measure the performance related to the activity.
5. **Comparable across projects different in size and type**. The product portfolio in a company may range from complex systems to minor accessories, which means the metrics have to either be unaffected by the complexity of the product they relate to or be *indexable* such that a fair comparison can be made between different products.

Criteria (Nice-to-haves)

1. **Easy to gather data**. The cost and effort of collecting, analysing and storing metrics should be low, since the majority of any optimisation initiative should focus on the actual improvement and less on the measurement of the improvement.
2. **Access to historical data**. Often, the interest for implementing a metric is being able to compare the performance after a change, e.g. a new development process, with the historical performance. Therefore, it is beneficial if it is possible to derive the historical data for the metrics.

3. **Motivate action**. An impact metric should measure a meaningful impact that could influence or motivate action. It is also beneficial if the metric can indicate the type and extent of action to be taken. Generally speaking, the further removed from cost/profit the less influential the metric is. In this sense, scrap rate is a more meaningful metric than number of specified dimensions or number of over-constraints in an interface.

The decision on how well the identified metrics met the requirements and criteria was made by the authors along with a quality manager and a technology manager from the case company – with an inherent risk that the results to some extent were biased by the experiences of this company.

3. Evaluation and Selection of Potential Metics

3.1 Parameters affected by Robust Design

Based on experience and descriptions in literature, e.g. Krogstie, Ebro & Howard (2014), the known effects of Robust Design implementation, as well as more broad quality engineering metrics (Buchheim, 2000) were identified in Table 1. For each of the effects, corresponding metrics were identified and held up against the requirements listed in the previous section.

Table 1 – Known effects of Robust Design implementation benchmarked against the identified requirements: 1) Accuracy, 2) Relevance, 3) Objectivity, and 4) Correct incentives

What will change	Metric	Fulfilment of requirements	
Time to market will become shorter	Manhours pr. project	☒Relevant ☒Objective ☒Incentive ☐Comparable	• Large and small projects are not comparable. • Accuracy is low due to unclear definition of when a project is started, eg. if pilot projects come before the actual project and in the case of platform architecture (projects may only develop variant solutions). • Meta-metric that can be affected by other and more dominant changes than RD
R&D Expenses pr. project	R&D Costs	☒Relevant ☒Objective ☒Incentive ☐Comparable	
Fewer and less demanding specifications on drawings	# of specifications IT-grade (Tolerance level) of specification	☒Relevant ☒Objective ☐Incentive ☐Comparable	The quality and information level of drawings are strongly dependant on the operator and can change dramatically e.g. due to the introduction of GD&T

Fewer late design changes	# of change notes	☒Relevant ☒Objective ☒Incentive ☒Comparable	Fulfils all requirements, although care should be taken regarding accuracy, since systems for logging change notes can be tweaked, e.g. by logging multiple design changes on the same change note.
Increased predictability in project execution	# of milestones being delayed (measured against project plan at previous milestone)	☒Relevant ☒Objective ☒Incentive ☒Comparable	Care should be taken about accuracy, because project plans typically change over time, making it difficult to exactly define a ‘delay’
	R&D resources used in late stage design	☒Relevant ☒Objective ☒Incentive ☒Comparable	Fulfils all requirements, although accuracy could be affected by the definition of late-stage design. In the case company, the late stage was defined as all activities coming after the Design Verification Milestone
Shorter ramp-up time	Weeks between *Design Verification* and *Product Launch* milestones	☒Relevant ☒Objective ☒Incentive ☒Comparable	Fulfils all requirements
Fewer recalls and customer complaints	Customer Complaint Rate	☐Relevant ☒Objective ☒Incentive ☐Comparable	Robustness related issues often occur when variation is increased, which could happen over time. An example of this is automobile recalls. Using customer complaints as a metric would require data from the entire lifetime of the product, which would strongly complicate data gathering. Furthermore, many companies have very low complaint rates e.g. due to effective quality assurance procedures.
Fewer quality issues in production	First-time yield (FTY)	☐Relevant ☒Objective ☒Incentive ☐Comparable	Difficult to make comparisons between different types of products. Yield can be attributed to other things than the product, e.g. issues with the production equipment.
Increased predictability in project execution and product launch	# of milestones/launches on time	☒Relevant ☐Objective ☒Incentive ☐Comparable	Lack of access to historical data Project plans are constantly changed – unclear which version of the plan should be used. Difficult to compare small and large projects.
Reduced variation in functional performance (Quality Loss)	?	☐Relevant ☐Objective ☐Incentive ☐Comparable	An accurate and absolute metric was not identified to describe the variation in functional performance of a product.

Evaluation of metrics against criteria
The metrics that fulfilled the requirements were then evaluated against the criteria listed in the Method-section, and the results were collected in Table 2.

Table 2 - Evaluation of how well the relevant metrics meet the criteria for good Robust Design Metrics.

	Criteria					
Metrics	Ease of gathering data		Access to historical data		Motivate action	
# of Change Notes	+	Already stored in Product Data Management (PDM) System	+	Simple lookup in PDM-system	+	Costs and inconvenience of reworking inventory, notifying suppliers, etc. is typically obvious
# of delayed milestones	+	Simple metric to gather on-the-fly	-	Risk of ambiguous historical data	?	It is not given that the consequences of milestone delays are apparent to all
% of R&D resources used after Design Verification	+	Merging milestone dates with time registration	+	Milestone dates are typically maintained in PDM-systems	+	Wrong use of experienced R&D resources and cumbersome firefighting
Weeks btw. Design Verification and Product Launch	+	Simple metric found in PDM system	+	Simple metric found in PDM system	-	Not necessarily a problem to have a long ramp-up, if only it is predictable

Summing up, two metrics were found to be particularly useful as Robust Design Metrics, namely the **% of R&D resources used after Design Verification** and **# of Change Notes**.

4. Case Results

The identified metrics were used in the case company, to validate the results. Four recent projects were chosen as historical case projects, that could act as a benchmark by which future projects could be measured.

Gathering data for the metric *% of R&D resources used after Design Verification*, was done by collecting project time registrations for the case projects, as well as the historical milestone dates, from the company's PDM system. Combining the two data sets, it was simple to calculate the absolute and relative use of R&D resources for each phase of the project. The data is represented in Figure 3. The company had expressed, that for an ideal project, the R&D expenditure after the Design Verification milestone would be limited, as the project would gradually be handed over to the production department. More precisely, it was expressed that after Design Verification only a further 20-25% expenditure would be experienced in an ideal project. As the figure shows, only 1 of the 4 projects (Project A) stayed remotely close to this target, whereas the 3 other case projects all experienced that more than half of the total R&D expenditure was used after the Design Verification Milestone. In the Introduction, it was mentioned that metrics could be used to evaluate the relevance of Robust Design.

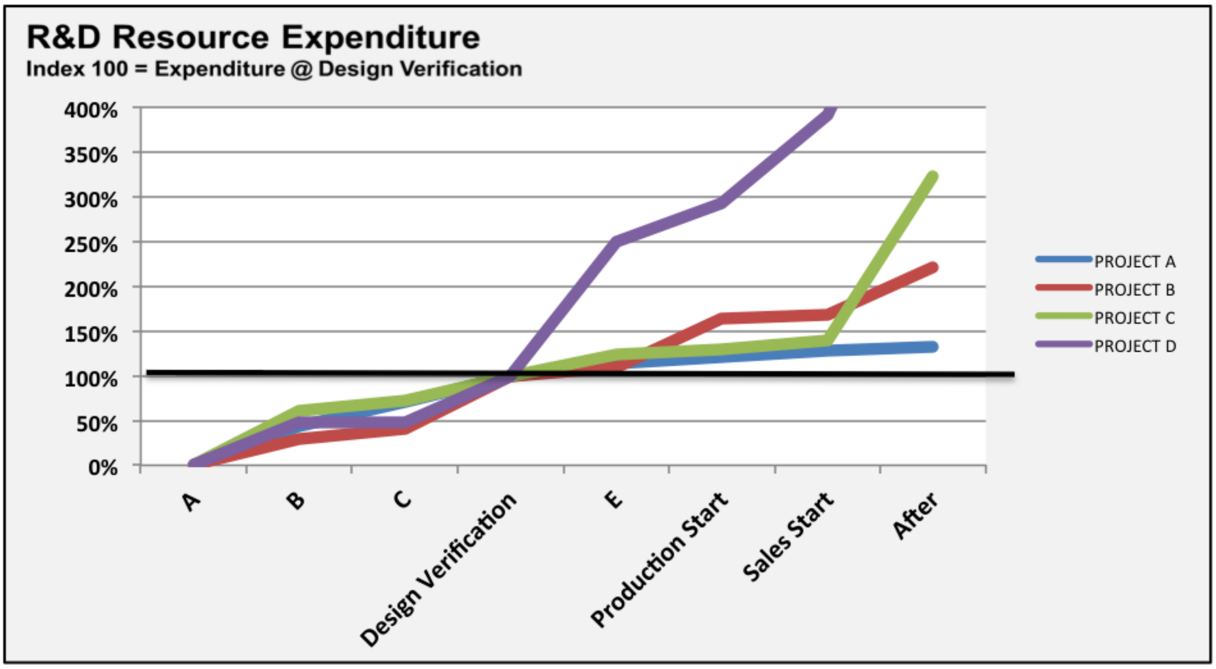

Figure 3 - R&D Resource Expenditure during project phases. Ideally, after Design Verification, R&D expenditure should be limited. It turned out that 3 out of the 4 projects had more than half of their total expenditure after Design Verification.

The second metric, *# of Change Notes*, was collected by making a simple query in the company's PDM system. This generated a report with 800 Change Notes, with a short description of what the problem was and what had been changed. A group consisting of the author, two quality managers and a technology manager categorised the change notes. First, they were categorised into software, hardware and mechanical issues and afterwards, the mechanical issues were subcategorised into structural failures, usability, tolerance issues etc. This procedure took app. 4 hours. The results are shown in Figure 4.

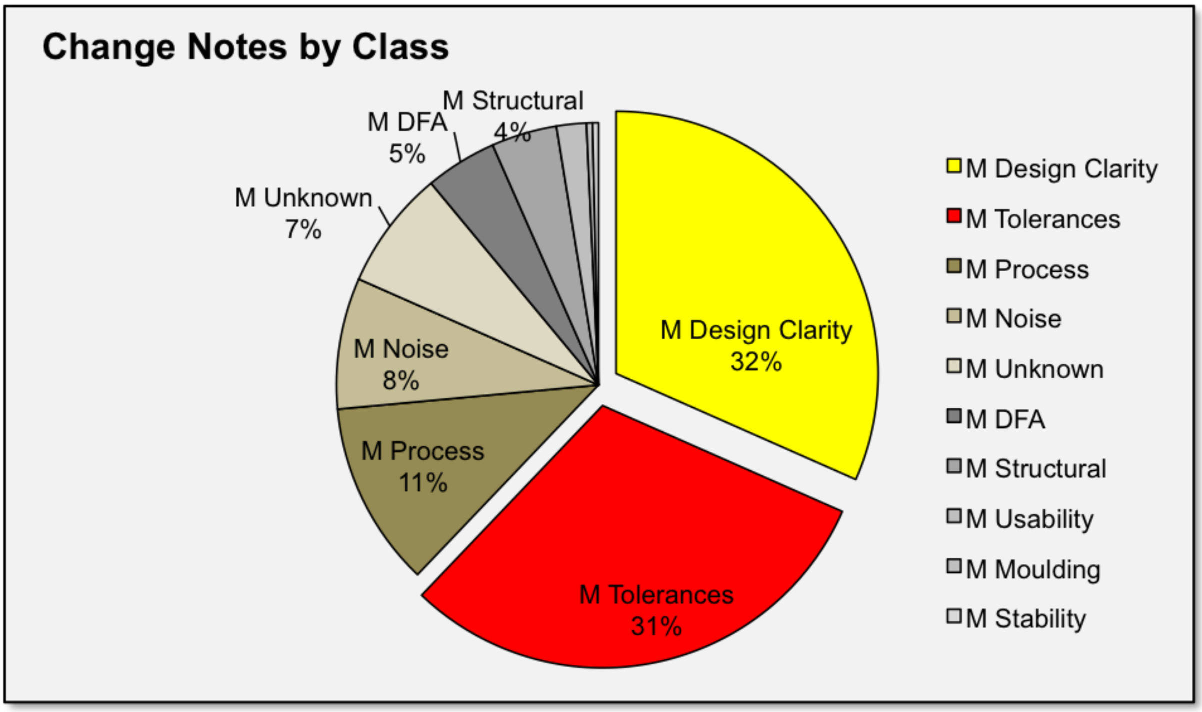

Figure 4 - Mechanical Change Notes subcategorised into various issue-types. 63% of the change notes were related to tolerance and so-called Design Clarity issues.

The first classification showed that 65% of the total number of change notes was related to mechanical issues. Out of these, a total of 63% were related to issues regarding *design clarity* and *tolerances*, which includes parts conflicting, functionality being outside specifications, suppliers not being able to meet tight tolerances etc.

5. Discussion & Conclusion

Two metrics have been selected as being useful for measuring the relevance and effect of applying Robust Design in an organisation. They were selected by first listing metrics related to robust design and then evaluating these against a set of requirements and criteria.

The metrics, *% of R&D expenditure used after Design Verification* and *# of Change Notes*, have been tested in a case company that had struggled to keep deadlines and launch dates. The metrics acted as an eye-opener to the case company and put quantitative data on what already existed as a gut-feeling; the issues were primarily mechanical and they were discovered in the late design phases, i.e. after design verification. This indicates that implementing Robust Design in the case company could be relevant, since one of the main foci of Robust Design is to reduce issues & failures related to variation, which is often first discovered during ramp-up, when the production volume is increased.

One notable limitation of the metrics is the role that non-robustness related reliability issues can have. For example, not having materials delivered on time, materials being delivered but out of spec, miscalculating engineering properties leading to unintended functionality (such as poor stress estimations) or overlooked safety or usability concerns that arrive late. All of these issues would have an effect on the chosen metric and are not robustness related. Therefore, a project may have prevented misplaced R&D resources through use of robust design, however, this may be overshadowed by the late R&D resources required to solve catastrophic reliability/ safety issues like those mentioned above.

The process of using R&D metrics in general (and not just related to Robust Design) was welcomed by the case company and rather than just being used for measuring the effect of Robust Design, which was the initial intent, it ended up also being used to support the need for a change in the development process.

The case company has now installed a series of Robust Design Methods, and a follow-up case study will be conducted to measure the effects of Robust Design. The first project, making use of the principles of Kinematic Design and Design Clarity (Christensen et al, 2012) has been conducted, and benchmarked against the other projects in Figure 5. Although one project is not sufficient to make any conclusions, it is included here to show the principle of how the metric can be applied.

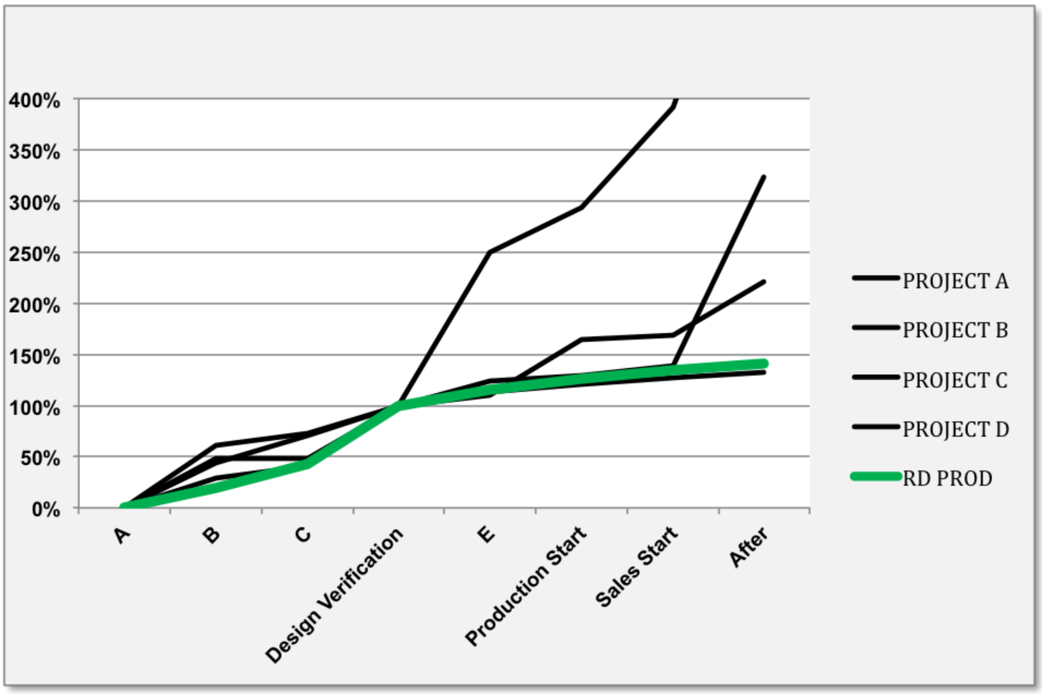

Figure 5 - Followup measurement of R&D expenditure after Design Verification. The black lines are historical projects, whereas the green line is the first project using Robust Design Methods.

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ISoRD 2014 CPH

Prediction of Glass Cartridge Robustness in Assembly Line Loading

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Novo Nordisk Device Research and Development, Competency Centre

Keywords: Safety factor, Robustness, Failure criterion, Statistical dependency

Abstract

Each year Novo Nordisk produces multimillion injection devices incorporating drug contained glass cartridges. These cartridges will inevitably be subjected to various loadings in both line feeding systems and in the device assembly rigs. It is obviously crucial to preserve the structural cartridge integrity and avoid any form of cracking and fragmentation of the glass for the full life time of the devices.

The robustness is quantified by a safety factor against cracking. As shown in figure 1, it implies that both assembly line loadings and the strength of the sub-supplied cartridges are determined along the location of max stress in relation to the rotatory position of the weakest region.

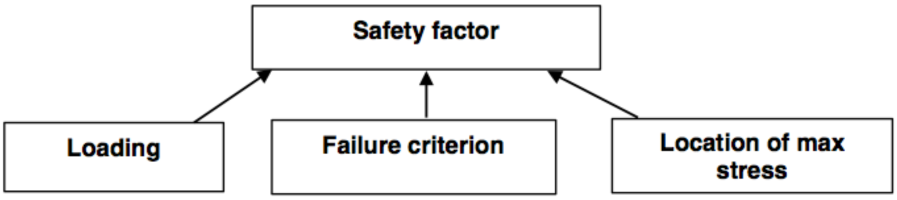


Figure 1. Safety factor dependencies

These figures can be used to specify the loading for the incoming inspection and prevent future device designs from overloading the cartridges.

The cartridge glass is brittle with a low cracking energy and sensitive to impact loading. The glass strength is determined by microscopic manufacturing related imperfections (which have no influence on the performance and integrity of the final device) and is both loading mode and rate dependant. Thus a conventional material property such as the ultimate stress cannot be used to calculate a safety factor.

Matters are further complicated by loadings being tolerance dependant and by the fact that each cartridge has a randomised position of the weakest region relative to the maximum loading. This calls for a statistical based calculation of the safety factor. Figure 2 shows an example on a safety margin without distribution overlap. In some cases a limited distribution overlap might be acceptable.

DOI:10.4122/dtu:2078

Reviewed by: *Thomas J. Howard*
Michael Walter

Cited as: Hansen, T. S. and Kristiansen, B. U., 2014. Prediction of Glass Cartridge Robustness in Assembly Line Loading. In: Howard, T. J. and Eifler, T., ed. 2014. *Proceedings of the International Symposium on Robust Design - ISoRD14*. Copenhagen, Denmark. pp. 11-16.

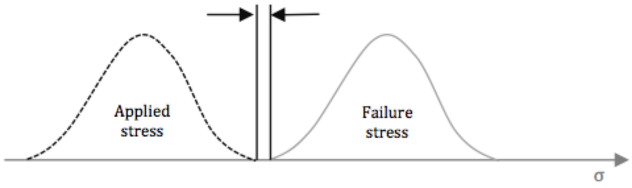


Figure 2. Statistically determined safety margin

1. Establishing a Failure criterion of the Glass Cartridge

1.1 Critical region

The critical region of the cartridge is the exterior surface of the open end of the cartridge. This is both due to the loading and due to the presence of microscopic imperfections in this region. Glass only fails in tension (R. E. Mould, 1953: 235).

1.2 Determination of the quasi-static cartridge failure stress

The quasi-static failure stress of the cartridge is found by pressurizing the cartridge as shown in figure 3. The pressure generates a uniform hoop stress on the exterior surface of the open end of the cartridge.

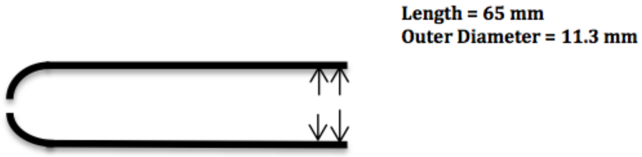


Figure 3. Rough sketch of the pressurising test used to find the quasi-static failure stress of the cartridge.

This uniform stress along the rim secures that the most critical imperfection will initiate the failure. The nominal hoop stress can be approximately calculated from the pressure at burst:

$$\sigma_{hoop} = \frac{p \cdot D_{inner}}{2 \cdot t} \tag{1}$$

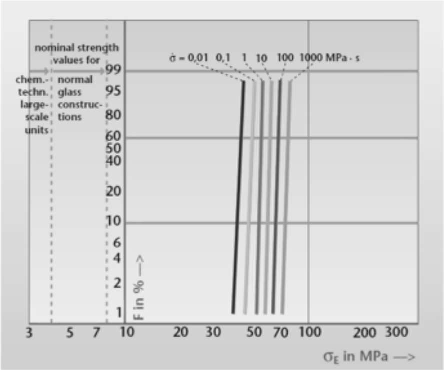
Where p is the pressure, t the wall thickness and D the diameter.
The theoretical strength of the cartridge is dictated by the size of the largest defect in the critical region. According to Griffith Criterion (A A Griffith (1920):

$$\sigma_f = \sqrt{\frac{2*E*\gamma}{\pi*a}} \tag{2}$$

Where σ_f is the failure stress, E is the youngs modulus, γ is the surface energy density, and a is the 1⁄2 crack length.

1.3 Loading rate

The failure stress of glass depends on the loading rate as depicted in figure 4. The figure shows the likelihood of failure vs. stress level for various loading rates. The failure stress increases approximately 15 % per stress rate decade.



Failure probability F of a predamaged surface for various rates of stress increase σ. (predamaged area: 100 mm², grain size: 600)

Figure 4. Loading rate dependency of failure stress for glass (SCHOTT Technical Glasses, 2010: 12)

1.4 Failure limit for the assembly application

Using the loading rate dependence of figure 4, the quasi static failure stress of the pressure test can be converted to the corresponding stress of the high velocity assembly loading.

The stress and strain rate of the test was calculated from the pressure ramp of the test equipment and a linear approximation between pressure and stress.

The strain rate of the analysis is an parameter of the field output. The stress rate can then be derived from the strain rate. The rate of the quasi-static pressure test is only 4.4 MPa/s. The app. 10 mm axial displacement of the assembly process is completed in less than 10 ms. The stress rate in the cartridge driven by the transient forces from the interfacing components during assembly is approximately 70 GPa/s, i.e. the ratio between the two is 1.6e4. Using the 15 % rule of figure 4 gives us the strength amplification factor of the glass due to fast loading (equation derived from the logarithmic form of figure 4):

$$S_a = 1.15^{log(1.6e4)} = 1.8 \tag{3}$$

So the glass failure distribution is estimated to be 80 % higher for the assembly loading considered here than the quasi-static pressure test.

2. Analysing the Cartridge Loading in the assembly rig

A set of four thermoplastic deformation ribs embedded in an interfacing device component determine the combined axial/radial loading of the Cartridge. The intention of these ribs is to compensate for rather large tolerances of the cartridge length which results in a high degree of post yield deformation.

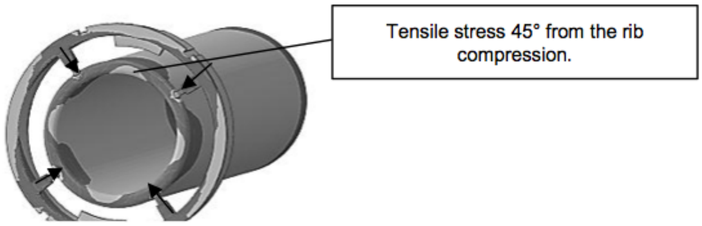


Figure 5. Radial rib loading pattern on the Cartridge

In order to capture the stress impact of the main key contributing parameters, a refined Explicit Finite Element model was made:

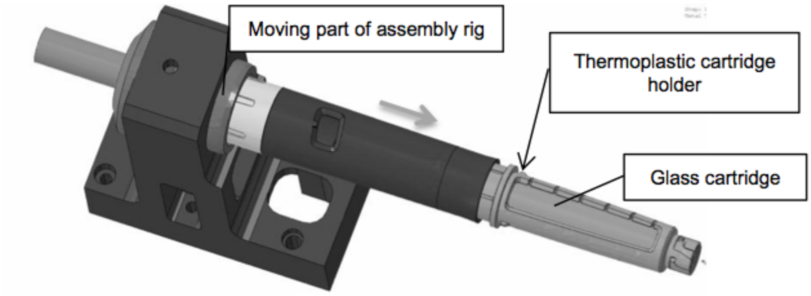


Figure 6. FEA explicit dynamic assembly analysis model

The model included all relevant geometry along with elastic and viscoelastic/plastic material response and velocity-load input. The maximum tensile stress of the cartridge was sampled over the critical cartridge rim region for a suitable number of time frames.
The key glass loading contributing parameters were identified as:

Table 1. Key parameters contributing to the glass loading

Pos	Parameter (type)	Expected distribution
D_1	Deformation rib thickness (dimension)	Normal
D_2	Deformation rib distance to centre line (dimension)	Normal
D_3	Cartridge to rib axial penetration (displacement)	Normal
D_4	Cartridge outer diameter (dimension)	Normal
D_5	Cartridge rotation relative to deformation ribs (angle)	Stochastic

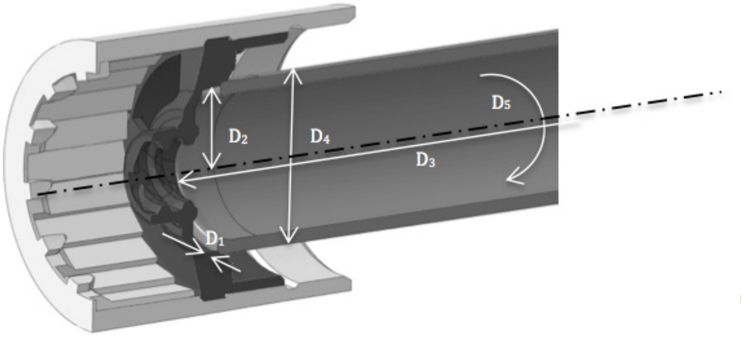


Figure 7. Section cut of the cartridge and interfacing components

3. Sensitivity of the Load Contributing Parameters to the Tensile Cartridge Stress

A design of experiments (DoE) study was based on 9 runs each having a randomised combination of the above parameters – except D5 which was not included initially due to the stochastic mature.

A statistical analysis performed in JMP software from SAS revealed the qualitative parameter sensitivity shown on the following page:

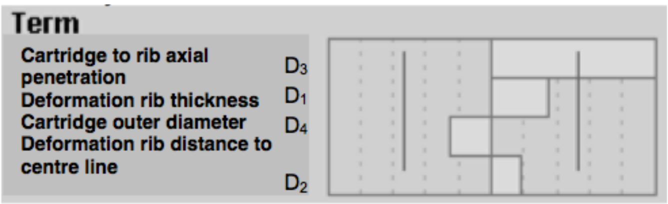
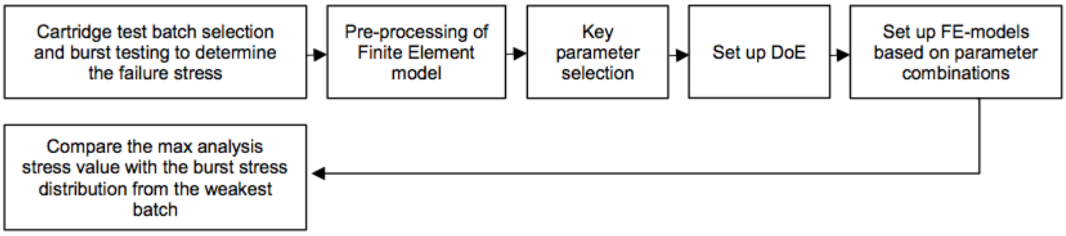


Figure 8. Parameters stress sensitivity – bars show relative impact & solid lines the significance limit

The workflow in summary:



4. Example on Evaluation of the Safety Factor

The safety margin towards failure obviously has to be calculated based on a statistically determined acceptance criteria. Such criteria are usually decided on a company level. In this example, the lower 10 % quantile of the measured cartridge failure pressure distribution and corresponding hoop stress distribution is selected for the safety factor calculation. In figure 9 the safety margin is depicted as the pressure between the highest stress value of the analysis DoE and the 10 % quantile value of the weakest batch. This distribution has to be calculated on a batch level (Figure 9) since a rather large inter batch variation is expected. Next the value of the lowest 10 % quantile can be held against the largest implied stress from the DoE calculation of section 3.

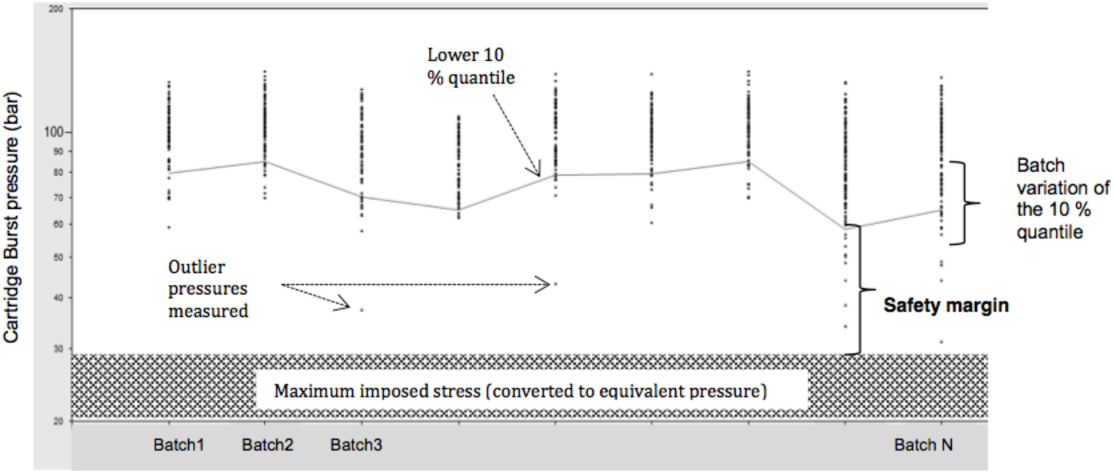


Figure 9. Measured cartridge burst pressures for various batches (each of 150 samples and a 99 % confidence interval)

The safety factor Sf can now be calculated as:

$$Sf = \frac{Lowest\ burst\ stress \cdot strength\ amplification\ factor}{Maximum\ imposed\ stress} \tag{4}$$

If using the 10 % quantile criterion and the weakest batch and calculating stresses using (1) & (3) we get a safety factor of:

$$Sf = \frac{27 \cdot 1.8\,MPa}{16\,MPa} = 3$$

It must be emphasised that Novo Nordisk of course uses more narrow criteria than the 10 % quantile.

5. Discussion and Further Refinement

From the beginning of this work it became evident that a traditional safety factor calculation where a nominal material loading is held against a given failure criterion would simply not suffice. The safety factor calculation as a robustness measure for such high volume production with many contributing parameters and a - inevitable - high batch variation requires a more comprehensive set of input data. The statistical assessment of both glass failure, distribution and geometry tolerances contributed to a much improved robustness against cartridge failure. This improved robustness can be achieved by securing high quality of the supplied cartridges (high pressure distribution) and production parameter adjustment (displacement profile and forces). In the FE-model it was mandatory to include rate dependency of thermoplastic deformation response (due to the viscoelastic nature of the thermoplastics used) for the best possible modelling of the loading safety factor prediction.

Further refinement of this model is needed to capture the effect of the stochastic rotational position of the cartridge in the device, which will have a positive impact on the safety factor. Also a more realistic statistical acceptance criterion has to be used.

Acknowledgments

We thank Tim Schwarting, Senior Project Manager, Novo Nordisk for his contribution with DoE modelling and statistical analysis.

We also thank Mads Reedtz Espersen, Principal Specialist, Novo Nordisk for providing essential information on glass failure.

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1st International Symposium on Robust Design
København, DK
14th-15th of August 2014

Scaling Under Dynamic Uncertainty Using Laws of Growth

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Keywords: scaling, dynamic uncertainty, wear, corrosion, size range development

Abstract

This paper gives an overview of methods used to describe uncertainty in size range development. Laws of growth, scenario laws of growth and probabilistic laws of growth are extended to allow the calculation of dynamic, size-dependent product behaviour. Dynamic product behaviour can depend on time or load cycles, such as corrosion and wear. Effects such as these can be size-dependent, an issue that is also considered in this paper. The extended methods are explained using a pushrod as an example product.

1. Introduction

When designing size ranges, a product developer faces a special challenge: in addition to the occurrence of uncertainty during the design process, production processes and the usage of the product are often size-dependent. This can be demonstrated with a pushrod as it is prone to buckling. Its critical load depends on production tolerances, which depend on the product's size [European standard EN IS 286-1:2010, 2010]. Its strength is also size-dependent if elastic-plastic buckling occurs. Size-dependency is also common for dynamic uncertainty. Dynamic uncertainty changes over time or a number of load cycles. In the pushrod, the influence of corrosion is time-dependent and constantly reduces the second moment of area, causing a reduction in the critical load and thus safety. If the rate of corrosion is constant and proportional to the exposed surface (ASTM, 2011), a large pushrod has its safety margin reduced at a slower rate than a small one. If there is degradation because of growing cracks (Schürmann, H., 2007), the dynamic uncertainty caused by stiffness reduction is also size-dependent but refers to the number of load cycles and the history of degradation rather than the time the product was in use.

Size-dependency refers to scaled product properties. That does not necessarily involve a change in geometric properties. Besides geometrical properties, force, power, temperature, stiffness, strength and various other mechanical, thermodynamic and optical properties can be scaled. An example that addresses these kinds of scaling is size ranges of combustion engines that can be found in the automotive industry. It is common to use one type of engine to cover a wide range of power needs. Changing the engine operating map, the amount of fuel burnt (and therefore the combustion temperature and mean pressure) and oxygen (provided by a turbocharger) are increased (Braess, Seifert, 2013), which leads to scaled loads, due to higher temperatures, and higher pressures during combustion.

DOI:10.4122/dtu:2083

Reviewed by: *Simon Moritz Göhler*
Thomas J. Howard

Cited as: Lotz, J. and Kloberdanz, H., 2014. Scaling Under Dynamic Uncertainty Using Laws of Growth. In: Howard, T. J. and Eifler, T., ed. 2014. *Proceedings of the International Symposium on Robust Design - ISoRD14*. Copenhagen, Denmark. pp. 17-27.

The literature contains various methods to describe wear, corrosion and aging ((Sommer, et al., 2014), (Grote K.-H., Antonsson E. K., 2008), (Elachachi et al., 2006), (Davis, 2000) and many more). However, the dynamic aspects of scale dependency are not taken into account (Lotz et al., 2014), or they are not directly applicable to size range development, e.g. Elachachi et al., 2006. The scale-dependency aspect of dynamic uncertainty is not part of the studies, e.g. Braghin, et al. (2006).

This paper proposes a general approach for handling dynamic, size-dependent uncertainty. The types of uncertainty that are addressed are stochastic (probabilistic) uncertainty and estimated uncertainty (Hanselka, Platz, 2010). Unknown uncertainty is not addressed in the following methods.

The aim is to describe product properties under uncertainty over the whole product lifecycle, including all its processes, and in correlation to its size. The size dependency is modelled using step factors and laws of growth as they are common in size range development (Feldhusen, Grote, 2013). Another possibility is to use dimensional analysis, which is not the focus of this paper.

2. Example Product

The example product is a buckling beam with either a full or hollow circular cross section since an ideal buckling beam, according to Euler, is simple enough to enable understanding of phenomenological problems of scaling and scaling tools can be applied. Since the approach of scaling under uncertainty introduced in Lotz et al (2014) is not time-dependent, the example product has to be amended to show time-dependent effects. Therefore, two case studies are used: one in which corrosion takes place so the product properties vary over time (this beam has a full cross section); and the other in which a buckling beam of hollow cross section has abrasion on its end planes.

In general, geometric similarity is maintained during the scaling process. This means that the inner diameter is 0.9 times the outer diameter of the hollow cross section beam for all sizes. The deviations created during production processes are growing, according to the law of growth of IT tolerance classes (European standard EN IS 286-1:2010, 2010). Uncertainty occurring in measurement is not taken into account since the product properties are expressed as nominal values process in product development. The limit slenderness ratio is calculated using mechanical properties from Saarstahl (2014), all sizes will reach elastic buckling before plastic deformation happens. All needed product properties are given in Tables 1, 2 and 3.

Table 1. General product properties of the buckling beam

Product property	***Smallest step factor***	***Basic size***	***Largest step factor***
step factor	0.2	1	5
length l	100 mm	500 mm	2,500 mm
deviation Δl	0.292 mm	0.5 mm	0.854 mm
outer diameter $D=2r_o$	2.4 mm	12 mm	60 mm
deviation ΔD	0.029 mm	0.05 mm	0.085 mm
inner diameter $d=2r_i$	2.16 mm	10.8 mm	54 mm
deviation Δd	0.029 mm	0.05 mm	0.085 mm
Young's modulus	E=210,000 N/mm² ± 5,000 N/mm²		
Law of growth for geometrical deviations	$\phi_\Delta = \phi_l^{1/3}$	$\phi_\Delta = \phi_l^{1/3}$	$\phi_\Delta = \phi_l^{1/3}$

These specifications can be used as input for laws of growth (LoG). Using laws of growth, all describing equations are written in step factors φ, which represents a nondimensional scaling factor for the size they represent, like $\varphi_l = l_1/l_0$ which describes the scaling factor of a length (index l) for a size range member (index 1) compared to the basic draft (index 0).

According to Euler (Grote/Antonsson, 2008), the critical load of the buckling beam (Figure 1a) with one end plane lying on a flat surface and having a simple support on the other is:

$$F_{krit} = \frac{EI(d_o,d_i)}{l^2} \tag{1}$$

Written with step factors defined previously, this leads to a law of growth for the critical load of the full section profiled beam (Equation 2 implies geometrical similarity).

$$\phi_{F_{krit}} = \phi_E \phi_l^2 \tag{2}$$

Two processes that affect product properties are used to examine time-dependent uncertainty: loss of material due to corrosion, which is size-independent; and abrasive wear, which is also size-dependent. Both are typical for uncertainty that occurs during usage of a product. All uncertainty measures in Tables 1, 2 and 3 are upper and lower bounds of intervals when calculating estimated uncertainty and, in the case of stochastic uncertainty, these values are considered to be six standard deviations away from the nominal (mean) value, following a Gaussian distribution.

Fig. 1

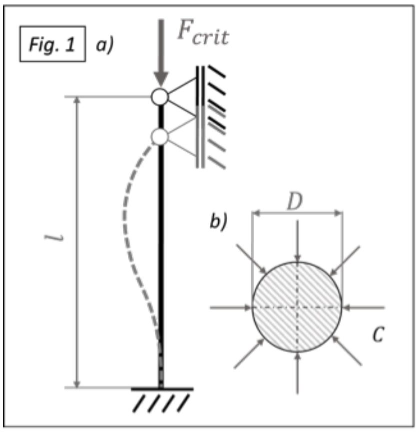

Fig. 2

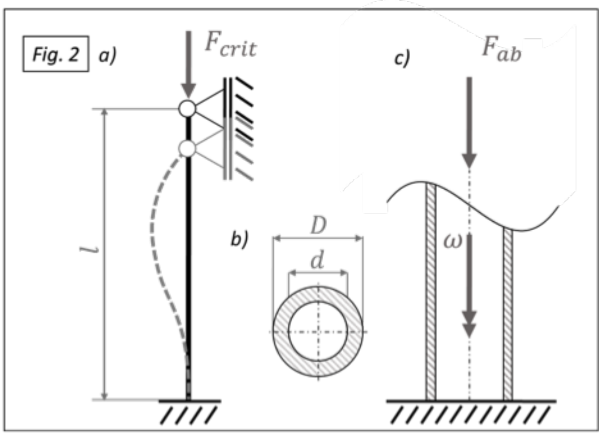

Figure 1. a) The buckling beam under corrosion and its supports. b) Corrosive loads are taking effect on the outside of the beam with full cross section.

Figure 2. a) The buckling beam under abrasive loads and its supports. b) The cross section is hollow to achieve a nearly constant sliding speed over the whole cross section. c) The beam is rotating around its longitudinal axis.

2.1 Corrosive Loads

Regarding the corrosive loads, the buckling beam with full cross section (Figure 1b) is exposed to corrosion on its whole length. It is assumed that the corrosion rate will be constant along the beam. The length itself should be unaffected by corrosion. The corrosion rate that describes the material loss per time is according to (ASTM, 2011) and given by Equation 3:

$$C = (K \cdot W)/(A \cdot t \cdot \rho) \tag{3}$$

With K as a constant factor, depending on the case that is examined (material, environmental parameters…), W = weight loss in kg, A = area exposed to corrosion in m², t = time in s and ρ = density in kg/m³. A common value for C, representing an ordinary low-carbon steel like 1.0402 (European standard EN 10027-2:, 1992) with 0.2% C in sulphuric acid (0.05%) at room temperature is taken from (Davis, 2000) (Table 2). Since the corrosion rate is very sensitive to concentration changes (at least at low concentrations like the one chosen) and is also influenced by the temperature, an estimated uncertainty of ± 20% is applied.

A full cross section was chosen because the corrosion would have lowered the wall thickness of a tube, like the one used for wear load calculations, to a value where the failure mode changes from global buckling to local buckling of thin cylinders under axial compression. If the stability bounds of both failure modes are known, the following calculation methods can also handle these cases, but with increased complexity in mathematic modelling.

Table 2. Corrosion-related product properties, step factors as in Table 1.

Product property	***Smallest step factor***	***Basic size***	***Largest step factor***
C	0.4 mm/a	0.4 mm/a	0.4 mm/a
deviation ΔC	± 0.08 mm/a	± 0.08 mm/a	± 0.08 mm/a

2.2 Wear Loads

To have a size-dependent product property affecting process, wear loads are applied to the buckling beam. The buckling beam is made of 1.0503 steel at 206 HV 10 and turning unlubricated on its end plane, which is in contact with an even plate of the same material and hardness (Table 3, data from (Sommer, et al., 2014), and Figure 2). For easy formulation of the wear process, it has a hollow cross section with the wall thickness being small compared to the diameter. More complex wear processes can be calculated in the same way, but require sufficient mathematic modelling. The small wall thickness allows the assumption of a constant relative speed for the whole cross section while turning. The axial force Fab causes the abrasion and should be proportional to the length of the beam $\varphi_{F_{ab}} = \varphi_{l}^{1,68}$. This proportionality results from the weight gain or loss of the geometrically similar upscaled or downscaled beam, the abrasive force is a result of the beam's own weight. Because the wear rate can be approximated in a linear relation to the axial force Fab for a constant sliding speed of 0.07 m/s (Sommer, et al., 2014), size-dependent wear is the result (Table 3).

Table 3. Wear-related product properties, step factors as in Table 1.

Product property	***Smallest step factor***	***Basic size***	***Largest step factor***
constant Load F_{ab}	0.48 N ± 0.048 N	8.55 N ± 0.855 N	128.3 N ± 12.83 N
avg. pressure p	1.75 N/mm²	1.25 N/mm²	0.75 N/mm²
avg. sliding speed v_s	0.07 m/s		
avg. wear rate w	10.5 mm/km	7.5 mm/km	4 mm/km

A linear approximation of the wear rate, depending on the pressure and valid for pressures between 0 N/mm² and 2 N/mm², can be calculated from the data given in Sommer, et al., 2014 as:

$$w = 6{,}3 \cdot p \tag{4}$$

To perform calculations that consider uncertainty, a deviation corresponding to Equation 4 is assigned to w, following the uncertainty of the diameters D and d as well as the uncertainty of the load F_{ab} and the uncertainty of the axial load. The sliding speed is considered to be exact.

3. Classification of Methods to handle Uncertainty in Size-Range Development

Several methods can support the designer with handling uncertainty in size-range development. Besides the use of dimensional analysis (nondimensional numbers and their deviation from the targeted mean value), which has been examined by the authors but is not included in this paper, there are several methods derived from laws of growth. Static scenario laws of growth (SLoG) and static probabilistic laws of growth (PLoG) have been published and evaluated (Lotz, et al., 2014). This paper tries to derive dynamic versions of these methods. Their relationship to each other can be found in Figure 3, where the information needed to perform calculations with those methods is plotted over their ability to handle dynamic uncertainty. The methods that need more information are also more computationally intensive, e.g. the Monte Carlo simulation for dynamic probabilistic laws of growth, and in some cases the dynamic scenario laws of growth. The approaches using dimensional analysis are especially suited to very low availability of information on mathematical modelling of the underlying physical effects, as long as measured data are available.

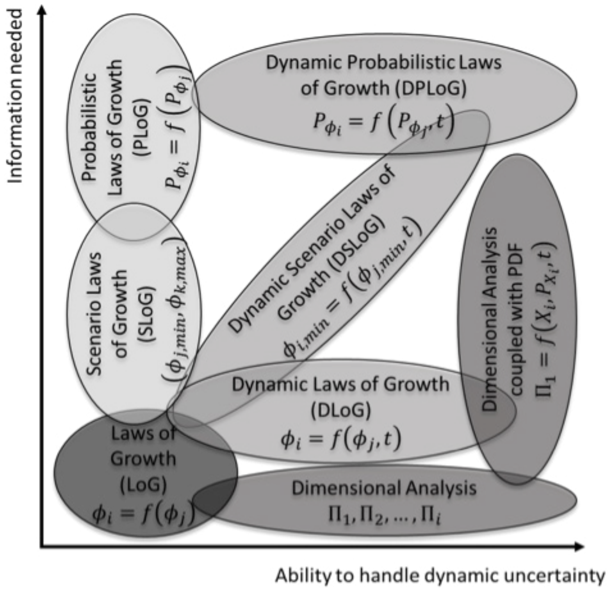

Figure 3. Different adaptations of scaling tools. Classification depending on the amount of information needed to perform their calculation and their ability to handle dynamic uncertainty.

3.1 Static laws of growth and static scenario laws of growth

Lotz et al. (2014) propose to assemble additional laws of growth, called scenario laws of growth. The most common are the best and worst case SLoGs. Therefore, the law of growth of geometrical deviations can be integrated into the law of growth for the critical load, and deviations of product properties, like Young's modulus, are written as minimum or maximum step factors. The minimum step factor that describes the worst case scenario is given by Equation 5; the maximum step factor, describing the best case scenario, can be assembled the same way, inverting addition and subtraction in the brackets (Lotz et al., 2014).

$$\phi_{F\,crit,min} = \frac{(l_0)^2\left(r_1-\Delta r_0\cdot\phi_l^{1/3}\right)^4}{(r_0)^4\left(l_1+\Delta l_0\cdot\phi_l^{1/3}\right)^2}\cdot\phi_{E,min} \tag{5}$$

The SLoG growth especially helps in handling static estimated uncertainty. Estimated uncertainty (Hanselka, Platz, 2010) occurs, for example, if an interval in which the possible values for a product property are contained, but it is uncertain how they are distributed within the interval.

3.2 Dynamic Laws of Growth

Dynamical product behaviour is well represented by the methods of size range development. There are various similar relations that describe dynamic system behaviour, for example Newton's, Cauchy's, Froude's or Reynold's numbers. However, the calculations performed with them are still static ones and do not take into account that input product properties change during processes such as aging, corrosion and wear. In order to have a distinguished understanding of dynamic laws of growth, the following definition is proposed: "*A dynamic law of growth describes size-dependent product properties that are changed by time or load cycle-dependent processes.*". A core element is that dynamic laws of growth are still meant to support size range development so they should use step factors as variables. An initial approach to describe time (*t*) or load cycle (*N*) dependent laws of growth is to make the step factors time or load cycle-dependent:

$$\phi_i = f(t) \quad \textit{or} \quad \phi_i = f(n) \tag{6}$$

They work in the same way and sometimes (if time and load cycles are coupled by the load cycle's frequency) can be converted into the other type.

Implementing a time dependency in step factors, the step factors are no longer nominal values as commonly used in size range development. They change with the time variable. The idea behind this is to have a justified tool to describe size and time-dependent product properties, like the scenario laws of growth do just for size dependency. The critical load is such a product property in the context of the introduced example product.

First, it is necessary to determine which of the step factors time dependency is influenced by. These step factors have to be adjusted to the dynamic behaviour of the product property. For the buckling bar under corrosion, as specified in Section 2, only the beam's diameter is affected. This means that there is no geometric similarity during the time of usage of this product. The loss of geometric similarity also happens when the geometric properties are affected in a different way to each other. Therefore, dynamic laws of growth usually will include more step factors then static ones. The time dependency is as shown in Equation 7 (compare with Equations 1 and 2):

$$\phi_{F\,crit}(t) = \frac{\phi_E \cdot \phi_d(t)^4}{\phi_l^2} \tag{7}$$

Taking into account Equation 6 for $\phi_d\ (t)$, this becomes

$$\phi_d(t) = \frac{d_1 - C \cdot t}{d_0} \tag{8}$$

This would cause the dynamic law of growth (DLoG) to consist of terms that have no step factors in common, which prevents the scaling problem from being solved using only step factors as an expression of a scaling factor. To avoid this, Equation 8 can be split into two step factors: one which represents the factor of geometric scaling of the diameter, and the other which represents the dynamic behaviour. In this case, the second step factor is equal to the loss of material due to corrosion. In general, it can be called the step factor of time ϕ_(t,i) with an index i for the parameter it has influence on.

$$\phi_d(t) = \frac{d_1 - C \cdot t}{d_0} = \frac{d_1}{d_0} - \frac{C \cdot t}{d_0} = \phi_d - \phi_{t,d} \tag{9}$$

The step factor of time only depends on time itself and factors being constant over the scaling process. It is a nondimensional number similar to that used in dimensional analysis (Gibbings, 2011). Using the step factor of time, Equation 9 can be written as:

$$\phi_{F_{crit}}(t) = \frac{\phi_E \cdot (\phi_d - \phi_{t,d})^4}{\phi_l^2} \tag{10}$$

For the second example, the DLoG has a direct dependence on the number of revolutions N fulfilled by the beam (which is mathematically the same as a time dependency). This eases the calculation of product properties at a certain point of the product usage. If the wear rate w is written as step factor ϕ_w and ϕ_p is substituted through $\phi_{F_{ab}}/\phi_A$, $\phi_A=\phi_l^2$, the wear rate can be written as a size-dependent change in the product property:

$$\phi_w = \frac{\phi_l^{1,68}}{\phi_l^2} = \phi_l^{-0,32} \approx \frac{1}{\phi_l^{1/3}} \tag{11}$$

Since the uncertainty of the wear rate is not equal to the uncertainty of the length it should not be written as a function of ϕ_l within the DLoG. The quantification of uncertainty depends on which calculation is performed. For dynamic scenario laws of growth (DSLoG), the Uncertainty of ϕ_w follows the defined scenarios, in this case a combination of values that create a best or worst case. For probabilistic calculations, the probability density functions for the underlying parameters have to be convolved for a quantification of ϕ_w's uncertainty. The DLoG for the beam under abrasive loads above is the following (if geometrical similarity is retained):

$$\phi_{F_{krit}} = \frac{\phi_E \cdot \phi_l^4}{\phi_l^2 \left(\frac{1-\pi \cdot N_1 \cdot w_1}{1-\pi \cdot N_0 . w_0}\right)^2} = \frac{\phi_E \cdot \phi_l^2}{\phi_l^2 \cdot \phi_w^2} \quad \textit{with} \quad \phi_w = \left(\frac{1-\pi \cdot N_1 \cdot w_1}{1-\pi \cdot N_0 . w_0}\right)^2 \tag{12}$$

If geometric similarity is not retained the dynamic law of growth gets very complicated and it should be considered as approximating the bulky terms with terms that depend on less parameters or are in a monomial form, depending form the main parameter (ϕ_l for the example product) that can be transformed into a law of growth easily.

3.3 Dynamic Scenario Laws of Growth

Referring to Paragraph 3.1, laws of growth can be supplemented by scenarios deriving best or worst case scenarios (or other specific ones, if needed). This approach can also be applied to dynamic scenario laws of growth. Equation 10 can be adjusted to scenarios, usually best and worst case. For corrosion loads like those in the example products, the parameters that have uncertainty are the geometric parameters, as well as Young's modulus and the corrosion rate. The time can be considered accurate if it is not one of the dependent product properties (a cycle time, for example). Best and worst case scenarios are given in Equation 5. Equation 13 gives the result of combining Equations 10 and 5:

$$\phi_{F_{crit,min}}(t) = \frac{\phi_{E,min} \cdot (\phi_{d,min} - \phi_{t,d,max})^4}{\phi_{l,max}^2} \text{ and } \phi_{F_{crit,max}}(t) = \frac{\phi_{E,max} \cdot (\phi_{d,max} - \phi_{t,d,min})^4}{\phi_{l,min}^2} \tag{13}$$

Scenarios of the step factor of time depend on the uncertainty of the corrosion rate. The boundaries of the intervals containing the product properties are identical to the tolerances given in Tables 1, 2 and 3. A representation of the dynamic scenario laws of growth is shown in Figure 4. Large deviations from the nominal product properties occur the longer the beam was exposed to the corrosive medium. Decreasing size of the product itself leads to larger deviations in product properties (the non-varying corrosion rate is larger compared to the diameter the smaller the diameter gets, in addition the relative tolerances are larger (Table 1)).

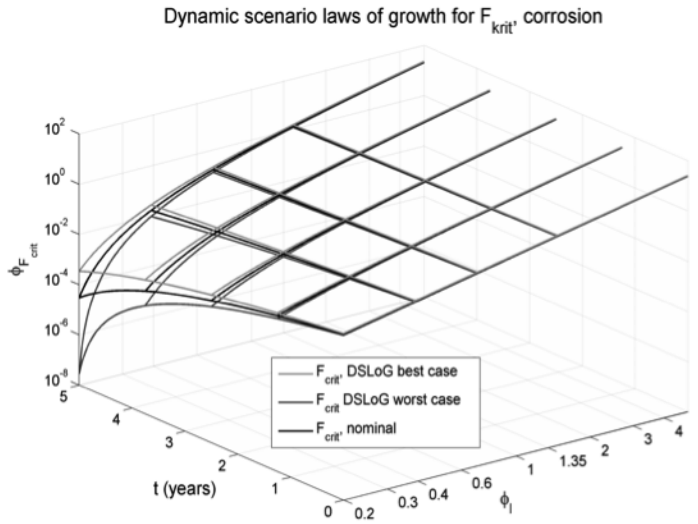

Figure 4. Dynamic Scenario Laws of Growth for the buckling beam under corrosion.

A schematic overview of the steps needed to calculate a DSLoG is presented in Figure 5.

3.4. Probabilistic Laws of Growth and Dynamic Probabilistic Laws of Growth

Probabilistic laws of growth (PLoG) are introduced by Lotz et al. (2014) and are an approach to handling size-dependent uncertainty. The main focus lies on stochastic uncertainty in the definition of Hanselka & Platz (2010). Using Monte Carlo simulation, the probability density functions (PDF) of the target parameter of scaling can be calculated from the PDF of the input parameters. Therefore, the static laws of growth for product properties and uncertainty have to be known. If the PDF of the input parameters are all uniform or all Gaussian in type, the calculations can also be performed analytically instead of numerically (Joint Committee for Guides in Metrology, 2008). In addition to Lotz et al. (2014), laws of growth can be approximated for statistical parameters such as standard deviation, skewness and kurtosis of the target parameter PDF. Procedures to derive laws of growth from data are introduced by Pahl & Rieg (1984), Most (1989) and Kloberdanz (1991). The data in this case are standard deviations or other statistical parameters calculated for several sizes of the type range.

The approach for how to derive DPLoGs is shown in Figure 5. The mathematical model of physical relationships between the input parameters is assembled and a static law of growth is derived. As in DLoGs, the initial values (for *t=0* or *N=0*) for the dynamic calculation of time-dependent product properties are obtained by performing the targeted product properties of the product's size range. This generates SLoGs or PLoGs, depending on what information about uncertainty is available. In a second step, the law of growth for the time dependency of product properties is derived: the DLoG. In the third step, the initial values are processed using the DLoG; this can be done in an analytic manner for SLoGs (Paragraph 3.3) or via Monte Carlo simulation for PLoGs, especially if the PDFs of the uncertainty are asymmetric.

Having carried this out using Monte Carlo simulation for the beam under corrosive loads, histograms can be plotted, which would be nondescriptive for the example product with only Gaussian PDFs as input, or the plot of a confidence belt (6σ or 99.99966% in this case) can be assembled (Figure 6). The beam under abrasive load shows similar behaviour, except the critical load grows because of the decreasing length of the beam. Due to limited space, plots cannot be given here but can be requested from the authors.

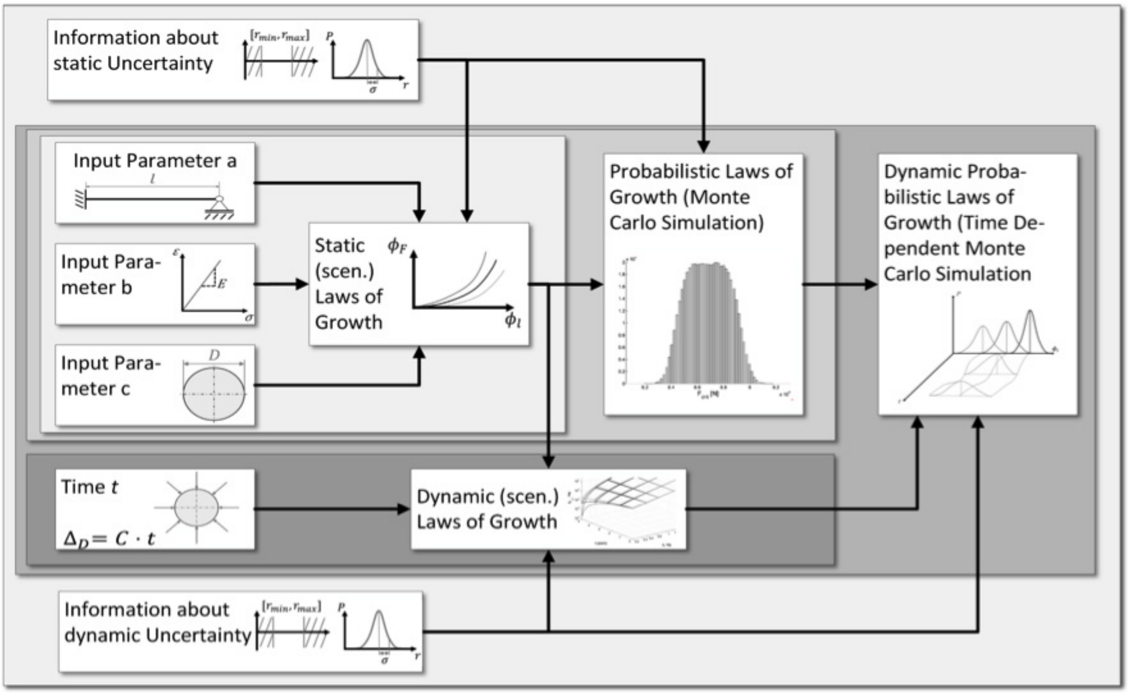

Figure 5. Approach for handling dynamic probabilistic uncertainty in size range development.

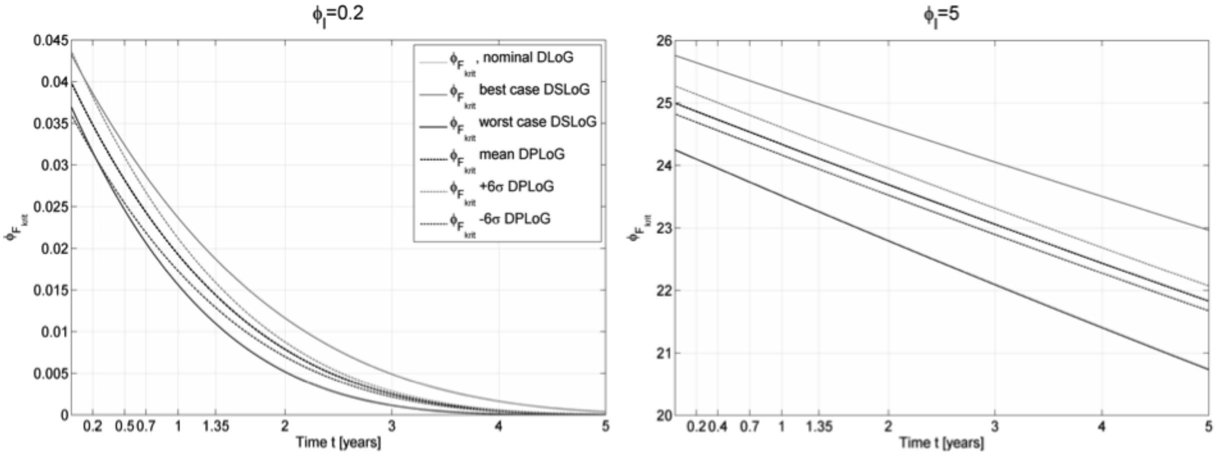

Figure 6. Comparison between the DSLoG and DPLoG for the beam under corrosive loads at different sizes. The legend is valid for both plots.

4. Comparison

The dynamic scenario laws of growth are consistent with the underlying physical laws and can be considered as a reliable source of absolute best and worst-case output values, especially for dynamic laws of growth. This is just the opposite to the behaviour that static laws of growth show, since they are not necessarily showing the absolute best or absolute worst case if compared to the PDFs calculated with Monte Carlo simulation for a targeted level of safety (Lotz, et al., 2014). The reason for this deviation in reliability of the outcomes lies in the way the probabilistic dynamic law of growth is calculated and its boundary conditions. If the Input parameters are changing with a high frequency compared to the time the product is exposed to this uncertainty, the product behaviour will only have minor deviations from the mean value. This is reasonable in terms of the law of large numbers: the more frequent the stochastic value changes, the better the mean value describes the product's behaviour (the mean value is identical to the nominal value for all symmetrical PDFs, like the Gaussian or uniform distribution). The important aspect is that uncertainty with adequate change frequency (in this case, 1,000 changes over five years or 1,000,000 load cycles were more than enough) and common strengths of effect on the product property lead to a product behaviour that can be predicted very well with DSLoGs. If a very precise prediction is needed, DPLoGs are a helpful way to reduce excessive margins of safety. Nevertheless, there is one exceptional case. If the further change in product properties depends on the history of change in this property, the standard deviation will be larger. A technical example is the degradation of fibre-reinforced plastics. If there are high loads in the first load cycles, and degradation starts because inter-fibre fracture occurs, the strength is decreased and smaller loads would cause progression of the degradation where they would not have degraded the material if it had not been damaged before (Schürmann, 2007). These processes can also be handled with probabilistic laws of growth, although the mathematical modelling is more complex since differential equations have to be solved. There are often more interdependencies between the different step factors. The calculation can only be performed by integration or use of numerical methods.

5. Outlook

The insights gained working with DSLoGs and DPLoGs create areas of interest for future research. A catalogue of time-dependent step factor modelling for scenarios of wear, abrasion, aging, etc should be assembled to ease the product developer's task of deriving dynamic laws of growth. Strategies for efficiently handling the computationally intensive calculation of DPLoGs should be integrated into detailed programming instructions. In addition, development of product and process models that focus on scaling effects could support the product developer in identifying the critical parameters that have to be examined in a detailed way, e.g. with DPLoGs, and those that can be handled with less costly methods, such as DSLoGs or even DLoGs. The models could also help find the limits to scaling of a product, which is an important issue when planning a size range.

Acknowledgment

We would like to thank Deutsche Forschungsgemeinschaft (DFG) for funding this project within the Collaborative Research Centre (CRC) 805.

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1st International Symposium on Robust Design
København, DK
14th-15th of August 2014

A Comparative Study on Tolerance Analysis Approaches

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Keywords: Computer-Aided Tolerancing, Skin Model, Tolerance Simulation

Abstract

Robust product designs are characterized by their insensitivity to disturbances and noise, such as geometric part deviations, which are inevitably observed on every manufactured workpiece. These observed deviations are covered by the axioms of manufacturing imprecision and measurement uncertainty, which convey the concepts of variability and uncertainty as fundamental aspects of robust design. In order to ensure the product function though the presence of these geometric part deviations without building physical artefacts, tolerance simulations are employed in the context of computer-aided tolerancing. Motivated by the shortcomings of existing tools, the concept of Skin Model Shapes has been developed as a novel paradigm for the computer-aided tolerance analysis. This paper presents a comparative study on the standard procedure for the tolerance analysis employing proprietary CAT tools and the tolerance simulation based on Skin Model Shapes. For this purpose, two exemplary study cases are highlighted. Based on the comparisons, general remarks on the use of CAT tools in the context of tolerance analysis and robust design are derived.

1. Introduction

Robust product designs are characterized by their insensitivity to disturbances and noise factors. In order to attain such robust product designs, Robust Design Methodology (RDM) is of high importance during all development stages of engineering design (Hasenkamp, Arvidsson and Gremyr, 2009), where a widely acknowledged definition of RDM is given by Arvidsson and Gremyr (2008): “Robust Design Methodology is understood as systematic efforts to achieve insensitivity to noise factors. These efforts are founded on an awareness of variation and can be applied in all stages of product design.” Based on this rather generic definition, geometric variations management can be seen as a branch of RDM that deals with noise factors, which are related to the part and product geometry, and aims at ensuring the product function though the presence of geometric part deviations. The need for geometric variations management in the context of robust design is based on the fact, that geometric deviations are inevitably observed on every manufactured workpiece since they are covered by the axiom of manufacturing im-

DOI:10.4122/dtu:2084

Reviewed by: *Simon Moritz Göhler*
Tobias Eifler

Cited as: Schleich, B., Anwer, N., Zhu, Z, Qiao, L., Mathieu, L. and Wartzack, S., 2014. A Comparative Study on Tolerance Analysis Approaches. In: Howard, T. J. and Eifler, T., ed. 2014. *Proceedings of the International Symposium on Robust Design - ISoRD14*. Copenhagen, Denmark. pp. 29-39.

precision and the axiom of measurement uncertainty (Srinivasan, 2006). These axioms convey the concepts of variability and uncertainty as two fundamental aspects of robust design.
In general, achieving the robust design principles, namely the insensitivity to noise, the awareness of variation and the continuous applicability, by implementing RDM in industrial practice requires support by operational tools. However, a low use of RDM in practice has been reported, which has been traced back to a lack of such operational tools (Eifler, Ebro and Howard, 2013) and a deficit in quantitative models that support design teams in decision making (Thornton, Donnelly and Ertan, 2000). In the context of geometric variations management, such operational tools are subsumed under the term "Computer-Aided Tolerancing (CAT)". They offer functionalities for the tolerance allocation and annotation in CAD models as well as for the tolerance simulation. However, these tools are quite specific and are often employed solely by experts. Furthermore, the implemented algorithms are only presented as grey boxes to the users and deciders. Thus, the benefit of these proprietary CAT tools is limited, since the results are hard to understand and to interpret, which may lead to insufficient tolerancing decisions in design and manufacturing (Mathieu and Ballu, 2007).

With the aim to emphasize the need for new paradigm shifts in the context of computer-aided geometric variations management, a comparative study on the standard procedure for the tolerance analysis employing proprietary CAT tools and the tolerance simulation based on Skin Model Shapes is presented in this paper. For this purpose, two exemplary study cases are highlighted. Based on the comparisons, general remarks for the use of CAT tools in the context of robust design are derived and future challenges for the development of operational tolerance analysis tools are carved out. The paper is structured as follows. In the next section, computer-aided tolerancing approaches are briefly explained and qualitatively compared. Thereafter, two case studies are presented in order to highlight the differences and similarities of both approaches. Finally, a conclusion and an outlook are given.

2. A Brief Review on Computer-Aided Tolerancing Approaches

Geometric variations management covers manifold activities from design to manufacturing and to inspection, which are performed by many actors employing various tools. However, the consideration of geometric tolerances at early stages of the design of physical artefacts is a key issue for achieving robust product designs. Computer-Aided Tolerancing (CAT) tools have been developed in order to support these tolerancing activities during design, such as the derivation of geometric requirements, the tolerance specification, the tolerance synthesis, and the tolerance analysis as can be seen from Figure 1. For example, the derivation of geometric requirements from functional requirements is supported by the functional key characteristics (FKC) flow-down (Thornton, 1999) or the functional requirements/dimensions matrix (Islam, 2004). The traceability of these geometric requirements throughout the product development process can then be supported by adequate product models (Dufaure and Teissandier, 2008). Based on the geometric requirements, approaches for the automated generation of datum references and tolerancing schemes (Anselmetti, 2006) as well as for single-part tolerancing (Anselmetti, Chavanne, Yang and Anwer, 2010) have been proposed. The manual annotation of geometric specifications to virtual product models in CAD environments is supported by automated validity checks in modern CAT systems (Clozel, Lacour and Rance, 2012). Finally, many mathematical models for the simulation of the effects of geometric deviations and specifications on the geometric requirements have been proposed (Prisco and Giorleo, 2002; Hong and Chang, 2002; Polini, 2012), and have also been used for the tolerance design in early design stages (Ziegler and Wartzack, 2013), for the tolerance-cost optimization of mechanism (Walter and Wartzack, 2013), and for the robustness analysis of compliant assemblies (Söderberg, Lindkvist and Dahlström, 2006).

In this context, particularly computer aided tolerance analysis has gained much research attention during the last decades, since the prediction of the effects of geometric deviations on the product quality without building physical prototypes is a key issue in the design and manufacturing of high quality products at moderate costs. Therefore, a focus is set on the procedure for the tolerance analysis in the following sections.

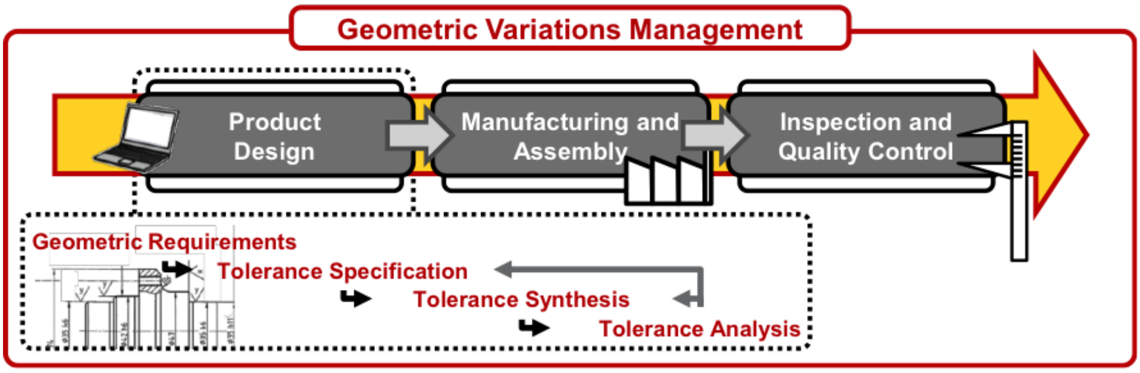


Figure 1. Main Geometric Variations Management Activities during Product Design

2.1 Computer-Aided Tolerance Analysis with proprietary software tools

Nowadays, proprietary software tools are often employed for evaluating the effects of geometric part deviations on relevant product characteristics, which are depicted as Key Characteristics (Thornton, 1999). In general, such proprietary CAT software involves the following elements (Prisco and Giorleo, 2002; Shah, Ameta, Shen and Davidson, 2007; Mazur, Leary and Subic, 2011; Clozel, Lacour and Rance, 2012):

1. Definition of the assembly CAD models and specification of tolerance types and values as well as definition of their individual distributions (e. g. Gaussian or uniform).
2. Definition of the assembly sequence (moves), the part/features relative positioning and the mating conditions (e. g. planar or cylindrical).
3. Specification of Key Characteristics (KCs) and geometric functional requirements, such as gaps or clearances.
4. Simulation of the effect of part tolerances on KCs using a worst-case or statistical approach (methods such as Monte Carlo simulation are used) employing a tolerance simulation model.
5. Analysis of the outcome data and identification of the main contributors to evaluate their sensitivity to the KCs and the tolerance design robustness. This step is supported by visualization techniques, such as histograms or KC plots.

These steps are usually performed by tolerancing experts and are illustrated in Figure 2.

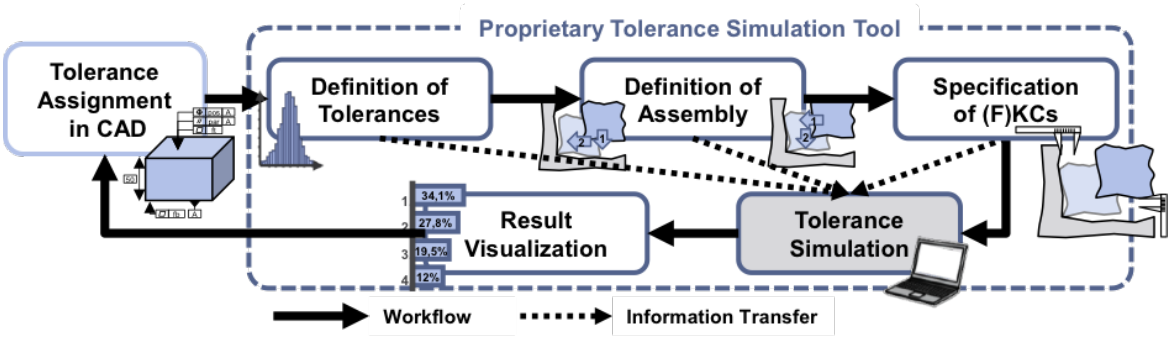


Figure 2. The tolerancing process with support of proprietary CAT tools

2.2 Skin Model Shape based Tolerance Analysis

As it has been pointed out, many mathematical models for the representation of geometric requirements, geometric specifications, and geometric deviations have been proposed during the last decades. However, most of these models make severe assumptions about geometric deviations (Ameta, Serge and Giordano, 2011; Shen, Ameta, Shah and Davidson, 2005; Hong and Chang, 2002), since they reduce geometric deviations to translational and rotational feature defects without considering form deviations. Therefore, they only partly conform to standards for the geometric product specification and verification (GPS) (Mathieu and Ballu, 2007). As a response to these shortcomings, the concept of Skin Model Shapes as a new paradigm shift for geometric variations modelling and computer-aided tolerancing has been proposed recently (Schleich, Anwer, Mathieu and Wartzack, 2014; Anwer, Schleich, Mathieu and Wartzack, 2014). It grounds on the Skin Model (Anwer, Ballu and Mathieu, 2013), which is an infinite model of the physical interface between a workpiece and its environment and a core concept of GeoSpelling as a coherent language for GPS (Dantan, Ballu and Mathieu, 2008). Skin Model Shapes are particular outcomes of the Skin Model and can be understood as virtual workpiece representatives. Though the concept of Skin Model Shapes is not linked to a specific geometry representation scheme, a discrete geometry framework for the generation of Skin Model Shapes has been proposed (Schleich, Walter, Wartzack, Anwer and Mathieu, 2012; Schleich, Anwer, Mathieu and Wartzack, 2014). This is because discrete geometry representations, such as point clouds and surface meshes, can be obtained and processed throughout the whole product life cycle. Figure 3 illustrates the differences between the Nominal Model, the Skin Model, and the Skin Model Shape concept.

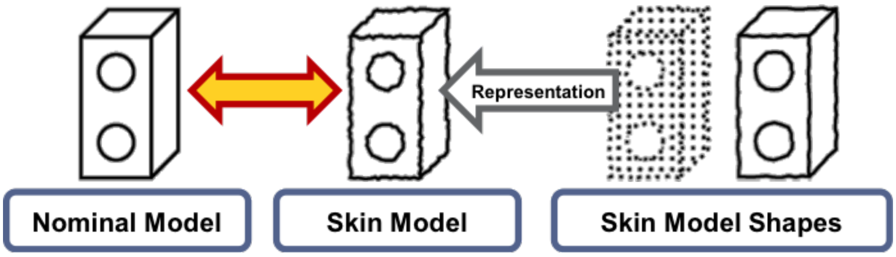


Figure 3. Difference between Nominal Model, Skin Model and Skin Model Shapes

The procedure for the tolerance analysis based on these Skin Model Shapes can roughly be divided in a pre-processing, a processing, and a post-processing stage as can be seen from Figure 4 (Schleich, Anwer, Zhang, Mathieu and Wartzack, 2014). In the pre-processing stage, Skin Model Shapes are generated either by employing mathematical approaches for the modelling of geometric deviations or by using results from manufacturing process simulations or measurement data (Schleich, Anwer, Mathieu and Wartzack, 2014). In the processing stage, these Skin Model Shapes are assembled following the defined assembly process employing relative positioning approaches (Schleich, Anwer, Zhang, Mathieu and Wartzack, 2014). Finally, in the post-processing stage, measurements on the resulting assemblies are evaluated and the results are visualized and interpreted.

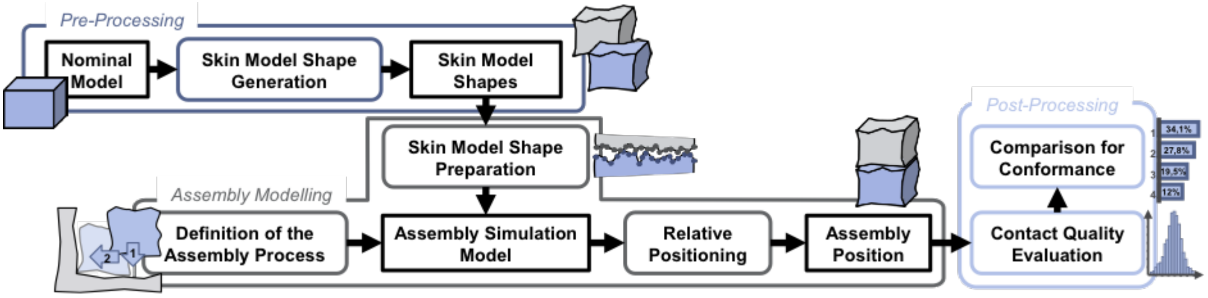


Figure 4. Tolerance Analysis Procedure based on Skin Model Shapes

2.3 Qualitative Comparison of the Computer-Aided Tolerancing Approaches

Due to the proprietary nature of the existing CAT software, it is difficult to determine which tolerance analysis methods are applied. Nevertheless, the review of tolerance analysis literature shows that the foundations of current CAT Systems rely on established tolerance analysis models (Prisco and Giorleo, 2002; Shah, Ameta, Shen and Davidson, 2007; Polini, 2011; Chen, Jin, Li and Lai, 2014). 3DCS, eM-TolMate, and VisVSA are based on variational models; CETOL uses the vector-loop model and the Direct Linearization Method; CATIA.3D FDT is based on TTRS and the matrix model; and Tolmate uses the Small Displacement Torsor model. The aforementioned tolerance analysis models partly conform to ISO and ASME standards, and many issues are still to be investigated in depth, such as the combination of 3D tolerance zones, envelope and independence principles, form tolerances, material condition modifiers, datum precedence, closed form solutions in the case of Monte Carlo simulations, and Solid/Rigid body assumptions (Shah, Ameta, Shen and Davidson, 2007; Polini, 2011). Furthermore, the assumptions made by these systems, regarding for example the generation of geometric part deviations, are often not conform to real-life situations in later stages and are presented as black boxes to the designer. Thus, it is hard to derive resilient tolerancing decisions on the basis of the obtained tolerance analysis results.

In contrast to the procedure supported by these systems, the tolerance analysis approach based on Skin Model Shapes is a new theory, which covers the whole product origination process from design to manufacturing and inspection to final product performance testing (Schleich and Wartzack, 2014). This is because Skin Model Shapes are based on discrete geometry representations, such as point clouds and surface meshes, which can be obtained from the nominal model by tessellation techniques during the design stage as well as from manufacturing process simulations or measurement data of part prototypes during manufacturing and inspection. Moreover, meshes obtained from FEA or CFD simulations can be directly used for the tolerance analysis. Furthermore, the approach allows the consideration of form deviations and is conform to current and future GD&T standards.

3. Experiments and Results

In the following, both approaches for the tolerance analysis are applied to two case studies in order to highlight their differences and to obtain a quantitative comparison, where 3DCS by DCS is used as a proprietary CAT tool. The first study case aims at testing the consideration of geometric specifications according to ISO standards, whereas the second case study targets studying the effects of the assembly sequence on the tolerance analysis results. Both case studies are inspired by the work of Anselmetti and Mathieu (2001).

3.1 Case Study 1 – Consideration of GD&T standards

The first case study consists of two perfect ashlars (grey) and a block with geometric deviations (blue) as can be seen from Figure 5. In order to evaluate and to appraise the effects of geometric deviations of the block on the assembly dimensions, several point-to-point distances as well as two angles are measured after the relative positioning. Multiple tolerances restrict the part deviations of the block, such as flatness tolerances of the mating surfaces and a parallelism tolerance as well as a position tolerance between the mating planes (top and bottom) as follows: pos=0.2, par=0.1, ft=fb=0.05.

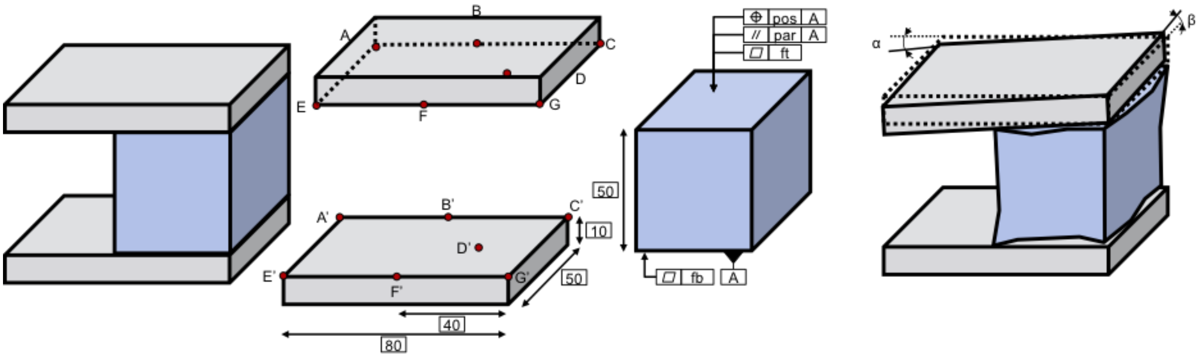
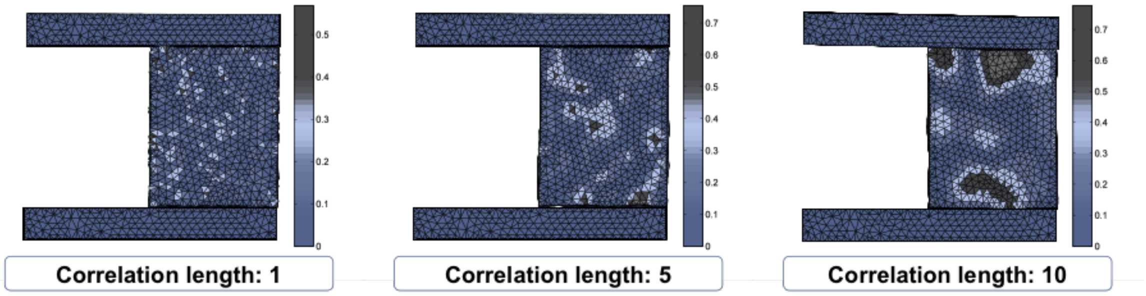


Figure 5. Case Study 1

For the tolerance analysis employing a proprietary CAT tool, the tolerance distributions are chosen as Gaussian with 6 sigma within the specified tolerance ranges, e. g. for the flatness deviation of the cube's bottom plane fb, a Gaussian distribution with mean 0.025 and standard deviation 0.0083 is considered. Furthermore, two three-point moves are defined in sequence between the cube and the bottom ashlar as well as the top ashlar and the cube. Moreover, the measurements between the point pairs from AA' to GG' are defined as point-point measurements. Custom measurements are employed for the angles α and β.

The Skin Model Shape based tolerance simulation starts with the generation of Skin Model Shapes. For the practical application, this can be performed by using results of stochastic manufacturing process simulations, whereas random geometric deviations are generated employing a random field approach in this contribution. For this purpose, each point of the surface mesh is shifted in the direction of its vertex normal. The amount of shifting is given by a set of spatially correlated random variables with the correlation length as a parameter that influences their spatial correlation. Some resulting assemblies for different correlation lengths can be seen from Figure 6.



Correlation length: 1 **Correlation length: 5** **Correlation length: 10**

Figure 6. Skin Model Shape Assemblies with different correlation lengths

The generated deviations are then "scaled" in order to fit the specified distributions for the assigned tolerances. For this purpose, all points of each toleranced feature are obtained by GeoSpelling partition operations (Dantan, Ballu and Mathieu, 2008). In order to comply with the flatness tolerances, these points are then shifted along their vertex normals as long as they all lie within the flatness tolerance zone. The parallelism tolerance is then ensured by rotating the toleranced feature, whereas rotations and a translation are applied to fulfil the position tolerance. However, slight violations of the specified tolerance distributions may occur as a result of this scaling procedure as can be seen from Figure 7 (for 1,000 samples).

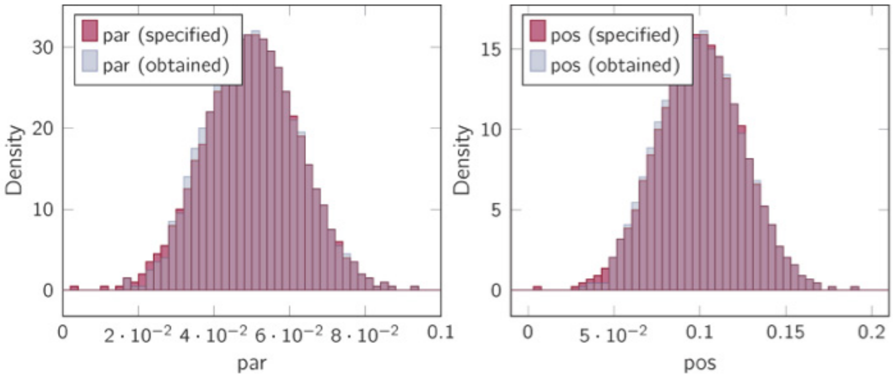


Figure 7. Specified and Obtained Tolerance Distributions

Thereafter, the generated Skin Model Shapes of the cube are assembled with the two nominal ashlars following straight three-point contacts. For this purpose, registration approaches are employed (Schleich, Anwer, Zhang, Mathieu and Wartzack, 2014). Finally, all relevant distances as well as the two specified angles are measured from the resulting assemblies. The results obtained by both approaches are given in Figure 8, where “SMS” indicates the Skin Model Shape based approach and “Prop” stands for the proprietary CAT tool. It can be seen, that the results obtained by both approaches are comparable regarding the scatter of the KCs. However, a slight mean shift of the sample distribution can be observed between both approaches. Furthermore, the proprietary software tool tends to overestimate the effect of the geometric part deviations on the tilt angles α and β.

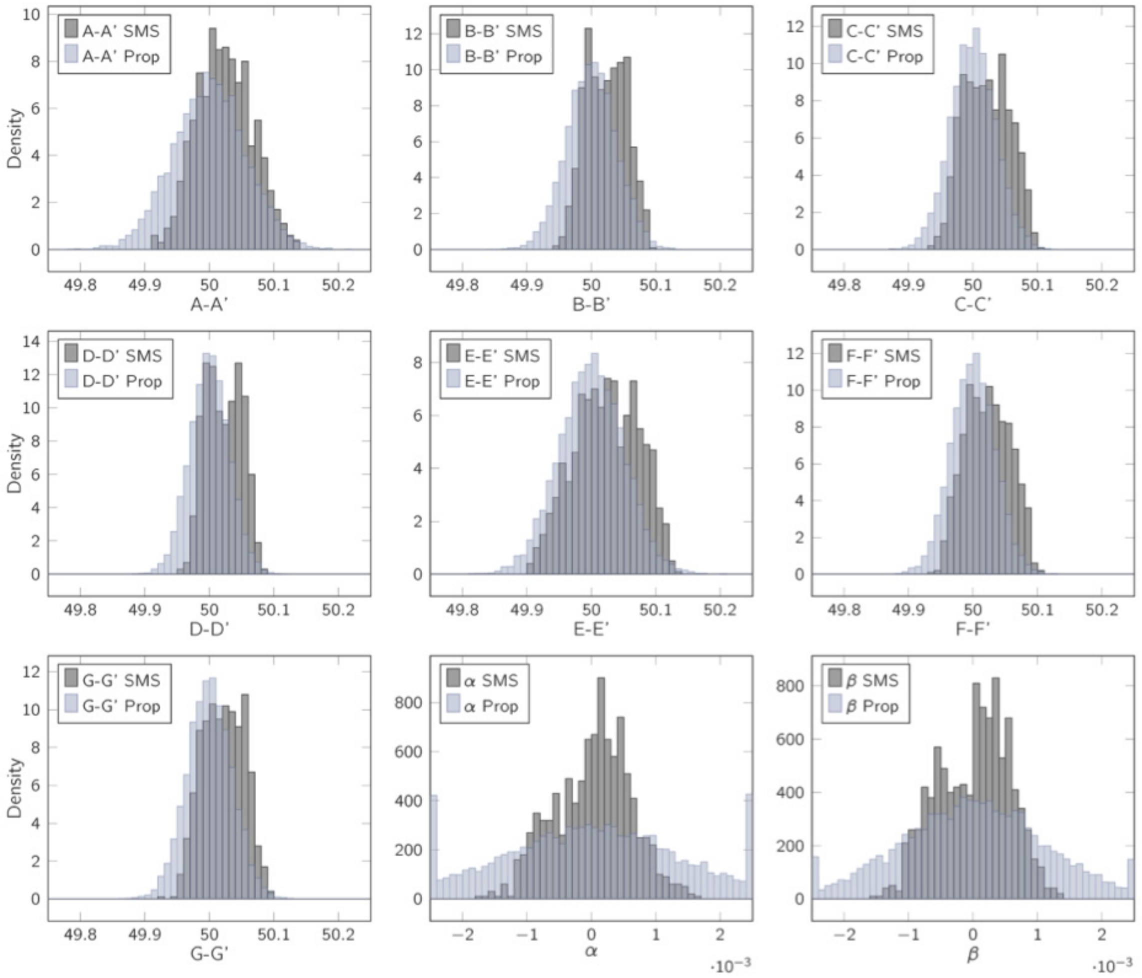


Figure 8. Results of Case Study 1 for a commercial CAT tool (Prop) and the tolerance analysis based on Skin Model Shapes (SMS)

3.2 Case Study 2 – Influence of the positioning scheme

The second case study consists of two parts, where the second part (blue) is assembled in the first part (grey) as can be seen from Figure 9. In order to ensure that the resulting gap s between the parts lies within some predefined requirements, flatness deviations of the mating surfaces and the measurement surfaces as well as perpendicularity and position tolerances are assigned to the parts as follows: ft=0.05, per=0.2, pos(A|B)=1, pos(C|D)=0.4.

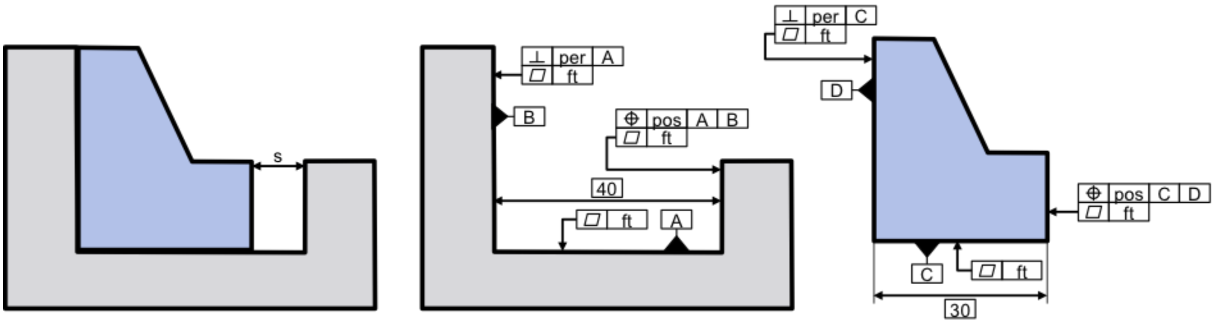


Figure 9. Case Study 2

Since the aim of this case study is the evaluation of the effects of different assembly sequences on the gap between the parts, two scenarios are examined (see Figure 10):

- Scenario 1: the primary contact between both parts is the y-direction and the secondary contact is in x-direction.
- Scenario 2: the primary contact is the x-direction, whereas the secondary contact is in y-direction.

It is worth mentioning, that the first scenario corresponds to the ISO specifications, whereas scenario 2 is not conform.

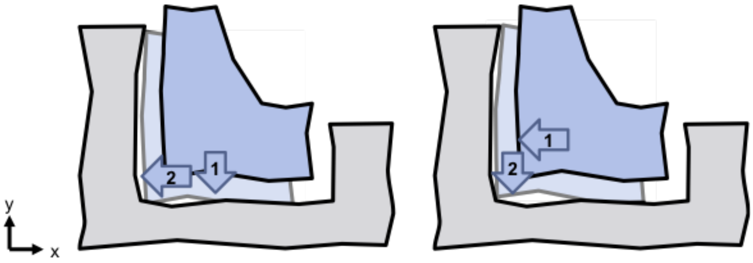


Figure 10. Assembly Sequences – Scenario 1 (left) and Scenario 2 (right)

The procedure for the tolerance analysis following the two presented approaches is performed in analogy to the first case study, where the gap s is measured as the distance between the mean points of both parts' plane features in the Skin Model Shape approach. The results for the gap s are given in Figure 11. It can be seen, that the influence of the assembly sequence is minor for this specific case study, which is due to the comparably small part deviations. Furthermore, in analogy to the first case study, a slight mean shift of the distributions for the gap between the proprietary software tool and the Skin Model Shape approach can be observed.

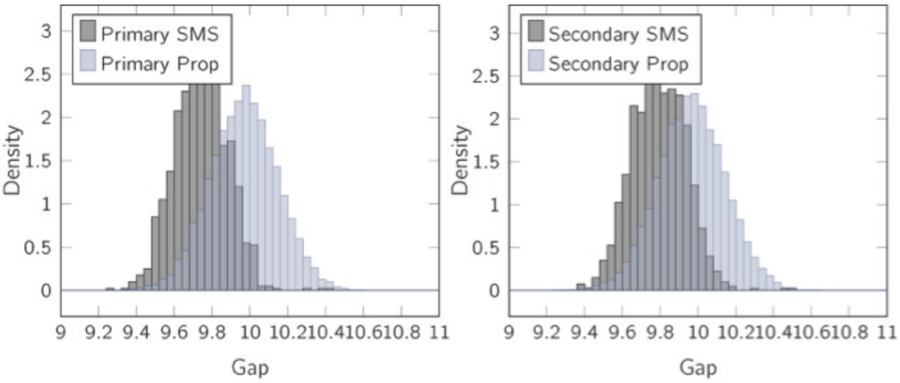


Figure 11. Results for the second case study (mean gap)

3.3 Quantitative Comparison of the Computer-Aided Tolerancing Approaches

The results of the case studies reveal a slight mean shift of the dimensional KCs between both tolerance analysis approaches. Furthermore, the resulting distributions of the tilt angles in the first case study are considerably wider following the proprietary CAT tool compared to the Skin Model Shape approach. Possible explanations for these results are the incomplete consideration of form deviations in proprietary CAT tools as well as slight differences between the approaches regarding the reproduction of geometric deviations according to the specified tolerance distributions. However, since the algorithms implemented in proprietary CAT systems for the generation of geometric deviations as well as for the tolerance analysis itself are presented as black-boxes to designers and researchers, it is impossible to clearly identify the underlying reasons for the slight differences in the tolerance analysis results between both approaches. However, some important benefits of the Skin Model Shape approach can be reported, though they come with increased computational efforts.

4. Conclusion and Outlook

Geometric variations management is a highly relevant issue for the design of functioning products at low manufacturing and inspection costs. In this context, particularly the tolerance analysis is a key activity which comprises the evaluation of the effects of geometric deviations on relevant key characteristics. In this paper, the standard tolerance analysis procedure based on a proprietary computer aided tolerancing tool has been compared to the tolerance analysis based on Skin Model Shapes, as a novel concept for CAT and geometric variations management. For this purpose, both approaches have been briefly introduced and applied to two case studies, where the first one aimed at highlighting the influence of geometric part deviations on multiple functional key characteristics and the second one considered the assembly sequence as another “design” parameter especially in the field of body construction, such as in automotive and aircraft industries. Based on a qualitative and quantitative comparison between these approaches, it can be found, that the tolerance analysis framework based on Skin Model Shapes overcomes major shortcomings of proprietary CAT tools, such as the limited conformance to GD&T standards, the lacking consideration of form deviations and the missing link to subsequent steps and activities of geometric variations management. However, additional efforts are required in order to develop a comprehensive CAT theory based on the Skin Model concept.

Future research in this field will focus on the consideration of further physical phenomena, such as friction and wear in the tolerance simulation models based on Skin Model Shapes, as well as on the processing of results obtained from computer-aided engineering applications, such as for manufacturing process simulations and structural reliability evaluation.

Acknowledgments

The authors gratefully acknowledge a mobility funding of the Bavarian Academic Center for France (BFHZ) under the reference number Az 15_13. The authors would also like to thank Beijing Municipal Education Commission (Build a Project) for its support.

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1st International Symposium on Robust Design
København, DK
14th-15th of August 2014

Design Guidance for Robust Design using Load-Strength and Design of Experiments

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Keywords: robust design, Load-Strength, design of Experiments (DOE), design guidelines

Abstract

The short product development cycle and the increased demand of robust, safe and reliable design has made the Test Analysis And Fix (TAAF) method obsolete. Closing the feedback loop on a design from field return (FRACAS) takes years. Closing the feedback loop from testing take months. Therefore a modern design has to build in robustness, safety and reliability during the design process. The paper describes how the Load-Strength theory and design of experiment (DOE) can be used to develop design guidance for a robust design. The influence of safety margin and loading roughness is described together with repeated loads. Real examples of design guidance for robust design are shown.

1. Introduction

Robustness is defined by IEEE as “the degree to which a system or component can function correctly in the presence of invalid input or stressful environmental conditions” (IEEE, 1991). The designer has to find a feasible design and optimize it within the constraints of specifications, environment conditions, costs and schedule. The system design will not be covered in this paper. After the system design a number of modules or assemblies will normally be defined. The detail design will then be made, designing modules by combining components and design details.

It will seldom be possible to optimize the system design or the detail design analytically for example by a response surface. Modern software allows response surface optimization for a larger number of parameters or constraints, but this will normally only allow a partial analysis. Therefore the designer has to use an iterative and heuristic design process. The robust design philosophy is concerned with taking into account variations in the manufacturing, environmental and usage conditions. For this there exist a number of methods. Some of these will be discussed in the following, and practical examples of their application are shown. The designer will normally have to apply and combine several methods for a given design task. This means that normally no single method will be enough to ensure a robust design for example used as a Key Performance Indicator (KPI) for the project.

2. Problem statement

A well known model for the design process is the V-model (Figure 1). The system specification is broken down into modules (assemblies) by interface specifications, which are again broken

DOI:10.4122/dtu:2085

Reviewed by: *Philipp Ziegler*
Tobias Eifler

Cited as: Valter L., 2014. Design Guidance for Robust Design using Load-Strength and Design of Experiments. In: Howard, T. J. and Eifler, T., ed. 2014. *Proceedings of the International Symposium on Robust Design - ISoRD14*. Copenhagen, Denmark. pp. 41-50.

down in component (design details) specifications. This consists of the left part of the V. On the right part of the V, the finished design is tested first on component/design detail level, followed by integration tests on module/assembly level before the final tests at system level.

3. Existing Approaches

Some 20 years ago the design philosophy in most companies was the Test Analyze And Fix (TAAF) method where the design was tested and after that the necessary few changes and improvements were made. To day this method is considered obsolete, since it takes too long time and with the high reliability and robustness requirement of to day's market it is not possible to verify the requirements by testing alone. Robustness and reliability have to designed into the product, not added in the test phase.

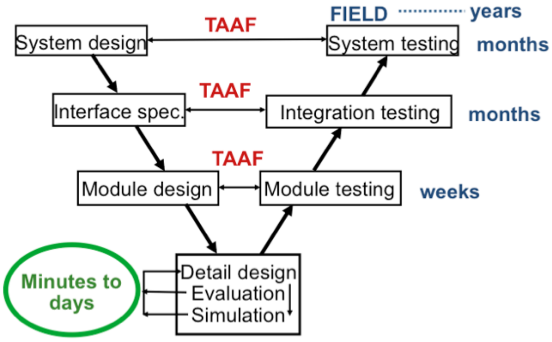


Figure 1. The V- model - Feed back delays

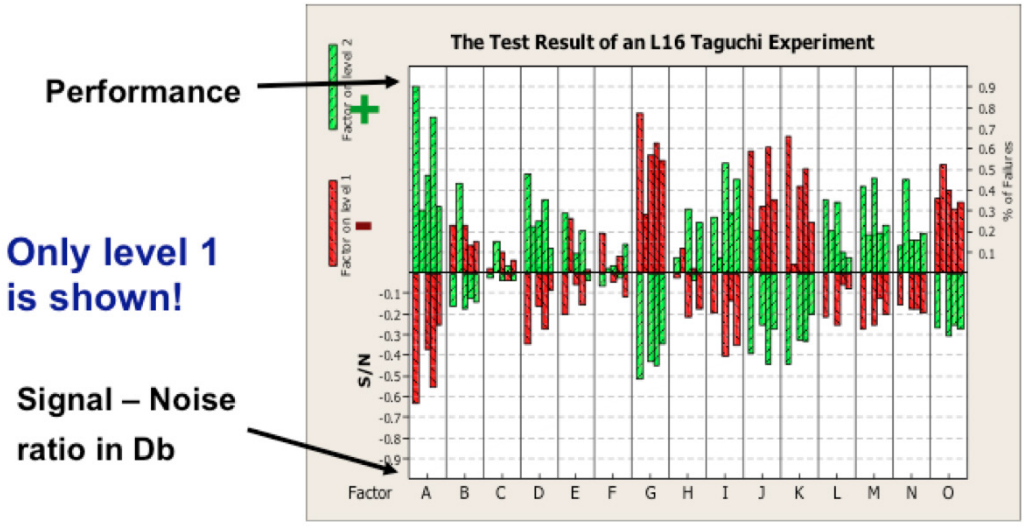
3. Proposed procedures

In an iterative and heuristic design process the designer need to have feed back on the performance of a proposed design. Therefore the time to close this feedback loop is critical. The feed back time from the field is typically years. The feed back time from system test, integration test and component test is typically months. Therefore it is not possible for the designer to make many design iterations. But at the bottom of the V, is the design process before any hardware is produced. It is proposed to make a large number of design iterations here. With a short feedback time more design iterations can be made, and the final design can be more robust and reliable. A number of methods are possible for this purpose (Arvidsson and Gremyr, 2008). These methods can often close the feed back loop in minutes to days. Examples are: Design review (IEC 61160), Failure Mode Effect Criticality Analysis (FMECA) (IEC 61160), Fault Tree Analysis (FTA) (IEC 61025), Design of Experiment (DOE) (IEC 60812), Finite Element Analysis (FEM), Tolerance Analysis (IEC 61160) and (Ebro, Howard and Rasmussen, 2012), Load-Strength analysis (Carter, 1972), Analysis of degree of freedom [9], interface analysis (Ebro, Howard and Rasmussen, 2012) and Monte-Carlo analysis (Dubi, 2000). Some of these methods will be discussed in the following. It is proposed that design guidelines are developed for critical design details, based on analysis, simulation and design of experiment (DOE). Practical examples of such guidelines will be described in the following.

4. Guidelines based on design of experiment (DOE)

Design of experiments was used to develop the design guidelines described in Clause 8. Most Design of Experiments requires hardware, but to day DOE is often used to reduce the number of simulations made (for example FEM simulations) (Jones and Johnson, 2009) Even if hardware is required DOE can be made on design details to save time and resources. For robustness the DOE is often combined with the Signal-Noise (S/N) philosophy of Taguchi (Phadke, 1989) and (Singh et al.) The Signal-Noise philosophy regards the parameters that the designer can change as the signal, and the parameters that the designer can not influence, for example environmental and usage parameters as noise. The concept S/N is well known from electronic design. If the signal noise ratio is high there is a strong signal relative to the noise. This means that the design is robust. If however there is a weak signal in a strong noise, the design is not robust. As in electronic design the S/N ratio is measured in dB. Based on a DOE the S/N ratio of different design options can be estimated, and the design with the largest S/N ratio can be chosen. The calculation of the S/N ratio depends on whether the required function has to be maximized (for example output), minimized (for example power consumption) or be close to nominal (for example precision). In the following an example shall be given of such a DOE.

The design was a product where 3 prototypes were finished. Testing had shown unsatisfactory performance. The project team could not agree on the reason. They listed 15 factors that may all influence the problem. It was decided to make a DOE to screen for the important factors. For screening purpose a DOE of a fractional design is often used. In this case a Taguchi L16 test plan was selected. It allowed 15 design factors to be varied, each on two levels. The test required 16 test items. By manufacturing some new parts, and change adjustments it was possible to modify the 3 prototypes to create 16 different test configurations. 3 parameters of performance for the product were recorded during the test. To verify the result the test was repeated with 2 of the performance parameters. In total 5 results for each test run. The test was performed during the weekend.


Performance

Only level 1 is shown!

Signal – Noise ratio in Db

Figure 2. DOE and S/N ratio used for robust design – Level 1 is A1, B1, C1,....,O1.

To report the results in a condensed format the 15 design factors were named A to O. For each the 5 performance results were plotted as 5 columns above the x-axis. Since the test was made with repetitions it was possible to compute the S/N ratio in dB. This was plotted as columns downwards from the x-axis. This means that the strongest design parameters are the highest columns upward from the x-axis, and the most robust design the largest columns below the x-axis. It could now be concluded that the strongest design parameters were A, G, I, J, K and O while C, E, F, H, M and N only had a weak influence on the performance. Fortunately the optimum combination was also the most robust, so no trade off was required. It was possible to define the optimum and most robust design combination as A2, G1, I2, J1, K1 and O1.

5. Guidelines based on tolerance analysis

A major factor in robust design is the variation of dimensions due to the manufacturing processes, as expressed by tolerances. There are different methods to optimize tolerance for example the Taguchi loss function (Phadke, 1989) that use DOE to find the optimum tolerances. Often several tolerances have to be combined to evaluate the influence on the function. This can be done using analytical methods as for example the square root of the sum of the standard deviations squared. For more complicated combination of tolerances, a Monte-Carlo simulation can be used.

To achieve a robust design the tolerances should be selected so they have the least influence on the output parameter as shown in Figure 3. The influence of dimension G on the output parameter. V(G) is shown as the slope of the straight line.

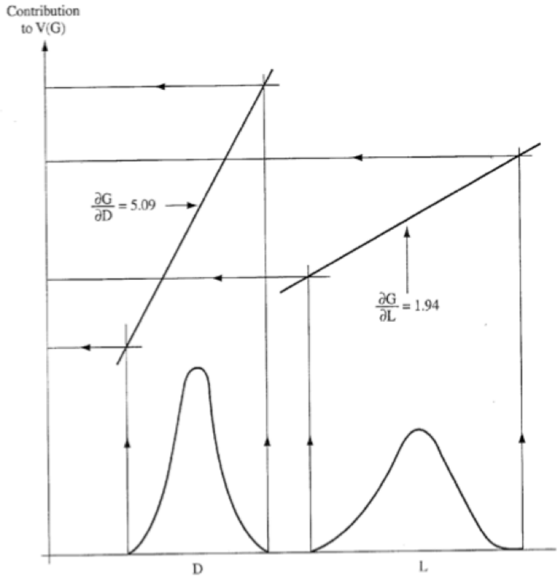
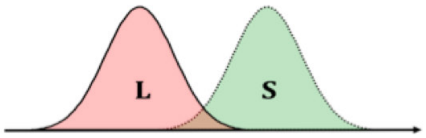


Figure 3. The sensitivity of the output parameter V(G) depending on the tolerances of G

A more general method is to compute the partial derivatives of the design function (Morrison, 2009). In this way it is possible to estimate the influence of each parameter on the output parameter. It is then possible to tighten the tolerances selectively on the dimensions that have the largest influence and relax the tolerances on the rest of the dimensions. This method was used in developing the design guidelines described in Clause 7.

6. Design guidelines based on Load-Strength

For mechanical failures the Load-Strength method was developed (Carter, 1972). The method has since been used also for electrical design. The idea is that the design will fail in the moment when the load (L) is larger than the strength (S). But the strength of the product is not one number, but a distribution due to variations in tolerances, material parameters and processing. Also the load can be modeled as a distribution. The load varies due to conditions of use and environments. It is now evident as shown on Figure 4 that the area of overlap between the two curves is proportional to the probability of failure. For the general case in Figure 4 the reliability (R) and the probability of failure (F) can be computed as a double integral as shown in Figure 4. Software programs like Weibull++ can solve this integral for Weibull distributed load and strength (L-S) curves. For description of the Weibull distribution see (IEC 61649). For power transistors $\beta=1.2$ and $\beta=1.8$ has been observed for the strength and $\beta=1.4$ and $\beta=3.1$ for the load.

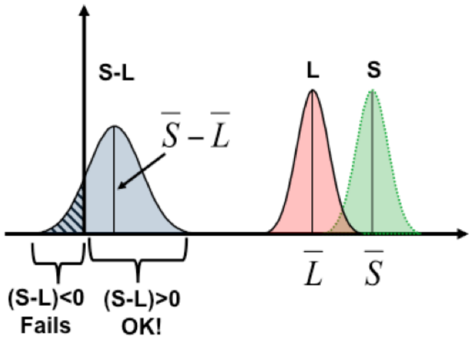


$$R = \int_0^{\infty} f_s(S)\left[\int_0^{S} f_L(L)dL\right]dS$$

$$R + F = 1$$

Figure 4. Load-Strength interference – the general case.

If both the load and the strength distributions are normal distributions (Gauss distributions) the computation is easier as shown in Figure 5.



Standard Dev. For S-L: $S_{S-L} = \sqrt{S_S^2 + S_L^2}$

Safety Margin:

$$SM = \frac{\bar{S} - \bar{L}}{\sqrt{S_S^2 + S_L^2}}$$

SM	Prob. of failure, F
2.326	10^{-2}
3.090	10^{-3}
3.719	10^{-4}
4.265	10^{-5}
4.753	10^{-6}

Figure 5. Load-Strength interference – Normal distributed Load and Strength

A.D.S.Carter (1972) developed the Load-Strength method to include fatigue. See also Keciceogolu (1972) and O'Connor (1995). Carter described two extreme cases of L-S curves based on two parameters Safety Margin (SM) (see Figure 5) and Loading roughness (LR) as shown on Figure 6. These two cases are discussed in (Loll, A).

$$LR = \frac{S_L}{\sqrt{S_S^2 + S_L^2}}$$

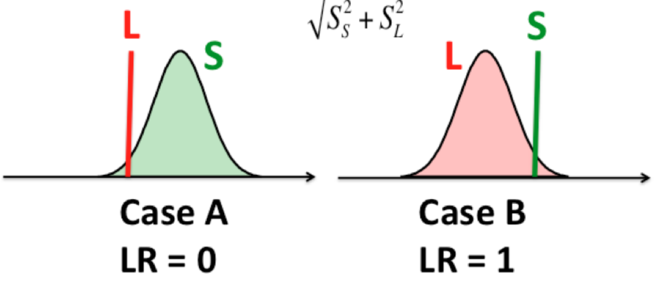


Figure 6. Carter Case A (often associated mechanics) and Case B (often associated with electronics).

A constant load have a loading roughness of zero (here called case A), while a design with constant strength have a loading roughness of 1 (here called case B). All real designs must be somewhere between case A and case B.

For repeated loads Case A has a constant reliability over time (wear and fatigue is not considered). For components connected in series (the system only function if all components function), the reliability of the system decreases rapidly with the number of components. For case B the reliability with repeated load decrease with the number of loads. But for case B it is possible to connect many components in series without decreasing the reliability. Carter performs a simulation of designs with different SM and LR together with different wear out function like corrosion and fatigue (Carter, 1972).

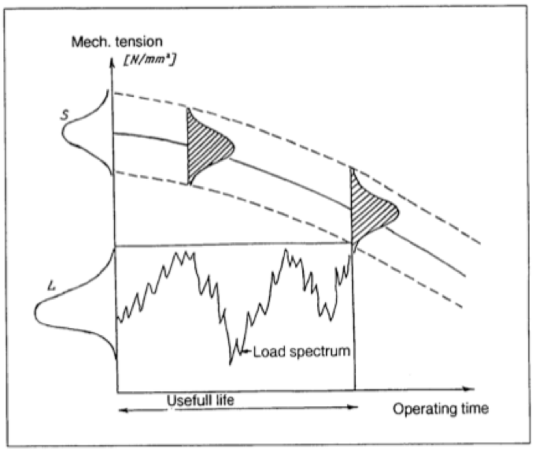


Figure 7. Design margin and degradation (damage accumulation)

A general design rule for Load-Strength is that there should be sufficient margin between the Load and the Strength distribution not only at zero operating time, but also by the end of the useful life, taking into account wear, corrosion and fatigue (see Figure 7). But the problem is how much margin is enough. The margins can be identified using the HALT test method (Otto, 2004) to identify the weakest part of the design and make them as strong as the rest of the design. The advantage of this is that it is not needed to increase the margin for the whole product, but only for those few components / design details (typically 2-3) that are weaker than the rest.

Carter [8] has developed a theory for selecting the necessary margin. The method is also described by O’Connor (1995). The failure rate is plotted on a logarithmic scale as function of the safety margin (SM) and loading roughness (LR)as shown on Figure 8.

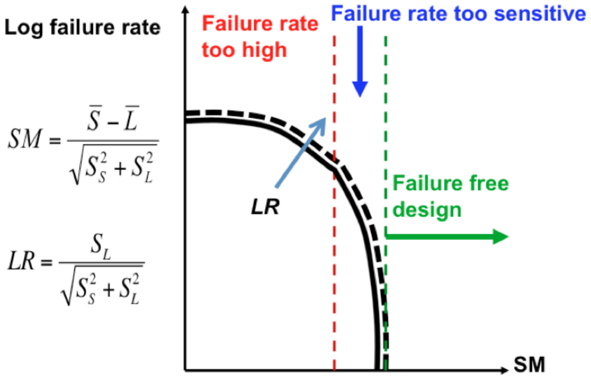


Figure 8. Failure rate as function of Safety Margin (SM) and Loading Roughness (LR)

It can be seen that the curve can be divided into 3 areas. For low SM the failure rate is too high. In the next area the design is not robust – the failure rate varies rapidly with the SM. In the area to the right however the failure rate is very low (the y-axis is logarithmic). To make a robust design the designer has to place the design just to the right of the curve. It is possible to draw several curves for different loading roughness (LR) as shown on Figure 8. O’Connor [15] also has curves for Weibull distributed L-S curves. The method is very promising, but more research is needed to make it practically applicable.

7. Design Guidelines for a mechanical mechanism using Load-Strength

The Load-Strength method can also be used to design moving mechanical mechanisms (Loll, B). Bang & Olufsen needed urgently to introduce a feature that would permit a turntable to automatically detect the diameter of the record and select the rotation speed accordingly. It was decided to use the weight of the record instead of the diameter. Different records have different weight, so the weight distribution of small records was measured. The spring that had to lift the record also had a force distribution. Further the switch that had to change the rotation speed added a friction with a distribution. That meant that three distributions had to taken into account for the design. The design was made by calculating the torque around the axis of the lifting mechanism taking into account the standard deviations of the distributions as described by Morrison (2009) (Figure 9).

To calculate the influence of the standard deviations the computation rules for combining uncertainties for sum as well as logarithmic design functions were used (Loll, B). The calculation showed a failure probability of 0.36%. The design was a success on the market.

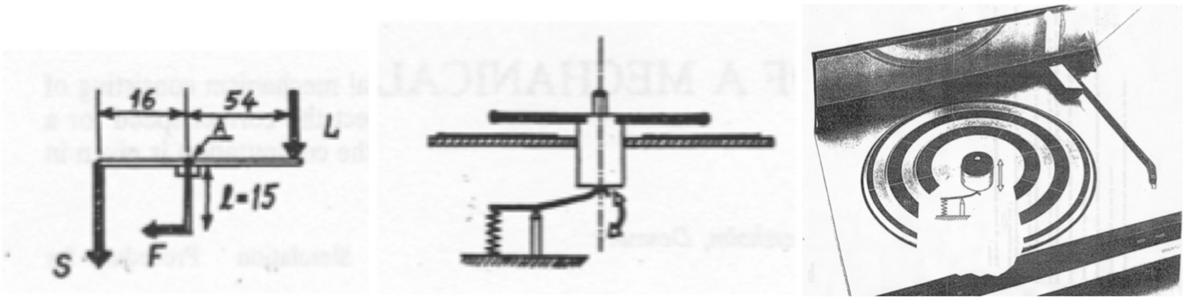


Figure 9. Load-Strength used to analyze a mechanical weighing mechanism.

8. Design Guidelines for screw towers using DOE

Bang & Olufsen had big problems with screw towers in plastic. The self threatening screws could sometimes not be screwed fully in during production. But in other cases the thread was destroyed so that the screw was loose. This caused it to fall out causing the printed wiring board (PWB) to be loose. Often the loose screw caused short circuit or other function failures. To solve the problem it was decided to make a DOE on test towers in cooperation with the screw manufacturer. Based on this DOE it was possible to set up design guidance for screw towers. The guidance was made as parameter design on a computer so that the designer could specify the dimensions and immediately have the correct drawing together with calculated screw torque and strength of the screw tower (Figure 10).

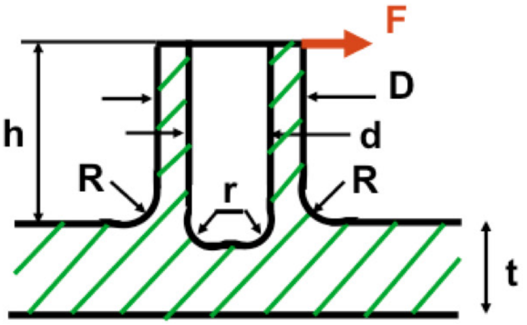


Figure 10. Design guidelines for a screw tower

9. Design Guidelines for a plastic snap lock using Finite Element simulation

Another problem for Bang & Olufsen was the plast snap lock for the remote controls. The snap lock kept the printed wiring board (PWB) in place, but it also had to take up the load when the customer pushed the buttons. The design is shown on Figure 11.

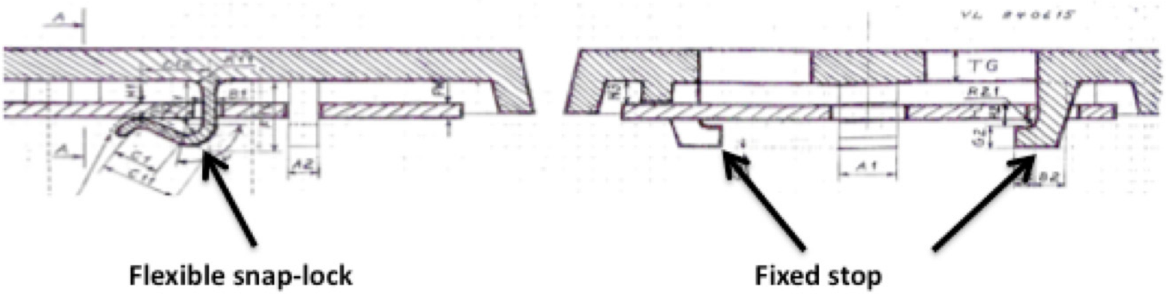


Figure 11. Design guidelines for a plast snap lock

The feed back from the market showed that the snap locks were breaking. The management ordered the snap locks to be strengthened, but this only made the problem worse. Finally it was realized that the tolerance of the PWB was ± 0.2 mm. So the snap lock should be made weaker and not stronger (stiffer).

The stress in the plast material was calculated using basic analytic equation (cantilever beam). Further the stress in the snap lock was calculated using a FEM program and finally the stress was measured using a stain gauge. It can be seen on Figure 12 that the results are very close. It is very important to verify simulations with measurements.

The calculation shown on Figure 12 show that within the constraints of the PWB thickness and tolerances and the fatigue limit of the plast material a robust design was not possible. It was therefore decided to divide the function into two different design features. One was flexible snap locks that should just keep the PWB in place. The other was ridgid supports that should take up the force when the customers pushed the buttons (see Figure 11).

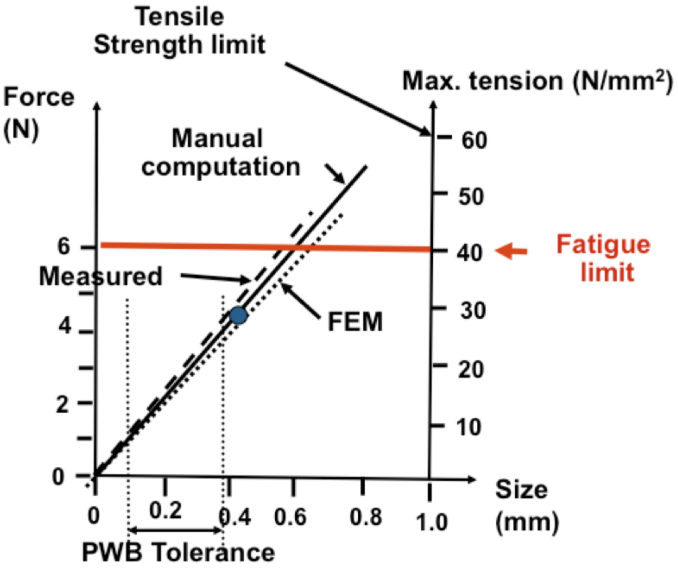


Figure 12. Stress, tolerances and fatigue limits for the snap lock

10. Design Guidelines for plastic moulding using Load-Strength

A major question from the designers at Bang and Olufsen was how much safety factor should be used when designing plastic parts. To give design guidance a number of simulations were made based on moulded test parts. Based on strength measurements and literature it was possible to give guidance for safety factors for different moulding conditions as described in (Loll, C).

11. Conclusion

Modern products require robustness and reliability to be designed into the product and not added by testing. Testing should only confirm the result of the design. Tolerances can be optimized using DOE and the Taguchi loss function or the partial derivatives of the design function. DOE can be used based on testing of design details, combined with the S/N ratio to optimize robustness. DOE with fractional design can also be used to reduce the number of FEM or Monte-Carlo simulations. Fractional design can further be used to identify the most important design parameters (screening test). It is proposed that the companies develop design guidance for the most important and critical design features in their products. Such design guidance will help the designer make more design iterations. A number of real examples of these methods were shown. Load-Strength analysis can be used to estimate the needed design margin for robustness of a static or moving design. More research is needed to make the method of robust design based on the SM and LR parameters applicable in industry.

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1st International Symposium on **Robust** Design
København, DK
14th-15th of August 2014

Robustness and Reliability of the GM Ignition Switch - A Forensic Engineering Case

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Keywords: Root Cause Analysis, Failure Diagnosis, Tolerance analysis, Robust Design

Abstract

This paper details forensic engineering from the perspectives of Robust Design and Reliability Engineering to review one of the most infamous recalls in automotive history, that of the GM ignition switch. The design, engineering and management failures in this case ultimately resulted in a fine of $35 million, the recall of 2.6 million vehicles and the death of at least 13 people. In a systematic approach, methods such as sensitivity analysis, tolerance stack-ups, design clarity, etc., are used to analyse the ignition switch itself and to extend the usual consideration of reliability issues to the impact of variation on the design. In addition to this quantitative analysis, the legal case files have been examined revealing multiple misjudgments and errors throughout the product development process. The analysis revealed a lack of overview regarding to interrelated functionality, a lack of respect for the requirement specification and clarity in the specification itself, and finally a culture of silence rather than confrontation and remedy.

1. Introduction

The influence of engineering design decisions on the resulting product quality is indisputable. Consequently, a large number of quality methods, aiming at the assurance of functionality and the reduction of quality costs, exist. Examples are approaches such as Robust Design, Reliability analysis and Design for Six Sigma, supporting the choice of promising product solutions during the early design phases (Eifler et al. 2013). At the same time, different challenges for the application of corresponding methods exist (Krogstie et al. 2014) and the availability of quality approaches seems to be contradicted by a large number of major recalls, recently launched by big automotive OEMs. Nothing appears to have changed since Hales (2003) stated that neither basic design principles, nor corresponding methods are fully understood, accepted or used in industrial development projects.

To provide deeper insight into the causes for corresponding quality issues as well as product failures, this paper describes a forensic engineering case study of the recent and major GM ignition switch recall. Current practices of forensic engineering that appear to rely mostly on expert knowledge and experimental approaches are thereby extended by methodical reasoning, i. e. available design models and methods. In addition, the whole case is examined in terms of design activities and decisions leading up to the recall.

DOI:10.4122/dtu:2086

Cited as followed: Eifler, T., Olesen, J. L. and Howard, T. J., 2014. Robustness and Reliability of the GM Ignition Switch - A Forensic Engineering Case. In: Howard, T. J. and Eifler, T., ed. 2014. *Proceedings of the International Symposium on Robust Design - ISoRD14*. Copenhagen, Denmark. pp. 51-58.

1.1 Example System: GM ignition switch

The starting point for a forensic analysis of the GM ignition switch was the different headlines and news articles published by international media in the first half of 2014. Severe accidents had shown that the switch can unintentionally shut off the engine during use, also affecting airbag inflation, power steering and power brake systems. The information available indicates that the unintentional shutdown of the engine and related accessories is caused by shock loads from rough road surfaces, the driver's knee or the weight of the key chain which can knock the key out of the run position (Rogers 2014; Picchi 2014).

Following the available information, the forensic analysis of the recent recalls concentrates on the ignition switch shown in Figure 1 a). As part of the car's steering column, it is connected to the steering wheel lock, the ignition lock cylinder and consequently to the key, see Figure 1 b). The main purpose of the ignition switch is to convert the rotational movement of the key into a signal, which is sent to the Body Control Module defining the actual mode of car.

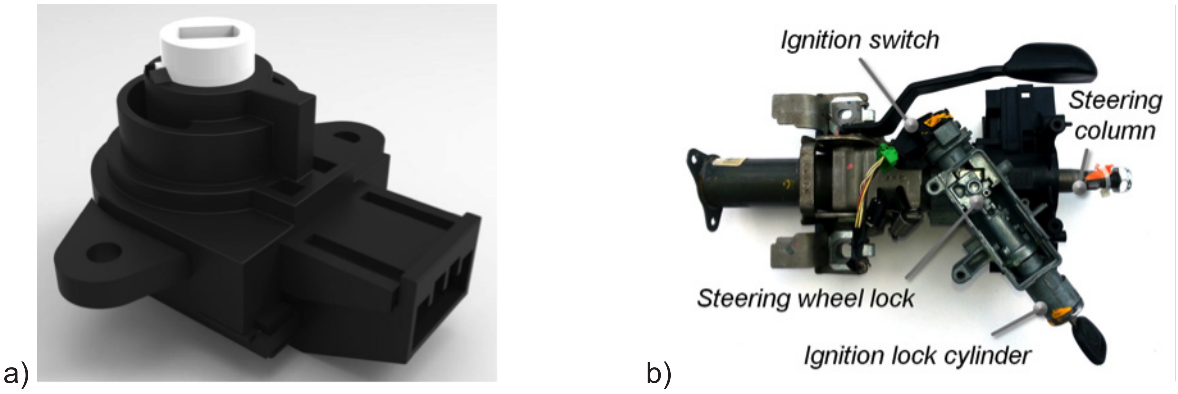

Figure 1. Example System a) Ignition Switch in b) the car's steering column

A closer look to the inside components reveals the switch's basic functionality. A movement of the key leads to a rotation of the switch plate, and thus to a change of the contact points between pins and circuit board, see Figure 2 a). While starting the car, the driver turns the switch plate to its end position "*crank*" allowing it then to rotate backwards. The steady modes of the car, "*run*" as well as "*accessories*", are defined by notches or "detents" in the switch plate. A plunger is forced into these detents by a spring, locking the mechanism, see Figure 2 b).

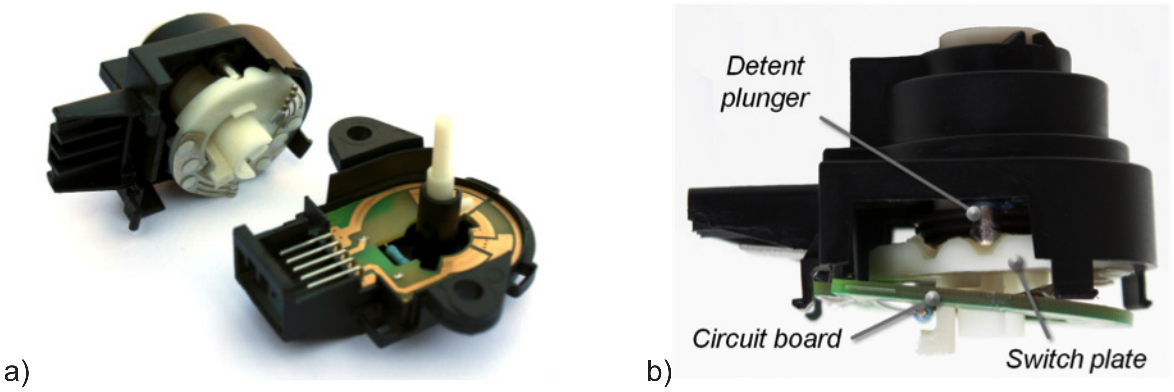

Figure 2. Product structure of a) rotating components and b) locking mechanism in the ignition switch

1.2 Forensic Engineering and related approaches

The term *Forensic Engineering* usually refers to engineers engaged in case of a threat of litigation. As expert witnesses they are investigating causes as well as the responsibility for product failures that had led to bodily injury and/or economic loss and consequently to judicial proceedings (Carper 2001). Moreover, literature emphasises the relevance of an analysis and a deeper understanding of malfunctioning products, defective buildings, etc. as information source for future projects (Carper 2001; Samuel 2007; Hales 2005). An aspect also commonly mentioned in basic literature on *Root Cause Analysis* or *Failure Diagnosis* (Andersen and Fagerhaug 2006, Carlson and Söderberg 2003). However, whereas available *Forensic Engineering* approaches are frequently reduced to experiential reasoning as well as an experimental analysis of the use conditions and the use procedure of the operator, suggested procedures for a Root Cause Analysis often focus on organisational drawbacks or business process issues (Andersen and Fagerhaug 2006).

Suggesting the technically oriented term Forensic Analysis, this paper therefore offers a far-reaching extension to the analysing procedures available. Based on methodical reasoning, the analysis of the GM ignition switch is carried out from a Robust Design/Reliability perspective[1]. It has to be noted though that in contrast to a search for solutions, the proposed approach focuses solely on the analysis of an existing product. As already pointed out in Eifler (2014) the complexity of the product under investigation is specifically reduced by means of suitable product and/or process descriptions offering insight into relevant characteristics and noise factors.

2. Forensic analysis of the GM ignition switch – a technical perspective

The analysis of the GM ignition switch is structured into five subsequent steps. First of all, failure modes of the switch, potentially leading to accidents, are identified based on the available information. Afterwards, the qualitative description is concretised by a first rough mathematical description of the failure mechanism, i. e. the governing equation. An analysis of the device at the system level, e.g. the consideration of relevant product characteristics in a linear tolerance chain or the detailed investigation of possible variation at part interfaces, is then extended to the description of unforeseen noise factors in a P-Diagram. Concluding, the importance of different influencing factors is evaluated in a sensitivity analysis.

2.1 Identification of potential failure modes

Approaches to support the identification and prioritisation of potential failure modes in a (complex) product system are usually largely qualitative. By means of an Failure Mode and Effects Analysis (FMEA), a Failure Tree Analysis (FTA), Flow charts, etc. (Eifler et al. 2013, Andersen and Fagerhaug 2006), the product is structured into different parts or its functions/sub-functions and potential failures are assessed. However, in the case of the GM recall, the information available already allows for an identification of the ignition switch's locking mechanism as one of the most relevant aspects of the overall system. In contrast to starting problems reported early in the switch's life cycle[2], a malfunction of the locking mechanism could lead to an abrupt change of the car mode and thus to severe safety issues.

2.2 Governing equation – Screening of relevant influences

As already seen in Figure 2, the rotating switch plate which defines the contact points to the circuit board is locked by means of a detent plunger. Forced into notches by the compression of an additional spiral spring, the plunger holds the switch plate in place and defines the steady power modes of the vehicle, i. e. "*run*" and "*accessories*". The switch's basic functionality can consequently be described by Coulomb's law of friction, see Figure 3 a). If the applied horizontal force exceeds the force at the contact surface, the locking mechanism fails and switch plate as well as key are knocked out of position.

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[1] Ebro et al. (2012) and Eifler et al. (2013) summarise Robust Design or Reliability Engineering methods.

[2] Customer Complaints and warranty claims regarding starting problems of cars could be traced back to the ignition switch in an intensive investigation shortly after it was firstly used in the GM Ion production in 2002. Especially in cold ambient conditions, the behaviour of the used grease affected the connection between contact pins on the switch plate and the circuit board (Committee of Energy & Commerce 2014).

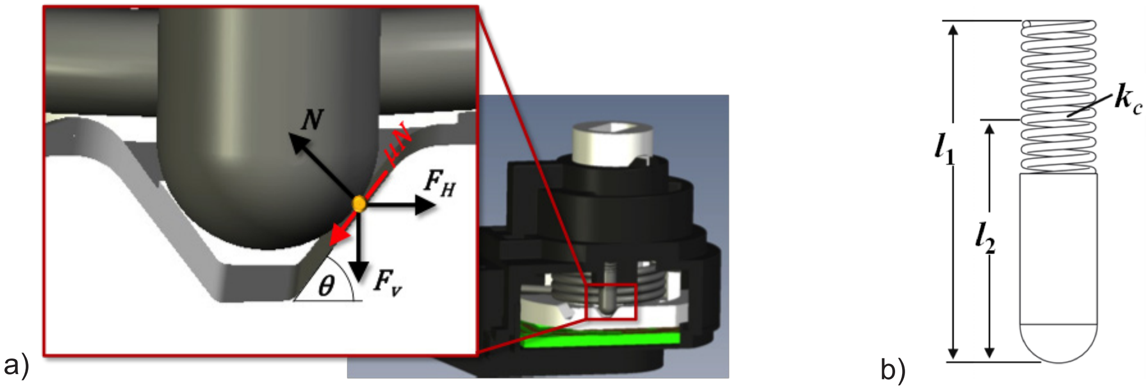
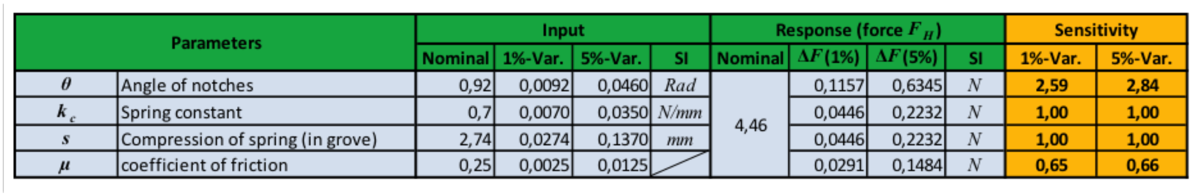


Figure 3. Simplified description of the switch's basic mechanical concept

A simplified mathematical description of the switch's basic mechanical concept allows for the first rough assessment of potential root causes for product failures by means of a quantitative analysis. Neglecting potential self locking effects between plunger and switch plate, the different parameters affecting the locking mechanism are summarised in equation 1.

$$F > F_H = F_v \frac{\tan\theta + \mu}{1 - \mu \cdot \tan\theta} \tag{1}$$

The generated holding force F_H is affected by the force of the plunger in vertical direction, the angle of the notches θ and the surface roughness μ. Extended by a decomposition of the plunger force F_v into the characteristics of the spiral spring utilised, i. e. the spring constant k_c as well as its compression $s = l_1 - l_2$ shown in Figure 3 b), the impact of potential deviations from a specified nominal value can be calculated. However, as any information about the ingoing variation is more an assumption than actual knowledge at such an early stage of the analysis, the calculation is reduced to a first estimate of the basic sensitivity. This change of the response value F_H due to a percentage change of the different input factors is summarised in Figure 4.



Parameters		Input				Response (force F_H)				Sensitivity	
		Nominal	1%-Var.	5%-Var.	SI	Nominal	ΔF(1%)	ΔF(5%)	SI	1%-Var.	5%-Var.
θ	Angle of notches	0,92	0,0092	0,0460	*Rad*	4,46	0,1157	0,6345	*N*	**2,59**	**2,84**
k_c	Spring constant	0,7	0,0070	0,0350	*N/mm*		0,0446	0,2232	*N*	**1,00**	**1,00**
s	Compression of spring (in grove)	2,74	0,0274	0,1370	*mm*		0,0446	0,2232	*N*	**1,00**	**1,00**
μ	coefficient of friction	0,25	0,0025	0,0125			0,0291	0,1484	*N*	**0,65**	**0,66**

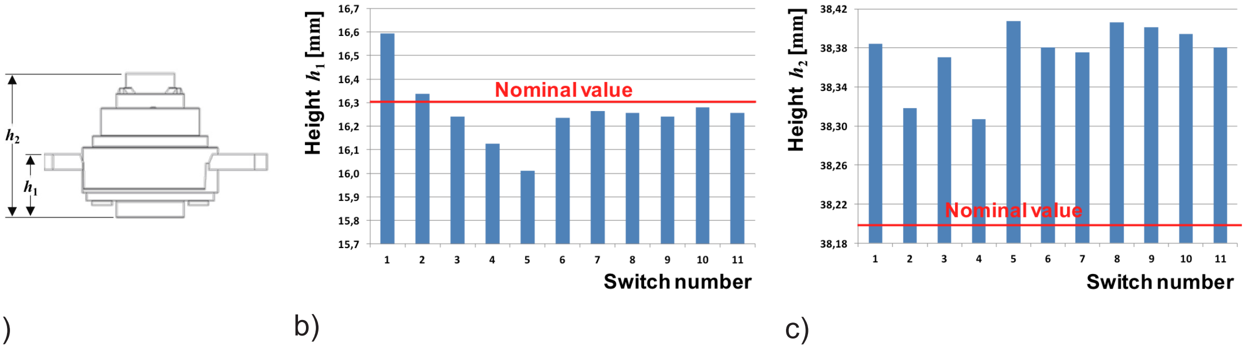
Figure 4. Simplified description of the switch's basic mechanical concept

By the calculation of sensitivity indices the relevance of geometric variation becomes apparent. An example is a potentially varying compression of the spring, where a one percent change of the length Δs leads to a corresponding change of the resulting force ΔF_H. The same holds true for the spring characteristic which is, next to the material properties, also defined by its' geometry. Of particular importance seem to be the geometry of the notches. As indicated in Figure 4 by the sensitivity values for a one as well as a five percent change, an angle variation $\Delta\theta$ significantly increases the resulting variation of the holding force and moreover does not show a linear behaviour. The wider the range of the ingoing variation is, the more sensitive the locking mechanism reacts. In contrast, the impact of a varying surface roughness $\Delta\mu$, seems to be negligible and is in case of a potential contact to both sides of the notch even reduced further due to self-locking effects.

2.3 System modelling – Analysis of dimensional and geometric variations

Sensitivity calculations by means of the governing equation allow for a first prioritisation of potentially varying influences. However, the result of this largely simplified analysis must on the one hand be verified, ideally by measurements of physical samples. On the other hand, a further decomposition of single influences is necessary. Especially in case of (complex) product systems, a large number of parts and their interactions need to be examined.

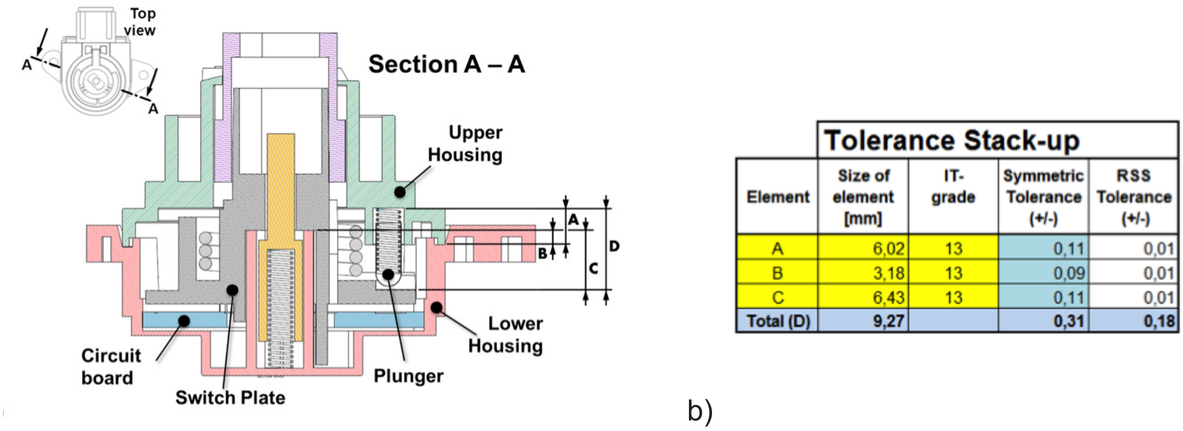
In the forensic analysis of the ignition switch, two easy to measure dimensions were chosen for verification purposes. For ten samples, measurements of a single component as well the assembled device, i. e. the height of the lower housing h_1 and the overall height h_2, were taken, see Figure 5 a). A comparison with the specified nominal value[3] thereby supports the assumption that geometric variations might be the root cause for the occurred product failures. Although dimensions of single components often seem to be under their specification level, the measured height of the assembled device persistently exceeds the specified nominal value as shown in Figure 5 b) and c).



a) b) c)

Figure 5. Measurement of a) physical samples and comparison of the b) component or b) device dimensions to specified nominal values

Accordingly, an in-depth analysis of geometric variations at the systems level needs to be performed following the measurement of physical samples. The first step is the calculation of a linear tolerance chain in axial direction since the displacement of the switch plate is very much dependent on the varying compression of the used spring. Relevant components and interfaces are shown by a cross section in Figure 6 a) including the rotating parts as well as the plunger.



Tolerance Stack-up				
Element	Size of element [mm]	IT-grade	Symmetric Tolerance (+/-)	RSS Tolerance (+/-)
A	6,02	13	0,11	0,01
B	3,18	13	0,09	0,01
C	6,43	13	0,11	0,01
Total (D)	9,27		0,31	0,18

a) b)

Figure 6. Linear tolerance chain in a) a cross section and b) the quantitative analysis

Based on the assumption of an IT-grade 13 for all dimensions (A, B, C)[4], a tolerance stack up calculation allows for a prediction of potential extreme cases, i. e. a maximum/minimum deviation of the distance between upper housing and switch plate (D) of **± 0,31 mm**. The results, shown in Figure 6 b), lead to a symmetric interval for the variation of the holding force **$\Delta F_H = \pm 0,51$ N**, i. e. a deviation of 11% from the nominal value provided that the other parameters in equation (1) remain constant.

However, although dimensional tolerance stack-up calculations are widely used and offer an initial overview about part interactions at the systems level, they can be highly misleading. Essential

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[3] Whereas the dimensions of the ignition switch were identified in a Reverse Engineering approach, i. e. based on measurements of physical samples, additional documents on nominal values as well as potential shortcomings during the development or the approval process are accessible as part of an official congressional hearing, see for example Committee of Energy & Commerce (2014).

[4] The assumption is based on the ISO code system for tolerances on linear sizes (ISO 286-2 2010).

aspects of the occurring variation as well as potential drawbacks of the design are for example completely neglected. Firstly, the analysis is therefore usually extended to a calculation of the Root Square Sum (RSS), also shown in Figure 6 b), assuming that most of the components fall to the mid of the specified value range rather than in its' extreme ends. Secondly, and particularly important from a Robust Design perspective, a consideration of geometric tolerances is necessary as the functional relevance of variation largely depends on the geometry of interfaces/active surfaces rather than on single dimensions.

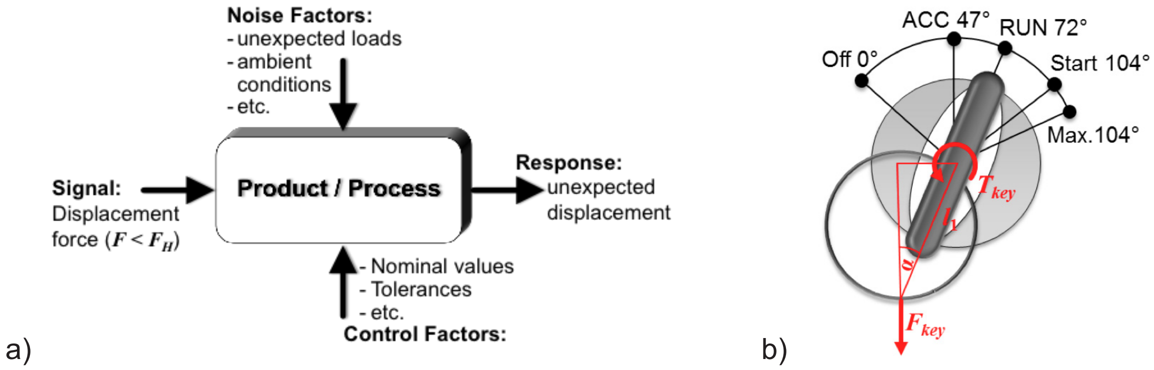
For simplification purposes and because basic Robust Design Principles seem to have been ignored in case of the ignition switch, this paper refers to the Design Clarity approach elaborated by Ebro et al. (2012) instead of to a full calculation of geometric tolerances. Accordingly, robustness issues of the switch's design can be attributed to the large contact surfaces between parts, e. g. between upper and lower housing or between housing and switch plate as illustrated in Figure 7 a) and b). These consequently ambiguous interfaces lead to a product which is highly sensitive to geometric variations and thus might affect the overall functionality of the ignition switch.


a) b)

Figure 7. Large contact surfaces between b) upper and lower housing, b) housing and rotating switch plate

2.4 P-Diagram – Identification of unexpected influences during use

Next to an analysis of the design itself as well as of the potential geometric variation due to manufacturing inaccuracies, a comprehensive forensic analysis also requires a deeper understanding of interdependencies between the product and the varying use conditions. Using a basic tool from Robust Design approaches potentially varying influencing factors are thus identified and visualised by means of a P-diagram, see Figure 8 a). Based on the consideration of the switch's functionality in section 2.2 that has shown a direct connection between the locking mechanism and the key movement, the analysis focusses on loads applied unexpectedly during use. An unintentional contact with the driver might for example increase the probability that the key is knocked out of position. Another possibility is an additional torque which results from an excessive weight of the key chain F_{key} and is at the same time influenced by the geometry key ring as well as of the key itself, i. e. the opening for the key ring, as shown by the resulting length l_1 in Figure 8 b).



a) b)

Figure 8. Analysis of unexpected influences a) using the P-diagram and b) calculation of unexpected loads at the key ring

2.5 Sampling based analysis of the GM ignition switch

The forensic analysis of the ignition switch suggests that the basic failure mode is purely mechanical. If the key torque T_{key}, or respectively the corresponding force F applied to the locking mechanism, exceeds the varying holding force F_H, the key is knocked out of position. The analysis of the governing equation (1) can thus be easily extended to a simplified, sampling based, robustness orientated analysis of the ignition switch in varying use conditions. Taking into account the relevance of different surface geometries, the varying force limits which would lead to a sudden and unintended change of the vehicle's power mode are calculated. In addition to extended information about geometric variation, i. e. the achievable flatness of large surfaces[5], extreme cases for the position of the key chain are considered leading to an average force limit of $F = 6{,}63\ N$ and a corresponding standard deviation of $\sigma = 0{,}41\ N$ in a worst case scenario, see Figure 9 a). Instead of the expected reliability, the transmitted variation is calculated afterwards. The results in Figure 9 b) indicate that two main drivers are decisive for an analysis of the occurring variation from a Robust Design perspective. In the first place, the ignition switch is highly sensitive to a variation of the spring compression s, i. e. of the dimensions and geometries. Moreover, potential forces during use, e. g. the variation of the key chain position l_1 need to be analysed further.

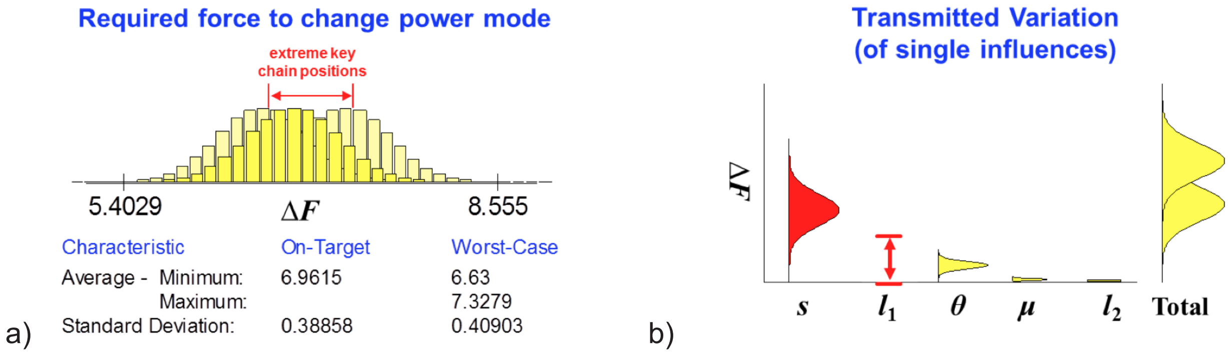


Figure 9. Identification of a) force limits and b) the transmitted variation

4. Conclusion

A large number of major recalls, recently launched by big automotive OEMs, suggest that basic design principles as well as available design methods and tools, specifically aiming at an increased product quality, are neither used nor fully understood in industrial practice. This paper, therefore, offers an overview about one of the most infamous recalls in automotive history, that of the GM ignition switch. The proposed, far reaching extension of usual Forensic Engineering and Root Cause Analysis practices by available design approaches offers a comprehensive overview about relevant design-, production- as well as use-related influences potentially leading to product failures.

The performed case study shows that especially the application of Robust Design methods and tools, such as Design Clarity, P-Diagrams, sensitivity studies, etc., in extension to basic reliability techniques allows for deeper insight into the switch's functionality and the impact of variation. It seems as if the case files regarding the recall tend to ignore that fact that the switch had large variations in performance (indicating a lack of robustness) and instead focused purely on the analysis of the "nominal design". Moreover, when deconstructing the whole case in terms of the design activities and decisions leading up to the recall, it becomes evident where current reliability engineering techniques are failing to be deployed or not solving the reliability issues faced and is dealt with in more detail in forthcoming publications.

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[5] In addition to the general dimensional tolerance windows of the ISO 286-2 (2010) standard, guidelines of the American society of the plastic industry are used (SPI 1998). For further information on dimensions of the switch and the performed analysis see also the downloads on www.RobustDesign.org/ISoRD

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Computer Aided Robust Design Session

Keynote: Rapid results with robust design

Robust design that is insensitive to component variation is of course vital for minimizing product quality issues and ensuring low cost.

However obtaining robust design requires the capability to evaluate the design robustness and eventually optimize it – and many producers find it difficult to “get started” – especially in a way, where results can be demonstrated fast.

It is our experience, that a good way to get started is to involve the right people from Marketing, R&D, production and QA/QC, and train dedicated people in the use of “easy to access” software such as Vartran for finding optimal targets (minimizing the effect of component variation on product functionality), and excel for tolerance analysis. This allows for a fast start where the tolerance analysis may be adapted to the special needs of the producer to ensure the most reliable results.

Torben Bygvraa Rasmussen
Senior Consultant
NNE Pharmaplan

The Session

The session on Computer Aided Robust Design (CARD) was designed to bring software vendors, practitioners from industry and academics together. The goal is to stimulate a fruitful dialog and discussion on the current capabilities of Computer Aided Robust Design and future challenges and requirements. To cover a wide range of different applications of CARD software, four vendors with different foci have been invited to demonstrate their software packages covering Tolerance Management, GD&T, Robustness Optimization and Reliability calculations. Latest software updates and features will be presented and demonstrated. Industry representatives and academics will then have the chance to ask questions and share their own view points, needs and challenges.

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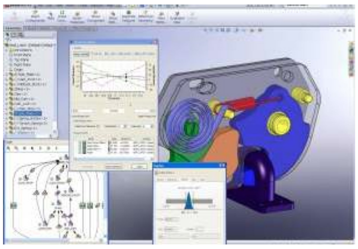

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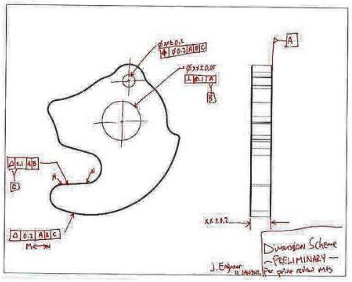

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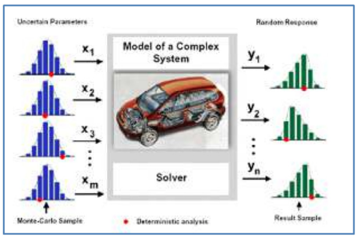

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Validation of Customer Requirements by System Simulation Taking Tolerances and System Variations into Account

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Keywords: tolerance, computer aided tolerancing, robust design, simulation

Abstract

The aim of the following contribution is to introduce an integrated process which allows the implementation of factors that have a significant impact on the limiting positions. These limiting positions and their effects on geometric deviations and displacements need to be investigated in order to ensure that functional aspects of an assembly are fulfilled for large quantities.

The presented approach involves the finding of these limiting positions using statistical methods and state-of-the-art tools as well as the simulation of the flexible and compliant components. It will be illustrated in connection with the environment of a modern vehicle entry. A simplified section of the geometry is used to explain the planned procedure.

The proposed process is divided into three major steps. The first step includes the implementation of a rigid tolerance simulation, which delivers information about probability distributions in order to determine the limiting positions. Second, a finite element analysis (FEA) of the door sealing system under geometric deviations in accordance to the results of the 3DCS simulation (state-of-the-art tolerance analysis tool implemented in CATIA V5) is performed. Third, a FEA of the door and the side frame, providing corresponding deformation data, leads to the limiting positions with regard to the elastic system behaviour.

Finally, this process enables the user to evaluate the system behaviour of a door assembly with respect to the limiting positions in more detail.

1. Introduction

From a company's point of view it is important to ensure that functional, as well as visual requirements of a product are fulfilled in series production. It is important to ensure that customer requirements are met for large quantities. Tolerance management and robust design methodologies are useful tools to grant this.

In the following piece of work an automotive door assembly will be examined. The focus of all activities will be on customer-relevant functional aspects. From the customer's perspec-

DOI:10.4122/dtu:2093

Reviewed by: *Stephan Husung*
Thomas J. Howard

Cited af follows: Ehlert, M., Stockinger, A. and Wartzack, S., 2014. Validation of Costumer Requirements by System Simulation Taking Tolerances and System Variations into Account. In: Howard, T. J. and Eifler, T., ed. 2014. *Proceedings of the International Symposium on Robust Design - ISoRD14*. Copenhagen, Denmark. pp. 61-68.

tive, one of the most relevant attributes is tightness. In order to build a proper design, it is the aim to make sure that the observed system guarantees tightness against the permeation of dust or humidity such as rain and condensation. Similar to aspects like the handling comfort, opening forces, aerodynamics, etc., the sealing system is affected by the limiting positions of the observed assembly. These limiting positions are mainly influenced by functional relevant components, which themselves have nominal dimensions on the one hand and corresponding geometric deviations on the other. In particular, the main components that belong to this assembly are the side frame, the door sealing system and the door inner panel (body in white, see Figure 1).

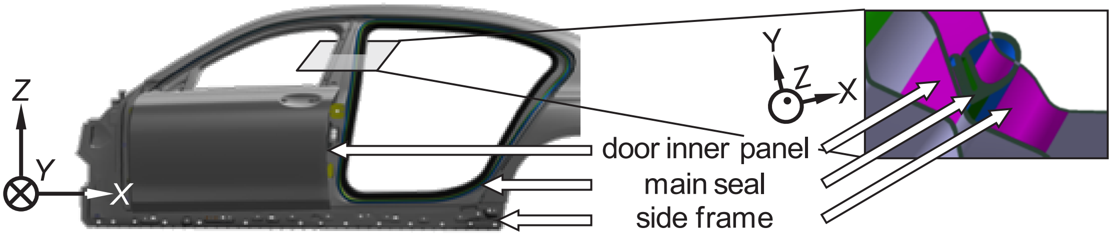

Figure 1. Schematic of the contributors belonging to the assembly

In the assembly process it becomes clear that all statistical deviations belonging to these single contributors will be chained together. This combination leads to the limiting positions in the end and in general can be seen as the largest deviations from the nominal dimensions that can occur (Kapici et al, 2013).

These limiting positions are of crucial importance for the functional, as well as robust construction and the corresponding validation. They can appear as a result of the production process, purchased parts, the assembly process and the system behaviour. Optionally, they should be located within the tolerance specifications (requirements set by the designer), which is not always the case at present.

The question therefore, is how to ensure these functional criteria of a product at an early stage if there is no hardware available. The use of stochastic simulations, in particular tolerance analysis, is considered a suitable approach.

The objective of this contribution therefore, is to introduce an integrated process which allows to take into account all deviations that have a significant impact on the limiting positions. These are geometric deviations as well as reaction forces which result in geometric deformations and displacements. This specifically developed methodology will be examined due to the fact that there is no other available.

First a determination of the limiting positions by using a rigid tolerance simulation is presented. It is used as a reference result. It will be used to show the advantages of taking into account the system behaviour (geometric deviations and displacements). Afterwards the sealing system will be investigated under geometric deviations. As a result both of the rigid tolerance simulation and the elastic behaviour of the sealing system the determination of the limiting positions is performed and outlined.

2. Determination of the limiting positions by using a rigid tolerance simulation

As previously stated, the process of developing the limiting positions (rigid) of the considered automotive door assembly is the first part. In this case, it consists of the side frame, the sealing system and the door inner panel (see Figure 1). Therefore, a CAD data set containing the geometry data, as well as deviation information from all contributors, needs to be available. Once all of the information is received, the rigid tolerance simulation can be performed using the state-of-the-art tolerance analysis tool 3DCS Analyst (3DCS). The latter is integrated into CATIA V5 as chargeable application. In the following a step-by-step guide is introduced to achieve these rigid limiting positions.

Step one, the mounting process needs to be implemented. Within this step, all parts involved in the process will be determined. Additionally, their mounting sequence and their adjustment concept are of great importance and need to be considered in order to reduce their six degrees of freedom. In Figure 2 a suitable approach is outlined regarding the mounting process. In this step, the mounting sequence is separated into two main parts:

- Figure 2 i) Positioning of the door inner panel on the workpiece carrier with regard to the alignment concept.
- Figure 2 ii) & iii) Positioning of the workpiece carrier along the side frame using adjustment points on the side frame.
- Note: The alignment concept is represented using circles that include respective axis directions showing the way one part is oriented on the other one.

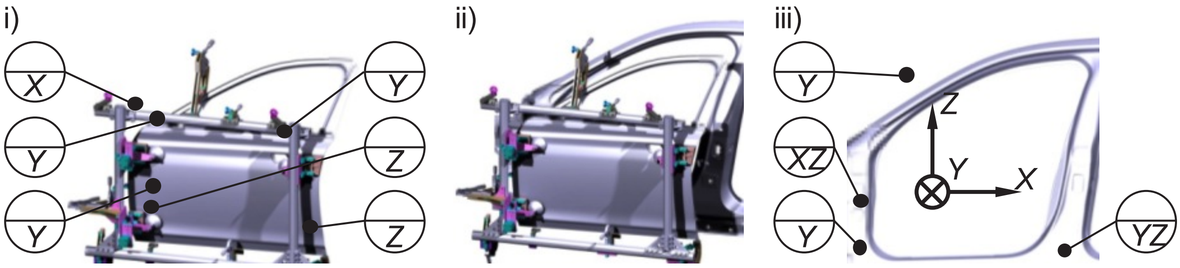

Figure 2. Illustration of one valid mounting sequence: i) Application of the door inner panel on the workpiece carrier ii) & iii) Positioning of the workpiece carrier along the side frame (Epple, 2013)

Input: single parts, workpiece carrier and mounting sequence
Output: the mounting process of the assembly is mapped virtually

The second step deals with the insertation of permissible dimensional deviations. These are integrated in the simulation via component tolerances as well as mounting tolerances.

Input: permissible dimensional deviation
Output: in addition, the simulation contains component tolerances and mounting tolerances

The positions of the measurement points are set in **the third step**. For the present case, this means that there are five positions determined empirically (X1Y1, X2Y3, X3Y4, Y2Z1, Y5Z2), each containing two measurements of key product characteristics (KPCs) in X and Y direction or in Y and Z direction. These KPCs are critical design features that monitor the relative position between several components in order to improve product quality (Ceglarek et al, 2004). As can be seen from Figure 3, there are three measurements having their largest part in X direction. Furthermore, one can recognize that there are five measurements in Y direction and two measurements in Z direction. In this case, and in order to capture door-sided tilting, two measurements are performed along the B-pillar.

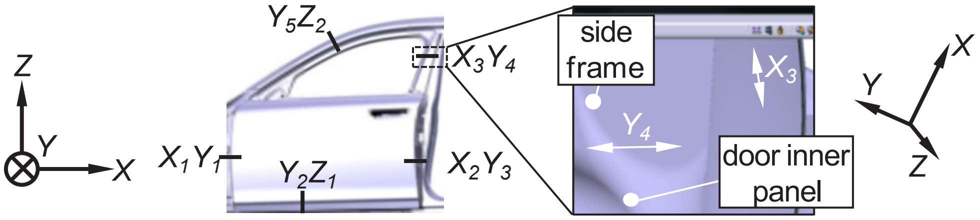

Figure 3. Illustration of the coordinate plane and measurement points between side frame and door inner panel (Epple, 2013)

Input: (empirical) knowledge
Output: the positions of the measurement points are set

In **step four**, the actual CATIA 3DCS simulation is carried out with the goal of building a virtual tolerance model. Dimensional deviations that have been defined up to this point will now be varied within their respective tolerance range. These variations will be carried out by the use of the Monte-Carlo-method that generates uniformly distributed random numbers, which themselves, will be transformed into predefined distributions. (Rubinstein, 1981, VDI, 1999) The virtual assembly follows as soon as all of the various deviations are charged with random numbers arising from these distributions. In the next step, the key product characteristics (KPC) are measured and stored. This step is repeated until the required sample size is reached. Thus, every measurement at every examined position contains just as much related key product characteristics.

Input: dimensional deviations are getting varied within their respective tolerance range in order to build a virtual tolerance model using CATIA 3DCS
Output: deviations (statistical information about local key product characteristics) at the measurement point

In **the fifth step**, the registered data is statistically evaluated in order to be able to determine the rigid limiting positions. That evaluation can be performed using both CATIA 3DCS and other software solutions. As previously specified, as a result of these examinations, the limiting positions, (see Table 1) as well as a corresponding contributor analysis, arise. This analysis shows the impact of every dimensional deviation on the key product characteristic. As stated in (Epple, 2013), from the user's point of view it is important to ensure these key product characteristics. Two different cases can be distinguished in the general proceeding. First, if the key product characteristics can be achieved, the tightest tolerances should be relaxed to reduce manufacturing costs. Second, if the key product characteristics can't be achieved, the contributor(s) with the largest impact on these characteristics need(s) to be reduced in order to solve this problem.

Table 1. Illustration of possible key product characteristics (KPC), standard deviations (S), lower and upper specification limits (LSL, USL) corresponding to the measurement points

	X_1	X_2	X_3	Y_1	Y_2	Y_3	Y_4	Y_5	Z_1	Z_2
KPC	15,16	17,35	13,47	26,61	29,00	29,00	21,97	16,04	15,00	13,64
S	0,42	0,40	0,40	0,31	0,31	0,31	0,40	0,40	0,32	0,31
LSL	13,17	15,47	11,59	25,11	27,51	27,51	20,07	14,13	13,51	12,16
USL	17,16	19,23	15,35	28,10	30,49	30,49	23,87	17,95	16,50	15,12

in mm

Input: deviations at the measurement points
Output: rigid limiting positions at the measurement points

3. The role of the sealing system under geometric deviations

The limiting positions that have an impact on functional requirements are not only founded on dimensional deviations arising from the rigid body in white, but from the door sealing system influences with its geometric deviations, stiffness conditions and corresponding reaction forces as well. Additionally, the process of closing and some other factors also have an impact.

A 2D finite element analysis (FEA) is realised in order to show the effect on the limiting positions of the sealing system under geometric deviations. Therefore, a uniaxial translation motion of the door inner panel towards the side frame is performed. For this purpose, both the nominal position as well as the limiting positions will be examined closely. The goal for each case is to supply counter-pressure information as well as deformation data. The geometries of the side frame and the door inner panel are not resiliently modelled. In summary, there are 30 2D FEA relevant for the case considered (10 measurement points, each having the 3 positions nominal, upper limiting position, lower limiting position). In this case, the procedure of a finite element analysis follows the classical model which can be seen in Figure 4.

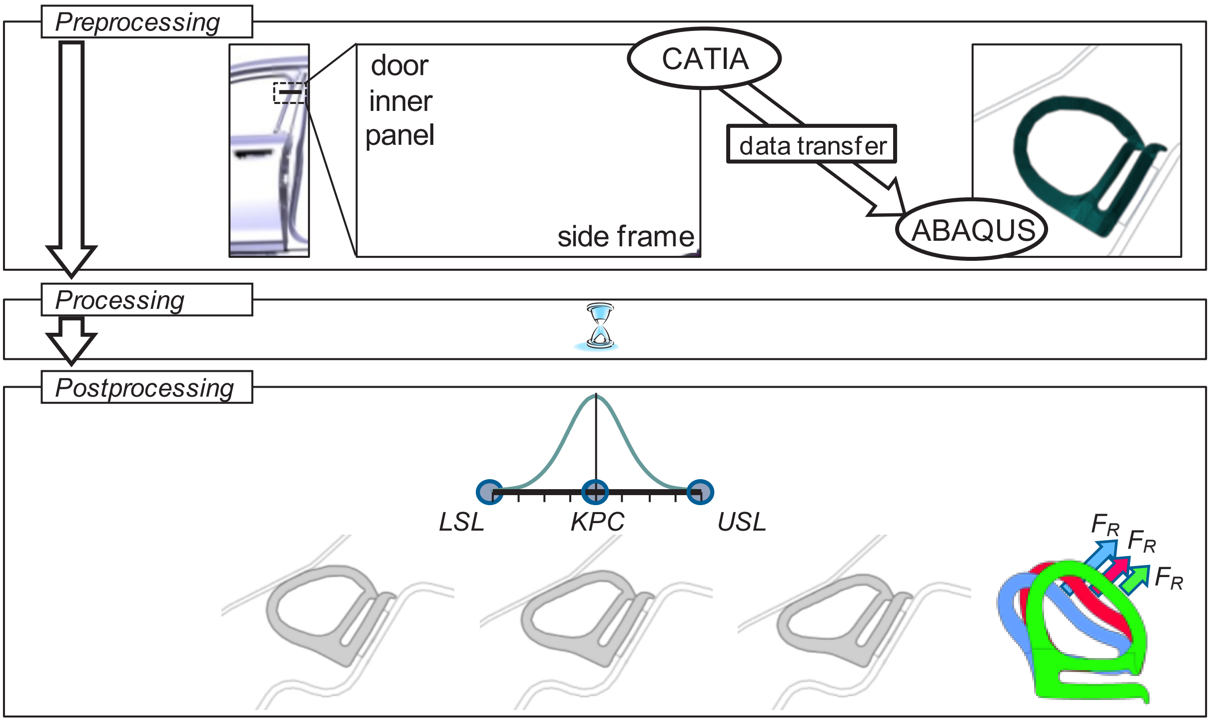

Figure 4. General procedure of a FE simulation

In the pre-processing stage of the 2D FE simulation, the 2D planar sections of interest need to be extracted from the 3D CAD data set (in this case: CATIA). Afterwards, the data needs to be transferred to the finite element software. It should be noted that an individual should ensure that the component's location and orientation are properly transferred during this procedure. Inside the software, the model building process takes place, concerning the FE simulation. Non-linear contact problems like this are characterised by different modelling parameters. Some of these modelling parameters that have an impact on the results of a simulation are as follows:

- Material models and the specification of all material parameters included,
- Specification of all contact conditions including multilateral relations between different components, friction coefficients and the self contact of the door sealing system,

- Relative displacement distances between the components,
- Relative position of the moving components to each other,
- Limitation of the degrees of freedom of all considered components (boundary conditions),
- Kind of meshing and meshing quality.

Taking these parameters into account, a 2D finite element simulation result occurs. In accordance to the respective 2D planar sections the reaction forces, calculated within this simulation, arise.

Thereafter, in the **processing** step the actual 2D FE simulation is carried out taking the modelling and boundary conditions into consideration.

Consecutively, the **post-processing** in connection with the 2D FE simulation is conducted. This step deals with the visualization of the results as well with their interpretation. The suggested process takes the counter-pressure information arising from the sealing system as well as its respective reaction forces FR into consideration. These factors are of crucial importance (see Figure 4). The reaction forces when performing the 3D FE simulation are applied to the side frame and the door inner panel - quasi static. In preparation for this aspect of the next stage, the transformation of the 2D reaction forces into the global 3D coordinate system must be executed in order to do an interpolation of these reaction forces along the sealing line. Figure 5 shows a schematic sample of interpolated data. In order to receive a reasonable result of interpolation it is necessary to produce more 2D FE simulations creating supporting points. At this point In order to understand the suggested process, this isn't necessary. In the end, this approach will lead to a more realistic result for the considered reaction forces based on the limiting positions along the sealing line.

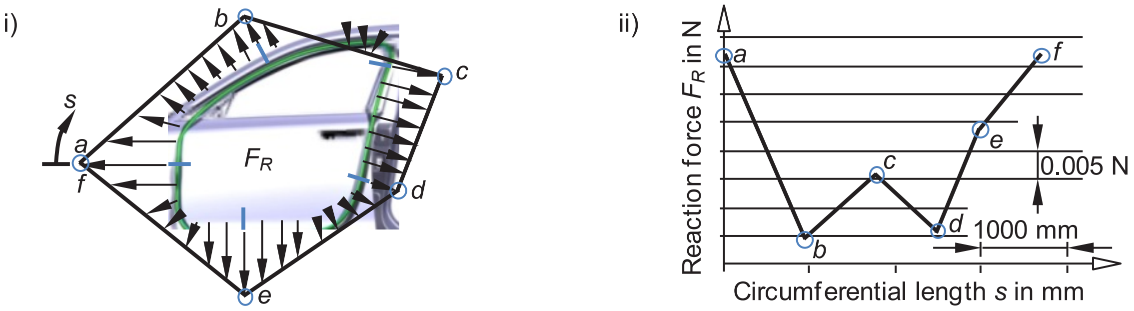

Figure 5. Reaction Forces FR as a result of the counter-pressure: i) Single reaction forces resulting from the 2D planar sections ii) Linear Interpolation of the reaction forces along the sealing line s

Due to the fact that the limiting positions are interdependent, mostly because of geometric boundary conditions, and to ensure that all positions are considered during the process, simulation series need to be carried out. In an attempt to limit the computation time a design of experiments needs to be conducted.

4. Determination of the limiting positions as a result both of the rigid tolerance simulation and the elastic behaviour of the sealing system

Following both phases of simulation, the determination of the elastic limiting positions is carried out. Therefore, the counter-pressure information (see Figure 5 i)), which arise from the sealing system and its respective limiting positions, are stamped on the side frame and the door inner panel. This is done within a quasi-static 3D FE simulation. The aim is to determine the corresponding deformations with respect to the imprinted loads. As a consequence, the updated limiting positions occur due to this linear superposition.

To achieve these objectives, the components, namely door inner panel and side frame, are fixed at their dedicated connection points. In this case, this is carried out via door-sided connections at both hinges and at the door lock. The simulation process during this process step changes insofar as the loads are now imprinted along the sealing line.

The simulation's outcome provides the effect of the sealing system on the resulting limiting positions. The influence is clearly noticeable at several areas within this automotive door assembly. For the most part, these areas have a relatively low structural rigidity or are situated relatively far from the connection points (door hinge and door lock). An example of one of these areas is the door-sided upper corner near the B-pillar of the vehicle. Additional influences can be seen in places where the gasket is situated opposite of edges. There can be specific situations, maybe limiting positions, where the contact surface between the gasket and the body in white reaches a certain minimum or no longer exists. In this case, the customer-relevant criterion tightness (against the permeation of dust or humidity) can be evaluated directly from the simulation.

Furthermore, the result of an overall limiting position simulation can be that the gasket cannot be kept from reaching a point of being solidified. If this happens, this does not ensure the sealing of the system a priori. On the contrary, it might also happen that the sealing layer loses its sealing capabilities due to folding. Moreover, such behaviour may end up damaging the sealing profile over the short or medium term. This may cause a negative effect on the considered functional aspect. Here, it should be noted that follow-up research studies are required.

5. Summary and outlook

The process which has been introduced in this contribution supports the ambition of a customer-oriented functional safeguarding of the tightness criterion in an early stage of the developmental cycle of an automotive door assembly. The primary motivation behind the results from various overarching objectives are as follows: An increasing quality of the results required when predicting the limiting positions, as well as, an improved design construction in order to avoid functional errors. In this context, one of the most relevant attributes is examined, concerning tightness against the permeation of dust or humidity.

On the basis of three process steps, the reasons for dimensional, as well as for position deviations, were discussed. Furthermore, stiffness conditions of the components, the restorative forces set up, etc. are causative for the so called limiting position formation. Designated process steps should be the determination of the limiting positions by rigid tolerance simulation, a finite element analysis (FEA) of the door sealing system under geometric deviation and a FEA of the corresponding deformation to finally determine the limiting positions with regard to the elastic system behaviour.

The results achieved indicate that a useful process is determined. Nevertheless, especially in the area of finite element simulations, the need for further action arises. In order to detail the proposed process through additional information, the following points will be considered: Quality of the results, required computational time, costs incurred. To improve the quality of the simulation results, there will be follow-up research activities in the future. On the one hand, these studies should provide additional insights with respect to the location and number of the regarded 2D sections. On the other hand, the quality of the results coming from 3D FE simulations should be examined. Finally, aims of these studies are to allow a comparison between 2D and 3D FE simulation and their respective results.

An additional step involving the opening and the closing of the door should be taken into account, and the effect of the sealing characteristics on the limiting positions and its corresponding key product characteristics should be illustrated more precisely.

In order to verify the quality of the simulation results, it is also useful to do comparative experiments. Therefore, an adequate design of experiments is required helping to reduce both the amount of simulations and experiments. Subsequently, it is the task to define a criterion which provides a good indication of the sealing capability. There are several options here: Numerically determined counter pressure information as well as the size of the contact surface of the gasket on the opposite component.

Finally, this process enables the user to evaluate the system behaviour of a door assembly with respect to the limiting positions in more detail. Thus, this simulation approach enables a more sustainable way of manufacturing which leads to a robust design in the end. Therefore, it serves the customer's, as well as the company's needs.

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1st International Symposium on Robust Design
København, DK
14th-15th of August 2014

A Robust Design Methodology Process

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Keywords: Robust Design Methodology, product development, product robustness process, medium-sized company

Abstract

Robust Design Methodology (RDM) has been established as an approach to design products that are reliable and have stable performance despite exposure to variation in uncontrollable factors. Research on RDM has traditionally focused on the application of various tools to support RDM. Less has been written on how RDM practices can be applied throughout a product development (PD) process. This paper presents a study of a medium-sized manufacturing company working with a Product Robustness Process (PRP). PRP is a sub- process in their PD, and focuses mainly on practices supporting RDM and the outcome in terms of increased robustness. An example of a practice is to systematically identify factors that will vary under operating conditions and affect product performance and reliability. By knowledge of such factors it is possible to take robustness into account in early PD phases. In some phases of the PRP, indications of suitable tools are given, however not as a compulsory prescription. The PRP shows how practices of RDM can be made a part of an established PD process. It also aims to focus on practices, rather than tools or techniques, to maximise RDM application. Case studies on RDM are often focusing on tools such as Design of Experiments; albeit important it is of value to consider daily RDM practices without necessarily involving a prescribed tool. This paper aims at contributing to the latter by means of a case study at a company working with a PRP for about two years. The purpose of the paper is to describe and evaluate a process for RDM practices throughout PD. The most important outcome of the PRP is that the development teams have reliased a systematic way to address quality and reliability on the agenda throughout PD.

1. Introduction

Robust Design Methodology (RDM) aims at creating products with stable performance despite exposure to variation in uncontrollable factors, so-called noise factors, e.g. variations in operational temperature or customer usage (Arvidsson and Gremyr, 2008). A common visualization of a robust design is the so called p-diagram (Phadke, 1989). This diagram displays the product as affected by control as well as noise factors, where the settings of the control factors are used to create a design that is insensitive to the influence of the noise factors. The outcome is a reliable and stable performance, which do not only have effects on customer satisfaction but also results in less scrap, waste and re-work. Thus, RDM is an engineering methodology that could enhance environmental or economic sustainability (Gremyr et al., 2014).

DOI:10.4122/dtu:2094

Reviewed by: *Søren Nygaard Pedersen*
Thomas J. Howard

Cited af follows: Arvidsson, M., Gremyr, I. and Siva, V., 2014. A Robust Design Methodology Process. In: Howard, T. J. and Eifler, T., ed. 2014. *Proceedings of the International Symposium on Robust Design - ISoRD14*. Copenhagen, Denmark. pp. 69-78.

Reduction of variation is an important area in quality management ((Shoemaker et al., 1991), (Thornton et al., 2000), (Taguchi et al., 2005)). As stated by Box and Bisgaard (1988) "The enemy of mass production is variability. Success in reducing it will invariably simplify processes, reduce scrap, and lower costs". A link to sustainability is pointed out when defining quality loss as "the amount of functional variation of products plus all possible negative effects, such as environmental damages and operational costs" (Taguchi, 1993).

As an engineering methodology it is argued here that RDM is not merely a set of tools or techniques, but also consists of a number of principles and practices. Principles are the basic assumptions that are implemented through practices, i.e. activities done in support of the basic assumptions (Dean and Bowen, 1994). Practices are then supported by various techniques. In line with this way of operationalizing concepts, RDM has been defined as "systematic efforts to achieve insensitivity to noise factors. These efforts are founded on an awareness of variation and can be applied in all stages of product development." (Arvidsson and Gremyr, 2008).

Textbooks, e.g.(O'Connor, 2002), present various statistically based tools for the development of robust and reliable products. Discussion of statistical tools supportive of RDM has taken place in a number of papers over the years e.g. (León et al., 1987), (Box, 1988), (Shainin and Shainin, 1988), (Welch et al., 1990), and (Robinson et al., 2004). The most commonly discussed tool is Design of Experiments, see e.g. (Shoemaker and Kackar, 1988), (Shoemaker et al., 1991), (Box and Jones, 1992) and (Ellekjær and Bisgaard, 1998). As much focus has been on the application of statistical tools supporting RDM, the early and more conceptual stages of product development have received less attention. However, (Ford, 1996) and (Anderson, 1997) points at the need of applying RDM efforts in the conceptual design. Further, it has been argued that there is a need to identify RDM practices suitable for all parts of a product development process (Hasenkamp et al., 2009).

The basis for this paper is a case study at a Swedish medium-sized manufacturing company, hereafter referred to as MC, aiming to develop a Product Robustness Process (PRP) as a sub-process in their product development. MC is developing, producing and selling their own patented high-tech product used by individual end users. The company is about 15 years old and has about 250 employees. The purpose of this paper is to describe and evaluate a process for RDM practices throughout PD. The continuation of this paper is structured as follows: a method chapter accounting for the study performed, followed by a description of the needs of the company related to robustness, and a description of the PRP. The final parts of the paper contain discussion and conclusions.

2. Method

The study has been performed by three researchers; one employed by MC (later referred to as internal researcher) and two university-employed external researchers. The study has taken place for a year, following MC's work on developing their PRP. For the external researchers the study has involved about ten meetings of 2-3 hours each discussing alternative designs of the PRP, as well as numerous e-mails and telephone calls reflecting on drafts of the PRP. The internal researcher is responsible for the PRP at MC. Hence, this research has been carried out as an action research, in other words research with rather than on local players with an explicit intention to improve the system studied (Coghlan and Brannik, 2008).

The empirical data consisted of meeting notes, drafts of the PRP, material related to MC's product development process, discussions with staff involved in the PRP and observations by the internal researcher. In order to strengthen the creative potential of the study and increase confidence in the findings, multiple investigators (internal and external researcher) worked jointly on the analysis (Eisenhardt, 1989). Further, the internal and the external researchers wrote the paper jointly as a means to increase credibility and internal validity ((Bryman and Bell, 2007); (Lincoln and Guba, 1985)).

3. The product robustness process

Before displaying and describing the Product Robustness Process (PRP) some of the experiences that motivated the need for this process at MC will be presented. Subsequently, the MC's product development process is introduced, followed by a description of the PRP and outcomes experienced from working with the PRP.

3.1 Experiences that formed the process

A number of experiences have led to the realization of the need of a PRP integrated in the product development process. Initially, the company viewed inferior product reliability primarily as a cause of high warranty costs. Actions to improve reliability were limited to measuring and monitoring the repair rates and customer complaints. In the cases where Failure Modes and Effects Analysis (FMEA) were applied, it was mainly done in a reactive manner. In other words it was not continuously updated with the purpose of avoiding possible failure modes. The need to further enhance robustness and reliability of the product was based on the realization that inferiority in these aspects not only creates high warranty costs, but also has negative effects on customer satisfaction and loyalty.

The FMEAs are used throughout MC on system, sub-system and component levels. Far too often though, it is used as a tool to identify possible weaknesses in designs and the subsequent parts of the FMEA on failure causes and mitigations are neglected. Besides serving as a tool for failure mode avoidance it is experienced that FMEAs could serve as an overarching document for reliability improvement, incorporating the design history with focus on earlier robustness and reliability issues.

At MC it has been realized that a key to the development of reliable systems is an adequate break-down of system requirements to requirements on sub-systems and components. The reason is experiences of reliability problems being caused by insufficiently specified reliability requirements on sub-systems or components. Clear requirements, traceable to the system level, provide a clear direction for design of sub-systems and components in terms of robustness and reliability.

3.2 The product development process

The product development process at MC is comprised of a number of different phases. In Figure 1 the six phases of the product development process related to the pre-project phase and the design phase are displayed.

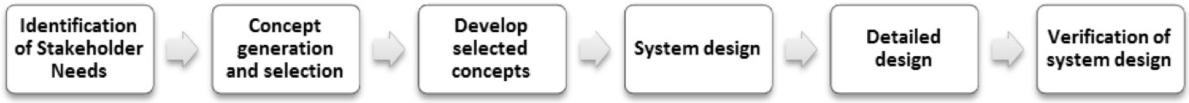

Figure 1. The Product Development Process

The pre-project phase involves: identifying the stakeholder needs, translation of needs to verifiable system requirements, and generation, evaluation and selection of concept solutions. Once a concept has been chosen these are further analysed and evaluated. In the last tollgate of the pre-project phase a decision is taken on whether the project should enter the design phase or if it should be terminated. A decision to terminate a project could for example be due to commercial reasons, low technology readiness, or a prediction of low reliability.

The design phase is based on the following stages: system design, detailed design, and verification and validation. In the system design stage the function of the system is broken down into a number of functions of sub-systems and requirements for these sub-systems. The detailed design phase includes the design of components with the starting point from the component requirements. The final activity in the detailed design phase is to verify the design in relation to the stated requirements. The verification and validation phase aims to verify that system requirements are met and that stakeholder' needs are fulfilled.

3.3 The PRP

The PRP is developed specifically to suit the needs and wants of MC, in terms of the company wanting a process focusing on practices and built on their previous experiences and competences. The latter can be exemplified by MC having previous experiences of FMEA and saw it as beneficial if the PRP could be described in ways that indicate where FMEA could be of use. Further, the PRP is focused on activities that should be performed at various stages in product development to foresee and prevent failure modes. An overview of the phases of the PRP and their link to the product development process is provided in Figure 2.

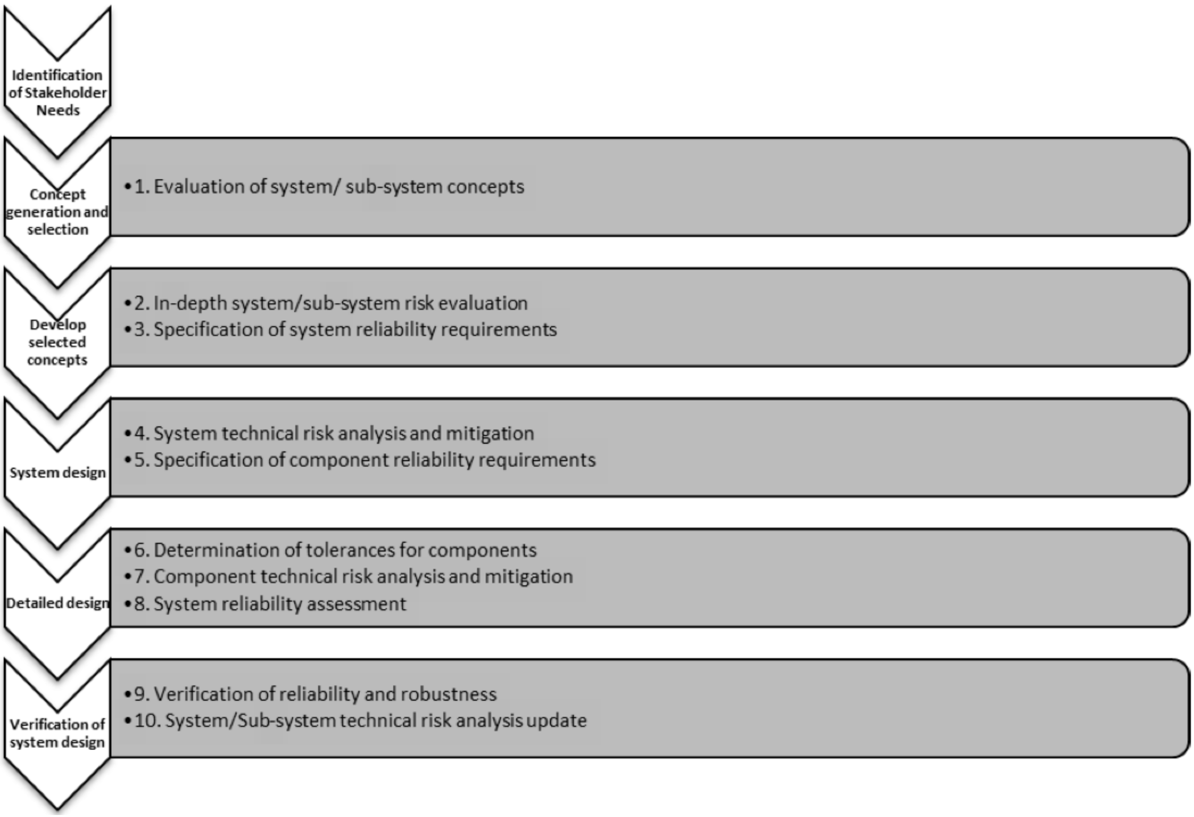

Figure 2.The phases of the product robustness process linked to the product development process

The intent of the PRP is to guide MC's engineering teams concerning RDM practices applicable in product development. However, even after a concluded product development project robustness efforts are continued, for example through updates of the FMEAs based on field data.

1. Evaluation of system/sub-system concepts

The purpose of this phase is to identify strengths and weaknesses of the evaluated systems/ sub-systems. The inputs to this phase are the initial demands on reliability and robustness. The evaluation of the concepts can, for example, be done by use of P-diagrams, Fault trees, and/or System FMEA. The output from this phase is relative strengths and weaknesses of the concepts. Based on the evaluation, concepts are improved in terms of robustness and reliability. The output should be one of the inputs to the choice of system/s. This activity should be performed in the Concept Generation and Selection Phase (see Figure 1), hence guiding the concept selection.

2. In-depth system/sub-system risk evaluation

The purpose of the In-depth system/sub-system risk evaluation is to develop the initial technical risk analysis of the chosen concept/s. An important input to this phase is the result of the initial evaluation of the strengths and weaknesses of the chosen concept/s. Initially performed risk analyses should be updated and subsequent mitigation may be necessary. Suitable tools for this phase are for example system FMEAs, P-diagrams, and Variation Modes and Effect Analysis (VMEA) (Chakhunashvili et al., 2003). Besides an updated system risk analysis and an improved concept the output is a decision on whether or not the reliability and robustness risks identified are acceptable. This activity is performed in the “Develop selected concepts” phase (Figure 1), and aims to give an understanding of the inherent robustness of the concept/s chosen.

3. Specification of system reliability requirements

The purpose of this phase is to determine system reliability requirements and to secure the possibility to verify these requirements. Stakeholder needs shall be analysed and reflected in System reliability requirements. The needs should be phrased so that they are possible to verify and have clear acceptance criteria. A draft version of the system reliability requirements should be available in the “Develop selected concepts” phase.

4. System technical risk analysis and mitigation

The purpose of this phase is to identify and eliminate failure modes in the system design. To foresee and prevent possible failure modes the risk analysis from the ‘In-depth system/sub-system risk evaluation’ should be updated and mitigation actions taken. In addition to tools suggested in earlier phases a FMEA focusing on possible risks in the interface between sub-systems or components can be useful. The outputs of this phase are identified failure modes as well as identification of mitigating actions needed. This activity should be performed in the System design phase (Figure 2).

5. Specification of component reliability requirements

The purpose of this phase is to determine the verifiable reliability requirements put on components. This work is carried out within system design as a means to maintain a high- level view when establishing the links between system requirements and requirements of various components. This function, or tolerance chain, should be analysed to assure the possibility to meet the reliability and robustness requirements. Further, it should be used as a basis for determining requirements on component reliability. After this phase it should be possible to design reliable components that assure that the system requirements are fulfilled. This activity should be performed in the System design phase, see Figure 2.

6. Determination of tolerances for components

The purpose of this phase is to assure that system reliability can be met by the manufactured product. Based on the component reliability requirements, tolerances on components need to be determined that assures that the manufactured product will be reliable. Methods for these tolerance stack-up calculations are, for example, worst case tolerancing or process tolerancing. Further, part of the output is to review capabilities of the manufacturing processes to verify that required tolerances can be met. This activity should be performed in the Detailed design phase, see Figure 1.

7. Component technical risk analysis and mitigation
The purpose of this phase is to identify and eliminate failure modes of the component design. The component reliability requirements serve as input to the component technical risk analysis and mitigation. To maximize the quality of the output from this phase it is essential that input data is of good quality. In this phase it may also be suitable to use simulation where the effect of different kinds of loads and design weaknesses can be identified, followed by design improvements. When physical system prototypes are available different design options can be evaluated, preferably by use of Design of Experiments and Accelerated Life Testing. When applicable, Highly Accelerated Life Testing (HALT) can be applied to identify weak areas in the design. This activity is performed in Detailed design.

8. System reliability assessment
The purpose of this phase is to assess whether the system reliability is acceptable or if additional risk mitigation is needed. Drawing on the system design thinking this last phase in the detail design aggregates from the component level to the system level to be able to evaluate the implementation of mitigation activities identified at different levels of design. Thus, it is possible to evaluate whether these efforts are sufficient from a system perspective. The output from this phase should be documented improvements of the design. This activity is to be performed in the Detailed Design phase, see Figure 2.

9. Verification of reliability and robustness
The purpose of this phase is to verify whether robustness and reliability requirements are met. The test methods used in this phase should be set already when the requirements are determined. The verification of design reliability should be performed on component as well as system levels to maximize the chances to identify as many design flaws as possible. This activity should be performed in the Verification of System Design phase.

10. System/Sub-system technical risk analysis update
The purpose of this phase is to update risk analyses based on the results of the system verification and, where needed, mitigate risks. In this phase technical risk analyses on system/sub-system/component levels are updated based on experiences from the earlier phases. If failure modes are identified that were not present in earlier technical risk analyses, or if the likelihood of occurrence of identified failure causes need to be upgraded, actions may be necessary to mitigate the corresponding risks. This activity should be performed in the Verification of System Design phase, see Figure 1.

3.4 Outcomes of the PRP

The PRP has been use at MC for 1.5 years, and is applied in all their product development projects. Due to the project lead times there is not yet a launched product that have been developed following the PRP from phase 1 to 10, hence it is not yet possible to evaluate effects of the PRP in terms of e.g. reduced levels of claims.

At MC, historically, there has been a focus on practices. Especially in a smaller organization a focus on tools could have hindered usage of RDM, as lack of training is often a common excuse for not applying a certain tool and training might be regarded as too costly. Overall, the process has established a framework of practices for how to integrate robust design and systems engineering; adopting a systems view on robust design, focusing relations between system, sub-system and components. Further, the awareness of variation and influential noise factors has increased at MC. The staff feels that the PRP has put focus on noise factors and how these should be dealt with by clever design solutions in early design phases, before simulation models or prototypes are available. This can be exemplified by a P- diagram on a component of MC’s product (see Figure 3); the diagram is developed iteratively during the PRP and is a means of assessing and mitigating robustness risks.

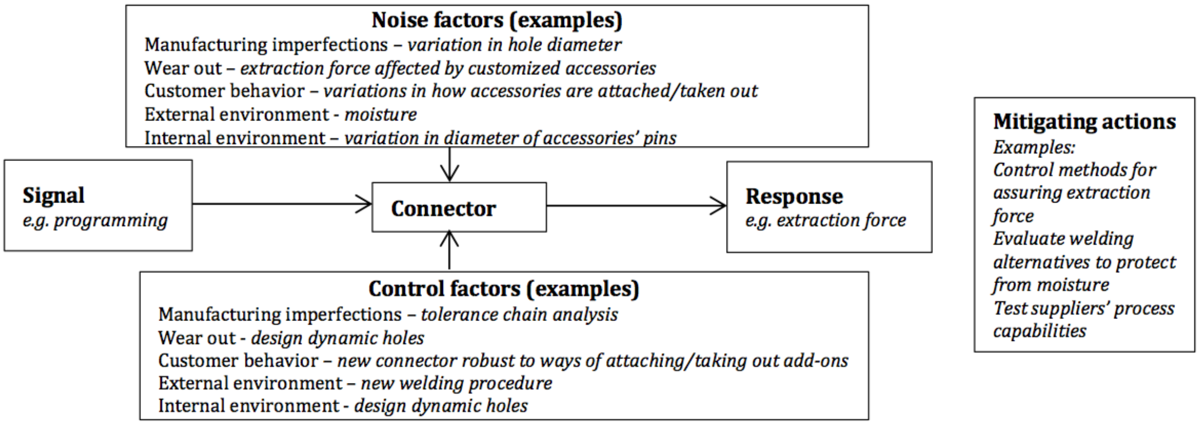

Figure 3. P-diagram for one components, to protect confidentiality information has been left out and phrasings have been revised

Use of the PRP has promoted more simulations and prototype tests to identify reliable and robust design solutions in early development phases. As an example, tests performed to assess and improve the performance and reliability of designs were often performed by applying loads equal to what the design should withstand according to the specifications. The conclusion from such tests was often that the design met the requirements and that no further improvements were necessary. After product launch, however, the product quality often proved to be worse than anticipated. To avoid such misjudgements, O'Connor (2002) argues that it is necessary to perform tests where designs are subjected to higher load than expected under operational use. The rationale is that all systems are subject to higher loads than specified, and should be designed to withstand some levels of misuse. In MC tests where the loads on the systems exceeds what is expected under operational use has been applied as a result of the PRP. This reveals possible weaknesses in the design and triggers improvement work.

4. Discussion

At MC the work on robustness and reliability started as a response to high warranty costs. Later it was also acknowledged that reliability and robustness had effects not only in terms of high warranty costs, but also on customer satisfaction and loyalty. Further, management saw possibilities that a more continuous and iterative way of working with certain tools, in particular FMEA, would be beneficial. Eventually questions were raised on how to get robustness and reliability to become an integrated part of the product development process. In essence the PRP was developed in response to these questions. On an overall level, a learning point at MC has been that it is important to promote not only tools but rather elaborate on what activities are needed and the anticipated outputs from these activities. The background is that MC has experiences of other quality related initiatives with strong focus on specific tools. This latter tool oriented strategy has often met resistance as people may have preferences for use of different tools for various reasons, or lack sufficient knowledge to use certain tools.

The design of the PRP is based on two overall ideas; to focus on practices, and to follow up on outcomes or results rather than on use of certain tools. First, the PRP has a strong focus on practices. To ensure that the practices related to RDM are carried out, review questions on robustness are included at the gate reviews in the product development process. This relates to a need for practices in support of continuous applicability of RDM (Hasenkamp et al., 2009). Second, the focus is on activities performed, and the required output from each phase is explicitly stated in the process documentation at the company. As the requirements on certain activities are explicit it is ensured that preventive work e.g. failure mode identification is not neglected.

The fact that the PRP focuses practices and is based on a strategy of non-compulsory use of tools, does not mean that tools that are often used within RDM such as Design of Experiments (DoE) (Box and Jones, 1992) are not feasible to use in the PRP. However, authors like Ford (1996) and Anderson (1997) point to the need of applying RDM efforts in the conceptual design; phases where tools like Design of Experiments might be less useful. As much focus within RDM has been on statistical tools suitable in later design phases the application in concept design can be challenging due to lack of appropriate tools. In MC this was a challenge; however, overcome by a focus on practices and outcomes rather than tools. At gate reviews in the product development process the questions are directed towards what has been done to achieve the outcome required, rather than exactly how it has been done.

An interesting area of future research would be to identify practical strategies to estimate the inherent reliability and robustness of a prototype to give the development teams information on the reliability and robustness of the design at a certain stage in the development process. In other words, an area of research would be to develop a set of indicators evaluating robustness and reliability efforts. Additional areas of future research could be follow-up studies of the result from the PRP, as well as applications in other companies. It is also of interest to evaluate whether or not the process approach applied in this paper is feasible for other companies, or if it could be modified to a set of practices in companies where an additional process is not seen as feasible.

5. Conclusions

The purpose of this paper is to describe and evaluate a process for RDM practices throughout PD. The PRP has been built around the practices of RDM and a focus on the required input and output of each phase, adapted to the characteristics of that specific phase. Thus, in earlier phases like the Evaluation of system/sub-system concepts the input are the demands on reliability and robustness and the output are relative strengths and weaknesses of concepts. The tools suggested for use are hence of a more conceptual nature, in line with what Ford (1996) and Anderson (1997) argue is needed for the use of RDM in conceptual stages of product development.

The PRP specifically focuses on the failure mode avoidance and mitigation; less focus is put on data gathering and estimation of reliability measures for example mean time between failures (MTBF). The results of failure mode avoidance in product design stages are reduced failures in product use stages. Therefore, the PRP contributes to reduced scraps and wastages caused by unreliable products. This could in turn enhance the environmental and economic sustainability.

In summary, three crucial characteristics of the PRP for integration of RDM efforts in the product development work have been identified at MC. First, there is a focus on practices rather than tools. Secondly, the PRP is fully integrated with the product development process and follow up on RDM practices are included at the compulsory gate reviews. Third, the PRP is followed up on RDM related outcomes and not on specific details of how the outcomes were achieved.

Acknowledgments

This work has been carried out as a part of the Sustainable Production Initiative within the Production Area of Advance at Chalmers. The support is gratefully acknowledged.

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1st International Symposium on **Robust** Design
København, DK
14th-15th of August 2014

An approach to identifying the ideal time to perform an FMEA during the product development process

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Keywords: level of information, Information-Quality Framework, FMEA

Abstract

The Failure Mode and Effect Analysis (FMEA) is one way to preventatively identify failures. In it, failures and their risks to the customer are analysed and valuated in order to define mitigation strategies for minimization or avoidance. Depending on this purpose, a division into functional, design and process FMEA is mentioned in literature. If the FMEA is used as early as possible during the product development process, the usable level of information is very low. It grows during the product development process and is understood as all available information, with different degrees of concretisations, according to an instant in time. It can be suggested that the available level of information influences the FMEA results as well as the point of time to perform. In order to identify an ideal point of time, a three-step methodology is considered.

First, the level of information is systematized by using product and process models. Subsequently, the quality of information is measured with the help of an Information-Quality framework. This framework contains the four target categories Accessibility, Representational, Intrinsic and Contextual, whereby each category can be described by different dimensions. Using this, the available level and quality of information to an instant in time during the product development process can be determined.

Second, specific requirements on information to perform a functional, design or a process FMEA are defined and evaluated by using the IQ-Framework too. So for every type of FMEA a needed level on quality of information is specified.

Third, the available and needed quality of information to perform a FMEA is compared. Based on that, for each type of FMEA the most appropriate period of time during the product development process can be estimated, whereby a contribution for a robust design of products is made.

DOI:10.4122/dtu:2095

Reviewed by: *Andreas Dagman*
Søren Nygaard Pedersen

Cited af follows: Würtenberger, J. and Kloberdanz, H., 2014. An approach to identifying the ideal time to perform an FMEA during the product development. In: Howard, T. J. and Eifler, T., ed. 2014. *Proceedings of the International Symposium on Robust Design - ISoRD14*. Copenhagen, Denmark. pp. 79-89.

1. Introduction

Failure Mode and Effects Analysis (FMEA) is a way of detecting and analysing failures that occur during the product development process. Failures and their risks to the customer are identified and valued in order to define mitigation strategies that minimize or prevent failures (Schäppi et. al., 2005). Failures are deviations between the actual status and the desired status of a product property. In practise, there is a gap between the emergence and the discovering of a failure (Figure 1).

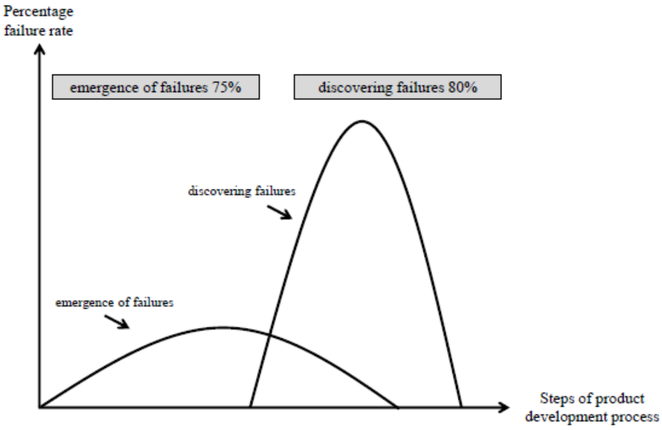

Figure 1. Emerge and discovering of failures [Pfeifer 2001]

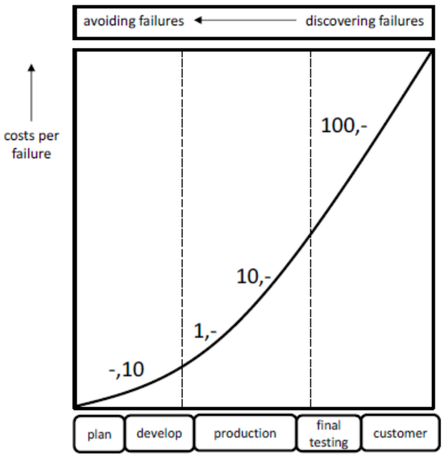

Figure 2. Costs per failure [Pfeifer 2001]

The point of detection of a failure is important because the costs of failure grow by an approximate factor of ten as the product development process proceeds (Figure 2). The earlier a failure is identified during the product development process, the lower the resulting costs of rectifying it. Detection should focus on discovering failures rather than avoiding them. Within the quality management framework there is significant economic potential in avoiding failures (Göbbert, 2003).

If the FMEA is used as early as possible, the usable level of information is very low. The level of information grows during the product development process and is understood as all available information, with varying degrees of concretisation, according to a certain instant in time. The growing level of information has an influence on the benefit of the FMEA. If a low level of information is used, the benefit of the results is low too. It is better to perform an FMEA later in the product development process. The literature contains varying recommendations on the best time to perform an FMEA.

The focus of the current research on this approach is on identifying the ideal time to perform an FMEA by analysing the dependencies between the level of information during the product development process, the quality of information and the existing FMEA types.

2. Using the FMEA during the product development process

The FMEA is a systematic methodology to analyze a system in order to identify failure modes and their causes and effects on the rest of the system, such as on the customer. It can be applied at any time during the product development process and contains five working steps. First, with the help of a failure mode analysis, every potential failure of a product that may occur is identified. Effects on the planned usage process for which the investigated product is needed are assigned for each failure. Causes of each failure are identified. Every combination of failure, cause and effect is evaluated with the help of a Risk Priority Number (RPN). The

RPN can be calculated using the probability, severity and detection of a failure. Finally, mitigation strategies are defined in order to avoid or lower severity and detection of a failure (DIN EN 60812 2006).

Depending on the progress of the product development process, different types of FMEA are used. A Functional FMEA identifies functional failures in early design phases in order to identify design weaknesses. With a reduced number of variants during the product development process, a Design FMEA is applied. In this context, structural faults are identified for every product component. (Göbbert/Zürl, 2006). A Process FMEA analyses production and assembly processes of components to detect process-caused faults. Therefore, a comprehensive level of product properties is necessary (Hering/Triemel/ Blank, 2003). The three types of FMEA are interdependent; for example, results of a Functional FMEA are used to perform a Design FMEA. The Process FMEA uses the results of a Design FMEA.

3. Method for identifying an ideal time to perform an FMEA

This paper demonstrates a way to identify an ideal time to perform an FMEA during the product development process, where the conflicting parameters 'costs per failure' and 'level of information' are analysed (Figure 3).

First, it is necessary to systematize the level of information at a certain instant of time. The systematized level of information is evaluated using the Information Quality Framework (IQ Framework). The framework contains dimensions whose trends change during the product development process, rendering the quality of information assignable. Second, requirements for performing a Functional, Design or a Process FMEA are identified. With this help, a comparison between the quality of information at an instant in time and the needed level and quality of information to perform a FMEA is conducted. This makes it possible to allocate the FMEA types to the steps of product development of VDI 2221.A recommendation on which type has to be used according to different points in time is given.

The minimum level of quality of information necessary to perform the chosen FMEA type is also discussed. Trends of the dimensions, such as the costs per failure, are optimized, limiting the possible range of performing the FMEA type. Each of the working steps is described in the following sections.

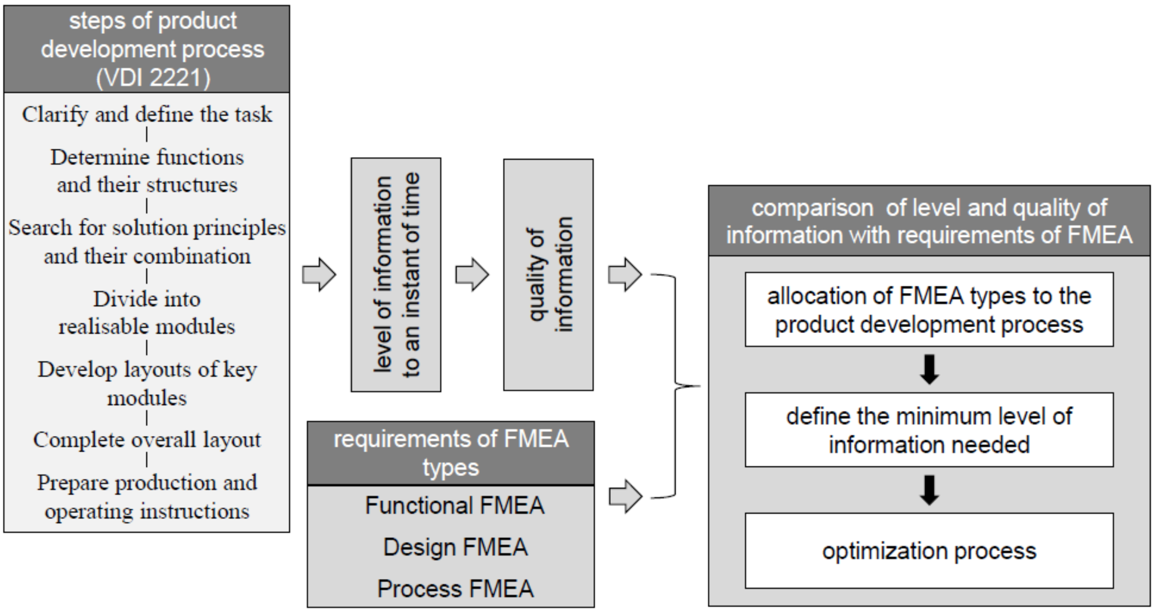

Figure 3. Approach presented in this paper

3.1 Systemizing information levels

Product and process models are used to systemise information levels in the product development process. Product models represent an early stage of the planned product with a certain purpose (Birkhofer/Kloberdanz, 2007); process models describe a time-dependant transformation of an initial state of an operand into a changed final state (Kloberdanz, 2009). This paper describes the adaptation of Heidemann's process model of Heidemann, shifting the focus onto the FMEA (Heidemann, 2001). It gives information about the usage process and the product itself, such as disturbances of product and process. A fundamental aspect of this model is the differentiation between the usage process of the customer and the product produced by the company (Kloberdanz, 2009) so the product itself interacts with the usage process in order to perform it.

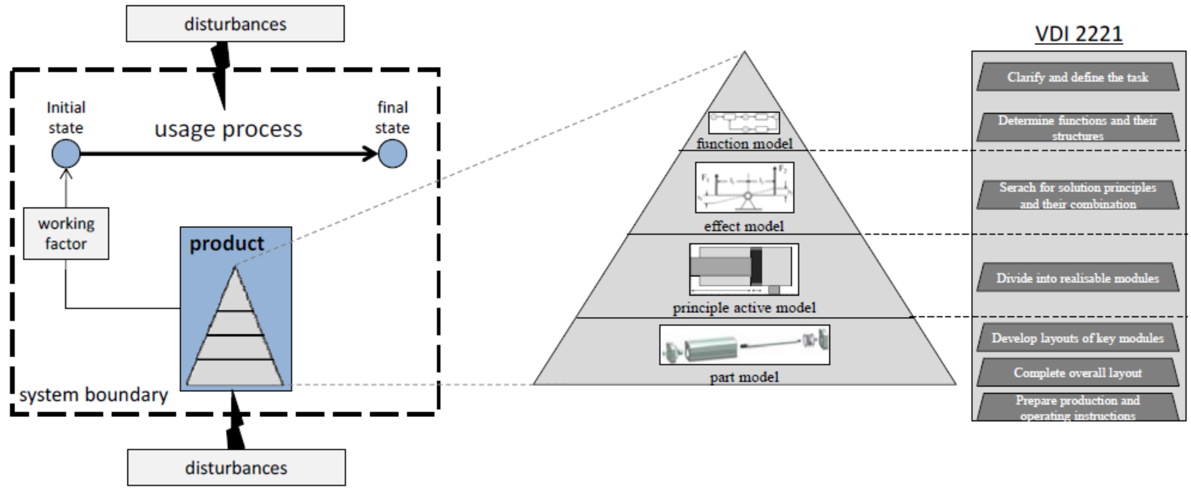

Figure 4. Systemization of level of information [Heidemann 2001], [VDI 2221]

The pyramid of product models is used to illustrate the progress of product development (Sauer, 2006). It consists of four levels: function, effect, active principle and part model. Each model can be allocated to the VDI 2221, which means that the pyramid can be used at any time during the product development process. The function model divides the task into sub-functions in order to describe them objectively. Each sub-function is concretised using physical, chemical or biological effects (Birkhofer/Kloberdanz, 2007). The principle active model combines these effects with material and geometrical parameters, giving a general solution to the task (Birkhofer/Kloberdanz, 2007). All information in the active principle model is specified until the final design of the product is achieved.

With the combined use of the Heidemann process model and the pyramid of product models, all information necessary to perform a FMEA can be systematised to an instant of time (Figure 4).

3.2 Using the IQ Framework to measure the quality of information

After systemizing the level of information, criteria are necessary to measure the quality of information. Mielke et al. developed a hierarchical framework to understand what the quality of information means to the customer (Mielke et al., 2011). This framework contains four categories with 15 dimensions, based on the survey of Wang/Strong (Figure 5). Each category has a specific context.

The category Accessibility analyses how the system deals with information. In this case, it refers to the working steps of the FMEA. The working steps are specified in a norm so their influence on the quality of information does not change during the product development process. This is why the category Accessibility will not be investigated here. The category Representational is also not relevant to this paper as t analyses the way information is presented, which is defined in FMEA worksheets: the effect of this category does not change either.

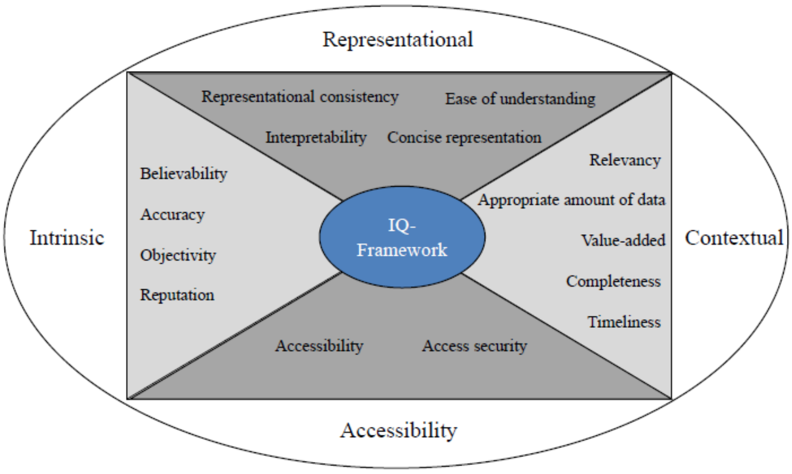

Figure 5. IQ Framework [Mielke et al. 2011]

The categories Intrinsic and Contextual deal with the content and benefit of information, and are the base of this paper. To measure the quality of information, the dimensions have to be applied during the product development process. With the help of the categories Intrinsic and Contextual, the systemized level of information is evaluated and the quality of information at an instant in time can be estimated.

3.3 Analysis of level and quality of information

The changing level and quality of information during the product development process is investigated using Heidemann's process model. The model is applied four times, as described in Figure 5, so that every working step of the VDI 2221 is considered. The quality of information is then evaluated using the dimensions *Objectivity, Accuracy, Completeness* and *Value-added of the IQ Framework* (Figure 6).

The dimension *Objectivity* shows a level of information downward trend with increasing concretisation. This is demonstrated by the decisions that have to be made during the development process. The function model describes partial functions in a solution-neutral manner, where the effect model concretizes them by assigning different effects. For example, it is possible to describe the partial function *transforming an energy* using a hydraulic or mechanical principle so that there are several ways to concretize it. It depends on the developer's view of the problem which effect fits best, which is why the dimension Objectivity shows a downward trend, especially between the second and third working steps of the VDI 2221. The dimension *Accuracy* also declines. With a growing possibility of solutions, the possibility of generating a model grows too, so there is a risk of making mistakes. Because of the dependencies between the product models, there is growing sensitivity along the product development process. The earlier a mistake or an inaccuracy is made, the more serious the consequences. This explains the downwards trend.

The dimension *Completeness* shows a continuously downwards trend because of the growing possibility of generating a model. There is a risk of forgetting an essential effect, which affects the completeness of the following models. The growing complexity increases the risk of missing essential information. Both reasons ensures a downwards trend in the dimension *Completeness*.

VDI 2221	level of information				quality of information			
					Intrinsic		Contextual	
	product		process	disturbances	Objectivity	Accuracy	Completeness	Value added
	used model	information						
clarify and define the task	function model	- partial functions - dependencies between partial functions - energies or signals between partial functions - Conduction/ transformation of energies or signals - conduct, convert or link energies or signals within a function	Planned usage process	- function fail - wrong granularity - missing partial function	very high	very high	very high	low
determine functions and their structures								
serach for solution principles and their combination	effect model	- physical, biological or chemical effects - parameter of the effects - equations of the effects - dependencies between effects		- missing effects - wrong effects are chosen - conflicting parameters because of the chosen effects	medium	medium	high	medium
divide into realisable modules	principle active model	- radius of action - geometric of bodies - motions of the bodies - active areas of the bodies - arrangement of the bodies		- wrong dimensioning of the bodies - friction, wear	low	low	medium	high
develop layouts of key modules	part model	- material properties - geometric properties - production methods - tolerances - design principles - assembly instructions		- temperature - corrosion - environmental influences - human influence - unintended effects	very low	very low	low	very high
complete overall layout								
prepare production and operating instructions								

Figure 6. level of information during the product development process

The dimension *Value-added* grows during the product development process, which is substantiated by the increasing concretion of the models. According to the FMEA, with concrete information a cause of an identified failure and the consequences to the costumer are much easier to identify because of the growing reference to the final product. The known disturbances also increase, which supports the analysis of a failure.

3.3 Requirements of FMEA types

A Functional FMEA is performed as soon as sufficient information is available to construct a functional model, as mentioned in the pyramid of the product models. The following information, as a minimum, is required (NASA, 2014):

- A functional block diagram of the item under development broken down to the subsystem and component level.
- A description of each function depicted in the functional block diagram, including required inputs and outputs for each block.
- The manner in which each of the required outputs can fail.
- The impact or effect of loss of each functional output depicted in the functional block diagram of the instrument.
- The compensating provisions designed into the item to mitigate the effects of a functional output failure.

A Design FMEA is performed when sufficiently detailed design information is available to identify all the constituent pieces and parts of the design item. In addition to the information necessary to perform a Functional FMEA, information about schematics and principles of operation for the design is required (NASA, 2014).
In order to perform a Process FMEA, process inputs, tasks and expected outcomes have to be developed sufficiently. The following information, as a minimum, is required (NASA, 2014):

- A detailed step-by-step procedure and flow chart for the process.
- A description of purpose of each step in the procedure, including required inputs and outputs.
- The manner in which each of the required steps can fail.
- The impact or effect of failure to achieve each output described in the procedure on the item or function being subjected to the process.
- The compensating provisions designed into the process to mitigate the effects of a process step failure.

3.4 Comparison of level and quality of information with requirements of FMEA

With the help of the identified level of information and depending on the progress of product development, the three types of FMEA can be allocated to a stage within the product development process (Figure 7).

A Functional FMEA needs a functional block diagram, including subsystems, such as inputs and outputs that are given by partial functions and their dependencies. The functions have to be described in order to perform a Functional FMEA. This information is also given by the transformation of energies and signals, so the Functional FMEA can be allocated to the first three working steps of VDI 2221.

In order to perform a Design FMEA, information about schematics and principles of operation for the design is required. The listed effects, such as the elements of the principle active model, contain this information so performing a Design FMEA is useful during the working steps three to six.

The overlapping area between Functional and Design FMEA refers to the requirement that the impact or effect of loss of each function has to be known. It is useful to perform a Functional FMEA, by considering the chosen effects, in order to analyse the impact or effect of loss of a function to define mitigation strategies. For example, when a partial function describes an energy transformation, it is good to know how the function is captured in the effect model. If the effect principle of the lever is used, it can be assumed that the customer will not be endangered by fluids. Risk from fluids could have occurred if the partial function is concretized by a hydraulic effect. This is why overlapping performance of the FMEAs is useful here.

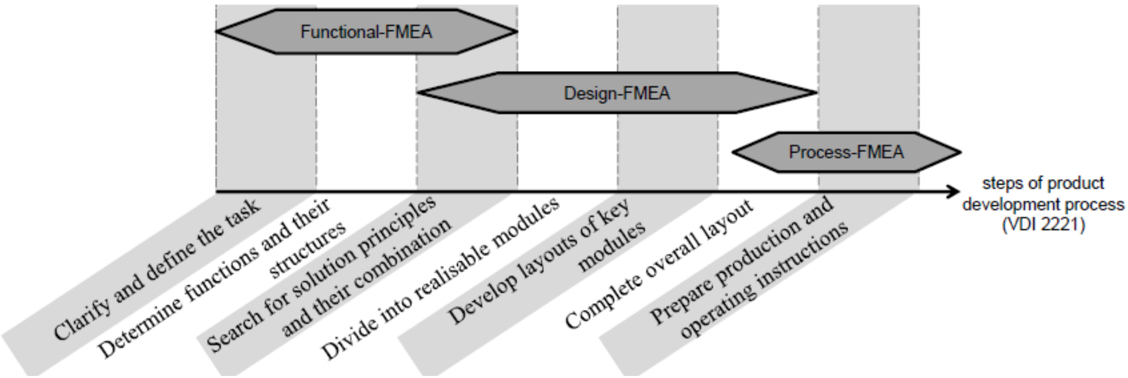

Figure 7. Allocation of the FMEA types to the product development process

In order to perform a Process FMEA, the production process has to be known, so it is useful to perform this type of FMEA at working step seven.

After allocation of the FMEAs to the product development process, a minimum level of quality of information has to be defined (Figure 9). First, the identified trends of the dimensions that represent the quality of information during the steps of product development are put together with the allocated FMEA types.

Compensation provisions have to be defined for each FMEA type. To identify the type, a minimum quality of information is necessary. For example, if a Functional FMEA is performed as early as possible, the Value-added part of the information is very low. Information is Value-added if its use fulfils a monetary objective. According to the FMEA, it is achieved if the information could indicate failures, for example. If it is performed at step one during the product development process, only information about clarifying the task is available. Value-added is very low where an analysis of compensation provisions is not possible, so a minimum Value-added is necessary. For the dimension Objectivity, a contrary argument is conducive. The Objectivity of information declines during the product development process because the modelling of an effect or a principle active model always depends on the point of view of the product developer. This implies that occurring failures cannot be detected, so a minimum level of Objectivity is necessary.

With this help, a minimum level of quality of information can be defined for each considered dimension, which is illustrated by the dashed lines in Figure 9. The possible range needed to perform an FMEA can be identified for each FMEA type, which is demonstrated by the striped area. If the rest of the dimensions are also considered in the optimization process, the possible range for performing a FMEA becomes smaller untl the ideal point in time is realised.
Costs per failure can also be integrated into the optimization process by filling in the cost curve in Figure 8 and minimizing them, as described above.

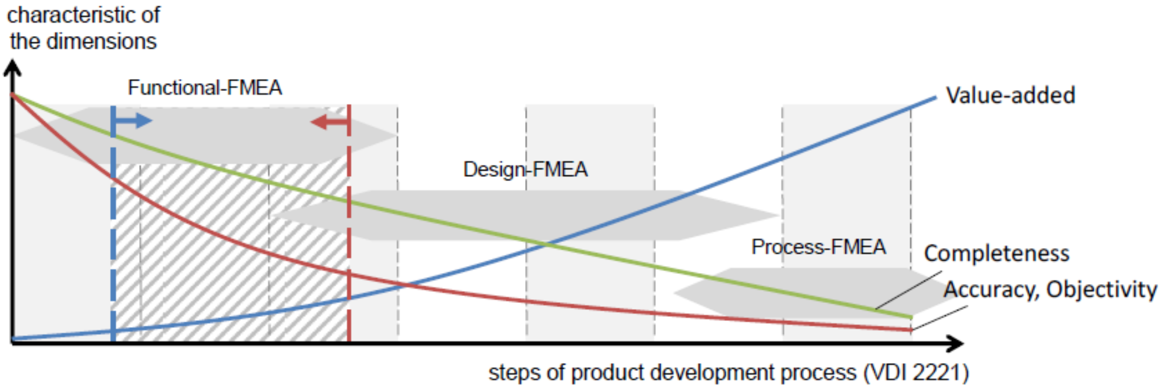

Figure 8.Optimization process to detect an ideal time to perform an FMEA

4. Evaluation of the approach

A pneumatic cylinder is used to evaluate the approach, which has to fulfill the use process lift a load. First, the level of information is illustrated using completed product models (Figure 9). The function model contains four partial functions, where energy is conducted three times and transformed once. The effects *Bernoulli's law, equation of continuity* and *stagnation pressure* realizes the concretization, for example, for the first partial function. In this context, it is possible that the effect stagnation pressure is incorrectly allocated. The allocation of stagnation pressure assumes that the air pressure is injected into partial function one, but it is possible that an allocation to partial function three is preferable. There is ambiguity where the air pressure is injected into the product. Because of the rising possibility of concretizing the partial functions, it could be that the effect *Coulomb friction* is missing. Both show that the dimensions *Objectivity* and *Accuracy* decline.

According to the dimension *Value-Added* the information concretizes the reference to the final product, especially at working step four. The more effects can be allocated to the functions, the better and more complete are the principle active and part models. With the help, the cause or effect on the customer of a failure can be analysed more comprehensively, so the dimension Value-added grows during the process of modelling. As shown in the example, modelling is a process in which information generation is delayed, which is why the dimensions change as well. According to the FMEA procedure, a minimum quality of information is necessary to fulfil the identified recommendations. For example, to perform a Functional FMEA, a minimum level of *Value-added* is necessary. This is accomplished if all partial functions are known, so the minimum level is set at the end of working step two. In the dimension Objectivity, the earlier a Functional FMEA is performed the lower the possibility of allocating incorrect effects.

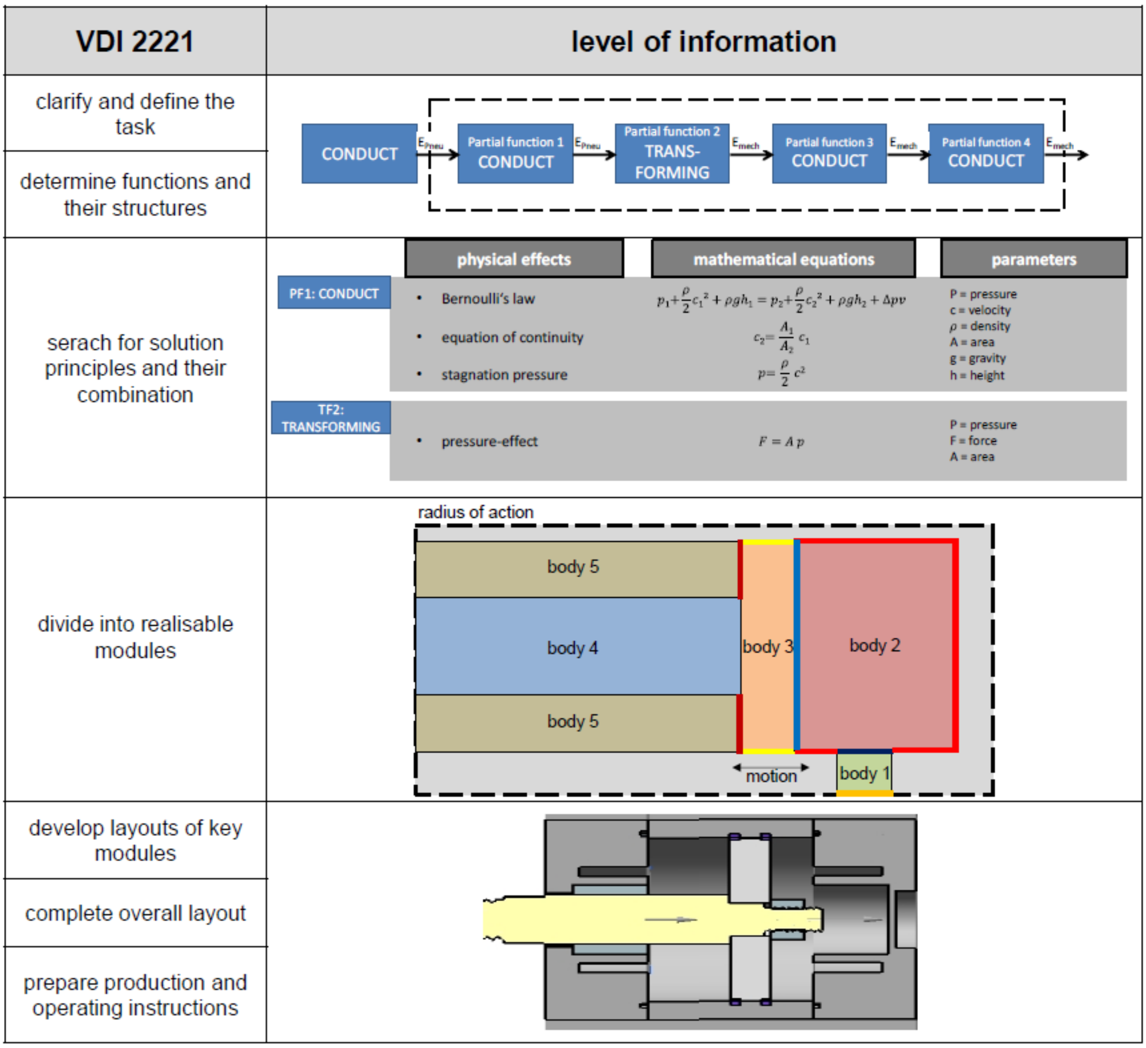

Figure 9. Completed product model of a pneumatic cylinder

5. Results

This paper showed an approach for systemising levels of information, such as the quality of information during the product development process, with the help of Heidemann's process model. Trends of different dimensions were considered. The level and quality of information was compared with the performance requirements of an FMEA. With this, it was possible to allocate the FMEA types to the product development process to determine the minimum quality of information required for each type. By defining the minimum information quality the possible range for each type is limited and can be optimized to an ideal point in time to perform each FMEA type (Figure 8).

6. Conclusions

The results demonstrate dependencies between the level of information, the quality of information using the IQ Framework and the requirements of the FMEA. The dependencies are used to identify trends of the dimensions during the product development process, which are used to optimize the point in time to perform an FMEA.

This is an important contribution to making products more robust because failures are analysed at the right time during the product development process. Designers have to think about the available level and quality of information used to perform an FMEA, so the product itself is analysed before the FMEA starts.

The approach can be used for every type of product where it is possible that the trends of the dimensions do not grow or decline continuously. In this context, more than one ideal point in time for performing an FMEA is possible.

In the future, this approach should be adapted into praxis to evaluate it. The identified trend in information quality during the product development process has to be quantified because the optimization process is based on it. For example, if a scale is defined at the level of information of a dimension the optimization process can be improved.

Acknowledgement

The results of this paper were produced by the Collaborative Research Centre SFB 805 "Control of uncertainty in load-carrying mechanical systems" in the project A1: Development of Models, Methods and Instruments for the Acquisition, Description and Evaluation of Uncertainties. We would like to thank the Deutsche Forschungsgemeinschaft (DFG) for founding and supporting the SFB 805.

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1st International Symposium on **Robust** Design
København, DK
14th-15th of August 2014

Sensitivity Analysis of Tolerances which Restrict Multiple Similar Features

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Keywords: Tolerancing, Tolerance Simulation, Sensitivity Analysis

Abstract

In tolerancing, the product quality has to be ensured in the presence of geometric variations of the product components. Therefore, tolerances restrict these geometric variations. Usually, functional key characteristics (FKC) are defined, most of them are geometric characteristics of the product. The required product quality then is ensured through requirements of the FKCs. Afterwards, geometric analyses of the FKC variations are performed employing tolerance simulations. These simulations have input parameters (geometric deviation parameters) and output parameters (FKC deviation parameters). To support the product developer in specifying suitable tolerances, sensitivity measures can quantify the impact of single tolerances with respect to a FKC (Ziegler and Wartzack, 2014). A common sensitivity analysis method bases on the conditional variance of the simulation output, which can be calculated by a number of different algorithms (Saltelli, et al, 2008).

Normally, a “tolerance object” is applied on one feature. In some cases, tolerances can restrict multiple geometry elements. In this case, multiple sensitivity values for the geometry elements are calculated by standard sensitivity analysis. This is disadvantageous if the influence of the tolerance which restricts the geometry elements is of interest, because the sensitivity values cannot be simply added together. This paper discusses the case, when a position tolerance is adopted on multiple similar geometry elements. A statistical sampling method for the sensitivity analysis algorithms is introduced. The method is adopted to a hole pattern to show its practical use.

1. Introduction

According to the axiom of manufacturing imprecisions (Srinivasan, 2003) “*all manufacturing processes are inherently imprecise and produce parts that vary*“. These variations can negatively influence the functions of the manufactured product. To avoid this, tolerances restrict these variations. Furthermore, tolerance management is the process of systematically analysing and specifying the tolerances with respect to the product functions. For this purpose, tolerance simulations support the tolerance expert by estimating the impact of geometric variations on the products functions.

As strict tolerances have an high impact on the product costs, it is very important to specify tolerances carefully. For specifying suitable tolerances, tolerance simulations consist of two

DOI:10.4122/dtu:2096

Reviewed by: *Simon Moritz Göhler*
Tobias Eifler

Cited as: Ziegler, P., and Wartzack, S., 2014. Sensitivity Analysis of Tolerances which Restrict Multiple Similar Features. In: Howard, T. J. and Eifler, T., ed. 2014. *Proceedings of the International Symposium on Robust Design - ISoRD14*. Copenhagen, Denmark. pp. 91-101.

different output quantities: First, the fulfilment of FKC-requirements is estimated. This can be done with worst-case methods (requirements fulfilled/not fulfilled) or with statistical methods (statistical process parameters, probability density estimations of critical dimensions, estimating the inappropriate parts per million, etc.). Second, sensitivity analysis is performed which characterises the influence of single tolerances on the fulfilment of requirements. Sensitivity analysis is a widely used method for analysing simulations in engineering.

2. Sensitivity Analysis

According to Saltelli, et al, (2000), "*sensitivity analysis studies the relationships between information flowing in and out of the model*". This generic definition is chosen here, because the influence of the model input parameters can be calculated with respect to different properties of the model output. There exists a wide variety of sensitivity analysis methods, for instance methods which estimate the impact of input parameters on the model output derivatives (Lockwood, 2012), on the model output variance (Saltelli, et al, 2008) or on the probability density function of the model output (Borgonovo, 2006). To ensure that a method is generally suitable for different models and different decision situations, Saltelli and Tarantola (2002) stated that sensitivity analysis methods should be "*global, quantitative and model free*".

While "local" sensitivity analysis methods only consider the model output variation for small variation of the input parameters, in "global" sensitivity analysis a neighbourhood of input parameters with its probability density function can be considered. A "model free" method requires no model properties like linearity or additivity, so it is independent of the kind of model. The former stated methods (derivative-, variance- and density-based) fulfil all three criteria of Saltelli and Tarantola. The most established method is the variance-based method, and therefore its strengths and weaknesses are best known. Therefore, the following approach is based on the variance-based sensitivity analysis method.

2.1 Variance-based Sensitivity Analysis

Variance-based sensitivity analysis measures, how much of the model output variance can be explained by the variation of a model input parameter. Basis for variance-based sensitivity analysis is the high dimensional model representation (HDMR) according to Sobol (Saltelli, et al, 2008). If the model has the form of a squared integrable function, the HDMR states that this function can be decomposed in orthogonal subfunctions, which are only dependent on input parameter subsets. The variance of the model output following also separates in parts, which can be assigned to subsets of input parameters. For an input parameter x_i the main effect sensitivity S_i is the part of the outputs variance, which only can be explained by the variation of this input parameter. The total effect sensitivity S_{Ti} of x_i is the part of the outputs variance, which can be explained by the variation of xi in combination with other input parameters. The sensitivity indices can be defined as terms of the conditional mean and conditional variance, what is briefly done in the following.

Let f be a generic model f:$(X_1,\ldots,X_n)\rightarrow Y$ with random variables $X_i \in [0;1]$ as input and the random variable Y as output. The variance $V(Y)$ of the model output then decomposes to

$$V(Y) = E\big(V(Y|X_i)\big) + V\big(E(Y|X_i)\big), \qquad (1)$$

where $E(Y|X_i)$ denotes the conditional expectation of Y with respect to X_i and $V(Y|X_i)$ the conditional variance of Y with respect to X_i, for further information see e. g. (Saltelli, et al, 2008). With the conditional expectation and variance, the main effect sensitivity S_i and total effect sensitivity S_{Ti} of the random variable X_i is defined as

$$S_i = \frac{V\big(E(Y|X_i)\big)}{V(Y)} \quad \text{and} \quad S_{T_i} = 1 - \frac{V\big(E(Y|\mathbf{X}_{\sim i})\big)}{V(Y)},$$

where $\boldsymbol{X}_{\sim i}$ denotes all input random variables aside from X_i. While the main effect represents the direct influence of the i^{th} random variable on Y, the total effect additionally considers interaction effects of the i^{th} variable with other input variables. Therefore, the total effect always is greater than or equal to the main effect $S_{Ti} \geq S_i$.

For estimating the sensitivity indices, there are two kinds of algorithms available: random number based (Sobol, Jansen) and spectral based (FAST, exFAST, RBD) algorithms (Saltelli, et al, 2008). Usually, spectral algorithms are more efficient and therefore have less computational costs than random number based ones.

2.2 Sensitivity Analysis in Tolerancing

According to Stuppy and Meerkamm (2009), there exist three common methods for sensitivity/contributor analysis (both terms are interchangeable) in tolerancing: Arithmetical contributor analysis, statistical contributor analysis and high-low-median (HLM) sensitivity analysis. All three are basis for sensitivity analysis in commercial tolerance software. However, these are local sensitivity analysis methods, so they do not fulfil the requirements of Saltelli for sensitivity analysis methods.

Furthermore, there exist only a few publications about global sensitivity analysis in tolerancing. Wu (1997) analyzed the impact of position tolerances on a functional characteristic. The approach is based on the averaged partial derivatives of polar coordinates for the position of a drill hole axis. However, this approach is limited to position tolerances and cannot be simply extended to other tolerances. Markvoort (2007) proposed to use variance-based sensitivity analysis in tolerancing, where a combination of response surface methods with the eFAST algorithm was preferred. Stockinger, et al, (2011) applied variance-based sensitivity analysis to an analytical expressed deviation model. However, the approach is performed with dimensional tolerances. Walter, et al, (2013) performed variance-based sensitivity analysis for a system in motion to identify interactions between the systems input parameters. However, the approach only considers dimensional tolerances and dynamic quantities and is also limited to the used vectorial tolerancing method. Caniou (2012) additional showed the practical use of global sensitivity analysis in tolerancing by an analytical expressed deviation model of an electrical pin. Variance-based and density-based sensitivity analysis in this context where compared and the influence of correlated input parameters was discussed. All sensitivity analysis approaches which are referred in this section are listed in Table 1.

Table 1. Sensitivity analysis methods in tolerancing

Sensitivity Analysis Methods		**Quantitative**	**Global**	**Model free***
In Commercial Software	High-Low-Median	Yes	No	No
	Arithmetic Contributor	Yes	No	No
	Statistical Contributor	Yes	No	No
In Scientific Publications	Derivative-based	Yes	Yes	No
	Variance-based	Yes	Yes	No
	Density-based	Yes	Yes	No
Variance-based with Deviation Characteristic		Yes	Yes	Yes

*For Tolerance Simulations, model free implies "*independent of the deviation representation model*"

2.2.1 The need for model free Sensitivity Analysis in Tolerancing

According to Wartzack, et al, (2011), the whole product lifecycle should be integrated into tolerance simulations. During the product development process the information about manufacturing and assembly processes steadily increases. This leads to an increasing complexity of tolerance simulations during the product development process, what may lead to a switch of the mathematical deviation representation. Following, the parameters which represent the geometrical deviations can change. In this context, sensitivity analysis results based on the deviation parameters of the tolerance simulation cannot be compared easily. Therefore, the former described global sensitivity analysis approaches in tolerancing are not model free in the sense, that they are not *independent of the deviation representation model.* A solution of this problem for assemblability studies is the model free sensitivity analysis approach based on the deviation characteristic (Ziegler and Wartzack, 2014).

2.3 Sensitivity Analysis based on the Deviation Characteristic

Framework for sensitivity analysis in this paper is to "*change the tolerance values, while all other conditions remain unchanged*" (e. g. the nominal geometry, the tolerance scheme, process parameters, etc.). Following, sensitivity analysis has to measure the connection between tolerance values and the FKC, while the influence of the kind of deviations indirectly is measured by the sensitivity indices of the tolerances (see Figure 1). For deviation representation models like Tolerance-Map® or Deviation Domain (Ameta, et al, 2011) or discrete deviation representation models based on Skin Model Shapes (Schleich, et al, 2014), consequently the parameters which control the deviating geometry are not considered by the sensitivity analysis.

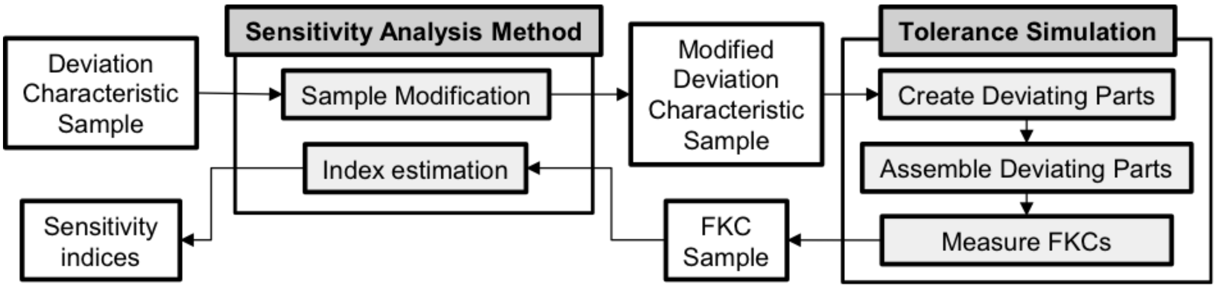

Figure 1. Sensitivity analysis process based on the deviation characteristic. The sensitivity analysis algorithm is "blind" for the simulation details, it only perceives the deviation characteristics and the measured FKCs.

2.3.1 Deviation Characteristic

Let f be a feature with an associated tolerance with tolerance value *t*. Let f_d be the mathematical representation for the manufactured feature which is associated with *f*. For the tolerance value *t'* which f_d just fulfils, the deviation characteristic is

$$\lambda_t(f_d) = \frac{t'}{t}. \qquad (2)$$

In Figure 2, the deviation characteristic λ_t for a deviating line is shown. The deviation characteristic 0.5 indicates, that the deviated line would fulfil a tolerance with the half tolerance value of *t*.

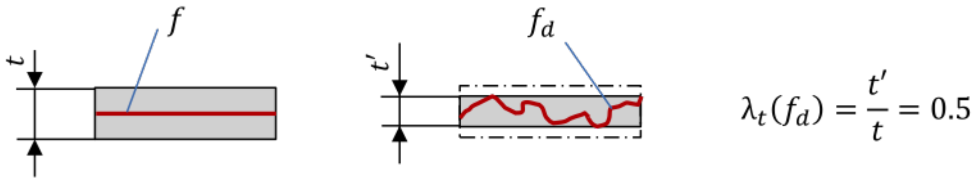

Figure 2. Tolerated line, associated deviated line and deviation characteristic.

The sensitivity analysis method then measures the relationship between the deviation characteristics of all adopted tolerances and the functional characteristics (Figure 1). The chosen deviation representation model and the virtual assembly representation is concealed for the sensitivity analysis algorithm. Therefore, the proposed sensitivity analysis method is independent from the chosen tolerance simulation (and associated parameters) and fulfils the *model free* requirement of Saltelli.

In the following, the Deviation Domain tolerance representation model (Ameta, et al, 2011) is basis for the sensitivity analysis. The model is widely used and capable of representing dimensional and geometric tolerances. The model represents deviating geometry elements (features) as transformation parameters for small displacements of the nominal geometry. A short outline of Deviation Domains with the explicit formulation of the deviation characteristic λ for this model can be found in (Ziegler and Wartzack, 2014).

3. Sensitivity Analysis of Feature Group Tolerances

In specifying the product's tolerances, often groups of features are restricted by one tolerance. This can have manufacturing reasons as for a hole pattern (Figure 3 a) or symmetric reasons as for two holes in a cylinder head for one pin (Figure 3 b). Furthermore, in these cases usually this scheme is invariable and only the tolerance value will be changed.

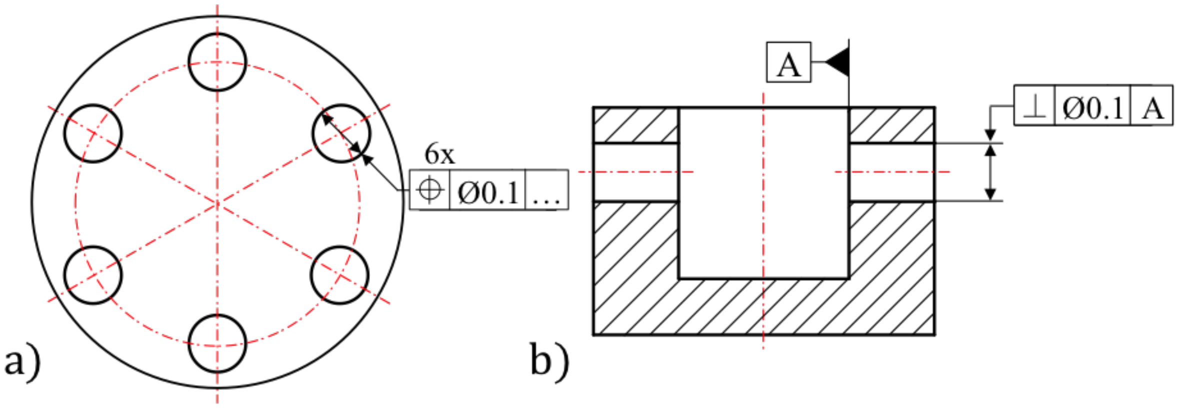

Figure 3. Examples for feature groups with one tolerance: a) position tolerance of a hole pattern and b) perpendicularity of two hole axes in a symmetric part

However, in a tolerance simulation deviations would be adopted independently on the individual together restricted features. Consequently, common sensitivity analysis would result in sensitivity indices for all deviating geometry elements.
In practice, a tolerance expert would possibly add the sensitivity values of the features together. This is problematic for the sensitivity total indices, because the total sensitivity indices consider interactions between parameters. These interactions would be summed multiple times, so the total effects would be overestimated (for more details see the Appendix). Following, the sensitivity values cannot be added together for tolerances of multiple features.

$$S_{T_I} \neq \sum_{i=1}^{n} S_{T_i} \text{ for } n \text{ features with } i \in \{1, \dots, n\}. \qquad (3)$$

Therefore, a possible approach is to define a deviation characteristic for a feature group with respect to the associated tolerance. For coherence with the definition of geometric tolerances, for a together tolerated group of n deviating features $\boldsymbol{f}_d = (f_d^1, \dots, f_d^n)$, the deviation characteristic λ_t is

$$\lambda_t(\boldsymbol{f}_d) = \lambda_t(f_d^1, \dots, f_d^n) = \max_{1 \le i \le n} \lambda_t(f_d^i). \qquad (4)$$

The deviation characteristic of a feature group can be formulated as the *maximal ratio of the tolerance value, for which all deviating features would be inside the associated tolerance zones.* An example can be seen in Figure 4, where a deviation characteristic of the axes from Figure 4 b) is shown. For both manufactured holes, the associated axes and their perpendicularity with respect to the datum A are measured. The maximum of both deviation characteristics is the deviation characteristic $\lambda_t = 0.8$ of the left axis, which is the quality of the together restricted feature group (f^1,f^2), where f^1 is the left axis and f^2 the right axis.

With this deviation characteristic, a FKC which is defined for a feature group can be measured. However, this measure also can be used for defining a sampling for the sensitivity analysis method. Thereby, the more uncertainty in the model is present, the more features and associated model parameters are evaluated together by the deviation characteristic. The dimensionality of these “hidden” parameters of the simulation is therefore not observed by the sensitivity analysis.

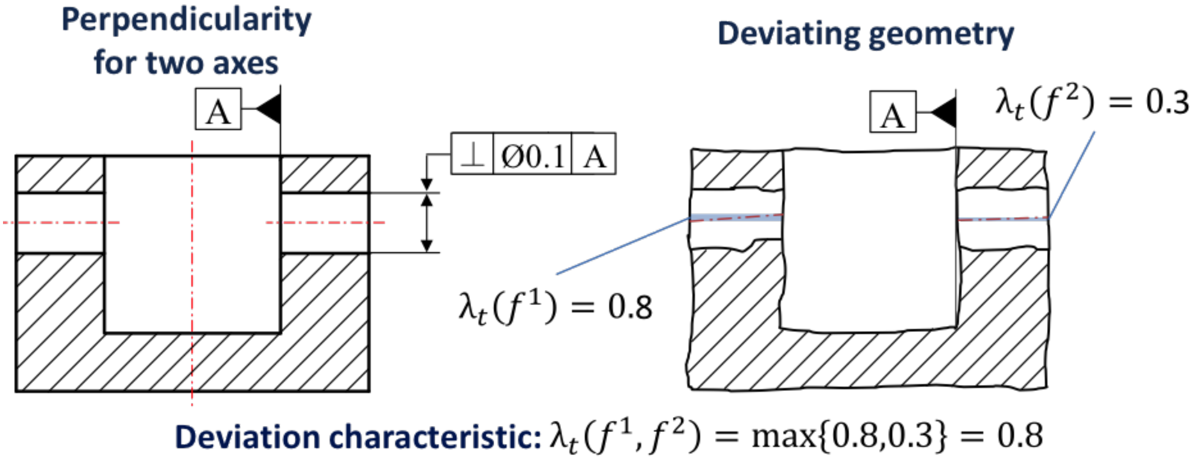

Figure 4. Exemplary deviation characteristic of the axes from Figure 3 b)

This is problematic if the “curse of dimensionality” appears. This term designates the phenomenon that analysis methods which require statistical significance become problems with rising dimensionality of the analysed model. This effect can also occur for the proposed model. In addition to the deviation parameters of the geometry, clearance deviations (not uniqueness of relative part positions due to clearance between the parts) can favour the appearance of the phenomenon. As the parameters which are responsible for the curse of dimensionality are hidden for the sensitivity analysis algorithm, the phenomenon is called “hidden” curse of dimensionality here. To reduce this effect, a simple and efficient countermeasure is presented in the following.

3.1 Avoiding the “Hidden” Curse of Dimensionality through coupled Deviation Characteristics

For reducing the unknown uncertainty of the model, one possibility is to reduce the number of free parameters of the simulation model. For this parameter reduction, global sensitivity analysis methods can also be used (Saltelli, et al, 2008). However, this can change the sensitivity analysis results if the fixed parameters are important. A model independent possibility is to couple all deviation characteristics of features which are restricted together by a tolerance, thus

$$\lambda_t(\boldsymbol{f}_d) = \lambda_t(f_d^1) = \lambda_t(f_d^2) = \ldots = \lambda_t(f_d^n), \quad (5)$$

in contrast to (4). This definition can be formulated following: *For generating a virtual set of jointly restricted deviating features, all deviating features have the same deviation quality but differ in the manifestation of the deviation*. An example for the part from Figure 3b) can be seen in Figure 5. The two generated deviating axes have the same deviation characteristic 0.8, but the manifestation of the deviation (in which direction the axes are tipped) can vary.

This approach reduces the number of free parameters significant and also if it has influence on the sensitivity analysis results, all considered features in the simulation still can vary. They just *vary together*, which means that all deviating features would hold the same tolerance value. Therefore interaction effects caused by the kind of deviations are still considered, only interactions caused by different deviation qualities are neglected. This is important, as the proposed sensitivity analysis based on the deviation characteristic has the distinction that a lot of interaction effects appear. In the chosen deviation representation model, for diameter parameters the problem arises that the kind of deviation is directly represented by the deviation characteristic. However, in this case coupled deviation characteristics can be seen as representations of systematic manufacturing errors and are therefore appropriate for feature groups.

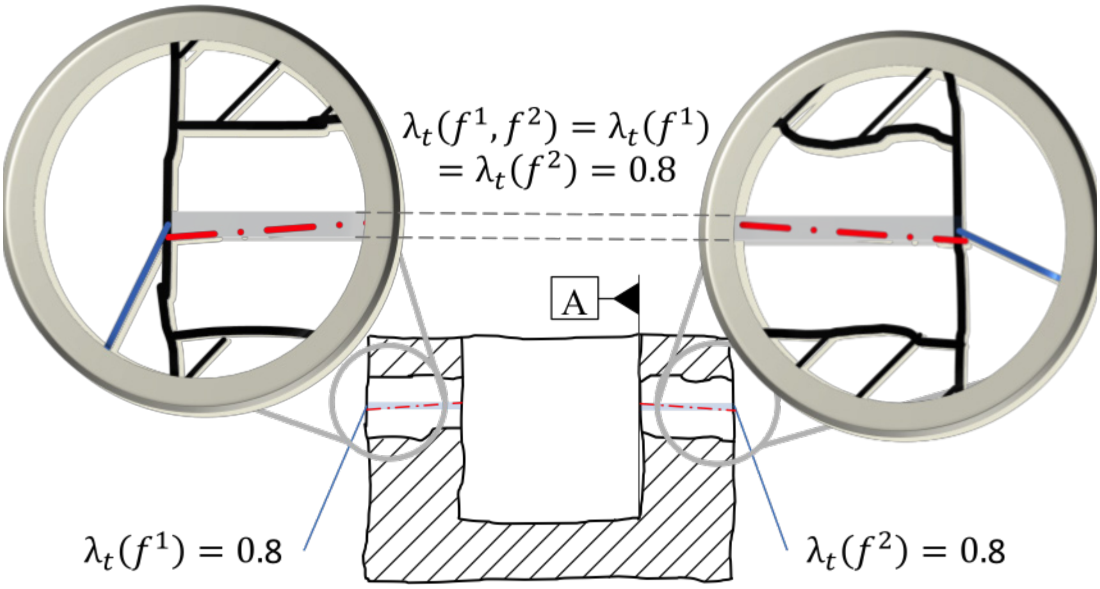

Figure 5. Generating two deviating axis for the example of Figure 3b): The deviation quality of the axes is equal, but they can vary in the tipping direction.

4. Application to Hole Pattern Tolerances

For demonstrating the proposed approach, the tolerances of a drill hole pattern are analysed in the following. In Figure 6, the geometry of the two plates and the three pins is shown. The drill holes are restricted by diameter tolerances and position tolerances for their axis. The pins have dimensional tolerances. Table 2 lists the tolerances with associated tolerance values. The diameter tolerances for the drill holes as well as the position tolerances for the drill hole axes are assigned for three features together, the pin diameter also is assigned for three pins. Aim of the tolerance expert is to reduce clearance between the two plates.

Note, that if the decision situation would not be considered and sensitivity analysis would be performed for every simulation parameter, there would be 21 sensitivity main and total indices. Additionally to the former discussed problems for decision making this would lead to higher estimation errors in the results.

Table 2. Tolerances of the application example

Tolerance	Part	Tolerance type	Tolerance value
t_d^u	upper plate	dimensional	0.3 mm
t_p^u	“	position	0.2 mm
t_d^l	lower plate	dimensional	0.3 mm
t_p^l	“	position	0.2 mm
t_d^p	pin	dimensional	0.3 mm

The functional key characteristic is the relative position of the upper plate with respect to the lower plate. Therefore, according to (Ziegler and Wartzack, 2014) the relative clearance domain volume of the upper plate with respect to the lower plate is defined as the output parameter of the assembly. The relative clearance domain volume is a parameter of higher order, which considers all translational and rotational deviations of a clearance together. The constraints for relative positions of the upper plate with respect to the lower plate can be formulated as

$$\text{distance}\left(\mathbf{a}_i^u - \mathbf{a}_i^l\right) \leq \frac{d_i^l + d_i^u}{2} - d_i^p, \qquad (6)$$

where i is the index of the pin-hole connection, $\mathbf{a}_i^{u/l}$ the axis of the i-th upper/lower hole and $d_i^{l/u/p}$ the diameter of the i-th upper plate hole/lower plate hole/pin. The geometrical context of formula (6) can be seen in Figure 6 (lower right) – the distance between the axes of the upper and the lower plate holes, which are connected by a pin, should be less or equal to the difference between the average of both hole diameters and the pin diameter. If this constraint holds, the pin fits in both holes.

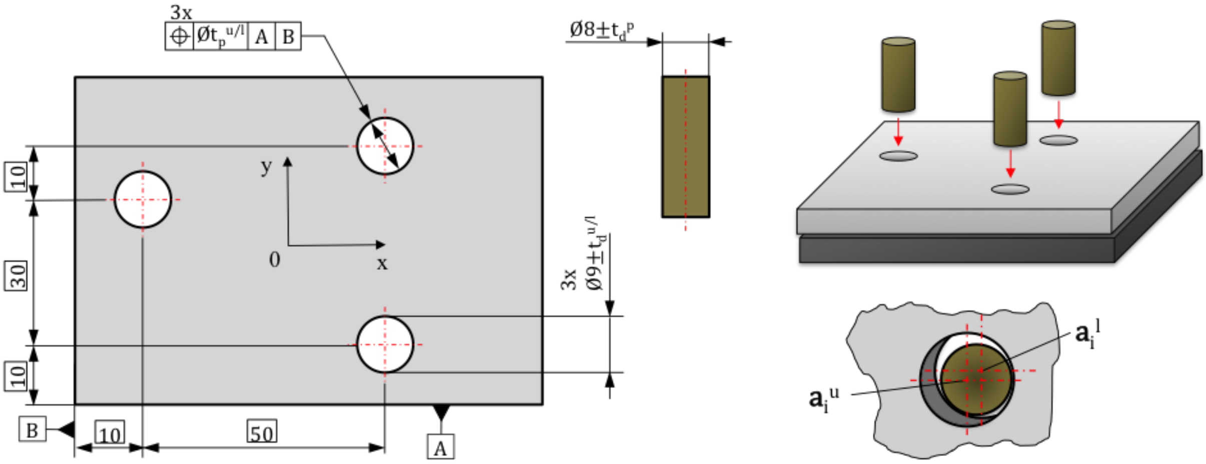

Figure 6. Considered tolerances of plates and pins (left), assembly (upper right) and geometrical context of constraint (6) (lower right)

The simulation was performed for 10,000 samples with sobol’s sequence, a quasi monte carlo sampling (Saltelli, et al, 2008). The deviation characteristics were sampled from an uniform distribution. The relative clearance domain volume, measure for all possible positions of the upper plate with respect to the lower plate, was estimated with a Monte Carlo filtering with 200 samples, from which 14 hit the clearance domain in nominal position.

Figure 7 shows the kernel density estimation of the relative clearance domain volume. There are no Monte Carlo samples with relative clearance domain volume zero, so all assemblies have clearance. Therefore, the second condition from (Ziegler and Wartzack, 2014) – a small number of unmountable assemblies – is met and the sensitivity analysis method can be performed.

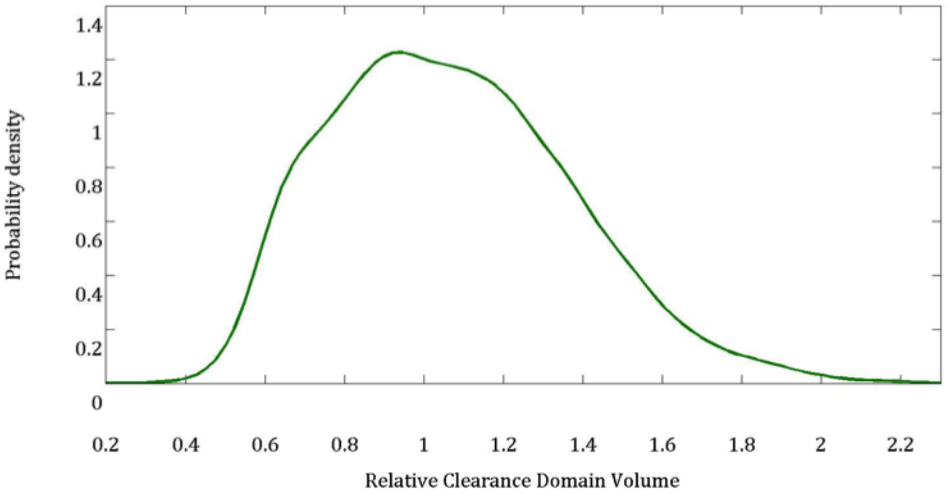

Figure 7. Kernel density estimation of the relative clearance domain volume

In Figure 8 the sensitivity indices for the five tolerances are shown. The sensitivity analysis showed small estimation errors already for 10,000 samples. As there are just little interaction effects between the tolerances, the relations between tolerances and FKC are nearly additive. The position tolerances have the lowest influence on the clearance. It is noticeable, that the pins diameter tolerance has significant higher influence as the diameter tolerances of the hole patterns. This can be explained with equation (6), where the hole pattern diameters are only considered with their half value, while the pin diameter is considered with full value. Resulting it can be stated, that for reducing the clearance, the pin diameter should be tolerated stricter.

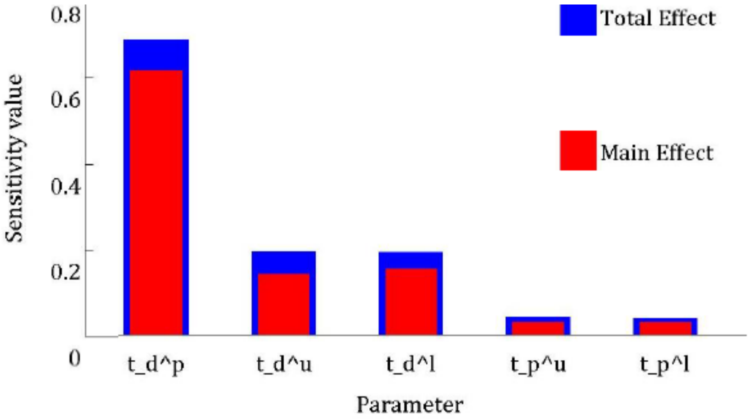

Figure 8. Sensitivity analysis results for the hole pattern and pin tolerances

5. Discussion and Conclusion

Basis for this paper was the situation that a tolerance restricts multiple similar features. The problem was displayed, that common global sensitivity analysis results cannot be simply added to get a sensitivity value for the feature group. A method to perform sensitivity analysis in this case was introduced and its practical use was shown for a drill hole pattern. The method is model free, which means it is “independent of the deviation representation model” (like Deviation Domain or Skin Model Shape). With the coupling of the deviation characteristics, the dimensionality of the input parameter space can be reduced. However, the proposed method is just a first step towards a better consideration of the tolerancing decision situation in sensitivity analysis.

Appendix

Originating from the HDMR, the variance *V(Y)* of the model output *Y* can be decomposed in the following way (Saltelli, et al, 2000):

$$V(Y) = V_1 + V_2 + \ldots + V_n + V_{12} + V_{13} + \ldots + V_{n-1\,n} + \ldots + V_{1\ldots n}. \tag{A1}$$

In this formulation, the total effect of the i-th random variable X_i can be expressed as the sum of its subvariances where the i-th index is considered

$$S_{T_i} = \frac{\sum_{i \in I} V_I}{V(Y)} \text{ where } I \subset \{1, \ldots, n\}. \tag{A2}$$

If for two parameters i and j the total effects are summed, their interaction terms are considered several times:

$$S_{T_i} + S_{T_j} = \frac{\sum_{i \in I} V_I}{V(Y)} + \frac{\sum_{j \in I} V_I}{V(Y)} = \frac{\sum_{\{i\} \cup \{j\} \subset I} V_I}{V(Y)} + \frac{\sum_{\{i,j\} \subset I} V_I}{V(Y)} = S_{T_{ij}} + \frac{\sum_{\{i,j\} \subset I} V_I}{V(Y)} \geq S_{T_{ij}}. \tag{A3}$$

Following, the total effects can only be added if the second term in (A3) (3rd term) becomes zero, what is only the case if there are no interaction effects of the i-th and j-th parameters. The simple application example in (Ziegler and Wartzack, 2014) already showed significant interaction effects, so the interaction terms generally cannot be neglected if sensitivity analysis based on the deviation characteristic is performed.

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1st International Symposium on **Robust** Design
København, DK
14th-15th of August 2014

Ahtola Industrial Research Project - Advanced Hybrid Method for the Tolerance Analysis of Complex Systems

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Abstract

Tolerancing decisions can profoundly impact the quality, the cost of the product and the number of scraps in mass production. Designers want tight tolerances to assure product performance; manufacturers prefer loose tolerances to reduce cost. There is a critical need for a quantitative design tool for specifying tolerances. Tolerance analysis brings the engineering design requirements and manufacturing capabilities together in a common model, where the effects of tolerance specifications on both design and manufacturing requirements can be evaluated quantitatively.

Current commercial software are not able to provide a tolerance analysis of complex overconstrained mechanism without simplifying the behavior model. The aim of the AHTOLA project is to provide methods to treat industrial cases using complex numerical modeling of mechanical behavior. This project is centered on problem of complementary industrial partners (Pierburg, Valeo SE, Radiall SA) from various fields of application (automotive for Valeo SE and Pierburg, aeronautic for Radiall SA).

The main scientific challenge concerns the development of hybrid approaches mixing worst case and probabilistic approaches to propagate stochastic and epistemic uncertainties for tolerance analysis (stochastic uncertainties = component variations ; epistemic uncertainties = gap configurations). The challenge is the deal between both and the probability computation in an acceptable computer time and managing the accuracy of the results.

1. Introduction

As technology increases and performance requirements continually tighten, the cost and the required precision of assemblies increase as well. There is a strong need for increased attention to tolerance design in order to enable high-precision assemblies to be manufactured at lower costs. Due to the variations associated with manufacturing process, it is not possible to attain the theoretical dimensions in a repetitive manner. It causes a degradation of functional characteristics of the product. In order to ensure the desired behavior and the functional requirements of the system in spite of variations, the component features are assigned a tolerance zone within which the value of the feature i.e. situation and intrinsic lie.

DOI:10.4122/dtu:2097

Reviewed by: *Thomas J. Howard*
Tobias Eifler

Cited as: Dumas, A., Dantan, J.-Y. and Gayton, N., 2014. Ahtola Industrial Research Project - Advanced Hybrid Method for the Tolerance Analysis of Complex Systems. In: Howard, T. J. and Eifler, T., ed. 2014. *Proceedings of the International Symposium on Robust Design - ISoRD14.* Copenhagen, Denmark. pp. 103-110.

Therefore, tolerance analysis is a key element in industry for improving product quality and decreasing the manufacturing cost. In addition, it participates to an eco-aware attitude since it allows industrials to manage and reduce scrap in production. Tolerance analysis concerns the verification of the value of functional requirements after tolerance has been specified on each component. Currently, this verification is totally dependent on the models chosen before. Currently, trial runs or very simple simulation models (1D linear tolerance charts for example) are used to check the quality criterion. This approach can be called into question: the trial runs are very costly and time consuming. Researchers have recognized the inefficiency of such simple simulation models based on explicit system response function which represents the variation accumulation. For complex systems, determination of explicit system response function is very complex, whereas this determination is easy for an open kinematic chain without gap. Research efforts have been devoted to developing an efficient simulation model for tolerance analysis.

Currently, the developed approaches depend on the type of geometrical model and on the type of system response function or simulation model (behavior model). Therefore, their scopes are limited and some problems are not addressed. Moreover, the industrial practices are based on the decomposition of the system kinematic configurations and the simplification of the system response function which are not efficient.

The main objective of the AHTOLA proposal is to develop hybrid approaches for a large scope which are independent of the type of system response function or simulation model (explicit or implicit functions, linear or nonlinear, analytic functions or numerical simulations). Those approaches have to be based on:

- worst case analysis approaches like Solution Space Exploration based on Interval Reduction Methods (Numerical Quantified Constraint Satisfaction Problem – Box consistency, …), Solution Space Exploration based on Evolutionary Methods (Genetic algorithm, …), and … to assess the worst gap configurations regarding to the assemblability and the functional requirements.
- probabilistic approaches like Simulation based method (Monte Carlo Simulation …), Most probable point based methods (FORM-SORM), Multi-FORM, FORM system, Meta-modeling based method (Kriging …), to estimate the probability of system conformity based on the process capabilities or statistical distributions of component deviations.

AHTOLA (ANR-11-MONU-013) is a national research project funded by ANR (French National Research Agency). AHTOLA includes 2 academic institutions (Arts et Métiers ParisTech – LCFC and IFMA – Institut Pascal), one Industrial Engineering Consulting firm (PHIMECA) and, finally, three French corporations (Valeo SE, Radiall SA & Pierburg) that represent the constellation of companies operating in highly dynamic industrial sectors.

The paper is organized as follows: Section 2 describes the mathematical issue and the project position. Section 3 shows a result comparison between two resolution methods.

2. Classification of issues & unified mathematical formulation

In this section, we propose a classification of issues of tolerance analysis based on the type of the behavior model with deviations. The behavior model is the assembly response function which represents the deviation accumulation. It could be an explicit analytic expression, an implicit analytic expression, or numerical simulation for which it is possible to compute a value for some functional characteristics given values of part deviations and gaps.

Tolerance analysis concerns the verification of the value of functional requirements after tolerance has been specified on each component. To do so, it is necessary to simulate the influences of component deviations on the geometrical behavior and the functional characteristics of the mechanism. The geometrical behavior model needs to be aware of the surface deviations of each component (situation deviations and intrinsic deviations) and relative displacements between components according to the gap. The model used in this paper is a parameterization of deviations from theoretic geometry, the real geometry of parts is apprehended by a variation of the nominal geometry.

The deviation of component surfaces, the gaps between components and the functional characteristics are described by parameters:

- $\boldsymbol{X}=\{x_1, x_2, …., x_n\}$ are the parameters which represent each deviation (such as situation deviations or/and intrinsic deviations) of the components making up the mechanism. Situation deviations correspond with the orientation and position deviation of a substitute surface with respect to a system reference. Intrinsic deviations are specific to the substitute surface, for example the diameter of a pin corresponds with an intrinsic deviation.
- $\boldsymbol{G}=\{g_1, g_2, …., g_m\}$ are the parameters which represent each gap between components. They model the possible displacement in orientation and position between two substitute surfaces.

In the case of analytic formulation, the mathematical formulation of tolerance analysis takes into account the influence of geometrical deviations on the geometrical behavior of the mechanism and on the geometrical product requirements; all these physical phenomena are modeled by constraints on the parameters:

- $C_c(\boldsymbol{X,G}) = 0$: Composition relations of displacements in the various topological loops express the geometrical behavior of the mechanism. They define compatibility equations between the deviations and the gaps. The set of compatibility equations, obtained by the application of composition relation to the various cycles, makes a system of linear equations. So that the system of linear equations admits a solution, it is necessary that compatibility equations are checked.
- $C_i(\boldsymbol{X,G}) \leq 0$ *and* $C_{i'}(\boldsymbol{X,G}) = 0$: Interface constraints limit the geometrical behavior of the mechanism and characterize non-interference or association between substitute surfaces, which are nominally in contact. These interface constraints limit the gaps between substitute surfaces. In the case of floating contact, the relative positions of substitute surfaces are constrained technologically by the non-interference, the interface constraints result in inequations. In the case of slipping and fixed contact, the relative positions of substitute surfaces are constrained technologically in a given configuration by a mechanical action. An association models this type of contact; the interface constraints result in equations.
- $Cf(\boldsymbol{X,G}) \leq 0$: The functional requirement limits the orientation and the location between surfaces, which are in functional relation. This requirement is a condition on the relative displacements between these surfaces. This condition could be expressed by constraints, which are inequations.

Mechanism can be divided into two main categories in terms of degree of freedom: isoconstrained mechanisms, and overconstrained mechanisms. Given their impact on the mathematical formulation for the problem of tolerance analysis, a brief discussion of these two types is given by (Ballu, et al., 2009) :

- “Isoconstrained mechanisms are quite easy to grasp. Geometrical deviations within such products do not lead to assembly problems; the deviations are independent and the degrees of freedom catch the deviations. When considering small deviations, functional deviations may be expressed by linear functions of the deviations.”
- “Considering overconstrained mechanisms is much more complex. Assembly problems occur and the expression of the functional deviations is no more linear. Depending on the value of the manufacturing deviations:
  - the assembly is feasible or not;
  - the worst configuration of contacts is not unique for a given functional deviation.
  - For each overconstrained loop, events on the deviations have to be determined:
  - events ensuring assembly,
  - events corresponding to the different worst configurations of contacts. As there are different configurations, the expression of the functional deviation cannot be linear.”

Therefore, in the case of analytic formulation for isoconstrained mechanisms or for simple overconstrained mechanism, it is possible to transform the previous formulation into an explicit function which is the assembly response function: $Y=f(\mathbf{X})$ where Y is the response (characteristic such as gap or functional characteristics) of the assembly. Figure 1. shows an isoconstrained mechanism whose functional characteristic Y is simply expressed by two geometrical deivations:

$$Y = f(\mathbf{X}) = x_2 - x_1 \tag{1}$$

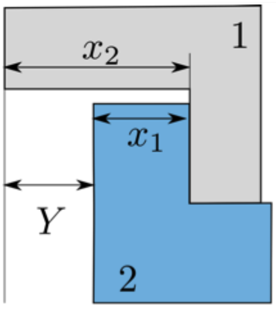

Figure 1. Example of isoconstrained mechanism

However, for overconstrained mechanisms, the functional characteristic cannot be expressed by a simple function. Figure 2. shows an overconstrained mechanism whose characteristic Y depends on the geometrical deviation values and on the configuration of mechanism. That is why the behavior model is considered implicit.

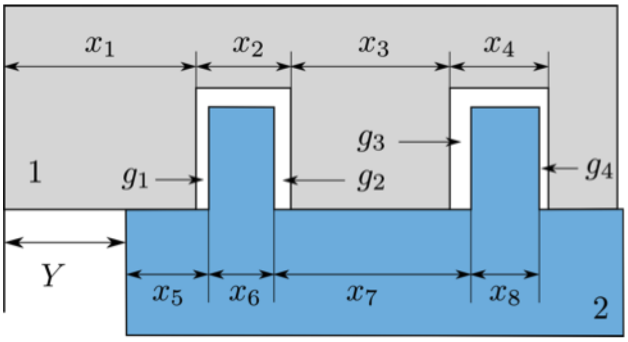

Figure 2. Example of overconstrained mechanism

In such mechanism, a possible compatibility equation is as follows:

$$C_c(\mathbf{X},\mathbf{G}) = x2 - x6 - g1 - g2 = 0 \tag{2}$$

Interface constraints in this simple example correspond with all gaps being positives:

$$C_i(\boldsymbol{X},\boldsymbol{G}) = -g_i \leq 0 \;\; \forall i = 1,\ldots,4 \qquad (3)$$

In some cases, the geometrical deviations impact some non-geometrical functional requirements. To simulate the influences of geometrical deviations on these requirements, an analytic formulation cannot possibly be employed. To do so, it is necessary to use numerical simulation for which it is possible to compute a value for Y given values of deviations and gaps: $Y=f_{numerical\ simmilation}(\boldsymbol{X})$ or $Y=f_{numerical\ simmilation}(\boldsymbol{X},\boldsymbol{G})$

In summary, the Figure 1 illustrates the issue classification and the link between these issues and the identified approaches in the previous section.

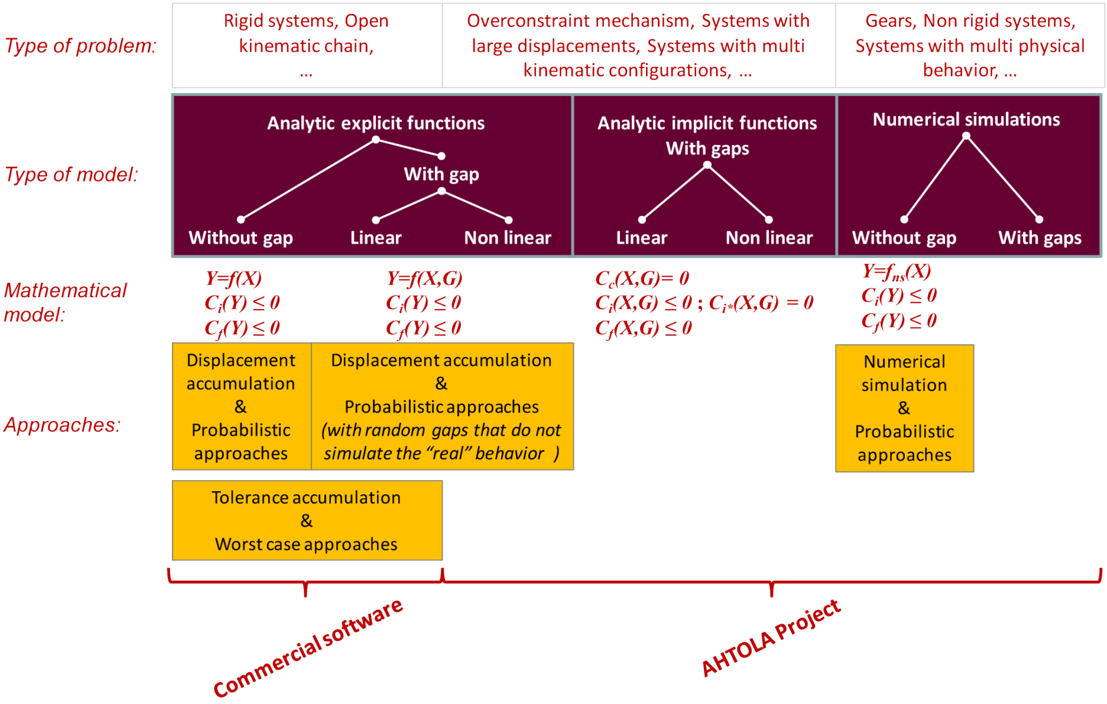

Figure 3. Overview of issues and tolerance analysis approaches.

Currently, few methods exist to study overconstrained mechanisms. The project is mainly devoted to develop tolerance analysis method to deal with this kind of mechanisms modeled by implicit analytic function. The method must be based on probabilistic approach. Indeed, to improve the tolerancing process in an industrial context, there exists a strong need for statistical tolerance analysis to estimate the probability expressed in ppm (defected product per million) with high-precision computed at lower cost. Two probabilities are considered:

- P_A: the probability of the assemblability for a given tolerance specification. Let AC be the event that the assemblability condition for a given assembly is respected. The condition of the assemblability describes the essential condition for the existence of gaps that ensure the assembly of the components in the presence of the part deviations. In order for a mechanism to assemble successfully, the different components in the presence of deviations should assemble without interference and should have a specific set of gaps that characterize the instance of the assembly. This condition stipulates the use of an existential quantifier for an initial search for the existence of a feasible configuration of gaps: “there exists an admissible gap configuration of the mechanism such that the assembly requirement (interface constraints) and the compatibility equations are respected” (Assemblability condition). The probability expression is written as follows:

$$P_A = P(AC) = P(C_c(\mathbf{X},\mathbf{G}) = 0 \cap C_i(\mathbf{X},\mathbf{G}) \leq 0 \cap C_{i^*}(\mathbf{X},\mathbf{G}) = 0) \qquad (4)$$

G is considered as free parameters

- P_{FR}: the probability of respect of the functional requirements. Let FC be the event that the functional condition are fulfilled. Once a mechanism assembles, in order to evaluate its performance under the influence of the deviations, it is necessary to describe an additional condition that evaluates its core functioning with respect to the basic product requirements. In terms of the tolerance analysis, the basic requirement becomes the maximum or minimum clearance on a required feature that would have an impact on the mechanism’s performance. The most essential condition therefore becomes that for all the possible gap configurations of the given set of components that assemble together, the functional condition imposed must be respected. In terms of quantification needs, in order to represent all possible gap configurations, the universal quantifier is required: “for all admissible gap configurations of the mechanism, the geometrical behavior and the functional requirement are respected” (functional condition). The probability expression is written as follows:’

$$P_{FR} = P(FC) = P(C_f(\mathbf{X},\mathbf{G}) \leq 0,\ \forall \mathbf{G} \in \mathbb{R}^m \{C_c(\mathbf{X},\mathbf{G}) = 0 \cap C_i(\mathbf{X},\mathbf{G}) \leq 0 \cap C_{i^*}(\mathbf{X},\mathbf{G}) = 0\}) \quad (3)$$

Two analysis methods are used in AHTOLA project:

- Monte Carlo simulation combined with an optimization algorithm in order to find the worst configuration for the functional requirement or to check if there exists a configuration of gaps verifying all constraints.
- The First Order Reliability Method (FORM) for systems is also used. The mechanism is decomposed into its main configurations of contact points. It is then possible to apply a system reliability method. This technique only works when verifying the functional requirement.

3. Industrial application

The application is based on a gear pump, see Figure 4, which has two parts positioned with two pins. The positioning of these two parts has an influence on the angle of both gear axes. The functionality of the pump can be reduced if the assembly precision of the parts is insufficient. Based on this pump, a simplified overconstrained mechanism is studied. Figure 2 shows the mechanism with amplified gaps between parts. The functional condition concerns the deviation of the point G of part (1) with respect to part (2). This point G can be seen as a functional point that is representative of one axis of the gear pump.

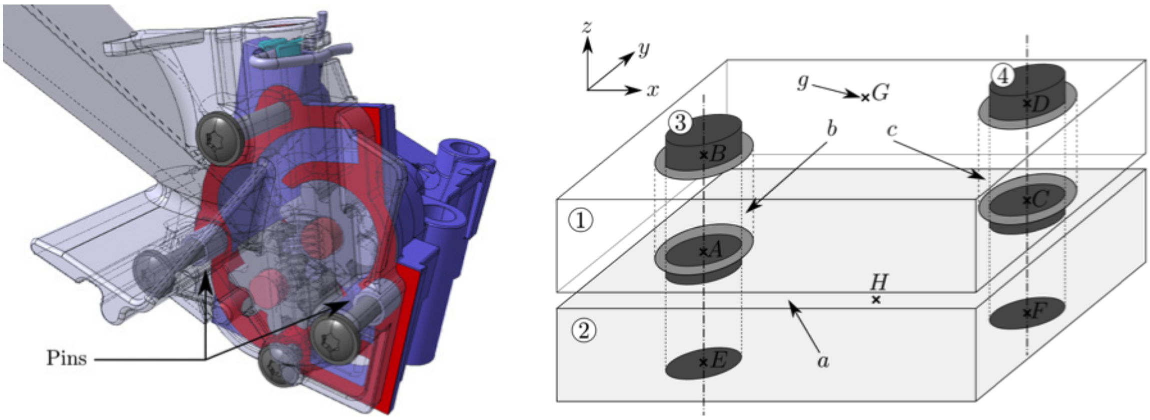

Figure 4. Full pump view with the simplified studied mechanism.

Both pins are fixed in part (2), so there are only gaps between part (1) and the pins. The planar contact is assumed to be perfect, so only the kinematic displacements of the joint are considered. Geometrical deviations are applied to surfaces a, b, c and g.
Characteristics of the mathematical behavior model are listed below:

- 38 random variables following a Gaussian distribution X ~ N(μX, σX).
- 15 gap variables ***G*** which are the optimizations parameters.
- 12 compatibility equations $C_c(\boldsymbol{X},\boldsymbol{G}) = 0$
- 4 quadratic interface constraints $C_i(\boldsymbol{X},\boldsymbol{G}) \leq 0$ which give N_c = 160 interface constraints after applying a linearization procedure.

Table 1. Comparison of results between two resolution methods.

	Monte Carlo simulation		FORM for systems
	Assembly	Functional	Functional
Probability of failure (ppm)	42	9.4	9.3
95% confidence interval	6.9	1.7	-
Computing time	3.5 days	3.5 days	2.35 min

The system method developed in the project in very efficient but it only allows dealing with the functional requirement so far.

4. Conclusion

The AHTOLA project aims at providing methodological solutions to deal with the tolerance analysis of overconstrained mechanisms. Currently, commercial software are not able to consider this kind of mechanism without great simplifications. The goal of the project is to propose a global method able to model the geometrical behavior of overconstrained mechanism using constraints on parameters and to provide the probability of failure using efficient methods. The solution method includes a Monte Carlo simulation combined with an optimization algorithm, this technique is able to deal with a large number of problem. For the functional requirement a system formulation has been developed in order to apply system reliability methods able to provide results faster than with the Monte Carlo simulation.

Acknowledgments

The authors acknowledge the support of ANR ``AHTOLA” project (ANR-11- MONU-013).

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1st International Symposium on Robust Design
København, DK
14th-15th of August 2014

Systematic Method for Axiomatic Robustness-Testing (SMART)

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Keywords: Robust Design, Axiomatic Design, Taguchi Method, Design for Reliability (DFR), Design for Six Sigma (DFSS), Product Development Process (PDP)

Abstract

SMART (Systematic Method for Axiomatic Robustness-Testing) is a method for the development of robust and reliable products. It combines elements from the robust design methodology with a holistic approach by using Axiomatic Design (AD) and the Taguchi Method (TM). These two methods were established and expanded by N.P. Suh (1990) (AD) and G. Taguchi (1949) (TM). SMART is based on the chronological sequence of the four phases of the Product Development Process (planning, conception, design and development) according to the VDI Guideline 2221. Using this chronological basis, the three process steps (System, Parameter and Tolerance Design) of the Taguchi Method are classified and integrated accordingly. The AD method is applied to the systematic examination of the robustness of designs.

During the conceptual stage, one or more designs are generated by means of AD. AD also helps analyze the design's complexity from the perspective of possible design modifications, thus assuring robust solutions. If a design has already been generated but needs improvement as things developed, AD is used as well. The design may not necessarily be changed in its basic structure but is examined in terms of its complexity. The results of AD support the setup of the P-Diagram according to Taguchi either after the conceptual stage or the design stage of the product.

The following step is the Design of Experiments (DoE) of the product's design parameters and noise factors that occur during its utilization. Testing may either be carried out by virtual or real tests. After analyzing the results of the tests, the design should be optimized accordingly in order to increase the robustness. A predicted reliability determination is possible as well.

The last step is the adjustment of the tolerances of the design for cost optimization purposes. After a final robust design has been established, the actual durability and reliability of the design can be determined on the basis of reliability testing using Design for Reliability (DFR) methods.

Basically, SMART can be used both in the initial stages as well as in the more developed stages of the development process.

DOI:10.4122/dtu:2098

Reviewed by: *Simon Moritz Göhler*
Tobias Eifler

Cited as: Kemmler, S. and Bertsche, B., 2014. Systematic Method for Axiomatic Robustness-Testing (SMART). In: Howard, T. J. and Eifler, T., ed. 2014. *Proceedings of the International Symposium on Robust Design - ISoRD14*. Copenhagen, Denmark. pp. 111-122.

1. Introduction

Product requirements grow with customer requirements. Thus, systems become more complex, but the demands for quality, reliability, safety and energy efficiency increase. In order to meet these requirements, the priority must be on the designing of robust products and their Design Parameters (DP) in the Product Development Process (PDP).

Here, a design can be realized by different DPs to meet customer requirements, Customer Attributes (CAs), or Function Requirements (FRs). The target of robust product development is to find the setting levels of DPs, in which the Ideal Functions (IFs) are insensitive to Noise Factors (NFs). This means that the spread of IFs has to be independent of the spread of the DPs (Yang, 2007). Here, for example, a DP of the design B determines a greater spread of the FR as a DP of design A; see Figure 1. In this example, the design B would be preferable for a robust design of the FR.

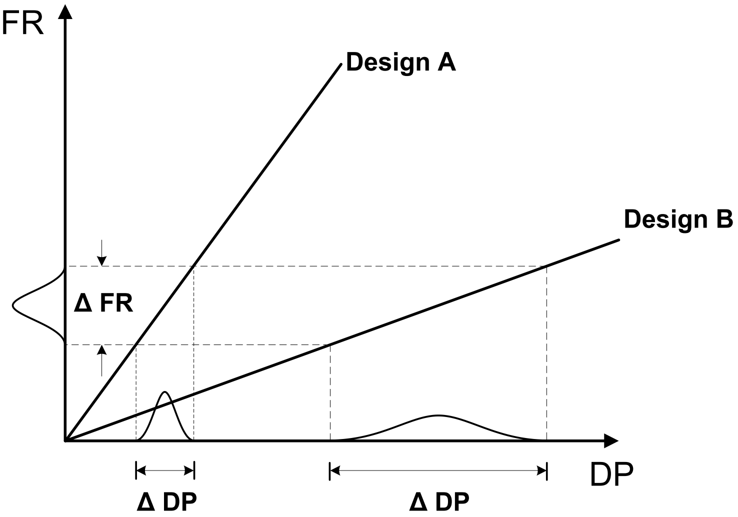


Figure 1. Robust-Design of an FR distribution from two designs (Suh, 2001)

For this purpose, two aspects must be considered. On the one hand, DPs need to be defined so that the possible design is insensitive (robust) to the NFs they are exposed to in practice. Second, whether an optimum of these parameters exists with regard to the product or the CAs must be clarified.

In order to clarify these aspects during early stages of product development, a systematic approach is required. The Systematic Method for Axiomatic Robustness Testing (SMART) is an approach with which robust products can be designed. In this case, SMART is oriented to the established methods of Robust Design methodology (Bergman, 2009) and combines Axiomatic Design (AD) of N. P. Suh [1990] and the Taguchi Method (TM) by G. Taguchi (1949). In addition, SMART applies other methods, such as Design of Experiments (DoE) or tolerance analysis. Those are components of both Design for Six Sigma (DFSS) as well as Design for Reliability (DFR) (Matthew, 2014). Using these methods, SMART may design reliability-centered robust products.

2. Guideline VDI2221 and Robust Design Methods

2.1 Guideline VDI2221

Guideline VDI2221, Verein Deutscher Ingenieure (VDI) [Association of German Engineers], recommends an approach to developing and designing new products. Figure 2 (VDI, 1993) shows a flow chart for this procedure at the bottom. The four stages describe the chronological sequence which has to be done to design a successful product in its development process. The four phases of Planning (Phase I), Conceptual Design (Phase II), Embodiment Design (Phase III) and Detailed Design (Phase IV) are of primary importance. These four phases represent the chronology of SMART, as illustrated in Figure 2.

In order to get from one phase to the other, the previous one must be completed. Several iterations within a phase are possible to achieve the desired goal.
The commonly-used design stages in the industry can also be assigned to the respective phases. Therefore, the labels A-, B-, C-, D-Sample and Start-of-Production (SOP) are used. A-Sample represents a conceptual design which can be used as a functional sample and for concept validation. B-Sample is equal to A-Sample. However, it is suitable for first testing in the overall concept and on the test. The mounting dimensions conform to the series. C-Sample is equal to B-Sample, but it safely achieves the specifications (tasks). Its parts consist of standard tools and near-manufacturing process. D-Sample is a design which consists of standard parts for the series and complies with the quality requirements which are statistically validated (Hab, 2013).

At the end of the System Design Phase, which corresponds chronologically to the Conceptual Design, the A-Sample is available. It is prepared to confirm the design concept and is not suited for durability testing. At the beginning of the Parameter Design Phase, which corresponds chronologically to the Embodiment Design, the A-Sample as well the B-Sample are available. The final B-Sample can be created at the end of the Tolerance Design Phase, Detailed Design Phase, which could also be used for durability testing; see Figure 2.

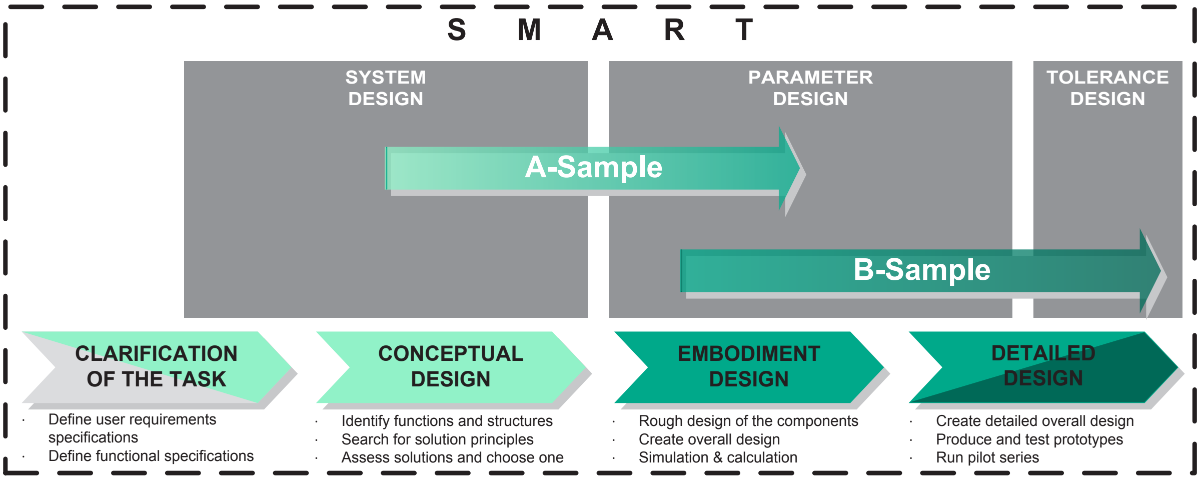
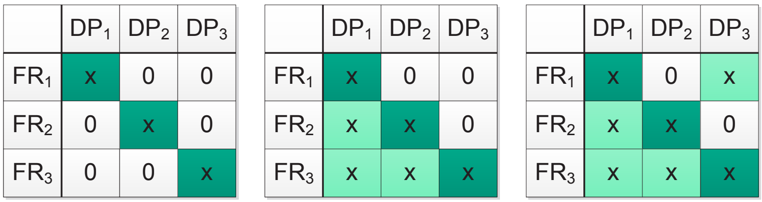


Figure 2. Three phases of Taguchi and SMART and the four phases after Guideline VDI2221 as a chronology

2.2 Taguchi Method

The Taguchi Method (TM) is a method of Robust Design methodology and was developed by G. Taguchi in the 1950s. Originally, the motivation was designing robust processes. Over the years, however, this method gained more and more importance for designing robust products. In his approach, Taguchi describes developing these products according to the three phases of development System Design (SD), Parameter Design (PD) and Tolerance Design (TD) (Fowlkes, 1995). Here, in the SD phase, the concept is developed regarding the product requirements. This phase can be chronologically assigned to the part of the Clarification of the Task phase and the Conceptual Design phase according to Guideline VDI2221; see Figure 2. If the concept or the design is already defined, the DPs can be determined and examined in more detail in the second phase, PD. This phase can be chronologically assigned to the Embodiment Design and partly to the Detailed Design of Guideline VDI2221.



	DP_1	DP_2	DP_3
FR_1	x	0	0
FR_2	0	x	0
FR_3	0	0	x

Uncoupled Design

	DP_1	DP_2	DP_3
FR_1	x	0	0
FR_2	x	x	0
FR_3	x	x	x

Decoupled Design

	DP_1	DP_2	DP_3
FR_1	x	0	x
FR_2	x	x	0
FR_3	x	x	x

Coupled Design

Figure 3. Comparison of the three design matrices according to the AD

Once the design parameters are identified to the extent that an optimum of the setting can be found, this phase is completed by the robustness analysis. Thus, the next step is the final phase, TD. In TD, a compromise must be found between the design tolerances and the design costs which are needed for the manufacturing process of the overall design (Fowlkes, 1995). Here, the design tolerance limits can either be further restricted or, ideally, expanded. Only at the end of the TD phase, when the robust design has been finally determined in terms of cost optimization and action can steps for implementation be recommended.

2.3 Axiomatic Design

AD is a Robust Design method for a structured and goal-oriented structured approach in the research, development and design. It can be classified according to its basic approach in the Design Systematics in VDI2221 to VDI2225 and VDI2206 (Morgenstern, 2009). In general, AD is a tool for managing the complexity of development (Tasi, 2009).

P. Milling (Milling, 1981) describes the complexity with the example of non-linearity whereby the complexity of a system increases as the number of elements and their links as well as their functionality increase. However, it must be noted that in today's developments, the complexity is enforced due to product and cost requirements and thus cannot always be avoided. Therefore, a compromise between these two aspects must be found, with the result that the complexity cannot be avoided. In this case, an Uncoupled Design, see Figure 3, cannot be achieved in most designs.

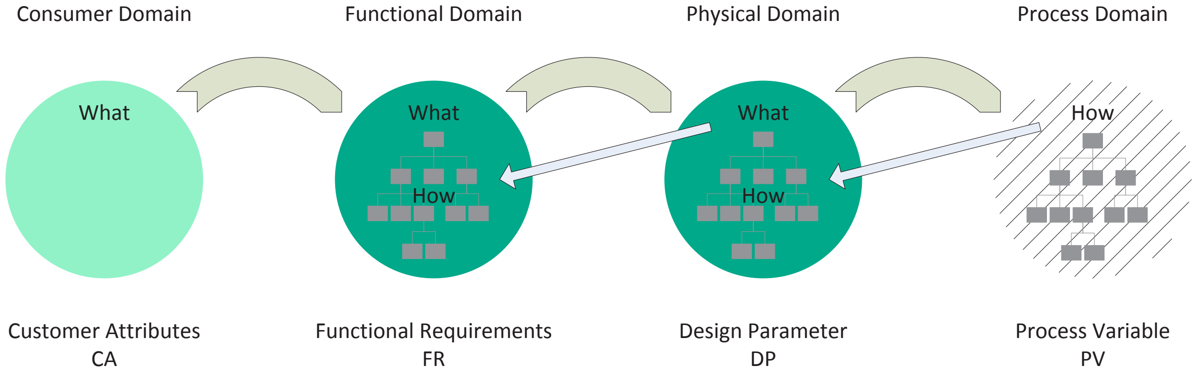


Figure 4. Four domains of the design world (based on Gumus, 2005)

The basis of AD consists of four domains (Consumer, Functional, Physical and Process Domain), see Figure 4. Using the Zig-Zag Method, one can jump back and forth between the domains to create the reconciliation for the subsequent domain. With the question "How can we achieve it?" the step to the next, correct domain is made. The question: "What does one achieve?" is oriented in the opposite direction, i.e. to the left domain; see Figure 4 (Suh, 2001).

Using AD, the relationship between the FRs and the DPs are described. This has the great advantage that a system or design is described at the functional level. For the following link, which describes the interference between the FRs and the DPs, the Design Matrix is selected as the representation of the form; see Figure 3, (Park, 2006).

If, at the beginning, no design or concept, SD phase, exists, a design can be converted to an Uncoupled Design by AD. This means that a feature request is to be implemented only through a DP. This has the distinct advantage that it can be designed independently of the other DPs. If you cannot avoid complexity in the system, these can be identified and described through the Coupled Design. If a design can be described almost in the structure of a Decoupled Design, one attains the information that there is at least one sequence in which the DPs must be implemented to ensure that the functional independence of the FRs involved is guaranteed. AD can be used as a stand-alone method for designing robust products. Due to the identification of complex contexts, AD should also be integrated only as an aid of a functional system analysis in SMART. Distinction must be made as to whether a design has already been in existence or a new design needs to be developed. Thus, AD has to be adjusted in his approach to the respective phase, System Design Phase or Parameter Design Phase, see section 3.

3. Systematic Method for Axiomatic Robustness-Testing (SMART)

SMART is based on the chronological sequence of the PDP of the VDI Guideline 2221 and at the three phases SD, PD and TD according to Taguchi. On the one hand, the systematic product development is guaranteed by the PDP and, on the other hand, it allows the introduction to the product development by the three successive phases of development.

3.1 System Design Phase in SMART

The basis of AD consists of four domains (Consumer, Functional, Physical and Process Domain). The Consumer, the Functional and the Physical Domain are significant for SMART. Defining process variables so that they can be ignored is not relevant for the design of robust products. As a first step, the Functional Requirements (FRs) and their respective Design Parameters (DPs) should be defined from the Customer Requirements (CRs). Immediately after that, the Design Matrix is set up; see Figure 5. The Design Matrix is reviewed by the Independence Axiom to see if it is satisfactory: If that is not the case, a detour over the reorganization of the Design Matrix must be taken, if possible. The reorganization can be done with algorithms by Suh, Lee, Acclaro or Benavides (Benavides, 2011 and Lee, 2006). Only if that effort proves unsuccessful should the affected DPs be redefined or new design levels in the Design Matrix implemented, in order to remove couplings.

If there are several designs, and hence several Design Matrices, they must be compared with each other using the Information Axiom in the interest of finding the best design. This could be implemented by testing or using probability calculations.

The transition into the second phase, the Parameter Design Phase, is made when the information content is satisfactory. Otherwise, a new loop in the System Design must be performed until a satisfactory A-Sample design has been defined.

AD in System Design Phase is used for designing a possible uncomplicated and Decoupled Design, ideally an Uncoupled Design. These DPs and their FRs can still be sufficiently redefined in the design phase with a link.

In the first step, you need information about the specifications that are assigned to the product's FRs is needed, in which the customer demands are listed. Subsequently, the FRs are weighted at the top level. Important and in the further step, all possible DPs can be listed using a morphological approach in order to design the respective FR contribution determined to realize a satisfactory low complexity. With the help of Independence and the Information Axiom, the decision can be made on a satisfactory design thereafter. During the definition of FRs and DPs, the two axioms should be considered by the system designer by default; otherwise more DPs would need to be determined and checked again with the above axioms. The Independence Axiom states that the FRs should be independent. The Information Axiom states that the information content of the design is to be minimized (Suh, 2001).

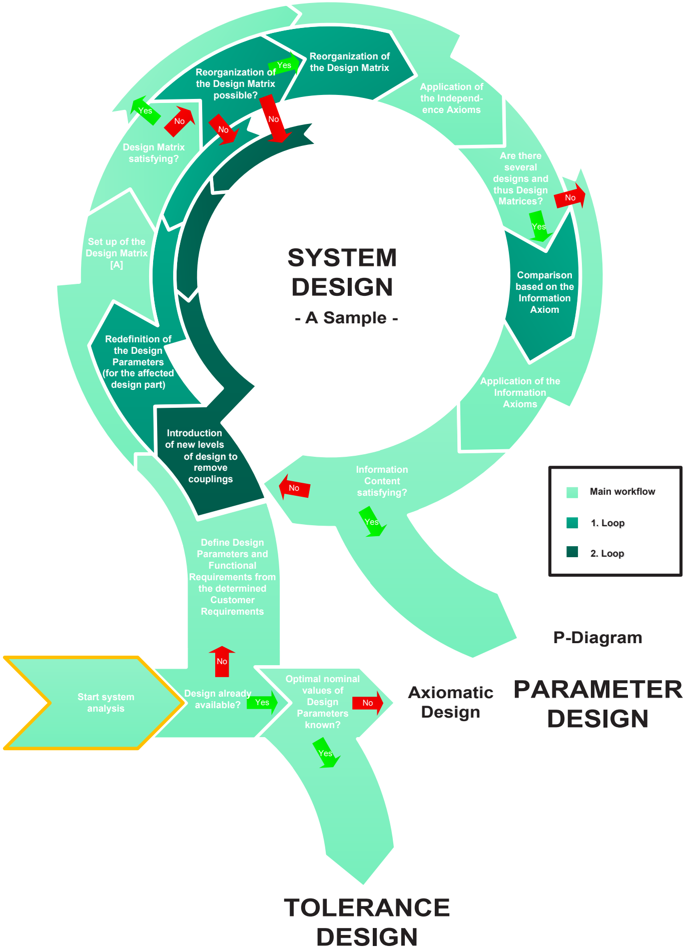


Figure 5. SMART – System Design

Developing more designs or concepts is recommended, so it may be a possible recourse in further product development of an alternative design.

3.2 Parameter Design Phase in SMART

The entry into the Parameter Design Phase of SMART can be made directly, if a concept or a design already exists and the optimal DPs are yet to be found; see Figure 6. In the case of entering directly at a later stage of the product development, AD should be used to reveal any design errors or to improve the given design; see Figure 6.

AD in the Parameter Design Phase is generally used for functional system analysis of the existing design. It is used only if SMART is applied at a later stage of the product development. As in the System Design, the FR-DP pairs can be set up using the Zig-Zag method. Depending on the development stage, the links of the identified FRs and DPs are available only when logically derived and verified using the laws of physics: If a prototype already exists, they are confirmed by DoE. The logical derivation can be expressed by the question: “Has DP been designed so that FR is affected?“

In addition, the Design Matrix is set up and, by using the Independence Axiom, the decision is taken whether the design is satisfactory. If the design is unsatisfactory, any design errors should be detected and improved. Following that, it can be transferred via the P-Diagram in the Taguchi experimental design to determine the robust design.

The mutual connecting hub is the P-Diagram. It illustrates the relationship between the Signal Factors (SFs), the Control Factors (CFs), the Noise Factors (NFs) and the desired Ideal Function (IF) (Fowlkes, 1995). The main advantage of this classification is the structural identification of the DPs according to their characteristics and functional connections. Therefore, AD may serve as a kind of filter. Due to the definition of DPs in AD all CFs can be identified through Customer Requirements or the requirements list. As a consequence, the remaining parameters can be assigned to the SFs and NFs.

In the next step, the TM describes the DoE based on the results of the P-Diagram. As mentioned previously, the P-Diagram represents a holistic consideration of all incoming and outgoing variables of the system. Under certain circumstances, not all factors can be considered for the DoE. Due to the fact that some critical factors are already identified with AD, investigating these should be preferred. The experiments are carried out and the results analyzed. If an optimization and a technical feasibility are both possible, the A-Sample design can be optimized by means of the experimental results. At this chronological step, the B-Sample is defined. The robustness of the B-Sample design is verified by confirmation experiments. However, when there is no prospect of an optimization or technical feasibility of the design, the P-Diagram needs to be examined again. In concrete terms, this means that the P-Diagram should be complemented with new findings from the first loop and possibly unrecognized factors should be added to the new DoE.

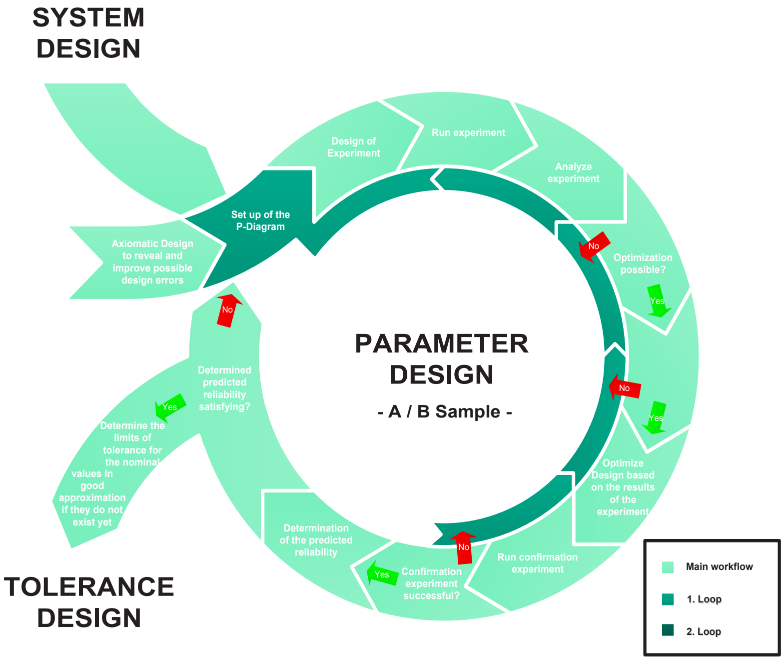


Figure 6. SMART – Parameter Design

The conclusion of the Parameter Design is carried out by one or more confirmation experiments. The way into the last phase, Tolerance Design, is open when the completion of the confirmation experiments is successful. Otherwise, another iteration must be carried out. The confirmation experiments could be carried out either by real or simulative experiments. It should be noted that the simulative experiments must be validated at a later time. At this chronological step, the B-Sample is defined. A predicted reliability determination is also possible after successfully completed confirmation experiments. At this state of the defined design, the reliability can be predicted to random failures and fatigue failures, which are based on simulation models. According to the predicted reliability, a first assumption of the reliability test-strategy can be given.

3.3 Tolerance Design Phase in SMART

The last stage of SMART can be entered either through successful confirmation experiments or directly with the knowledge of an optimal parameter setting, TD, commences. First, however, tolerance limits for the nominal values in good approximation need to be established for the given optimal parameters, if they do not already exist.

At the beginning, the Loss Functions of the design tolerances according to Taguchi should be set up; see Figure 7. Afterwards, the design tolerances which are sensitive to changing performances, should be narrowed. These design tolerances can be both manufacturing tolerances and process tolerances. With regard to the definition of the tolerance limits, a good compromise between narrowing the tolerances and the technical feasibility should be found. What follows is a cost optimization by expanding other tolerances which are not sensitive to changing performances. Steps of action regarding the design of the product can be recommended, if a good compromise between robustness, costs and technical feasibility is found.

After a final robust design has been established, the actual durability or reliability of the design can be determined and the more detailed reliability test-strategy can be provided on this basis.

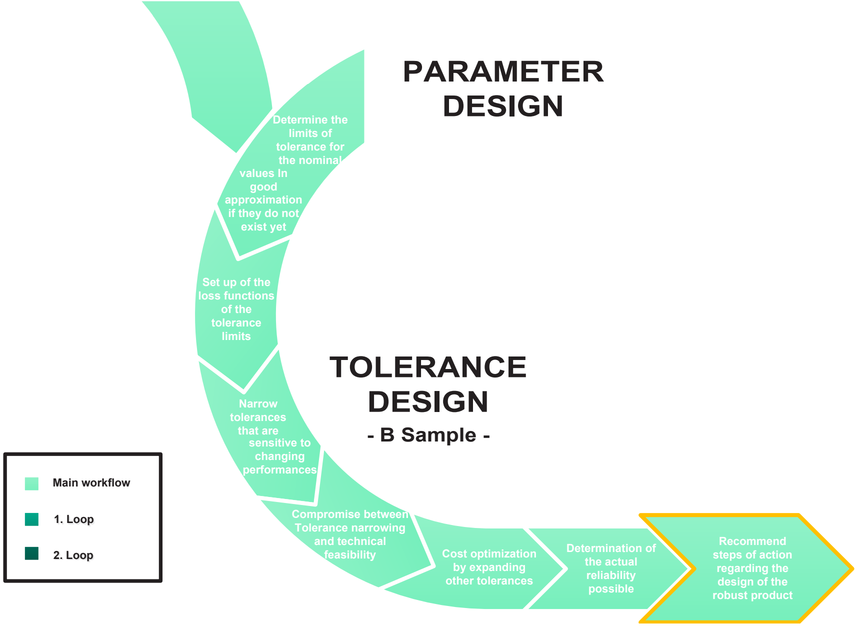


Figure 7. SMART – Tolerance Design

3.4 The holistic method

Figure 8 illustrates the overall layout of SMART and gives a more detailed approach. SMART is illustrated in the shape of a circular roadmap, which will help to improve the comprehensibility of the basic procedure. More detailed views and descriptions of the various phases are presented in the previous subsections.

The starting point of SMART lies in the middle of Figure 8. If there is no design available as SMART begins, the roadmap leads the way into the System Design. In this phase, the circular loop is run iteratively until the desired design is determined.

The transition to the second circular loop, PD, is represented by the P-Diagram according to Taguchi. Additionally, it is also used as an entry into SMART at a later stage of the PDP. The objective of this loop is a robust setting of the DP. If the objective is achieved, the path leads into the last phase of SMART, TD. This stage of development could also be entered directly. The tolerances of the design are optimized in this final stage with respect to the cost aspect.

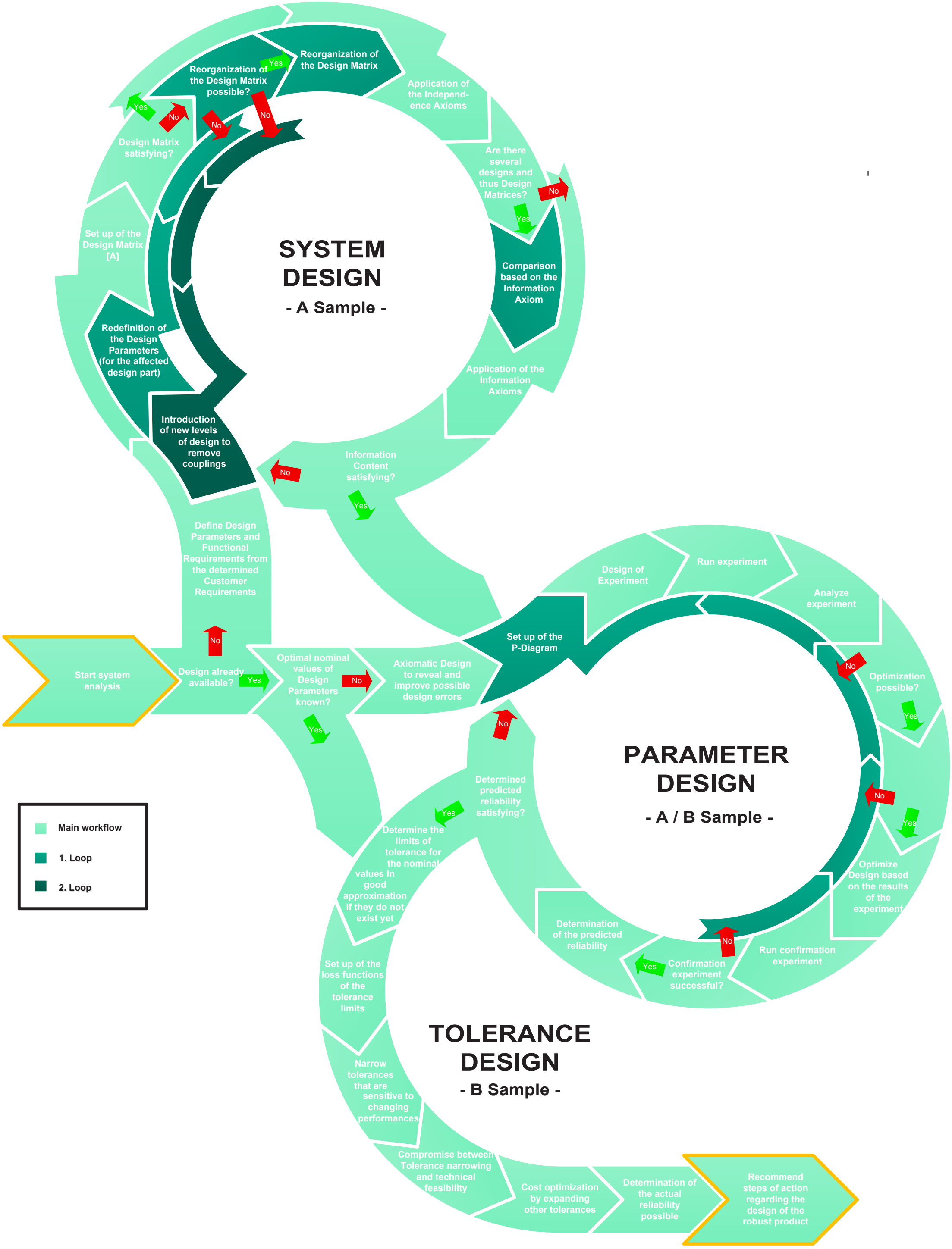


Figure 8. SMART – Overview

More specifically, this means some of the tolerances could either be narrowed or, at best, be widened. Additionally, at the end of the PD, as well as at the end of the TD, the reliability of random failures and fatigue failures can be determined. Furthermore, the reliability test strategy can be provided.

4. Discussion

SMART is based on established methods and procedures according to VDI2221 and the TM. In addition, it integrates the Robust Design method AD. Hence, SMART refers to already successfully applied methods and experiences. Compared to the known and established methods, SMART goes even further by adapting and combining these methods to a holistic approach.
AD was developed by N.P. Suh et al. as a Robust Design method that can be used independently. However, AD is not transparent when applying it to today's products. A complex design cannot be ruled out with regard to the aspects of implementation of Customer Requirements and cost minimization. Additionally, the application of AD to a complex design cannot be implemented without a considerable amount of time. Therefore, AD has to be adjusted according to its approach. Within SMART, AD is used as a system analysis tool. With the aid of AD, a design can be analyzed on a functional level, in order to achieve a Decoupled, ideally an Uncoupled, Design. Furthermore, AD contributes to a better system understanding with respect to its functions and reveals possible design errors if necessary.

Another great advantage of SMART is the TD procedure. The TM specifies ways of implementation, which, however, require a more detailed description. A clear tolerance design procedure has yet to be described sufficiently.

Two conflicts of objectives have been discussed in the approach of SMART. On the one hand, a compromise between the complexity and the given conditions for development must be found. The need for high functional density with low possible design space forces the developer to design complex products. On the other hand, the technical feasibility conflicts with complexity. A robust optimum of the DPs, ready for manufacturing, cannot always be achieved. Thus, the technical feasibility should always be checked in the Parameter Design phase. In addition, the process tolerances that result from the manufacturing must also be considered during the definition of the production tolerances. SMART considers these aspects and leads the user to initial steps in designing robust products in early development stages. No additional effort during the implementation of the product is given in later phases.

If, for example, the DPs are not yet known or cannot be defined, SMART enables the DPs to be defined in early development stages without great financial effort. This frontloading is supported by appropriate simulation models. Since sensitive DPs are already identified by the simulation and the confirmation experiments, real experiments could be planned better and reliability can be predicted more accurately. This allows the testing costs to be reduced as the system behavior regarding resilience can more likely be estimated early in the design process.

5. Conclusions and future research

In this paper, SMART is presented as a holistic and reliability-oriented method for the design of robust products. SMART is based on and combines the two established methods of the VDI2221 guideline as a chronological sequence with the four phases of the PDP and the TM with the three phases of the offline quality control. In addition, SMART arranges the Sample Phases to the respective phases of the chronological sequence of the VDI2221 guideline as well to the three phases of the Taguchi Method. In this way, SMART allows the integration of existing experiences from verified procedures, on the one hand and, on the other, the entry into the respective phase and therefore the entry into the use of SMART.

In addition, AD is adjusted to the given development stage. It has been shown how AD can be applied to achieve the goal of a robust design.

It should be noted that SMART provides a way to find not only an optimized robust design but also a compromise in terms of costs and technical feasibility (manufacturing), which will be discussed as well.
SMART is applied to a technical design and has been situated in the PD phase so far, which allows all the described steps to be successfully confirmed. In the next step, the TD phase is applied and further developed to describe the previously mentioned compromise in detail. Finally, the method should be verified in its overall approach based on a technical example.

Acknowledgments

The authors thank Lukas Coulon (B.Sc.) for his intensive cooperation, and his constructive comments and suggestions.

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1st International Symposium on Robust Design
København, DK
14th-15th of August 2014

A Framework for the Application of Robust Design Methods and Tools

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Keywords: Robust Design, Classification, Facets, Methods and Tools

Abstract

Robust Design (RD) Methods have become a powerful concept to design more reliable products. However, there is still confusion and doubts in the industry about the use and effectiveness of these methods. Mostly the problems experienced in industry are related to a poor application or knowledge of the methods by the companies. Expectations to the output are sometimes misleading and imply the incorrect utilization of tools. A framework for the application of tools and methods typically associated with Robust Design Methodology (RDM) in the literature is provided in this paper. It is proposed to organize the tools and methods by means of a faceted classification in terms of their purpose and premise. An example is used to illustrate the differences of the facets. This framework clarifies the underlying premises of RD tools for professionals working with design processes and can serve as guidance for an organization on how to structure its development process and how to make most efficient use of the existing tools.

1. Introduction

The idea of Robust Design is to reduce a design's sensitivity to variation and noise factors. Generally, these can be categorized as manufacturing and assembly variations, load deformations, variation due to ambient conditions and variation over time (Ebro et al., 2012). Arvidsson and Gremyr (2008) summarized the principles of robust design methodology as awareness of variation, insensitivity to noise factors, application of various methods and application in all stages of a design process. They defined Robust Design Methodology as "systematic efforts to achieve insensitivity to noise factors" (Arvidsson and Gremyr, 2008). Robust Design Methodology (RDM) has a long tradition since Quality Engineering pioneer Taguchi first started to promote the principles in the 1950s adapting the signal to noise ratio from communication systems. RDM spread firstly over Japan and then to Western industries, mainly US companies in the 1980s (Wu and Wu, 2000). However, studies conducted in companies in Sweden, UK and the USA (Gremyr et al., 2003), (Araujo et al., 1996), (Thornton et al., 2000) showed that the application of RDM in industry is poor. The lack of knowledge regarding the general idea of RD and the potential benefits were among the identified reasons. It has also been shown that even among companies considered to be mature in the field of robust design, the practices and processes are quite different with no single framework or process (Krogstie et al., 2014).

A literature study on the topic of Robust Design reveals a lot of different methods, techniques, tools, principles, frameworks and visualizations with the goal of improving the design to be less sensitive to variation. The complexity ranges from simple design rules to sophisticated

DOI:10.4122/dtu:2099

Reviewed by: *Lars Krogstie*
Valter Loll

Cited as: Göhler, S. M. and Howard, T. J., 2014. A Framework for the Application of Robust Design Methods and Tools. In: Howard, T. J. and Eifler, T., ed. 2014. *Proceedings of the International Symposium on Robust Design - ISoRD14*. Copenhagen, Denmark. pp. 123-133.

time-consuming computer simulations and optimizations. Previous literature reviews and classifications for RDM tools had various foci. Eifler et al (2013) focused on the phase of application of RDM tools in the development process and if they are lagging or leading methods. Park et al (2006) classified methods in three coarse categories of i) Taguchi Method, ii) Robust Optimization and iii) Axiomatic approach and reviewed the state of the art in these areas. Other reviews focused on Robust Parameter Design (Robinson et al, 2004) or on practices to address the principles of RDM as defined by Arvidsson and Gremyr (Hasenkamp et al, 2009). However, due to the different foci of the mentioned reviews and classifications, the issue of poor understanding and application of RD tools is not addressed. The authors believe that understanding the premises rather than attributes of the methods supports the correct and successful application. This paper makes an attempt to create a framework for the application of tools and methods typically related to Robust Design in the literature by means of a faceted classification. The goal is to increase the understanding and provide support for the application of RD methods. The proposed facets are (i) Robust Design Guidance and Principles, (ii) Robustness Evaluation, (iii) Robustness Optimization and (iv) Robustness Visualization. The framework aims at professionals working with design processes to increase the awareness of premises and goals of methods. It can serve as guidance for structuring the development process. Further, this framework could be of interest for researchers from the field of design processes to derive a generic landscape for RDM built upon the main premises and goals of each method.

The outline of the paper is as follows. Firstly, Robust Design is delimited from related fields. Secondly, a framework for RD methods and tools is proposed by means of a faceted classification. Thirdly, selected methods and tools are reviewed and described to support the framework. An example is presented to show the nature of the individual facets. Finally, the findings are discussed and conclusions drawn.

2. Delimitation of Robust Design

In the following section the criteria for the selection of tools and methods being reviewed and used for creating the framework will be described. Generally, a distinction between Robust Design and related areas and frameworks such as Reliability Engineering, Risk Management and approaches such as Design for Assembly, Manufacturing or Six Sigma is necessary. This however is not always clear since mentioned areas are interlinked and overlap occasionally.

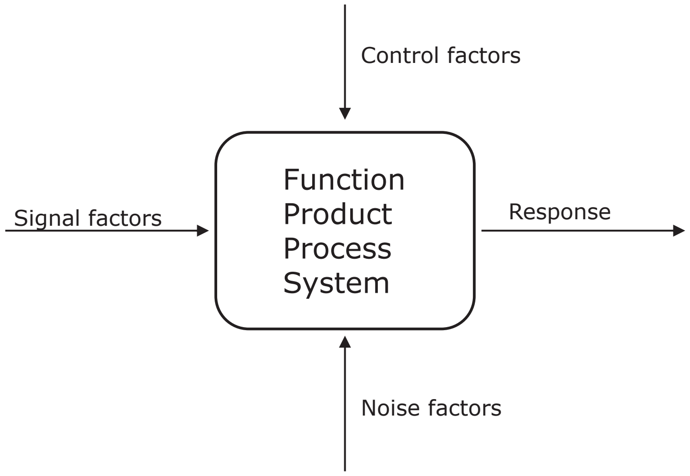


Figure 1. Generic P-Diagram

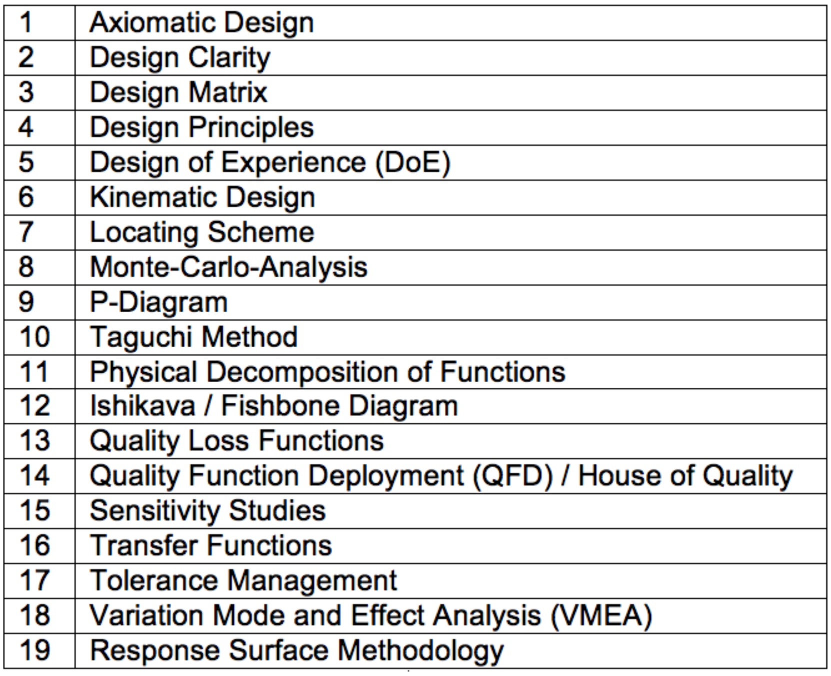
Robust Design provides the framework for the development of designs and products insensitive to variation and for the assessment of the sensitivity of functions to variation. Variation in this context could be in terms of control factors i.e. design parameters but also uncontrollable noise factors like environment, usage etc. Figure 1 shows a generic P-diagram visualizing the input and output – i.e. Signal and Response factors - as well as control and noise factors to a function, product, process or system.

Methods from related fields like Reliability Engineering and Risk Management, Design for X, Design for Manufacture and Assembly **which are not aiming at understanding or reduction of sensitivity to variation** have not been taken into account for this study. Complexity Management and Systems Engineering also have overlaps with Robust Design but will not be discussed as such in this work. Further, management frameworks such as Variation Risk Management (Thornton, 2004) are not part of this study.

3. Faceted Classification of Robust Design tools

The following section proposes a new framework for the application of methods and tools related to RD by organizing them by means of faceted classification. The methodology used to derive the facets is described. As mentioned above, there have been previous attempts to classify RD tools and methods. The review from different angles and with different goals led to the fact that there are methods that occur in one review but not in the others. For this study methods that are commonly associated with RD as delimited in Section 2 have been collected from other review papers in this field. Additionally, the authors augmented the list with some methods based on their experiences in product development. Table 1 lists the methods and tools related to RD that have been selected.

Table 1. List of reviewed RD tools and methods



1	Axiomatic Design
2	Design Clarity
3	Design Matrix
4	Design Principles
5	Design of Experience (DoE)
6	Kinematic Design
7	Locating Scheme
8	Monte-Carlo-Analysis
9	P-Diagram
10	Taguchi Method
11	Physical Decomposition of Functions
12	Ishikava / Fishbone Diagram
13	Quality Loss Functions
14	Quality Function Deployment (QFD) / House of Quality
15	Sensitivity Studies
16	Transfer Functions
17	Tolerance Management
18	Variation Mode and Effect Analysis (VMEA)
19	Response Surface Methodology

After the selection of the commonly used RD tools, the literature has been reviewed to find the main premise of each of the methods and tools. Four main premises of application have been found and used as facets to classify the reviewed methods and tools.

1. Robust Design Guidance and Principles
2. Robustness Evaluation
3. Robustness Optimization
4. Robustness Visualization

The description of the associated methods and an example case is used to elaborate the reasoning of and the differences between the facets. Tools and methods do not necessarily need to be bound to one facet but can have multiple purposes and benefits. For detailed descriptions of the methods, the authors recommend the review of cited references or other available books and publications.

3.1 Example introduction

The design of a sled for the laser in a DVD player was chosen as an example to illustrate the premise of each facet by applying a related method. For simplicity reasons only two requirements shall be considered: firstly, the force required to drive the sled for the selection of an appropriate motor and secondly, the position accuracy of the laser. Generally speaking these functions can be described as follows:

1. Sled driving force = f(mass, materials, lubrication, play of sled on rails)
2. Laser position = f(rail positions, play of sled on rails)

The sled driving force is a function of mass that needs to be accelerated and the friction on the rail. Let's assume the weight and the material of the sled as well as the lubrication are fixed and not part of the design space. That leaves the play for the connection between sled and rail and the resulting friction losses for the whole operating distance as main contributor to the required driving force. Secondly, the positioning of the laser on the sled in the horizontal plane is of interest. Figure 2 shows two proposed concepts in a principle sketch. The example will be used to illustrate the proposed facets by applying some of the RDM tools associated with them.

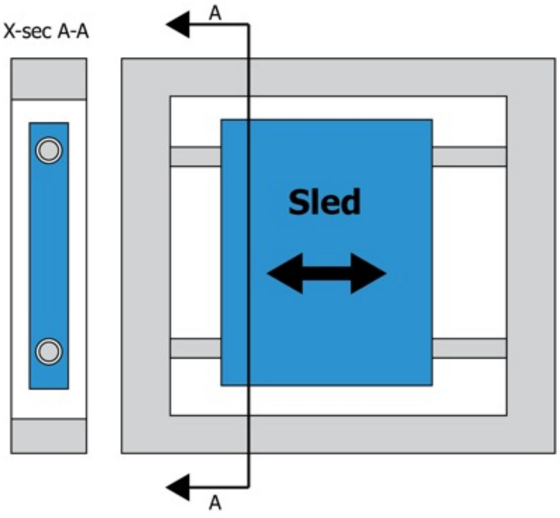


Figure 2a. Design Concept A for DVD player sled

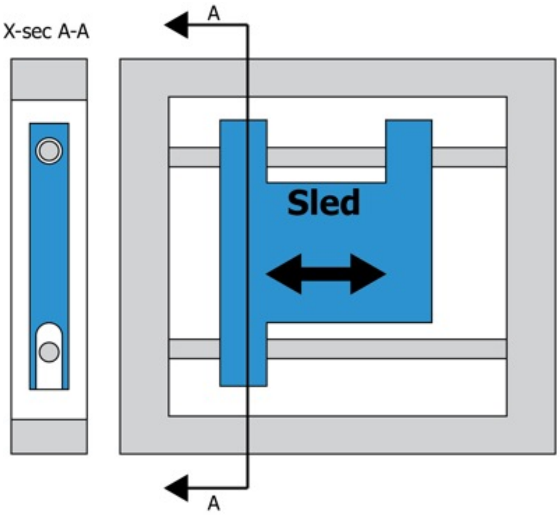


Figure 2b. Design Concept B for DVD player sled

3.2 Robust Design Guidance and Principles

Axiomatic Design was firstly proposed by Suh (2001). In his approach he argues that basic robustness against variation builds upon two basic principles i.e. axioms. Firstly, the independence axiom stating that functions should not be coupled, and secondly, the information axiom which can be reduced to the principle to design functions as simple as possible not having unnecessarily many design parameters that influence a function. In summary the idea is to un- or decouple all functions from each other to get independent functions that are adjustable by a set of design parameters that do not interfere with other functions. *Physical Decomposition of Functions* is a way of utilizing the concept of *Axiomatic Design* and maintaining the independence of functions. Andersson (1996) argues that different concepts have different optimums and that considering Design Principles in the concept phase leads to design solutions with a higher baseline robustness and potentially more opportunities for improvement. Matthiassen (1997) describes *Design Principles* as a “tool conveying knowledge of what tends to be good or poor design practice”. Pahl and Beitz (2007), Matthiassen (1997) and Mørup (1993) elaborate over general design rules that make the design more robust to variation but also less sensitive to failures. Examples are to avoid tolerance stack-ups (*Tolerance Management*), utilize self-adjustment, unambiguous loading and many more. Work done by Ebro and Howard follows some of these principles. *Design Clarity* and *Kinematic Design* ensure to avoid over-constraints and to create unambiguous interfaces to make to the design insensitive to variation (Ebro et al., 2012). A similar approach is proposed by Söderberg using *Locating Scheme* Methods to find and optimize the number and position of the constraints (Söderberg et al., 2006). Methods and tools in the facet of Robust Design Guidance and Principles can be applied in the sketch phase and don’t require a detailed design.

All methods and tools mentioned in this paragraph support the designer from the concept level to the final product in designing in robustness. Simple design rules and proposals from experiences in mechanical design are utilized to decrease the sensitivity to variation.

For the example design problem of the DVD laser sled, Design for Clarity and Kinematic Design can be applied in the early design stage on concept level. Figure 2a shows a design solution where the sled is fully guided on both rails. Considering nominal values and checking the Degrees of Freedom (DOF) for the sled indicates that this design would work. However, evaluating the intended and actual constrains following the Kinematic Design approach, it shows that the design is over-constrained, which could lead to high required forces to drive the sled, the mechanism jamming or excessive wear in the case of variation especially if the rails are not parallel to each other. In that case the design is also ambiguous with respect to the positioning requirement and which of the rails locates the sled in each of the directions. Using Suh’s Axiomatic Design philosophy it can be seen that both requirements (force and position) are dependent on the angle between the two rails and therefore violate the independence axiom – the functions are coupled. Figure 2b shows a sketch for the improved design following the Design for Clarity and Locating Scheme Methodology. The connection to the rails has been reduced to two bearings and a fork giving the ideal number of constraints. For this design the friction and therefore the force required to drive the sled is only dependent on the play of the bearings and decoupled from the positioning requirement.

3.3 Robustness Evaluation

To predict the robustness of products in production and service it is of high importance to evaluate the robustness during the development process. Robust Design tools for Robustness Evaluation give relative or absolute (metric) information about how sensitive to variation a design is. Per se these tools do not improve the robustness of a product but give an important input for comparisons of design solutions or even estimated yield rates and the prediction of reliability as a support in the decision making process. In an early design stage these methods build upon general attributes of the design concept that could be for example first sketches of working principles or the general composition of the design without details and return a value for the estimated level of robustness against variation. They often relate to design guidelines that have or have not been or could not be taken into account. Ebro and Howard have utilized the principles of *Design Clarity* and *Kinematic Design* to derive objective scores for over-constraints and mobility and therefore for robustness (Ebro et al., 2012). Expert experience is also utilized to evaluate a design. *Variation Mode* and *Effect Analysis* (VMEA) is - like Failure Mode and Effect Analysis (FMEA) for reliability - a tool to judge the sensitivity to variation. Whilst the values are somewhat subjective it still gives a first estimation of robustness (Johansson et al., 2006). *Transfer Functions* relate the change in design parameters to the effect on the function. In the case that a transfer function can be derived analytically (from the working principle for example), *Sensitivity Studies* can be run before the actual design has been fixed to give insights of how to design in the most robust way. The further a design solution matures the more options of predicting the robustness of the final product arise. *Taguchi's* Signal-to-Noise-Ratio can be used to evaluate the robustness. But also sensitivity scores from parameter sensitivity studies, probability distributions from *Monte-Carlo-Analyses* and tolerance chains (*Tolerance Management*) give an indication of robustness. *Design Matrices* as proposed by Suh (2001) that connect the functional requirements with the design parameters can be seen as Robustness Evaluation since the entries reflect the sensitivity of each function to the related design parameters. Once CAD models of the design are available, assessments with other advanced simulation software packages are possible, like for example Finite Element Methods (FEM), Computational Fluid Dynamics (CFD) etc. Sophisticated *Transfer Functions* and *Response Surfaces* can be derived that show functional sensitivities to variations on a detailed level. Once there is more detailed information about the design and maybe first samples from production are available, the *VMEA* can be updated and filled with objective values.

In the example design case of the DVD laser sled, engineers could be interested in evaluating the robustness with respect to the required driving force of the sled to select an appropriate motor. Deriving the Transfer Function and running a Monte-Carlo-Analysis with the expected production variation would enable them to calculate the variation and distribution of the driving force and select the motor.

3.4 Robustness Optimization

Optimization implies that a solution exists that can be improved. This solution can be optimized with respect to functional performance, durability, reliability, robustness, etc. Optimization builds upon knowledge of the system and how functions behave for changes in the design parameters. Generally speaking the optimization process can be divided into two phases. Firstly, the analysis phase where insight to the problem is gained. Where possible it is desirable to have an analytical expression to define the behavior of the system, as changes can be made quickly at early stages without excessive prototyping. However, in many real world situations there are simply too many variables and noise factors to formulate an analytical expression, so experimentation or simulation has to be conducted in order to derive an approximate one. Secondly, there is the phase of the actual optimization of the then fully formalized problem. Both phases are subject to excessive research themselves. The aim is to efficiently conduct experiments or simulations with the maximum information content and the least effort. The same applies for the optimization. Trail-and-Error and simple *Sensitivity Studies* (change of one parameter at a time) are the most obvious and intuitive approaches and still used for Robustness Optimization in industry. Also experience plays an important role in this context. For design problems where *Transfer Functions* can be derived, an optimization of the design parameters can be run to find the most robust solution. For problems with higher complexities i.e. as the number of design parameters and functional requirements increase, the number of necessary experiments or simulations rises exponentially. The need for a structured experimental design arises to keep the amount of testing and simulations as low as possible.

The first work on Experimental Design was conducted by R. A. Fisher in the 1920s ("The Arrangement of Field Experiments" (1926) and "The Design of Experiments (1935)) (Antony, 2003). Since then Design of Experiment (DoE) has been developed further, ranging from Orthogonal Arrays to Combined Arrays proposed by Welch (1990), *Response Surface Methodology* by Box and Wilson (1951) and many more. The approach of designing a system, optimizing it and finally managing the tolerances in the light of a design that is insensitive to variation was firstly developed by Taguchi, quality consultant and pioneer of Robust Design, in the 1950s (Wu and Wu, 2000). He divided the development process in System Design, Parameter Design and Tolerance Design covering creation, optimization and tuning in terms of quality and cost respectively (*Taguchi Method*). In the optimization phase Taguchi utilized Orthogonal Arrays for conducting efficient experiments and tests. With the data gained from these experiments it was possible to maximize the Signal-to-Noise-Ratio (SN-Ratio) and optimize the tolerances (*Tolerance Management*) for the most robust design. Taguchi used the SN-ratio to solve the optimization problem but there are numerous methods and algorithms to do so which form their own field of study. The complexity of the optimization techniques to derive the optimum rises with the amount of information drawn from testing. Taguchi's work has triggered also critics and improvements. The most recent achievements have been summarized by Robinson (Robinson et al., 2004) following among other sources a panel discussion summarized by Nair (Nair, 1992).

When designing the dimensions of the sled in the DVD player example, the play and tolerances around the holes need to be taken into account. Usually there is a design envelope within which the dimensions can be adjusted. A robustness optimization will find a combination of design parameters so that minor variations have less effect on the two main functional requirements, sled driving force and laser positioning.

3.5 Robustness Visualization

Robustness Visualization refers to tools for instance figures, diagrams or matrices that help increasing the awareness of robustness to variation without improving or quantifying the robustness of the design. The *House of Quality in QFD* is used to integrate marketing, engineering and manufacturing and link customer requirements through to manufacturing (Hauser, Clausing, 1988). The "roof" in the house of quality visualizes potential couplings and contradictions of engineering requirements that could potentially lead to robustness issues and gives a relative indication without returning a score for robustness. The *Ishikava* or *Fishbone Diagram* developed by Japanese engineer Ishikava visualizes the causes and influencing factors that affect a problem. The general categories are Equipment, Process, People, Materials, Environment and Management. In the light of robust design, noise factors can be mapped and an overview drawn of how many and which noise factors need to be taken into account without quantifying them. The *P-Diagram* shows the product, process or function with its input and output parameters but also including control and noise factors to visualize potential robustness issues and adjustment possibilities. Taguchi's *Quality Loss Function* is another way of visualizing the robustness of a function with respect to the quality perceived by the customer or user.

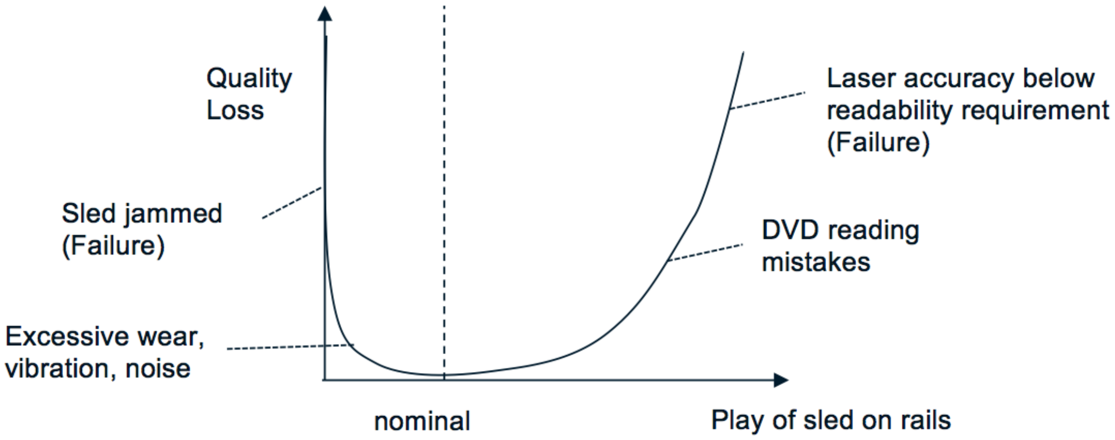


Figure 3. Quality Loss Function for example design case

Figure 3 visualizes the quality loss associated with a variation in play of the sled on the rails in the DVD player example case. For small deviations from the nominal there is no quality loss for the customer. For too little play of the sled or interference with the rail, the risk of excessive wear, vibrations and noise as well as jamming the mechanism rises. For the sled being too lose on the rails the positioning accuracy and therefore the ability to read the DVD drops from single playback mistakes to a function failure.

4. Discussion

A framework for the application of methods and tools commonly associated with RD has been proposed in this paper by means of faceted classification. The proposed facets are (i) Robust Design Guidance and Principles, (ii) Robustness Evaluation, (iii) Robustness Optimization and (iv) Robustness Visualization. Table 2 gives a summary of the faceted classification of the RD methods and tools that have been reviewed in this paper. It can be seen that some methods have more than one facet. Some tools for Robust Evaluation are also being used in the optimization process to check the result of each iteration or build upon design principles. The evaluation methods marked with a star indicate applicability in an early design stage. Tools related to Robustness Visualization can be utilized to illustrate and present robustness correlations. Most important after all, visualizations can help building up awareness of sensitivity to variation of the design and is in that respect very valuable.

Table 2. Summary of Faceted Classification of RD Methods

		Robust Design Guidance and Principles	Robust Design Evaluation	Robustness Optimization	Robustness Visualization
1	Axiomatic Design	X			
2	Design Clarity	X	X*		
3	Design Matrix		X		
4	Design Principles	X			
5	Design of Experience (DoE)			X	
6	Kinematic Design	X	X*		
7	Locating Scheme	X			
8	Monte-Carlo-Analysis		X		
9	P-Diagram				X
10	Taguchi Method		X	X	
11	Physical Decomposition of Functions	X			
12	Ishikava / Fishbone Diagram				X
13	Quality Loss Functions				X
14	Quality Function Deployment (QFD) / House of Quality				X
15	Sensitivity Studies		X	X	
16	Transfer Functions		X*	X	
17	Tolerance Management	X	X	X	
18	Variation Mode and Effect Analysis (VMEA)		X		
19	Response Surface Methodology		X	X	

X Robust Evaluation in early design stage*

Previous publications proposed different classifications of Robust Design tools and methods. Park et Al (2006) classified RD tools in three types of methods: i) Taguchi Method, ii) Robust

Optimization and iii) Robust Design with the Axiomatic Approach. In contrast to this paper, RD philosophies were discussed rather than the actual methods. Taguchi's approach is considered as its own method although significant overlaps to the second category, Robust Optimization, exist, as for example the optimization nature of parameter design. Eifler et Al (2013) reviewed RD methods and tools in the light of 3 success criteria for implementation in industry: i) leading indication of robustness, ii) quantifiable metrics and iii) early design applicability. Different to the classification proposed in this paper the premise of each method was not taken into account. Hasenkamp et Al (2009) addressed the same problem as discussed in this paper stating that "applying a tool without being aware of its underlying and motivating practice may easily lead to incorrect or suboptimal application". To overcome this shortcoming they used the principles of RDM i) insensitivity to noise factors, ii) awareness of variation and iii) continuous applicability as proposed by (Arvidsson, Gremyr, 2008) to put the tools and methods into perspective. In agreement with the reviews conducted by Eifler et Al (2013) and Hasenkamp et Al (2009) the literature study for this paper also gave the impression that the majority of contributions in this field focus on statistical and optimization oriented RD methods. Tools and methods for the evaluation of robustness in an early design stage are comparably seldom subject of investigations.

After all, the presented framework has a different goal and focus than the other reviews. It gives designers and engineers the overview of what tools and methods are available and what are the underlying premises. That eases the choice of the appropriate RD method and gives an idea of what output to expect. A weakness of this framework is the ambiguity for some methods that have multiple premises and goals.

5. Conclusion

There are many different ways of classifying methods for robust design. The aim for the approach taken in this paper was to classify tools and methods with respect to their purposes and premises to increase the understanding and give guidance for the application of RD methods. With this framework as starting point it could also be possible in the next step to specify what the input and output parameters to each tool or method are to derive a structured approach to integrate these tools into a generic development process. Weaknesses and strengths of each tool could be augmented with the overall goal of an efficient use of the existing tools.

The classification of the tools and methods of the RDM also shows a lack of options for Robustness Evaluation in early design. Furthermore, the literature study has shown approaches to combine different tools and methods. The proposed classification can help to identify overlaps as well as differences between methods and finally lead to successful integrations and combinations of tools.

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1st International Symposium on **Robust** Design
København, DK
14th-15th of August 2014

Robust Design Principles to Evaluate Additive Manufacturing Capabilities

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Keywords: Robust Design, Taguchi Design of Experiment, Additive Manufacturing, 3D Printing, Rapid Manufacturing.

Abstract

Additive manufacturing (AM) is generating a paradigm shift by expanding the manufacturing capabilities. However, quality of AM produced parts is dependent on a number of machine, geometry and process parameters.

The impact of inputs, such as the machine technology, the part orientation, the part location and the quality of the digital data, affects the AM outcomes drastically. A new user faces the problem of selecting optimal sets of input variables and therefore, it is necessary to support this selection process that is based typically in tacit knowledge of the machine operator or service suppliers.

The present research has proposed a “composite” methodology integrating Taguchi design of experiments, multi-objective optimization and statistical process control, to optimize the manufacturing process and fulfil multiple requirements imposed to an arbitrary geometry. This study provides a comparative assessment of AM technologies and optimal process parameters. During the experiment, three conflicting requirements were imposed to a case geometry. Two of them, at the macro level, evaluated dimensional and geometrical tolerances. The third one, at the micro level, evaluated the surface quality of the produced parts.

The outcomes of the experiment indicate that only one machine (M1, Stereolithography), was feasible to simultaneously fulfil macro and micro level requirements. In addition, the process was capable but not centred according to production standards. Future study including mechanical performance variables, interaction between variables and impact of noise factors is planned.

1. Introduction

Research evidences show that Additive Manufacturing (AM) technology can potentially replace conventional manufacturing methods (Campbell, et al., 2012). AM systems are capable to directly manufacture functional engineering components at low cost (Levy, et al., 2003). This could potentially limit the high initial investment in injection moulding tooling of small series production and therefore, reduce cost and time-to-market during the product development. Over the past years, mechanical properties of the materials as well as the reliability and re-

DOI:10.4122/dtu:2101

Reviewed by: *Thomas J. Howard*
Tobias Eifler

Cited as: Flores, I., Coatanea, E., Salmi, M. and Tuomi, J., 2014. Robust Design Principles to Evaluate Additive Manufacturing Capabilities. In: Howard, T. J. and Eifler, T., ed. 2014. *Proceedings of the International Symposium on Robust Design - ISoRD14*. Copenhagen, Denmark. pp. 135-145.

peatability of AM processes have improved significantly. It is expected that AM systems will move soon from being a Rapid Prototyping (RP) tool to be a Direct Component Manufacturing (DCM) method (Wholers, 2013) and (Mellor, et al., 2013).

However, those expectations require significant developments on the technology. AM machines have different architectures and material processing capabilities. The characterization of the machines and materials is not yet mature and the differences are substantial in terms of achievable mechanical and dimensional properties (Clemon, et al., 2013). Technical parameters of the technology are not fully understood and capabilities have not yet been fully investigated by the engineering community (Gibson, et al., 2010).

Geometrical stability and material properties of AM produced part are strongly dependent on part geometry and machines parameters. Therefore, the final quality of the produced parts is subordinate to a list of variables including the machine and process variables. Research has indicated that the effect of the part orientation and the location on geometric stability of AM produced geometries need to be studied further to drive the technology to become a DCM method (Anand & Ratnadeep, 2011), (Brajlih, et al., 2010) and (Dimitrov, et al., 2003).

In addition, manufacturing community still faces basic problems when selecting the optimum AM technology and process parameters for DCM. For instance, Laser Sintering (LS), Stereolithography (SL) and Polyjet technology are some of the most promising alternatives to produce engineering functional parts, but the final quality of the produced parts changes substantially from technology to technology (Wholers, 2013).

Previous work has developed decision making tools for optimal AM systems selection, based on balancing the manufacturing cost, production capacity and quality (Williams, et al., 2003). Researchers have used Design of Experiments (DOE) to select optimum manufacturing parameters (Hsu & Lai, 2010), (Wang, et al., 2007) and (Rahmati, et al., 2007). However, these experimental methods have not been combined.

In practice, parts have to fulfil simultaneously different types of geometrical and dimensional requirements. Frequently, the manufacturing parameters can have contradictory influences on different requirements. Selecting an optimized combination of machine and process parameters for fulfilling simultaneously multiple requirements has still to be tackled. There is then a need to combine a systematic experimental approach with a multi-objective optimization, as proposed in similar manufacturing context (Konda, et al., 1999).

In this research, a predictive method is proposed to tackle this problem. Taguchi robust DOE is applied, and then combined with multi-objective optimization based on Pareto optimum and Statistical Process Control principles to evaluate the robustness of the manufacturing process (Montgomery, 1992). The aim is to assist the machine selection and optimum processes parameters to fulfil multiple requirements. The long term vision of this work is to develop a computer aided tool providing an automatic selection of manufacturing parameters, including machine technology, by analysing the technical requirements of the geometry to be produced.

2. Materials and Methods

2.1 Geometry of the Case Study

The geometry used for this experiment is a typical ABS injection moulded plastic part found in mass produced consumer devices, such as mobile phones. As a purely functional inner structural plastic part, the requirements in are exclusively dimensional and geometrical. The final produced sample requires very tight geometrical and dimension tolerances as well as good surface quality in order to be feasible for the mechanic assembly of the product. The nominal size of the part is 68.12 mm x 37.24 mm x 14.85 mm and its theoretical volume is about 3308 mm3.

2.2 Methodology

The methodology used during this research is illustrated by the process diagram in Figure 1. Initial steps of the process imply to select the geometry and the material of the geometry. These parameters will guide the selection of suitable machine alternatives. In this DOE, the machine alternatives included three different process categories described in the ASTM, Standard Terminology for Additive Manufacturing Technologies, ASTM F2792 − 12a (ASTM, 2013).

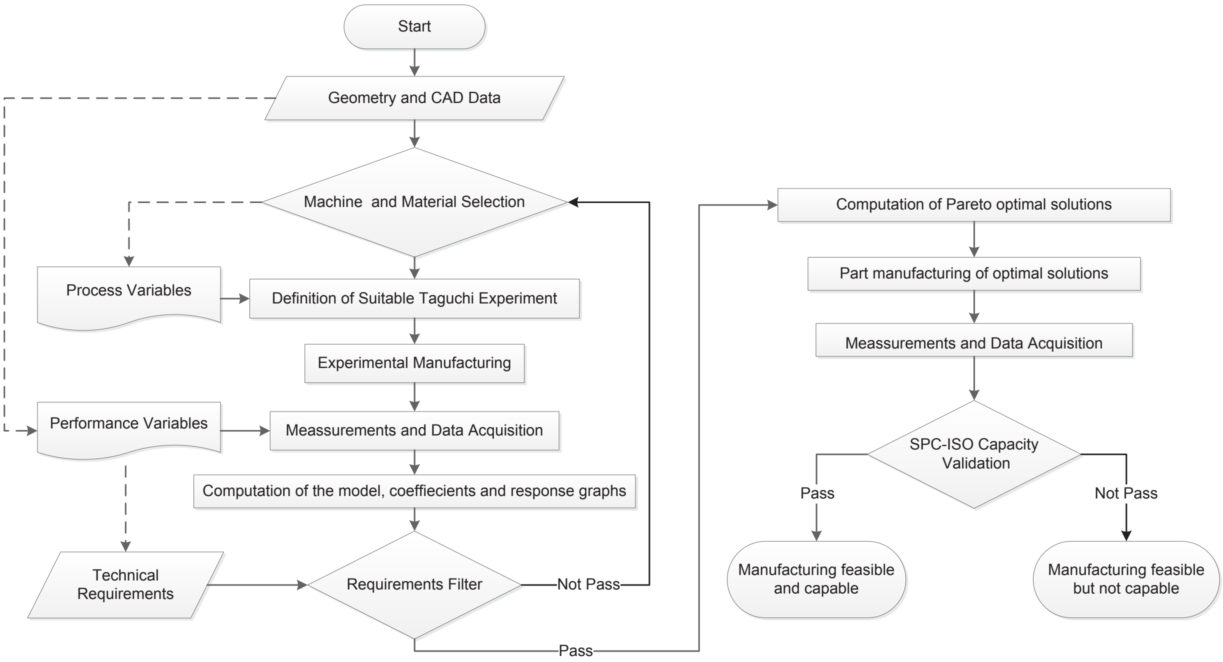


Figure 1. Methodology and its process diagram

2.1.1 Selection of the performance variables, process variables and factor levels

This research has considered the following factors affecting to the AM process, which can be separated into three categories, Signal Factors, Noise Factors and Control Factors. Figure 2 shows the P-diagram of the explored variables.

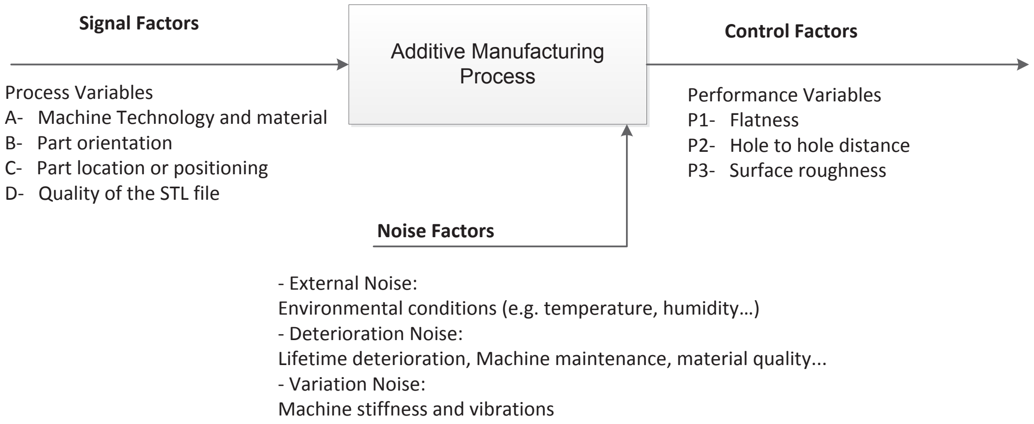


Figure 2. Parameter diagram used during the DOE

The impacts of the noise factors have been omitted in this experimental set-up. A total of three performance variables and four process variables with three factor levels are included in the DOE. The first process variable (A) describes the machine and material selection, the factor levels of this DOE are explained in Table 1.

Table 1. Process variable (A), machine and material

Machine Specifications	M1	M2	M3
Machine supplier	3D Systems	Stratasys	EOS
Machine Type	Viper SI2	Objet 500	Formiga P110
Industrial Process Category	Stereo Lithography (SL)	Polyjet	Laser Sintering (LS)
ASTM Process Category	Vat Photo-polymerization	Material Jetting	Powder Bed Fusion
Layer Thickness (Z-Axis)	50 µm	30 µm	100 µm
Material	Accura 25 Plastic	ABS Like	PA2200

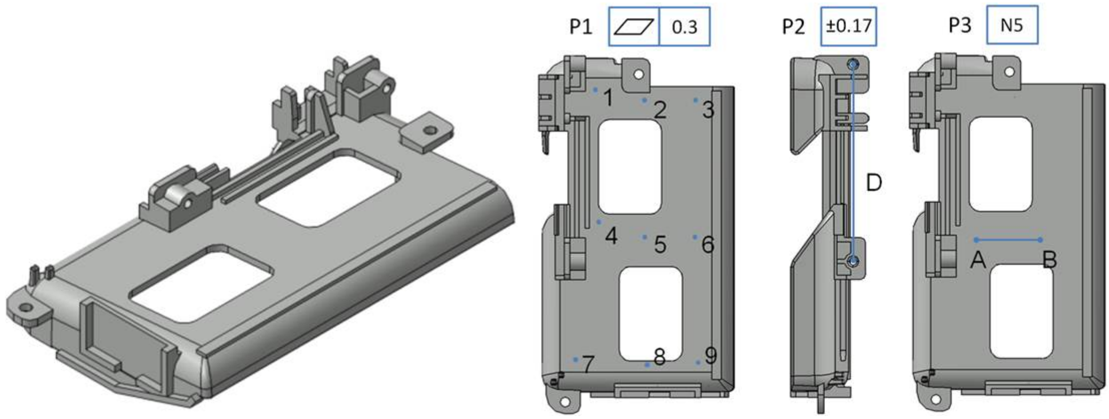
The second process variable (B) is the part orientation on the machine build platform, in which the geometries are manufactured in horizontal, vertical and diagonal orientation (i.e. diagonal 45 deg. from the XY plane which corresponds to the build tray of the AM machines). The third process variable (C) studies the effect of the part location on the machine over the manufactured part. In this case, the levels included parts printed on the top left, centre and bottom right of the build platform. The last process variable (D) studies the quality of the digital data, in which intentionally the cordal errors of the STL files are pre-established. All these variables behave in a non-linear manner. Thus, three levels have been selected per each process variable. The summary of the process variables and factor levels is explained in Table 2.

Table 2. Summary of process variable and control levels

Process variables		Level 1	Level 2	Level 3
A	Machine and Material	M1	M2	M3
B	Part Orientation	Horizontal	Vertical	Diagonal
C	Part Location	Top Left	Centre	Bottom Right
D	Digital Quality	High (0.001mm)	Medium (0.01mm)	Low (0.1mm)

Regarding the performance variables, three measurable variables are included in order to integrate typical manufacturing requirements present in Injection Moulded parts. The combination of these three requirements is an important constraint to the AM process. Two of them, at the macro level, the flatness (P1) and the distance from hole to hole (P2) studied the geometrical and dimensional stability of the produced parts. The last variable, at the micro level, measured the surface quality (P3) of the produced parts

Figure 3 makes a summary of the performance variables and their requirements, as well as the optimization objective per performance variable. P1 required having a dimensional tolerance lower or equal to 0.3mm. P2 required having a dimensional tolerance within the range of +/- 0.17 mm of the nominal value D=37.55 mm. P3 required to be lower or equal to Ra = 0.8 µm, equivalent to N5 quality in the ISO standard, Geometrical Product Specifications (ISO1101, 2012). The optimization objectives of these performances are the following, the Flatness (P1) should be minimized, the hole to hole distance (P2) should lead to a target value and the surface roughness (P3) should be minimized.



Performance Variables		Optimization Objective	Requirement
P1	Flatness (mm)	Minimize	0.3 mm (max.)
P2	Hole to hole distance D (mm)	On target	37.55 +/- 0.17 mm
P3	Surface roughness Ra (µm)	Minimize	0.8 µm (max.)

Figure 3. Optimization objective and schematic views of the performance variables, flatness (P1), hole to hole distance "D" (P2) and surface roughness (P3).

2.2.2 Definition of the Design of Experiment (DOE) and suitable Taguchi Orthogonal Array

When planning a DOE, several process variables or input factors can be varied simultaneously in a controlled manner in order to obtain reliable, repeatable and structured data. Therefore, the variance of the experiments can potentially be minimized and the obtained data can be used to predict causal relationships of the system. This idea was introduced by Fisher and is nowadays widely used in experimental sciences (Fisher, 1935). By approaching the presented experiment in a full factorial fashion, a total of 34=81 potential experiments would have been performed, if only one variable was changed after the other. To simplify and limit the experimental approach and safe time and resources, a Taguchi DOE was implemented. Taguchi methods allow to use set of orthogonal arrays specially created for automatically randomizing the experiments and to create an optimal DOE.

An L9 orthogonal array has been selected to drive the experiment. The Table 3 shows the Taguchi array used in the DOE. The columns represent the process variables and the rows correspond to the individual experiments.

Table 3. Taguchi L9 orthogonal array for the DOE

Exp.	A (Machine & Material)	B (Part Orientation)	C (Part Location)	D (Digital Quality)	Encoding of the Experiment
1	M1	Horizontal	Top Left	High	1HLH
2	M1	Vertical	Centre	Medium	1VCM
3	M1	Diagonal (45deg)	Bottom Right	Low	1DRL
4	M2	Horizontal	Centre	Low	2HCL
5	M2	Vertical	Bottom Right	High	2VRH
6	M2	Diagonal (45deg)	Top Left	Medium	2DLM
7	M3	Horizontal	Bottom Right	Medium	3HRM
8	M3	Vertical	Top Left	Low	3VLL
9	M3	Diagonal (45deg)	Centre	High	3DCH

2.2.3 Measurements and experimental set-up

The experiments in the L9 array were repeated three times to take into consideration the variance. In addition, each sample was measured twice per performance variable for integrating the variance of the measurement processes. However, more measurement repetitions would be needed to improve the experimental set-up. Altogether, 54 measurements were taken, 6 measurements per each experiment. In the SPC capacity validation phase of the methodology, 3 more parts were produced per feasible solution and measured again using the same process described previously.

Figure 4 shows the picture of all samples number 1. In the top side of the picture the part code is shown. Each of the produced part had embossed digitally the part code to assure the traceability of the part during the whole experiment.

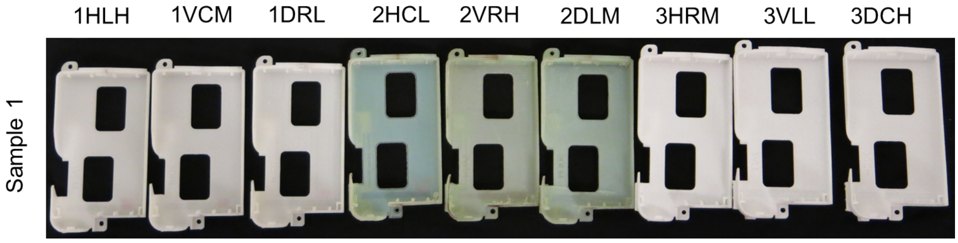


Figure 4. Manufactured sample 1 during the DOE

The measurement of the performance variables P1 and P2 was performed with an image based 3D laser coordinate measurement system, Nikon VMR-3020. The machine calculated the flatness by computing the differences in the vertical axis of the points described in Figure 3. Regarding the performance variable P2, the machine measured directly the distance between hole centres. Last measurement of the performance variable P3 was obtained by using a profilometer, Taylor-Hobson Surtronic 3 Roughness Gage, the measuring distance or sampling length for calculating Ra was set to 4mm shown in in Figure 3.

2.2.4 Multi-objective optimization and Statistical Process Control (SPC)

After obtaining the data, the next phase implies to compare all combination results of the model against the requirement of the system, by doing so an initial filtering of not feasible solutions is implemented. If results are obtained after this filter, there are potentially feasible solutions to manufacture the part within requirements. Otherwise, new machine alternatives or less restrictive requirements need to be considered (see process diagram in Figure 2).

In case of obtaining results after the filter, the dominance between solutions is studied. Pareto optimal solutions need to be non-dominated solutions, a pairwise comparison algorithm is used in this research to compute the Pareto optimal solutions (Miettinen, 1999).

The final step consisted on applying a SPC capacity test to the manufactured Pareto optimal solutions (Shewhart, 1986). This is performed to evaluate the robustness of the manufacturing process (i.e. robust to noise and deviations in the process). For that purpose, the standard ISO was used (ISO7870-2, 2013).

In this research the minimum level for an acceptable capability index was set to 1. Hence, the process is capable if Cp > 1, else the process is not capable. The higher the Cp value, the smaller the dispersion of the data is. Cp should be used in conjunction with Cpk to account for evaluate spread and centring. If Cpk > 1 then the process is centred, else is not centred. The larger is the Cpk, the less variation between the process output and specifications. Cpk and Cp will be equal when the process is centred on its target value. If they are not equal, the smaller the difference between these indices, the more centred the process is (Larsson, 2002).

3. Results

Figures 5, 6 and 7 display the response graphic of the performance variables P1, P2 and P3 respectively. The mean values, standard deviation and the requirements are represented per process variable and per factor level.

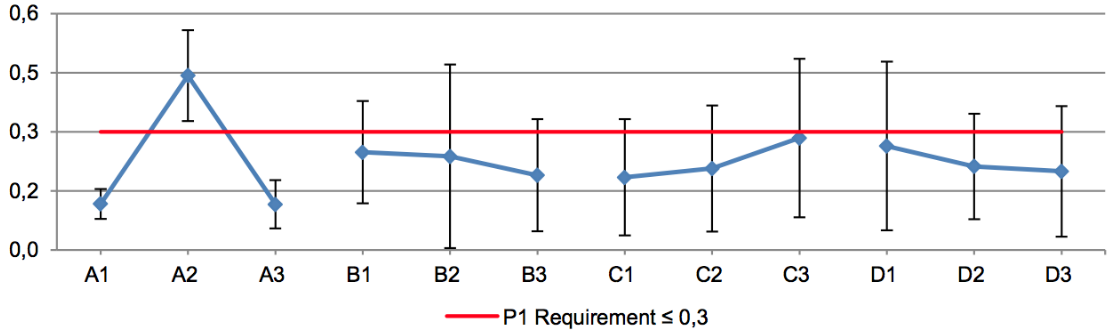


Figure 5. Response graphic of the performance variable P1 (Flatness)

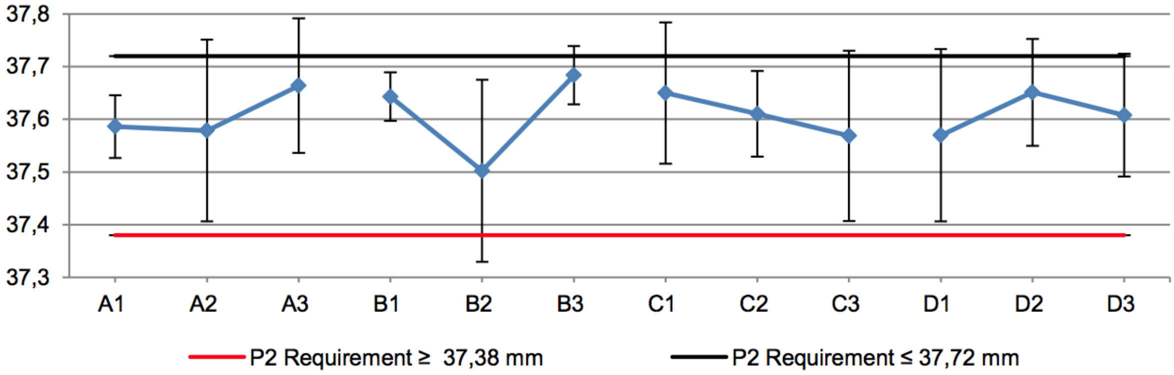


Figure 6. Response graphic of the performance variable P2 (Hole distance)

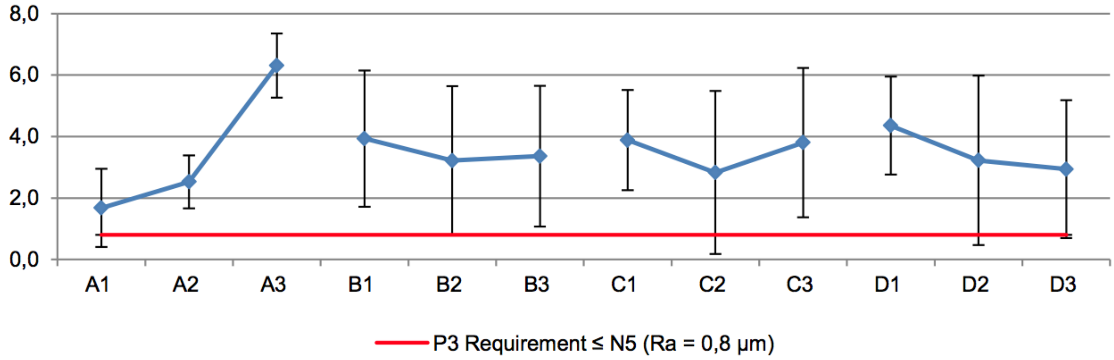


Figure 7. Response graphic of the performance variable P3 (Surface quality)

Based on the results displayed in the response graphics, most of the combinations of process variables will not be feasible to produce the part within the manufacturing requirements. Nevertheless, certain combinations of the process variables could potentially be feasible to produce parts that fulfil the imposed requirements. In order to evaluate this possibility, an initial filtering of the objective function was implemented. The filter result in this DOE was a set of four theoretical solutions able to satisfy the requirements. The following move is to study if these four solutions are Pareto optimal or non-dominated solutions. After studying the dominancy between solutions, only three Pareto efficient solutions were potentially feasible to fulfil all the requirements simultaneously. The feasible solutions are displayed in Table 4.

Table 4. Feasible non-dominated solutions to manufacture the case geometry

Process variable	Solution 1	Solution 2	Solution 3
A (Machine and material)	A1 (M1)	A1 (M1)	A1 (M1)
B (Part Orientation)	B2 (Vertical)	B2 (Vertical)	B3 (Diagonal)
C (Part Location)	C2 (Centre)	C2 (Centre)	C2 (Centre)
D (Digital Quality)	D2 (Medium)	D3 (Low)	D3 (Low)

At this stage two AM processes, the material jetting (M2) and the powder bed fusion (M3) have been eliminated. In addition, the results indicate that only parts produced in the centre of the tray can satisfy the requirements of the system. Results also show that Vat Photo-polymerization (M1) is better than the two other processes for surface quality (P3) and as good as the best option for the two other performances (Flatness, P1 and hole distance, P2).

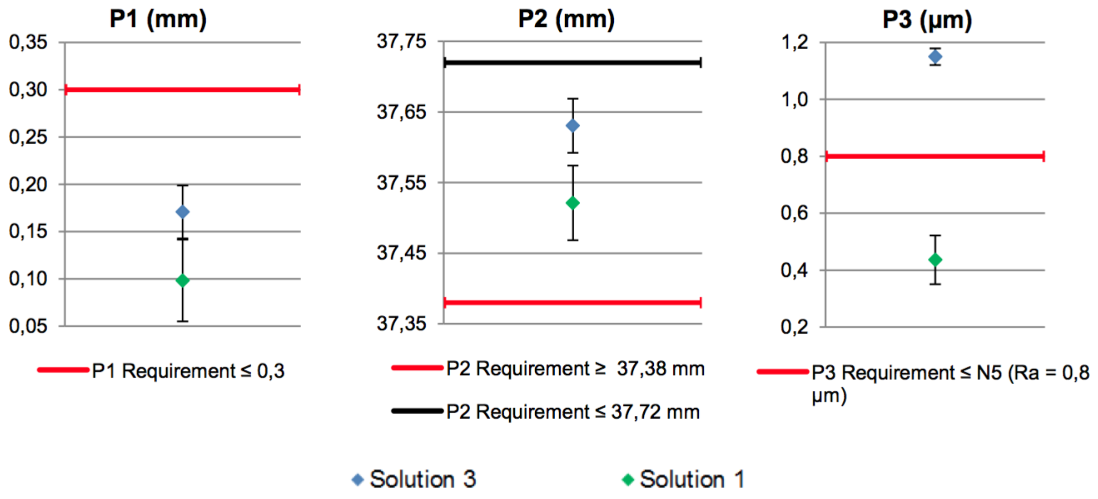


Figure 8. Representation of the mean value, standard deviation and requirements for the solution 1 and solution 3

Considering the set of 3 feasible solutions, the SPC capability analysis is performed. To drive this analysis, for simplification reasons, solution 2 has been ruled out and only solution 1 and 3 were manufactured and measured again. The initial evaluation of Figure 8 indicates that the mean value of solution 1 is within the requirements for all the performance variables. This is not the case for Solution 3, in which the mean value of the roughness is outside the requirements, thus the solution is not feasible. The last step as described in the process diagram of Figure 2 is to evaluate the capability of each solution (i.e. its robustness to deviations in the process).

Table 5. Capability analysis for the solutions 1 and 3

Solution 1	P1		P2		P3	
Cp	1.156	Capable	1.074	Capable	1.560	Capable
CpK	0.756	Not Centred	0.892	Not Centred	0	Not Centred
Mean	0.098		37.521		0.436	
Stdev	0.046		0.053		0.085	
Solution 3						
Cp	1.78	Capable	1.48	Capable	4.52	Capable
CpK	1.53	Centred	0.78	Not Centred	0	Not Centred
Mean	0.171		37.631		1.150	
Stdev	0.028		0.038		0.029	

The results of the ISO-SPC capability analysis are displayed in Table 5. Cp and CpK indexes of solution 1 show that the process is capable but not centred. This is due to a too high standard deviation of the measured sample. The mean values of solution 3 are within the limits for 2 performance variables but failed for the roughness requirement, thus manufacturing is not feasible despite the fact of being capable.

4. Discussion

The results of the research demonstrated that the implementation of DOE, Multi-objective optimization and SPC analysis can be combined effectively to assess Additive Manufacturing (AM) feasibility and robustness for Direct Component Manufacturing. The results demonstrate that machine and process parameters have a fundamental impact on the final outcome as described in (Anand & Ratnadeep, 2011), (Brajlih, et al., 2010) and (Dimitrov, et al., 2003). By looking at the response graphics, P3 (Surface Quality) was the most difficult requirement to satisfy, followed by P1 (Flatness) and P2 (Hole distance) and results of Pareto optimum show that only three solutions were theoretically feasible. Based on the validation phase and SPC results, only one solution was feasible and capable; however, the process was not centred.

To select optimum factor levels for the process variables, results show that only M1 was potentially feasible to fulfil all the requirements of the system. M2 had flatness values out of specification and the surface quality of M2 and M3 was not within requirements. Moreover, only parts produced vertically and diagonally could potentially be used, the part location had a major impact and only parts manufactured in the centre of the build platform were feasible for the manufacturing. Process variable C (Digital quality) was not critical; the effect of the digital quality is often visible in geometrical features, such as round surfaces. The selected performance variables did not measure this effect quantitatively, future research is planned to address this relationship.

To describe the research limitations, the experiment did not include interactions between process variables, such as orientation and part location. For instance, a Taguchi L18 can be implemented to improve the experimental quality and study variable interactions. In addition, the sample size to compute Cp and CpK capability indexes was too low, as officially a sample of 50 data sets is required. The impact of noise factors have not been evaluated quantitatively in this initial research, further analysis using signal to noises ratio and analysis of variance would be necessary to evaluate the robustness of the model. Future research is planned to address all these issues in a new extended methodology.

5. Conclusion

The proposed methodology based on robust design principles can be used to create design guidelines for machine users and increase the automation level of machine and process parameters selection. In the future, standardized SPC methods will need to be applied to evaluate the robustness of AM systems for direct component manufacturing method. Based on the results, typical requirements imposed to injection moulding plastic parts for consumer devices are challenging to fulfil by AM technology. Specially, AM surface quality hardly can compete with injection moulding, when the requirements are very tight.

In addition, full production feasibility and robustness cannot be yet met with AM technology when geometrical, dimensional and especially surface quality requirements are high. Future research is planned to evaluate robustness of AM systems by including interactions between variables, mechanical performance variables and the effect of noise factors associated with AM technology (e.g. environmental noise, deterioration noise and variation noise).
Acknowledgement

This research project has been funded by the Agency for Technology and Innovation, Tekes from Finland (grant number 3055/31/2012), together with a consortium of Finnish industry partners including: DeskArtes, Genimate, Multiprint, Nokia, Nokian Renkaat, Relicomp, TP-Tools and Wartsila.

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1st International Symposium on **Robust** Design
København, DK
14th-15th of August 2014

Robust Design of Active Systems - An Approach to Considering Disturbances within the Selection of Sensors

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Robust Design, uncertainty, modelling, metal forming, flexibility

Abstract

Uncertainty occurs in every phase of the product lifecycle, while the properties of the product and thus its corresponding behavior regarding influence parameters are mostly determined during the development phase. One goal of product development is therefore the systematic support of the development of robust products. To achieve this goal, uncertainty must be methodically identified, analyzed and finally controlled by purposeful operations. One way to control emerging uncertainty is the application of active systems, for example the application of a feed-forward controller within a machine to compensate for reduced stiffness compared to a regular machine. On the other side, the use of active-control-systems generally increases a system's complexity and creates additional uncertainty.

In order to handle these conflicting factors a methodical approach is presented within this paper that contains apropriate models, criteria and procedures to asses the inherent uncertainty of active/adaptive systems.

The information obtained can then be used to develop robust active-/adaptive-systems.
The SFB 805 process model is based on the SADT model and is used to detect uncertainty along process chains. The uncertainty is allocated to the process and the influencing parameters resources, people, information and disturbances. In addition, for the investigation of active systems, interactions between process and product must be taken into consideration. Accordingly, the process model is extended with reference to Heidemann whereas the product model is designed similar to the model of technical systems according to Nordmann. The various model elements are designed as a modular kit and can be combined to consider particular product structures.

In order to evaluate the model a multi purpose machine and a free bending process supported by an adaptive feed-forward controller is being modeled. Hence, the sensor/controller-behavior considering the influence of disturbances is examined by using the list of normalised disturbances. The control of the occurring uncertainty finally takes place using a design catalogue for sensors enhanced about aspects of uncertainty, to support the designer at their selection.

DOI:10.4122/dtu:2102

Reviewed by: *Søren Nygaard Pedersen*
Thomas J. Howard

Cited as: Freund, T., Würtenberger, J., Calmano, S, Hesse, D. and Kloberdanz, H., 2014. Robust Design of Active Systems - An Approach to Considering Disturbances within the Selection of Sensors. In: Howard, T. J. and Eifler, T., ed. 2014. *Proceedings of the International Symposium on Robust Design - ISoRD14.* Copenhagen, Denmark. pp. 147-157.

1. Introduction

Uncertainty exists when the process properties in technical systems cannot be determined completely and deviations of these properties arise. Uncertainty occurs in every phase of the product lifecycle; product properties and their corresponding response to influence parameters are mostly determined during the development phase. Because of this, it is possible that a product will not fulfil expectations and the customer cannot gain the required benefit.

In order to handle or avoid uncertainty, one goal of product development is systematic support of the product development process. It is possible to design robust products, which means uncertainty can be controlled. To achieve this, uncertainty has to be identified, analysed and controlled methodically using focused operations.

One way to control occurring uncertainty is to apply active systems. With the help of manipulated variables, active systems can influence the process and react to deviations. However, the use of active systems generally increases a system's complexity and creates additional uncertainty.

To seize the potential of active systems, there is a need for a methodology that can handle the resulting, additional uncertainty. The approach discussed in this paper aims to control the uncertainty that relates to sensors, which is part of the overall objective.

2. Methodical approach to analysing active systems

A methodical approach to analysing active controlled systems implies a model that is capable of displaying the technical system in the context of appearance. According to (VDI 2221, 1987) a model is an abstract representation that contains only purposeful elements for a certain task. The model presented in this paper is mainly characterized by a combination of existing process and product models designed to achieve the required properties. Even though the approach presented in this paper is used for the design of robust sensors, the model has been developed to be valid for every design task related to robust design or uncertainty analysis.

2.1 Modelling technical systems

The process model developed in the collaborative research center SFB 805 is used and meaningful enlarged by purposeful elements. The basic model is shown in Figure 1. The model is based on the structured analysis and design technique (the SADT Model developed by *SofTech*, 2014) by describing data flows between processes. It uses the descriptions of states before and after a process, as proposed in the process model of Heidemann (2001).

The SFB 805 process model focuses on the description and visualization of uncertainty in all states of the product lifecycle by a division into states, processes and influencing parameters. The process is realized by appliances during usage, e.g. forming, machining, assembly devices or the product (Eifler et al., 2011). The states before and after the process can be described using properties such as material, geometric or usage.

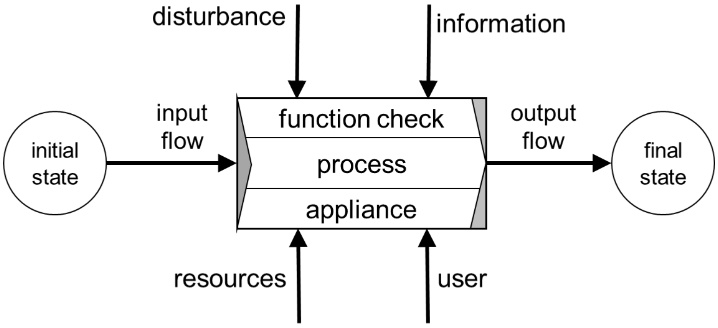


Figure 1. SFB 805 process model according to Eifler et al. (2011)

During the transformation from one state into another, the process is influenced by the influencing parameters disturbance, information, resources and user.

With the aim of modelling active systems, the appliance and its interactions with the process and the environment have to be analysed in more detail than the SFB 805 process model actually does, because active systems are able to affect the process by adapted working factors. Hence, the model is additionally required to be able to analyse the interactions between product and process. Therefore, separation of the appliance and the process is necessary, which is also realized in the Heidemann process model (Heidemann, 2001).

Analysing active systems, an adequate product model must be chosen that is capable of displaying the transfer behaviour of the appliance in terms of its functional parts, their interactions and the flows of material, energy and signals. For this purpose, the model of technical systems according to (Birkhofer, Nordmann, 2002) fits perfectly with the SFB 805 process model, because it already contains the separation between process and appliance, as mentioned above (Figure 2). The model is used to analyse mechatronic systems and is realized as a combination of common block diagrams used in control engineering and functional modelling, as in (Feldhusen, Grote, 2013). The available elements are storage, conduction, change, transmission, sensor and controller.

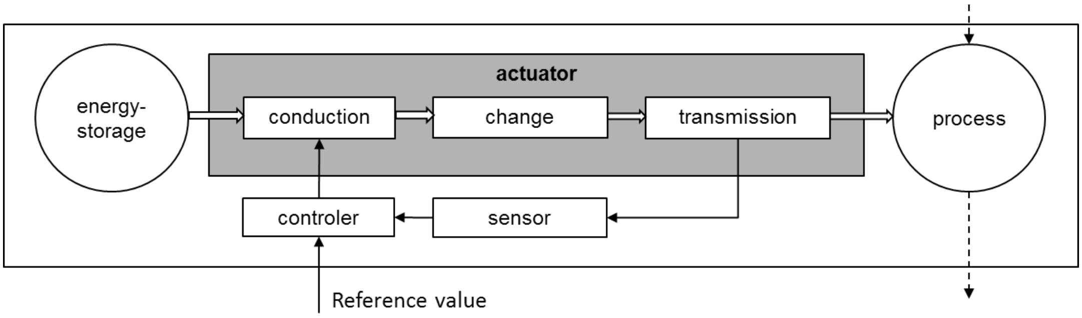


Figure 2. Model of technical systems according to Birkhofer & Nordmann (2002), as a combination of block diagram and function model according to Feldhusen & Grote (2013)

To adapt the model to the requirements of robust design tasks, these elements have to be adjusted to general purpose. To obtain detailed information, more elements than just the actuator are of interest. Therefore, the functional model kit elements proposed within this paper are Storage, Actuator, Transmitter, Sensor and Controller. The intended interactions between these elements are modelled as material, energy and signal flows.

To investigate active systems, the interactions between elements of the appliance, process and environment have to be considered. According to Kloberdanz (2009), interactions between objects can generally be modelled as arrows. Additionally, these arrows can be used to mark intended or unintended interactions by their inclination. Diagonal arrows mark an unintended interaction or influence; vertical or horizontal arrows mark intended interactions. This notation is transferred into the SFB 805 model of technical systems.

2.2 Extended SFB 805 model of technical systems

The proposed model contains a separated perspective on process, appliance and its interactions, a differentiated appliance model, and a detailed model of interactions and disturbances between user, resources and environment. Although disturbances and information are not depicted specifically, they can be considered through the interaction arrows shown in Figure 3. The example application of the model is shown in the following section.

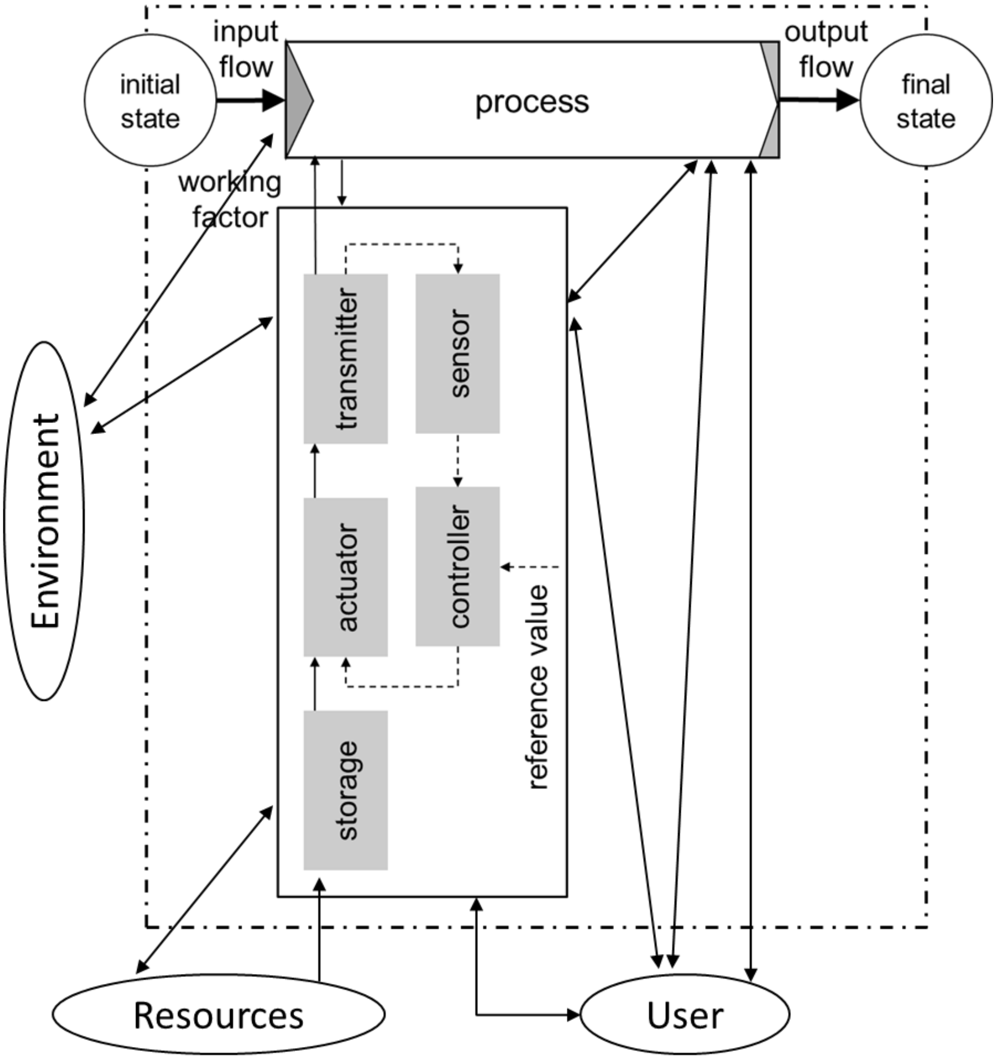


Figure 3. Extended SFB 805 model of technical systems

3. Model of a flexible bending process on a multi-purpose machine

The extended SFB 805 process model derived above is applied to a manufacturing process and analyzed in this section. In the context of production engineering, a manufacturing process is the focus of the process model. Consequently, the appliance is the forming machine, e.g. a press. Before the sample process is described using the extended process model, the 3D servo press, which is used as the appliance, will be explained. Conventional presses have the disadvantage that they provide the required forces and stroke rates but cannot adjust to fluctuating process conditions. Whereas incremental forming machines often do not offer forces and performance for efficient mass production (Calmano et al., 2013). The 3D servo press described in the following section closes this gap.

3.1. Application of the 3D Servo Press

The 3D Servo Press is a multi-technology machine which performs a flexible ram motion with various degrees of freedom (DoF).

It combines a stroke-controlled mode, provided by servo motor driven screws, and a force-controlled mode, provided by servo drives in conjunction with a crank mechanism. For special applications like wobbling, a combination of both operating modes is possible. The three independent drive systems are arranged in a star-shape, with an offset of 120°, as presented in

Figure 4. Due to these drive mechanisms, the ram of the 3D Servo Press is able to perform a conventional vertical stroke, as well as two additional rotational DoFs φ_1 (pitch) and φ_2 (roll) (Groche et al., 2010b).

In addition to the DoF of the press ram, this option allows a supplement of flexibility in the manufacturing of work-pieces. A wide variety of new processes and combinations of processes can be developed, for example, a combined flexible blanking and rolling process (Groche et al., 2010b) or an orbital forming process (Groche et al., 2010a).

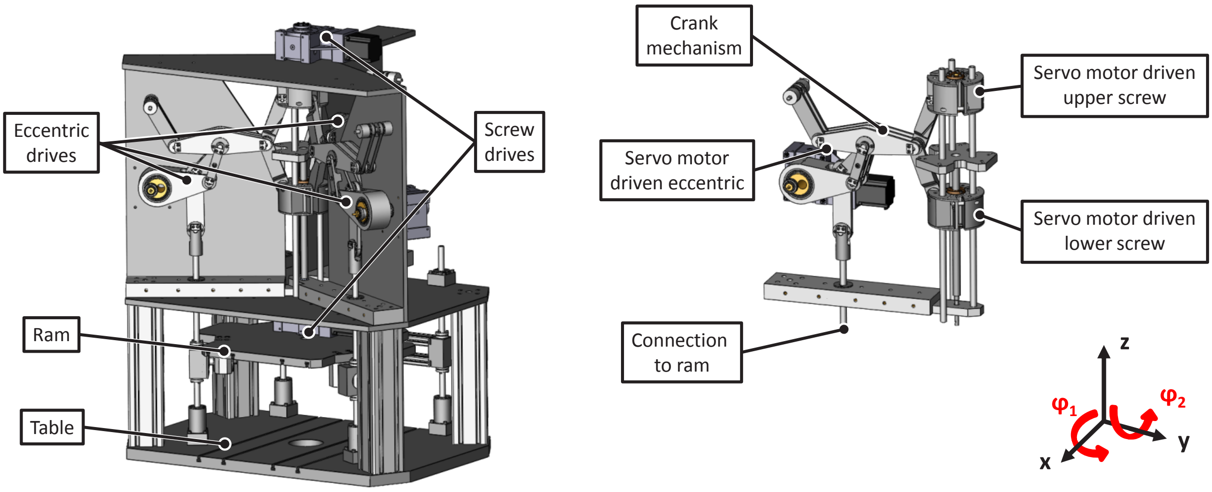


Figure 4. Prototype and lever system of the 3D Servo Press according to Avemann et al. (2014)

3.2. Process and tool concept of a flexible bending process

The 3D Servo Press and a special tool system serve as appliance to the flexible bending process. It produces a heat dissipater with individual bending angles of all four fingers. A star-shaped sheet metal blank is used as the semi-finished part. The blank is fixed on a clamping block, as displayed in Figure 5. The tool tip, which is driven by the 3D Servo Press via the tool system, bends the sheet metal by performing a vertical motion with the path length h (Avemann et al., 2014).

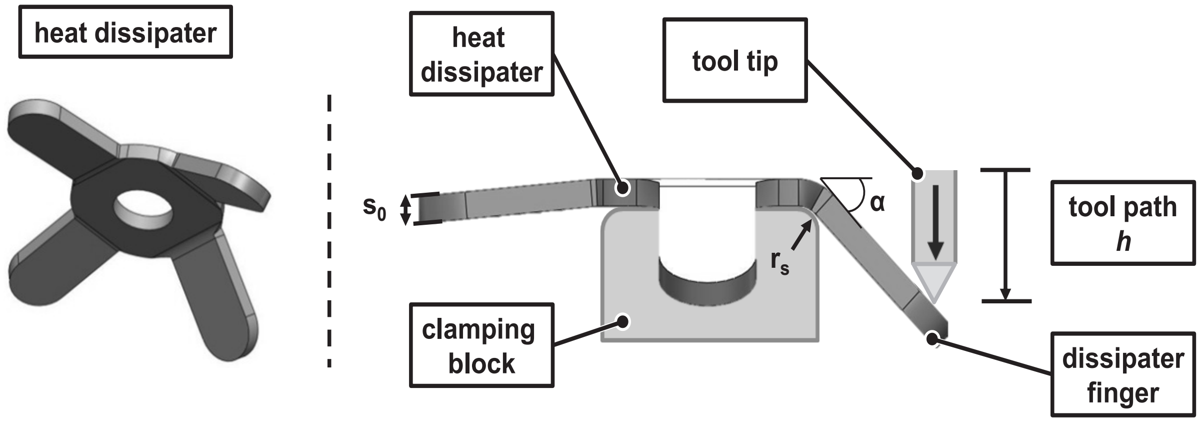


Figure 5. Three-dimensional and process view of the heat dissipater (Avemann et al., 2014)

The angle α_{act} that results after dismounting the part is dependent on the actual path length h_{act} and on the amount of spring of the material. Since the drive system and tool system deform depends on the load, h_{act} is expected to be smaller than the set-point value h_{set}. In addition, the spring-back angle of the part depends on the fluctuating properties of the processed semi-finished part: mainly sheet thickness and material. As described in (Avemann et al., 2014) and (Calmano et al., 2013), these uncertainties are controlled by the application of an adaptive feed-forward controller. The following section analyses the process control algorithm in relation to the extended process model, with the aim of analysing which uncertainties are controlled by the system and which additional uncertainties arise from integration of the necessary components.

3.3. Analysis of the manufacturing process with the extended SFB 805 process model

Figure 6 displays the components of the appliance used for the bending process. The forming process is performed by the x-y-z motion of a tool tip, which is driven by the machine. The resulting forming force $F_{x,y,z}$ acts on the tool tip and is transmitted to the tool system and ram, which acts as a transmission system. The tool system's purpose is the transforming between the 3 DoFs of the tool tip (*x, y, z*) and the 3 DoFs of the ram tool centre point (TCP: *z, pitch, roll*). The ram is attached to three independent drive systems, each consisting of a lever system (transmission) with force (F_{zi}) and position (z_i) measurement, and an electrical servo drive (actuator x_i) with a rotary angle sensor (x_i). The three drive systems are illustrated only once, denoted with the index *i* for clarity of the diagram. The actuators generating the drive motion x_i as well as the sensors measuring x_i are attached to the drive position controller. The input for the drive position controller is a vertical z-position z_{set}, which has to be transformed to drive coordinates using kinematic relations. The machine position controller uses the measured position of the outputs of the lever system zi to compensate the deformation of the lever system under the load F_{zi}. The set-point tool path hset is generated by the process controller, which is designed as an adaptive feed-forward controller. It makes use of the properties of the semi-finished parts, determined by a detection algorithm from force and position information Fzi and zi (Calmano et al., 2013).

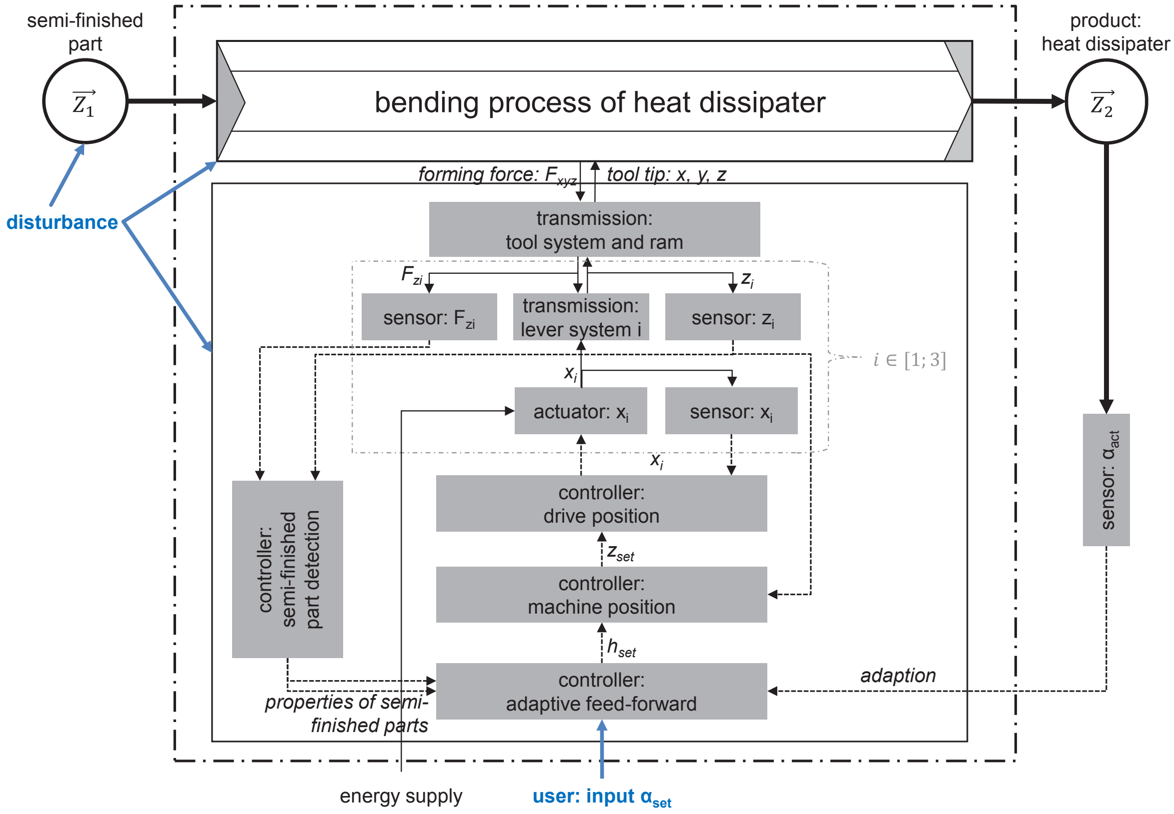


Figure 6. Flexible bending process described using the extended process model

The iterative feed-forward controller has to predict the transmission behaviour of all components in the described drive system. Since a technological consideration and description of all components, which is necessary to analytically derive a model function, is complex and time-consuming, a linear approximation of the global behaviour of the machine, tool system and part is implemented. The model parameters of this approximated model are determined iteratively from recent experiments by linear regression of the relation between stroke *h* and resulting angle α_{act}. Thus, the geometric property of the product, α_{act}, has to be measured externally after the process. This offers the additional benefit of taking into account the fluctuations in the transmission behaviour of the machine and tool as well as in the spring-back behaviour of the part. Disturbances to the drive system and part can thus be controlled in an iterative process control. The advantages and shortcomings of this approach are discussed in the following section.

3.4 Advancement of the process control using in-line angle measurement

The process controller in the design described above predicts the necessary machine stroke *h* to produce the desired set-point angle αset without detailed information about the actual tool tip position and the current bending angle $\alpha_{act}(t)$. Disturbances affecting the product properties can only be detected and controlled iteratively after the current part is manufactured and measured externally. For detailed monitoring during the process and part properties during the process, an in-line measurement of the current bending angle is aspired. However, there are severe challenges when integrating sensors into a forming process. Whereas forces and positions of the drive system are easy to acquire, the benefit of controlling the forming process is low. The actual properties of the part on the other side are highly interesting for process control but are usually difficult to measure (Calmano et al., 2013).

In the presented bending process, the current bending angle $\alpha_{act}(t)$ could be measured by implementing machine vision cameras, for example. This measuring system consists of components additional to the components described in Figure 6: the camera as a sensor and a controller with implemented algorithms for image processing and analysis. All additional components are affected by disturbances, leading to additional uncertainties in the overall process. In order to minimize global system uncertainty, the benefits and disturbances caused by additional sensors have to be balanced. The analysis of sensors and measuring uncertainty, as described in Section 4, is part of this.

4. Design of robust sensors

To control uncertainty, especially in sensors, first, the additional uncertainty caused by these elements has to be analysed.
In the second step, the information is used to create a particular design catalogue to support the designer during the development process of appliances containing sensors. The catalogue includes diverse measurands and measuring principles related to its behaviour under particular disturbances. Finally, the benefit of the approach is shown using the model of the bending process presented in Section 3.

4.1 Additional uncertainty caused by sensors

The transmission of the measurand into a signal is subject to errors and is therefore a source of additional uncertainty (Figure 8). Some of the reasons are:

- **Measuring range**
  The implemented measuring range of the sensor has to generally fit with the range of the measurand in order to be acquired. Deviations of the measurand that exceed the measuring range can cause unstable system behaviour.

- **Measuring resolution**

  Changes of the measuring variable may result in transmitting errors if the sampling rate of the measuring system is not high enough. According to the Shannon Theorem, the sampling rate must be at least double the highest frequency of the measurand. In practical applications, normally the resolution frequency is up to 10 times higher than the measurand frequency (Nordmann, 2005). This is a heuristic rule to control uncertainty.
- **Influencing parameters**

  Deviations in disturbances have a big influence on active systems. They affect the input measurand, the output signal, the transmitting behaviour or any combination of the three. Therefore, one of the key factors in controlling additional uncertainty in active systems is to design them to be resilient against these impacts.

4.2 Design catalogue for robust sensors

According to Mathias et al. (2010), there are three purposeful robust design (RD) principles to control deviations in influencing parameters. *These principles are eliminate disturbance, eliminate influence and eliminate impact.*

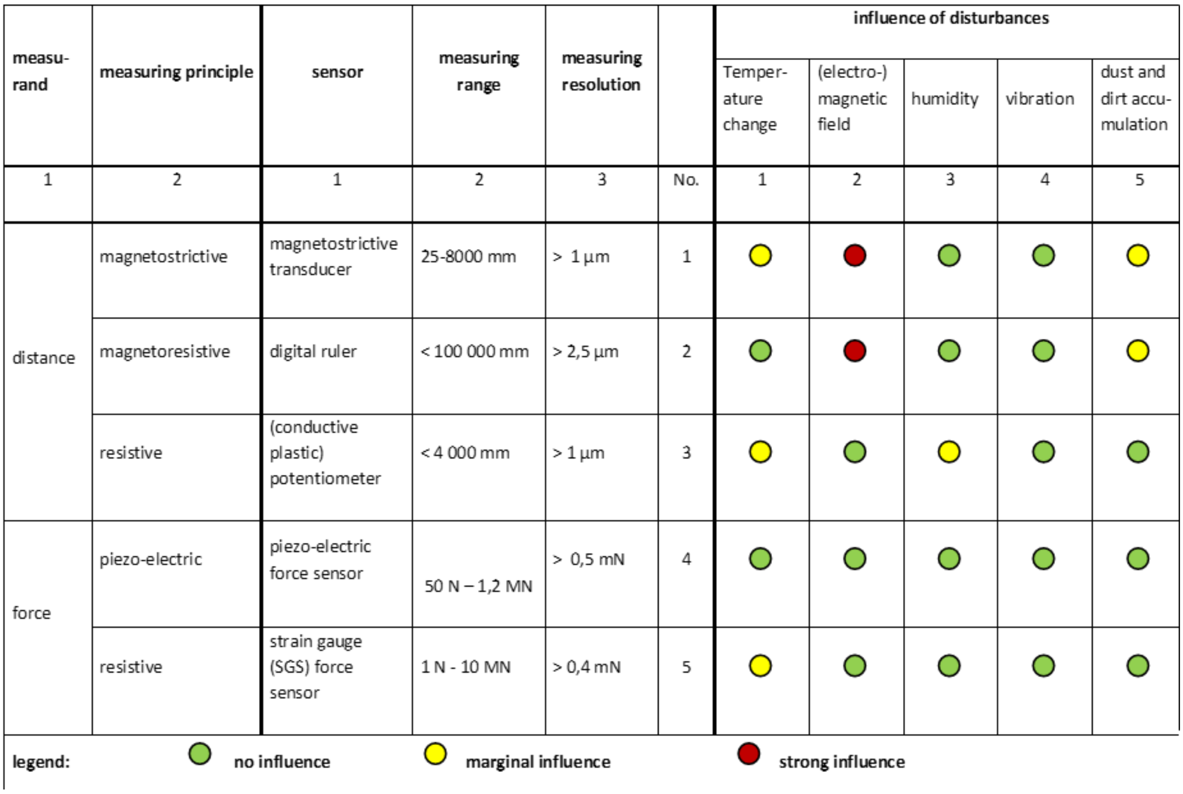
In order to design robust sensors, a design catalogue containing particular information about sensors and their behaviours, depending on disturbances can support application of these robust design principles (Figure 7). It closes the gap between general robust design rules and very detailed, specific information the designer gets from the manufacturers of sensors and therefore supports the design process. The information presented in the catalogue is based on intense literature research. The structure of the catalogue is related to the structure recommended by Roth (1982). He proposes a particular order to systematically access information during the design phase, which builds the structural frame for the catalogue. Future work will focus on a database approach to performing search operations more efficiently.

In order to apply the presented catalogue, the following procedure has to be executed by the designer:

The first part of the catalogue contains the measurand and the measuring principles so the designer choses a measurand and, based on this information, obtains access to related information about the sensors, their properties and their sensitivity to disturbances. In addition, the catalogue provides some measures to eliminate the influence of the disturbances (which is not included in the depiction of the catalogue in this paper).

The designer can use the checklist of disturbances in (Mathias, 2012) to determine the disturbances occurring in a certain environment. Using this information, the designer can now choose an appropriate sensor for the situation.

Since the robust design principle *eliminate disturbance* should be avoided (Mathias, et al., 2010), the measures given in the catalogue focus on the principles *eliminate influence*, for example, protection against electromagnetic fields, and *eliminate impact*, for example, recalibration of the system.



measurand	measuring principle	sensor	measuring range	measuring resolution		influence of disturbances				
						Temperature change	(electro-) magnetic field	humidity	vibration	dust and dirt accumulation
1	2	1	2	3	No.	1	2	3	4	5
distance	magnetostrictive	magnetostrictive transducer	25-8000 mm	> 1 µm	1	🟡	🔴	🟢	🟢	🟡
	magnetoresistive	digital ruler	< 100 000 mm	> 2,5 µm	2	🟢	🔴	🟢	🟢	🟡
	resistive	(conductive plastic) potentiometer	< 4 000 mm	> 1 µm	3	🟡	🟢	🟡	🟢	🟢
force	piezo-electric	piezo-electric force sensor	50 N – 1,2 MN	> 0,5 mN	4	🟢	🟢	🟢	🟢	🟢
	resistive	strain gauge (SGS) force sensor	1 N - 10 MN	> 0,4 mN	5	🟡	🟢	🟢	🟢	🟢

legend: 🟢 **no influence** 🟡 **marginal influence** 🔴 **strong influence**

Figure 7. Example depiction of the design catalogue for robust sensors.

4.3 Example application of the design catalogue

The model of the flexible bending process shown in Figure 5 contains 2 different types of sensors. At the actuator and the lever system there are distance sensors, while at the lever system forces are also measured. A third type of sensor is outside of the investigated system and is used to measure the bending angle after the process. This information is used to close the control loop by adapting the feed-forward controller.

Since the product (3D servo press) already exists in this setup, the application of the catalogue has to be executed in inverse. The information is accessed through the type of the sensor instead of the type of measurand. Based on the type of sensor, the disturbances and their influence can be determined.

In order to demonstrate the procedure, the distance sensor of the lever system is investigated. The sensor is a magnetostrictive transducer with a measuring range of 10*mm* and a measuring resolution of 10*µm*. The catalogue shows it is strongly influenced by magnetic fields and marginal influence by temperature change and dirt accumulation (Figure 8). This information can now be used to predict the system behaviour in several environments and to design particularly robust solutions using the robust design principles.

Assuming that in a demonstration strong temperature changes occur, a possible solution for the principle *eliminate impact* could be an adequate and easy-to-use calibrating system. The principle *eliminate influence* could lead to a reflecting coating. The third principle, *eliminate disturbance,* could, for example, lead to a capsuled 3D servo press with an air-conditioning system. If no solution can be found, the catalogue can be used to choose alternatives, using the procedure mentioned in Section 4.3.

The same procedure can now be applied for the inline–angle measurement presented in section 3.4. to demonstrate its additional value.

5. Conclusion

The approach presented in this paper demonstrates that complex technical systems can be modelled, using the extended SFB 805 model of technical systems, to identify and analyse uncertainty. The model explicitly combines the executed process with the appliance and is therefore capable of being used to investigate interactions between them. The appliance model focuses on the main elements of active systems. Additionally, the interactions between a technical system and its environment can be modelled, while the consideration of disturbances is especially important to robust design tasks.

The design catalogue presented in Section 4 is an approach to closing the gap between general information about measurement principles and detailed information about specific sensors given by manufacturers. It contains information about sensor measurands, measurement principles and qualitative information about sensitivity to particular disturbances. It can be used to design robust products through the selection of sensors that are not sensitive to disturbance, or to adapt to new circumstances. For these purposes, the SFB 805 process model provides the necessary information.

Future work should have the objective of validating the model in practical design tasks. Additionally, the RD approach should be enhanced to control uncertainty of active systems in general, including controller and peripheral equipment.

Acknowledgments

The results of this paper were achieved by the Collaborative Research Centre SFB 805 “Control of uncertainty in load-carrying mechanical systems” in subprojects “A1: Development of Models, Methods and Instruments for the Acquisition, Description and Evaluation of Uncertainties”, “A2: Robust Design – Methodology for the Design of Systems with Optimum Uncertainty Solutions” and “B2: Forming – Production families at equal quality”. The authors wish to thank the Deutsche Forschungsgemeinschaft (DFG) for funding and supporting the SFB 805.

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1st International Symposium on **Robust** Design
København, DK
14th-15th of August 2014

Impact of Geometric Variation on the Performance of Cold Formed Bearings

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Keywords: Cold forming, geometrical/dimensional features, process capability analysis, finite element analysis, robust design.

Abstract

Plain spherical bearings are precision assemblies with a low frictional moment finding wide application in industry where they operate in harsh environments. They are manufactured using a cold forming process known as 'nosing'. An experiential approach is currently used by a manufacturer to develop new bearings and determine associated process settings. Typically, inefficiencies can be observed for the bearing assembly post-nosing where any one of nine different failure modes may occur leading to rework or scrap costs due to a number of component and process inconsistencies. The initial focus is the outer bearing shell component and the geometrical relationships of the end chamfer features. Process capability measures are developed for a bearing model, with parts individually tracked through the nosing process to examine the influence out-of-tolerance variation on process integrity, measured forming loads and frictional moment. A validated Finite Element (FE) model is used to predict the complex elastic-plastic material behaviour at high strain-rates in the nosing process to support the simulation of in-process failure modes. These models take into account the geometrical and dimensional variations of the chamfers, material property variation and coefficient of friction. Predictions are made for feature process capabilities which produce lower failure rates in production.

1. Introduction

The applications of the plain spherical bearing are wide and varied, including within the aerospace, locomotive, automotive and food industries. Figure 1a) shows a schematic of a plain spherical bearing indicating three common components: a central inner race which enables the bearing to be axially supported; an outer sleeve provides a platform for other components in the assembly and a composite liner in between the inner and outer races, affixed to the latter, provides self-lubrication and frictional properties during operation. Figure 1b) shows a typical bearing in a locomotive application. Nosing is the cold-metal forming process primarily used in the manufacture of plain spherical bearings (Orsolini & Booker, 2012; Woodhead & Booker, 2013). In this process the outer race is formed on each side simultaneously whereby it is placed, together with the inner race and composite liner, in between two identical spherical dies as shown in Figure 2a). The upper die displaces along the bearings axis, and the bearing is subjected to compression at the contact interface between the die and the outer race as the

DOI:10.4122/dtu:2103

Reviewed by: *Thomas J. Howard*
Tobias Eifler

Cited as: Woodhead, J., Booker, J. D. and Truman, C. E., 2014. Impact of Geometric Variation on the Performance of Cold Formed Bearings. In: Howard, T. J. and Eifler, T., ed. 2014. *Proceedings of the International Symposium on Robust Design - ISoRD14*. Copenhagen, Denmark. pp. 159-170.

force is translated axially. This causes the outer race to undergo elastic-plastic deformation, until it geometrically conforms to the shape of the inner race, Figure 2b). Custom-made press machines are used to produce the level of force required, up to several hundred Metric Tons.

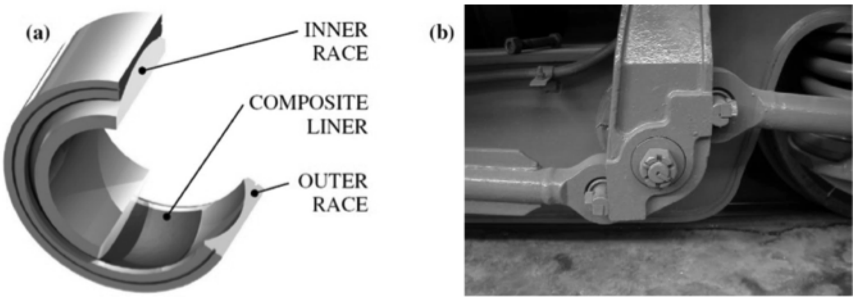

Figure 1. Plain spherical bearing; (a) CAD cut-away view (final bearing product, after the nosing process and additional machining of the outer race has been completed), (b) example application (rail locomotion)

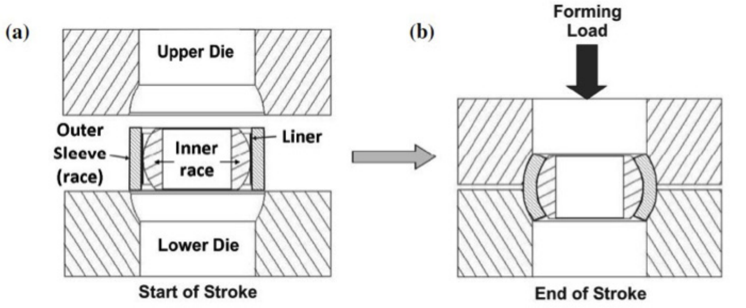

Figure 2. Schematic of the nosing operation (a) start and (b) end of the stroke

Undesirable failures can occur during the nosing process, resulting in either extensive re-working or scrapping if the correct geometric conformity or target frictional moment cannot be achieved. Nosing is a complex process, with the root cause of a process failure being an interaction of many factors (Antony, 2003). Incorrect pressure, displacement, number of cycles (i.e. the number of consecutive times the press will lower), machine specifications and pre-form design are just a few contributing factors, and can produce any combination of the failure modes identified in Figure 3. The failure modes were discussed with company machine operators (with a combined experience of over 40 years), as part of an ongoing project to generate scientific and engineering knowledge to be used in future product developments. Using this experience, a system of weightings (roughly following an FMEA approach) was developed to produce an overall risk score (Figure 3), based upon the complexity of the various causes, the production impact and the frequency of occurrence. The system diagram in Figure 4 outlines key factors/variables which may influence the nosing process.

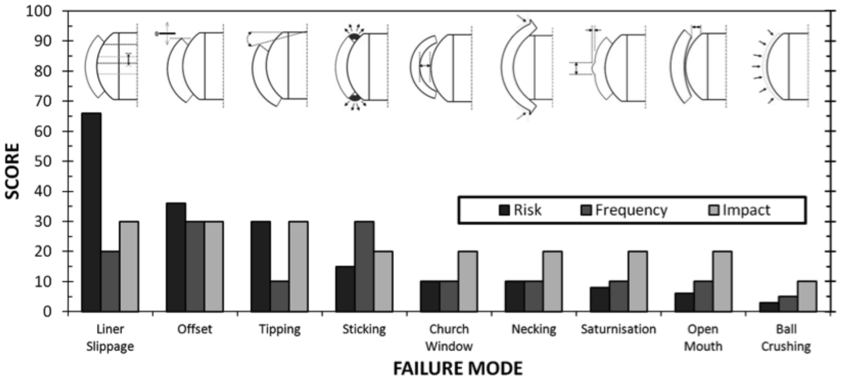

Figure 3. Nosing failure modes, their relative occurrence and impact upon production

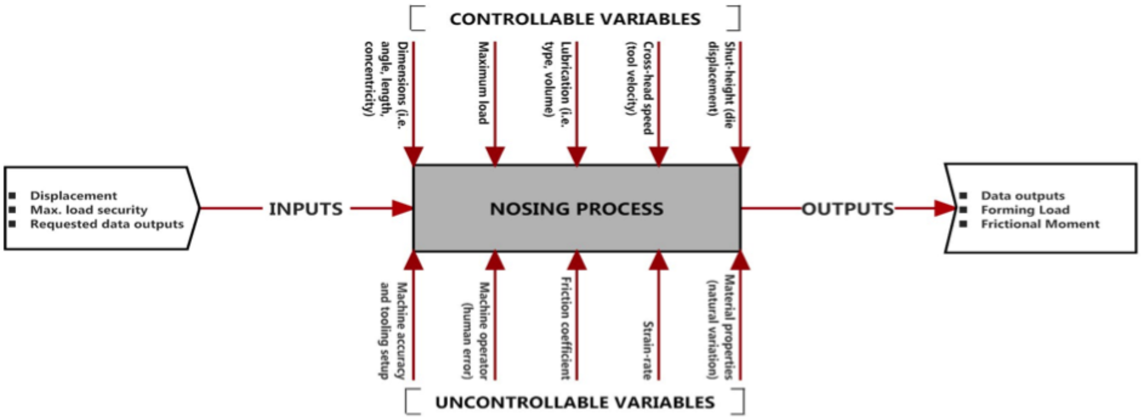

Figure 4. System diagram showing inputs, controllable/uncontrollable variables and outputs

Process failure causes commenly attributed to the most prevelant failure modes are unequal geometry on the outer race of the bearing and variations in tooling set-up. Variations in press tooling and any inherent variability in the machine itself are difficult to control and challenging to model. However, the geometric features of the bearing can be controlled, specifically the chamfers, which are initially set by the design engineers and subsequently machined within the business. The chamfers are the first point of contact with the die, and this initial contact plays an important role in influencing the nosing process, as they promote easier formability of the component in order to achieve a greater geometric conformity between the outer and inner race. The chamfer length of the investigated component is 1.315mm ± 0.142mm by 15º ± 2º on the outer race (Figure 5). Tolerances are usually set based on:

- **Waste reduction:** The least volume of material required to produce the final design speified by the customer;
- **Cost effectiveness:** If sleeve dimensions that fit an existing die set also maintain compatibility with the customer specifications;
- **Performance:** The sleeve needs to accommodate enough liner to produce the required frictional moment at the correct geometric conformity;
- **Compatibility:** The sleeve needs to be compatible with existing tooling i.e. sleeve inner diameter small enough to fit press machine location pin, sleeve length short enough to stay within die set without protruding into the bore.

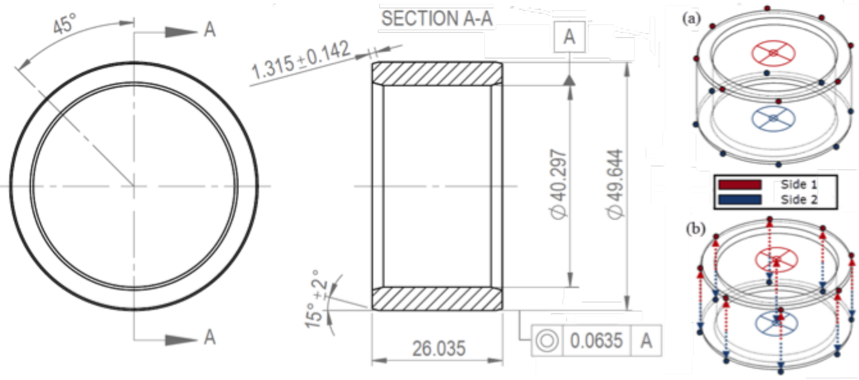

Figure 5. Baseline bearing model outer race, with section view indicating key geometric features with tolerances (dimensions in mm), and isometric views indicating the measurement points (a) on either side of the bearing, (b) between bearing sides

If tolerances are exceeded the company know that, through experience, the risk of certain failure modes occurring increases i.e. too long a sleeve length leads to ‘necking’, too large a sleeve outer diameter leads to ‘saturnisation’, too small a sleeve inner diameter leads to ‘liner slippage’ etc. Some feature dimensions on the bearing outer race will be manufactured to a minimum and others to a maximum. Should any features fall within this 97th percentile of the statistical distribution, it is not known exactly what effect this would have either during the nosing process or on the final output. However, a 2-factor/2-level DoE on the angle and length of the bearing chamfers using FE simulations shows a correlation between these two key dimensions (Figure 6). Furthermore, no geometric tolerances are specified on engineering drawings, leading to the statistical possibility that the opposing sides of the bearing outer race may have minimum and maximum extreme values respectively (e.g. one side having a minimum chamfer angle and the other having a maximum). Empirical evidence suggests this may contribute to any number of failure modes, in particular ‘offset’ and ‘tipping’, contributing also to ‘liner slippage’.

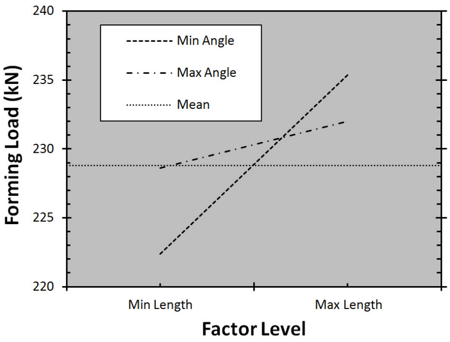

Figure 6. Combined effect of minimum/maximum chamfer angle and length on forming vload

2. Methodology

2.1 Objectives

The objective of this study is to ascertain the batch variation of geometric features of a high-volume production bearing model, in order to understand the impact upon the measureable process outputs of forming load and frictional moment. This knowledge is used to enable new, more robust, geometrical tolerances to be set. The stages involved and presented are;

- Measure bearing outer race dimensions (i.e. chamfer outer and inner diameter, angle and geometric length) prior to the nosing process;
- Record nosing process outputs (i.e. forming load and frictional moment) of all measured bearing samples;
- Statistically analyse the data to access whether there is a statistical significance between the key features of either side of the bearing outer race;
- Calculate process capability indices, and provide recommendations as to process performance.

2.2 Measurements

The measurements were taken using a high precision optical comparator (Figure 7) with accuracy in the order of ±10-6 m. The bearing was mounted on a V-block with a 360° turn-table in order that the bearing could be rotated to measure the both sides with minimal handling. Lights on the machine can be directed at close range toward the sample to project an image onto the screen. A green light is used to project the shadow of the bearing onto the screen for precise measurement of edges, and a white light can be used to view any detail on the bearing surface. Mechanical levers operate the 4-axis table to position the point of interest on the viewing screen. The x, y, z coordinates relating to the cross-hairs in the centre of the screen were recorded from the digital display. Each bearing sample was marked every 45° of each side, to indicate where to take measurements around the circumference. The detail view was used to measure the chamfer inner diameter, whereas the shadow view was used to measure the chamfer outer diameter, geometric chamfer length (the true length of the chamfer from edge-to-edge) and the chamfer angle. Both inner and outer diameters were measured on one side, the bearing was rotated 180°, and the process repeated. The bearing was then placed onto a V-block with the flat sides normal to the table surface, in order that the chamfer length and angle could be measured on both sides.

Figure 7. Optical comparator with bearing outer race in-situ, showing; lens and lights directed at the part mounted on the 4-axis table (left), and shadow-view of the bearing outer race (right)

A CAD program was used to calculate the offset in concentricity between the outer and inner diameter of the chamfer. This was due to the number of points measured, as well as providing a convenient method of visualising the results. The recorded x, y co-ordinates were imported into the software in order that the centre point of both the inner and outer diameters was calculated accurately, and the total shift between each side of the bearing (geometric eccentricity) could also be measured.

2.3 Analysis Tools

Statistical analysis is performed on the bearing outer race, and the data provides an indication as to the extent of variation in the key features of the bearing outer race. The process is under statistical control; hence, Normal distributions are assumed and parameters are determined using the linear rectification method (Booker et al., 2001), except for concentricity. For features which have negative values such as those with a target value of zero (zero-bound data), or data that is recorded as absolute deviations from a target value, additional statistical processing is required. Concentricity is a truly zero-bound form of feature data; therefore, once the distribution is plotted, one tail of the distribution is negative. Although this is mathematically correct, in reality there are no negative values allowed, and the normal density function must be 'folded' (Kotz & Lovelace, 1998) at zero. The folded standard normal distribution (equation 1), the population mean (equation 2) and the standard deviation (equation 3), are then calculated as follows:

$$f_1(x) = \frac{1}{\sigma\sqrt{2\pi}} Exp\left(-\frac{1}{2}\frac{(X-\mu)^2}{\sigma}\right) + Exp\left(-\frac{1}{2}\frac{(X-\mu)^2}{\sigma}\right) \tag{1}$$

$$\mu_{f_1} = \mathrm{E}(\mathrm{X}) = \mu\left[1 - 2\Phi\left(-\frac{\mu}{\sigma}\right)\right] + \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(\mu/\sigma)^2} \tag{2}$$

$$\sigma_{f_1}^2 = \mathrm{E}\left[\left(\mathrm{X} - \mu_{f_1}\right)^2\right] = \sigma^2 + \mu^2 + \mu_{f_1}^2 \tag{3}$$

Where σ is the normal standard deviation, μ is the normal population mean, X is the variable of interest and Φ is a function of the standard normal distribution. Using the statistical data, a process capability analysis is then performed, which will indicate current process performance using C_p/C_{pk}.

2.4 Part Details

The key features and dimensions of the component to be measured are detailed in Figure 5. The outer bearing race material properties, determined previously via uniaxial compression testing to ASTM standards (Woodhead & Booker, 2013), are detailed in Table 1.

Table 1. Mechanical properties of bearing outer race

Property	Symbol	Value
0.2% Proof Stress	σ_y	1.080 [GPa]
Poisson's Ratio	ν	0.33
Young's Modulus of Elasticity	E	199.80 [GPa]
Strength Coefficient	K	1.750 [GPa]
Strain-hardening Exponent	n	0.13

3. Results from In-process Tracking

3.1 Geometric Variation

3.1.1 Concentricity

Chamfer centre-points on either side of the bearings are shifted away from one another at various different angles (Figure 8). Some shifts between sides can be in the same direction or opposed to one another, and this difference between the centre-points of each side is the geometric concentricity. The type of shift between the two sides will affect how contact between the chamfer and die initiates, potentially having a significant effect on the remainder of the nosing operation; therefore, a more significant factor during the nosing process may not simply be the individual shift in chamfer concentricity, but rather the geometric concentricity (offset in concentricity between either side). Throughout the following figures, samples 2 and 14 from this batch of bearing outer races have been highlighted as samples of interest. The mean offset in concentricity (for both sides of the bearings together), is 0.01mm which is within the general tolerance limit of 0.0635mm. Larger distributions were calculated for the offset in geometric concentricity, resulting in a population mean of 0.05mm which, while still being within the tolerance limit, is very close. Furthermore, in terms of geometric concentricity, 3 standard deviations is more than a 0.2mm shift. If a bearing were to have an offset in geometric concentricity within the extreme tail-end of this distribution, it may contribute to one or more of the failure modes highlighted in Figure 3. The population means for concentricity are almost identical on either side of the bearing outer race. Both distributions correlate well, with the distribution range of side 2 being slightly larger than that of side 1. The tail-end of the distribution exceeds the upper tolerance by approximately 0.02mm; however, less than 2% of the total distribution is outside tolerance. The concentricity data appears well behaved, but a further analysis of the geometric concentricity, once the negative part of the data is folded back, reveals a large standard deviation of over 0.2mm. Up to 3 standard deviations is approximately 0.6mm, resulting in over 60% of the distribution being outside tolerance. The disparity between concentricity and geometric concentricity can be seen Figure 9.

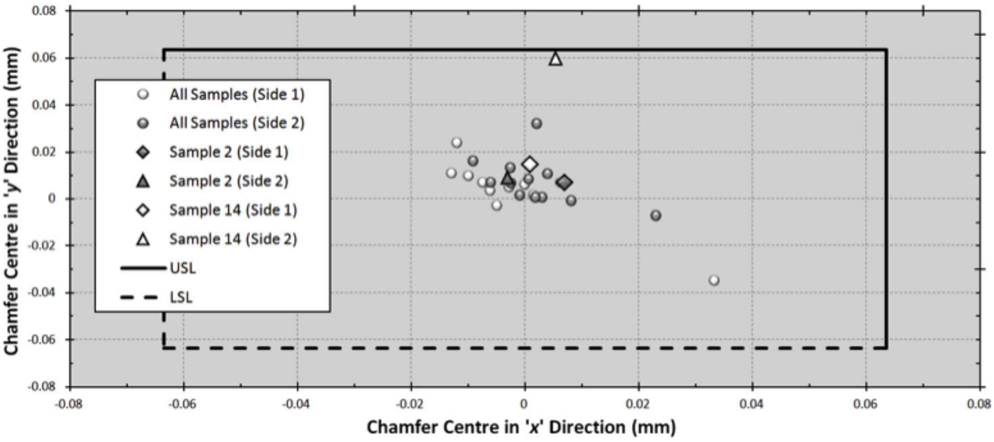

Figure 8. Cartesian coordinates of chamfer centre-points for both sides of the bearing sleeve (origin of the represents the sleeve outer diameter centre, tolerance limits = ±0.0635mm)

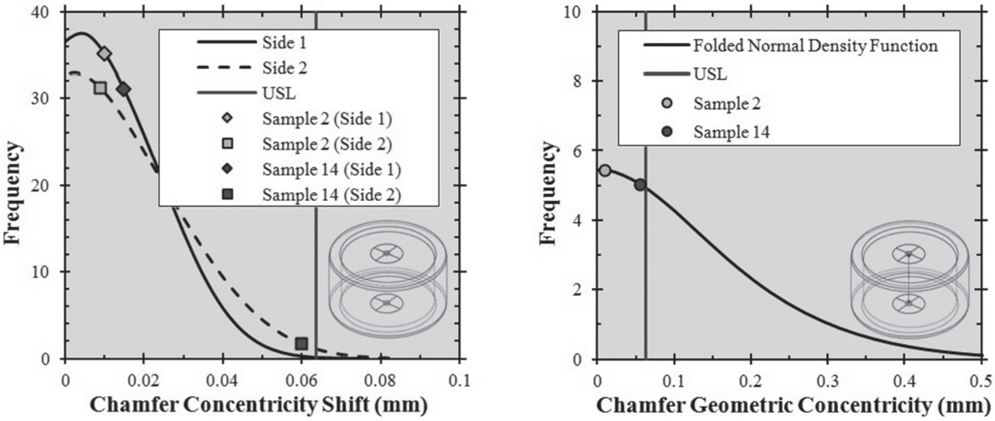

Figure 9. Folded normal distributions (NDf) for; (left) shift in chamfer concentricity (target mean 0mm), and (right) shift in geometric chamfer concentricity (tolerance limit 0±0.0635mm)

3.1.2 Angle

The population means for the angle of the chamfers between sides 1 and 2 of the bearing outer races are similar, to within two decimal places, indicating high precision. The process capability, Cp, index is acceptable, indicating that the process is capable, but the chamfer angle tolerance is large (±2°) and therefore the process capability index will be high, as even 2 standard deviations of the SND curve is well within the tolerance limits. The distribution is not perfectly centred though, and is shifted towards the lower specification limit (Figure 10 – left); however, this is within 1.5 standard deviations which is a normal shift for any process (Booker et al., 2001). The tail-end of the distributions for both side 1 and 2 is less than 1% outside the lower specification limit (LSL), but this results in the Cpk index being reduced to 1.0, indicating that the process is not capable. Further analysis was conducted firstly, on the difference between the angles opposite each other on the same side of the bearing, and then secondly, on the difference between the angles opposite each other on different sides of the bearing (Figure 10). This transforms the data into zero-bound data, similar to concentricity, because the target value is zero degrees (i.e. no difference in chamfer angles between measurement points), therefore; a folded normal density function (equation 1) was calculated to remove any negative data, as before. Analysis indicated that the mean difference in chamfer angle between sides 1 and 2 shows the largest shift at almost 0.6°.

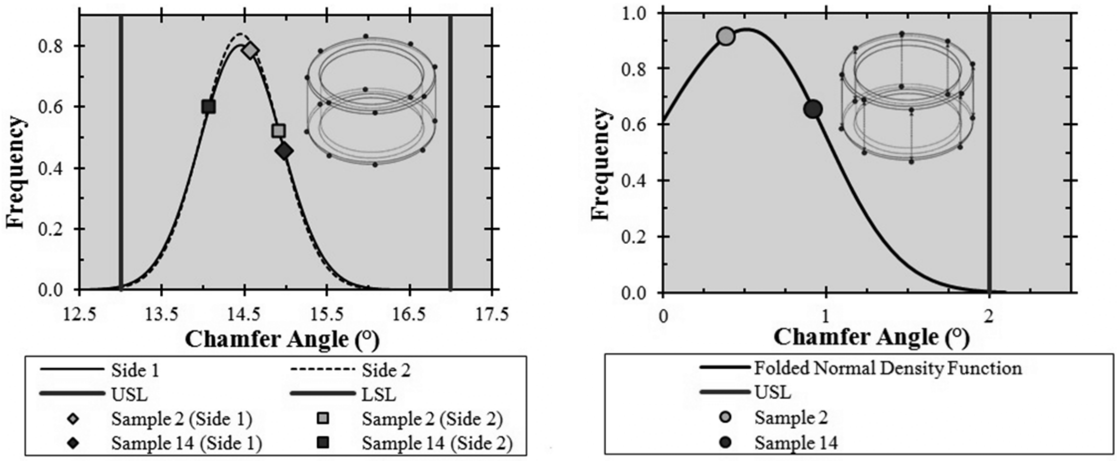

Figure 10. Standard normal distributions (SND) and folded (NDf) for; (left) chamfer angle for sides 1 and 2 (target mean 15°), and (right) difference in chamfer angle between sides 1 and 2

3.1.3 Length

The population means, μ, of side 1 and 2 are shifted towards the lower specification limit, and side 1 even falls fractionally outside tolerance (Figure 11 – left). Further analysis was again conducted firstly, on the difference between the lengths opposite each other on the same side of the bearing, and then secondly, on the difference between the lengths opposite each other on different sides of the bearing (Figure 11 – right). Once again, this transforms the data into zero-bound data, similar to concentricity, because the target value is zero millimetres (i.e. no difference in chamfer lengths between measurement points); therefore, a folded normal density function (equation 1) was calculated to remove any negative data within the normal distribution. Analysis indicated that distributions for both sides 1 and 2 for the difference between chamfer lengths both fell within tolerance (data not provided here), and had high Cpk indices, however; the population mean, μ, for the difference in chamfer lengths between sides is 0.15mm, placing it outside tolerance with less than 25% of the distribution within tolerance (Figure 11 – right). This indicates that there is a manufacturing issue in producing this feature, and a more detailed analysis revealed that the de-burring process caused an excessive amount of material to be removed from the chamfer on Side 1.

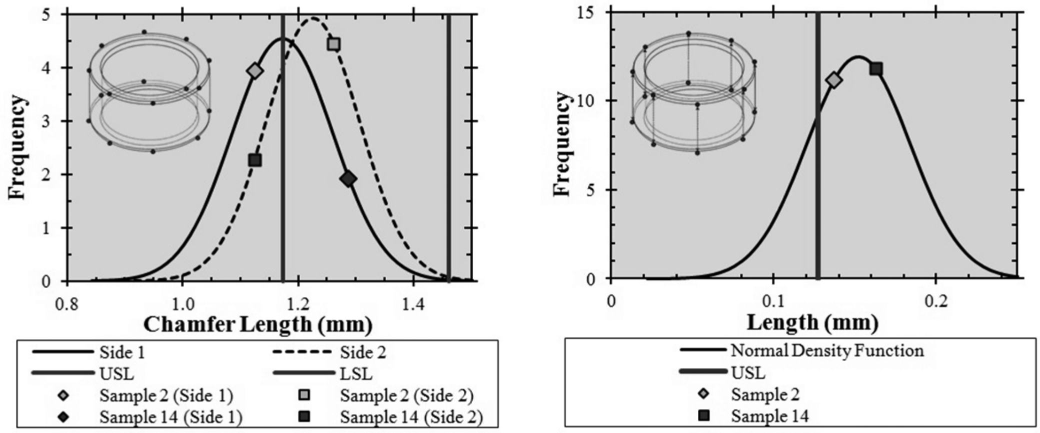

Figure 11. Standard normal distributions (SND) for; (left) chamfer length, for sides 1 and 2 (target mean 1.315mm), and (right) difference in chamfer length between sides 1 and 2

3.1.4 Inner Diameter

There was not predicted to be any large variation in measured values for the inner diameter of the outer race, but the measurements were taken for completeness. The statistical analysis confirms that the population mean, μ, is within tolerance, with a low standard deviation, giving this variable a high Cp index. Furthermore, the mean is almost exactly midway between specification limits, with the SND curve spanning less than 15% of the range between them. Hence the Cpk index is 8, indicating that this dimension may be expensive to produce and production machines utilised are not optimum.

3.2 Volumetric Variation

On further analysis, the volume of each bearing sample was calculated, and the results were analysed statistically (Figure 12). The company do not specify tolerances for the volume of parts, but theoretical limits were calculated based upon the combination of geometrical tolerances that are specified on the engineering drawing for this component. Sample number 14 was recorded as having consistently one of the highest forming loads, highest frictional moments and largest volumes; whereas, sample number 2 was recorded as having consistently one of the lowest forming loads, lowest frictional moments and lowest volumes. The larger the volume, the greater the energy required to produce the same amount of deformation, consistent with metal forming theory (Caminaga & Gentile, 2005). Additional factors such as contact between dies and bearing surface and lubrication used, and adverse shear stresses (Woodhead et al., 2014), all increase the amount of energy required to complete an operation resulting in higher local pressures and temperature rises. These factors together with the repeated impact of the dies and the sliding of the bearing materials, in time, can lead to failure of the dies through wear, thermal fatigue, mechanical fatigue and plastic deformation (Grote, 2009). If the lubricant breaks down under high pressure, the heat generated due to friction can cause micro-welds to form between the sliding surfaces. This may damage the surface of either the die or bearing.

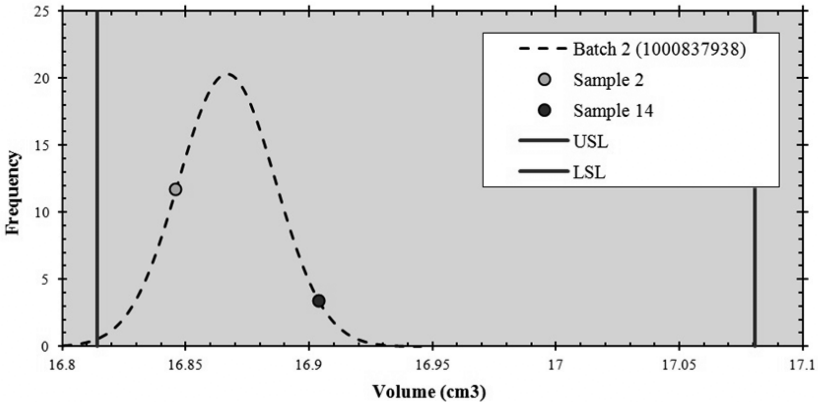

Figure 12. Normal distribution of bearing sleeve volume

3.3 Forming Load

As part of this analysis, the forming load data was collected from the press machine for later use with model validation (Figure 13). The data was processed in the standard way, using the linear rectification method (Booker et al., 2001). An appropriate curve was then fitted through the statistical data points. The experimental data curve is a regression fit, named the reciprocal logarithm, from the exponential family of numerical models. The curve fit has a strong correlation coefficient (0.996), ensuring a good correlation with the experimental data. Abaqus was used to perform finite-element (FE) analysis on the bearing, using a 3D model with the explicit analysis module. The dies, inner race, outer race and composite liner were all modelled as individual parts in a CAD package, to ensure precise reconstruction of geometry using data collected from the experimental analysis. The parts were then exported into Abaqus CAE for numerical analysis. Firstly, the global friction coefficient of the models was tuned using bearing parts modelled with mid-tolerance dimensions, as per company engineering drawings. Simulations were run using these parts, with friction coefficients ranging from 0.05μ to 0.45μ. As the FE forming load curve for 0.15μ displayed the highest correlation to the final forming load of the experimental curve, this value was calibrated as the input parameter for the coefficient of friction for future simulations. In reality the friction coefficient changes markedly with pressure (Cora et al., 2008).

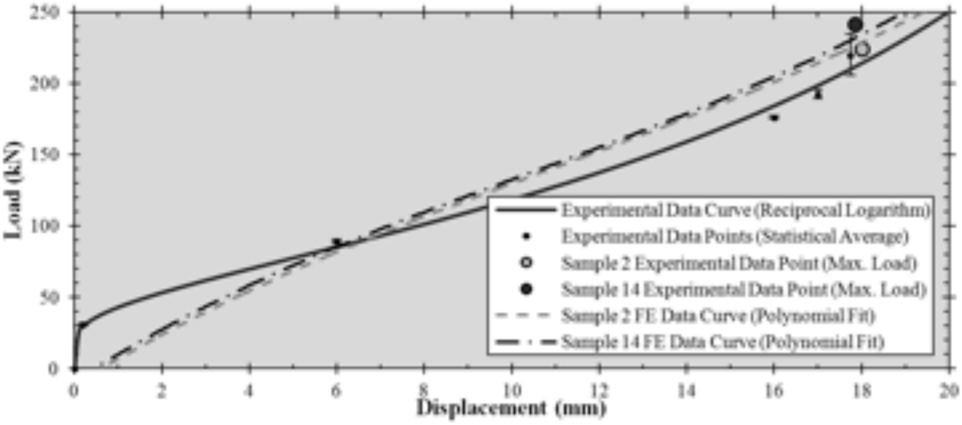

Figure 13. Load-displacement graph for nosing

3.4 Frictional Moment

The measured bearings were tracked through the frictional moment adjustment process, whereby each bearing is fine-tuned to the correct frictional moment (the torque required to overcome sticking friction and rotate the bearing outer race around its natural axis). Each bearing sample was tagged to ensure traceability, including through washing and drying processes, and the frictional moment recorded at each stage. Due to the 'stick-slip' nature of plain bearings, a single value for frictional moment is challenging to obtain. The average values for frictional moment in the first and last stages are displayed in Figure 14. It can be seen that the first stage post-nosing are best described using a 2-parameter Weibull distribution, as the values are skewed from a zero threshold; whereas, recorded values in the last stage, after they have been adjusted, are near-Normal.

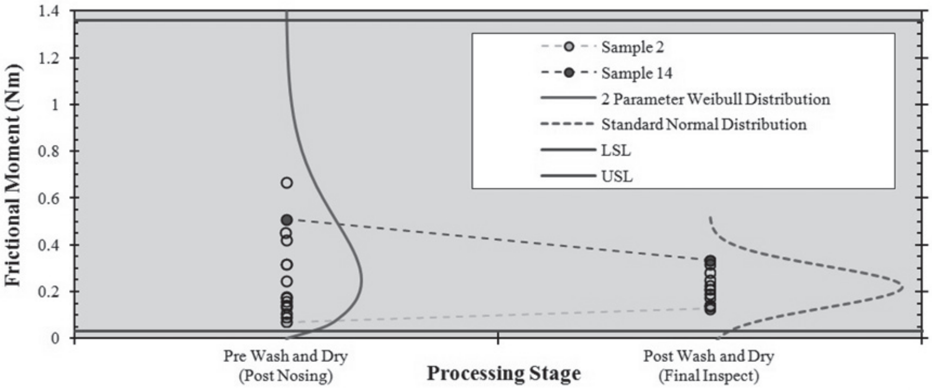

Figure 14. Bearing frictional moment distributions post-nosing and at final inspection

Adhesive bleed-out caused sample 14 to experience the “sticking” failure mode (Figure 3), and produced one of the highest frictional moments consistently throughout the adjustment process. Empirical evidence suggests that this sample had some of the highest values for chamfer geometric concentricity, and difference in chamfer length between either sides of the bearing. Sample 14 also had the most extreme difference in chamfer angles between either sides of the bearing. This will affect the interaction between the dies and bearing sleeve, as the point(s) of contact differ between the upper and lower dies. The stress will increase at any point-contact around the circumference, and may contribute to the variation in forming load at the beginning of the nosing process. An imbalance may even be large enough to produce one of the in-process failure modes outlined in Figure 3, specifically the ‘tipping’ failure. Conversely, sample 2 produced one of the lowest frictional moments throughout the adjustment process. Empirical evidence also indicates that this sample had some of the lowest values for chamfer geometric concentricity, and difference in angle and length between bearing sides.

3.5 Process Capability Data

There is no definitive answer as to exactly how ‘capable’ a feature is (Kotz & Lovelace 1998). Generally, capability targets specify that Cpk < 1.33 (30ppm) implies that the process is not capable. A value of between 1.33 and 2.5 implies the process is capable, and a value higher than 2.5 indicates that the high precision is potentially expensive. Results from the statistical analysis can be seen in Table 2, and the process capability index of each geometric feature can be compared to that in standard tables for process capability indices (Kotz & Lovelace, 1998).

4. Conclusions

An analysis of geometric tolerances for concentricity, angle and length indicate that the bearing outer race chamfers can be eccentric, with an angular and length disparity between either side. During manufacture, if values of these variables were to fall within the last 5% of the calculated distributions, i.e. a maximum or minimum extreme value, this could easily contribute to the variability within the nosing process. This would be especially true of the start of the process, whereby uniform contact between the dies and outer race is crucial. If tolerances of certain parameters were to be reduced this would reduce the variation in volumetric change between parts. For example, if the minimum/maximum tolerances for chamfer angle, outer chamfer length (axial) and sleeve length were set to 14/16°, 1.2/1.3mm and 26.0/26.1mm respectively, this would reduce the percentage volumetric change to ±0.7%. Ideally an increase in the Cpk value may reduce variability within the nosing process, however, an increase in the Cp value would still be beneficial in order to reduce batch-to-batch variability. An increase in process capability indices for some features may not be the only solution to reducing variation in the nosing process though.

Table 2. Process capability data for measured features and conformance levels

Variable	Mean (μ)	Standard Deviation (σ)	Tolerance		C_p Index	C_{pk} Index	Parts Non-conforming (ppm)
			LSL	USL			
Concentricity (mm)	0.01	0.02	0	0.06	1.3	1.0	1641
Geometric Concentricity (mm)	0.05	0.19	0	0.06	0.1	0.03	-
Angle (°)	14.45	0.48	13	17	1.4	1.0	1183
Length (mm)	1.20	0.09	1.17	1.46	0.5	0.1	617,912

Consideration must be given to geometric tolerances if the outputs of the nosing process are to be better controlled. Samples 2 and 14 displayed some of the smallest and largest geometric concentricity values, as well as comparably low and high forming loads respectively. Similar behaviour was observed throughout the frictional moment adjustment process. This evidence indicates that extreme variations in the values of geometric features, especially a large disparity between either side of the bearing outer race, negatively impacts on forming load. Therefore, in order to ensure that the process is more robust, it is recommended to the collaborating company that geometric tolerances be introduced on part drawings. The usual target of Cpk = 1.33 for the machining process reflects a geometrical tolerance for concentricity of ±10μm (Booker et al., 2001) for this sized chamfer, far below that currently achieved, strengthening the case for a process change. Future work includes sensitivity analysis of these geometric features using FE modelling which may indicate which features should be assigned new geometric tolerances as a priority and a cost benefit analysis of the changes.

Acknowledgments

The authors kindly thank the sponsoring company for providing the opportunity and support required to perform this study.

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1st International Symposium on Robust Design
København, DK
14th-15th of August 2014

The Variation Management Framework (VMF) for Robust Design

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Keywords: Robust Design, Quality Loss, Variation Management, Reliability Engineering

Abstract

Robust Design is an approach to reduce the effects of variation. There are numerous tools, methods and models associated with robust design, however, there is both a lack of a process model formalising the step of a robust design process and a framework tying the models together. In this paper we propose a framework for robust design and variation management by combining central models to Robust Design, namely, the Quality Loss Function, the Transfer Function and the Domains of Axiomatic Design. The framework shows how variation can be mapped from production right through to quality loss in the market place and identifies areas where action can be taken against variation. An additional benefit of the framework is that it makes the link between visual/sensory/perceptual robustness, product robustness, and production variation (Six Sigma).

1. Introduction

Despite the known benefits of Robust Design, studies have shown that the uptake in industry has been limited (Krogstie et al 2014) and that a lack of process or framework may be the reason for the inability to utilise the many tools available (Eifler et al 2013).

Robust design is a subset or reliability engineering. Where reliability engineering focuses on approaches to prevent the product from failing (or causing related systems to fail), robust design only concerns reliability related to variation. Robust Design is therefore defined as a methodology for designing products and mechanisms that are insensitive to variation. Here, ‘insensitive’ means that the product’s performance, reliability and quality are consistent despite the ingoing variation. The types of input variation considered are related to (Christensen et al. 2012):

1. Manufacturing – part level deviations from the specified/nominal geometry
2. Assembly – misalignment of parts during assembly
3. Time – changes as a result of time such as creep, fatigue or wear.
4. Ambient conditions – changes due to environment, such as heat expansion
5. Load – variation caused by changing loading conditions
6. Material – batch to batch variations in material properties

Material variations were not mentioned in the original list but have since been added.

DOI:10.4122/dtu:2104

Cited as: Howard, T. J., Ebro, M., Eifler, T., Pedersen, S., Göhler, S. M., Christiansen, A. and Rafn, A., 2014. Variation Management Framework (VMF) for Robust Design. In: Howard, T. J. and Eifler, T., ed. 2014. *Proceedings of the International Symposium on Robust Design - ISoRD14*. Copenhagen, Denmark. pp. 171-175.

As robust design is defined by the term variation (as well as sensitivity), it is important to also consider where variation is introduced into product development and where it takes effect. This article proposes a framework to which attempts to describe robust design, sensitivity as well as variation throughout product development through the Variation Management Framework (VMF). In doing so the model brings together three central model based theories of robust design, namely, the transfer function, the quality loss function and axiomatic design.

2. Related Robustness Models

In this section we introduce the three model based theories related to robust design that compose the Variation Management Framework (VMF).

2.1. Axiomatic Design

Suh's Axiomatic Design, first proposed as the Principles of Design (Suh 1990) followed by Axiomatic Design, the Advanced Formulation (Suh 2001). In this model based theory, there are four key domains proposed, but each domain only has a relationship with (or through) the domain next to it in figure 1. An important thing to note is that variation can occur in all of the domains. Figure 1 describes the simplest form that the four domains occur and that actually there may be multiple levels to the process domain as well as multiple levels of Design parameters and function requirements linking to a single customer attribute. This simplification is also made in the VMF proposed in section 3 which uses all four domains to describe the framework.

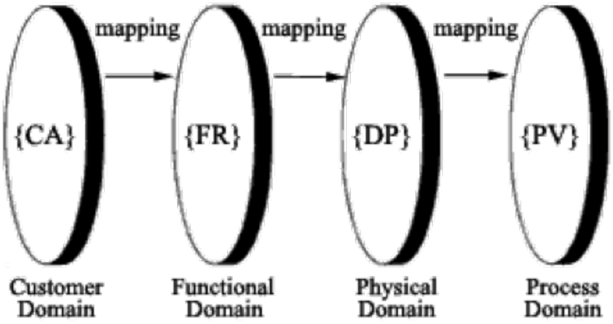

Figure 1. The domains of Axiomatic Design

2.2. Transfer Function

The transfer function is almost synonymous to the definition of Robust Design. On the X axis is placed an input variable (or the design parameters) which relates to the output variable (the functional requirement) through a transfer function. The gradient of this function represents the sensitivity of a function to a change in a parameter, in other words its robustness. The transfer function is an excellent way to represent the conversion of input to output variation, where the output variation is the performance variation and the input variation is the process capability (Okholm et al 2014). The transfer function is centrally placed in the VMF.

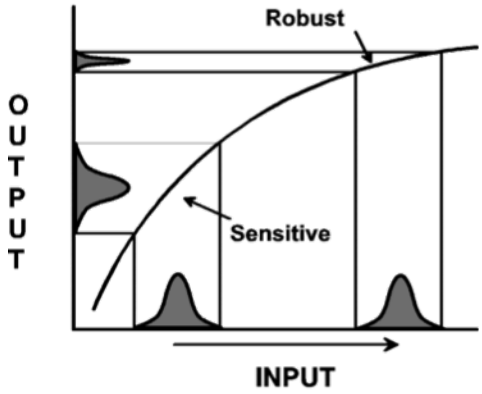

Figure 2. A Model of Variation Transfer (Transfer function)

2.3. Quality Loss Function

Taguchi in various works, e.g. (Taguchi et al 2005) discusses the concept of quality loss. Until this, the notion of upper and lower specification limits represented the cut off point for the allowable variation in a part/product and between these limits all variations are equally as acceptable (as shown by the red line in figure 3). The quality loss function describes a more accurate way to describe how acceptable a part/product is to the customer/user/operator. It suggests that any deviation from a correctly defined nominal value, will result in some quality loss experienced by the user. Minimising quality loss (or expenditure to achieve it) is ultimately the goal of robust design and is well represented by the quality loss function which is also integrated into the VMF in the following section.

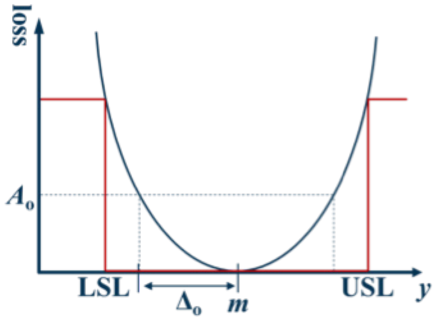

Figure 3. Quality Loss Function

3. The Variation Management Framework (VMF)

The VMF proposed in this paper consists of three main quadrants and a fourth representing tradeoff as shown in figure 4. The example data within figure 4 represents the variation of the pull off force required to remove a pen lid. The four axes of the VMF represent each of the four domains described by axiomatic design.

The upper left quadrant of the VMF represents the Quality Loss Function related to the removal force of the pen lid. The Quality Loss function is actually inverted to better fit the axiomatic domain of the customer attribute, terming it the degree of customer satisfaction (%). In figure 4, the example is constructed to show that a nominal force of 10N is not correctly set as the customer is most satisfied at 15N and thus over-spec lids will be preferred by customers. The 10N nominal removal force occurs due to the values of certain design parameters. For simplicity, the model in the upper right quadrant shows how this force varies with variation of a single design parameter - the lid diameter (assuming the lid fits to a nominal pen and all other lid parameters are constant, such as its thickness). This is represented with a Transfer Function (in Design). The lower right quadrant is also represented with a transfer function but for production. In order to achieve the 8mm nominal diameter of the lid, a mould with the correct diameter core must be created to achieve it (assuming all other Process Variables are kept constant). With the example VMF now in place it is easy to see at least 7 areas where the variation can be traded-off (blue circle).

Table 1. Variation Intervention and Trade-off points

0	Accept variation in the marketplace
1	Reduce sensory/perceptual robustness (perhaps add more tactile features to lid)
2	Reduce outgoing variation by increasing outgoing quality control (product sampling)
3	Reduce the sensitivity of the design
4	Reduce ingoing variation by increasing ingoing quality control (part measurement)
5	Reduce production sensitivity (design of experiments)
6	Reduce production variation (iteration and re-working of moulds)

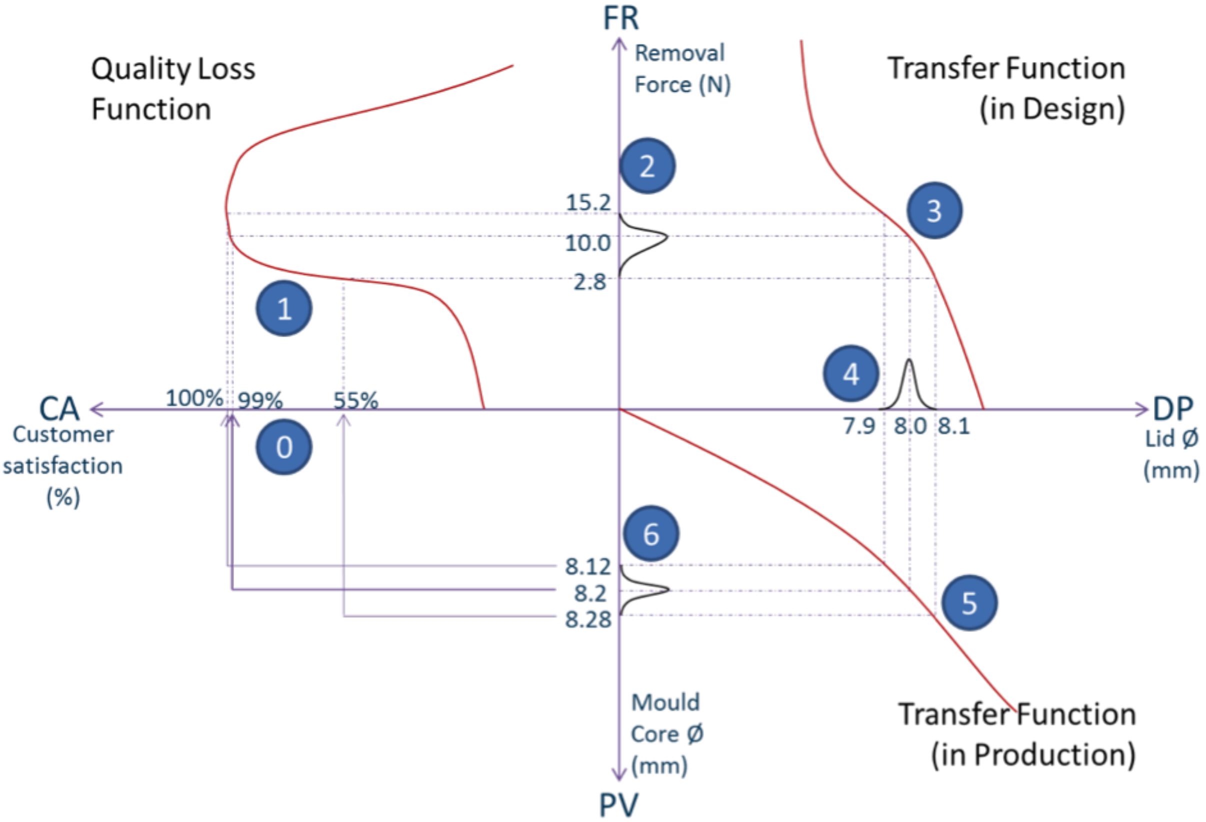

Figure 4. Variation Management Framework (VMF) modelling an example of a pen lid removal force

4. Conclusion

The Variation Management Framework (VMF) has successfully integrated several central theories related to robust design. The framework is perhaps the only one of its kind linking variation in production to the quality loss experienced in the marketplace. The VMF has so far proven to be a useful framework to communicate robust design and variation at both engineering and senior management levels.

In addition to the VMF's descriptive utility, it has also been shown as a potentially useful model on which to base variation-cost tradeoff decisions in product development. It illustrates, that a robust design can be achieved by applying other strategies that merely applying parameter optimization, which is often described as the main focus of robust design The VMF has also been adopted for use in framing a robust design research programme between Novo Nordisk and the Technical University of Denmark, where the work packages have been positioned in each of the four quadrants to delimitate the project work.

The model does bear a number of limitations dues to its simplified nature, the main limitation being its lack of ability to describe complexity. In axiomatic design terms, issues arise when multiple Design Parameters areinteracting with Multiple Functional Requirements in a coupled manner. As the VMF only represents a one dimensional view such coupling and complexity issues are not captured. The same is true for the numerous Process Variables and noise factors at play when producing a part.

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