Linköping University | Department of Management and Engineering
Master Thesis, 30 ECTS | Mechanical Engineering - Division of Machine Design
Spring Term 2020 | **LIU-IEI-TEK-A–20/03748—SE**
2020/06/18

Development of improved determination process

– Adapted for nominal setup at Volvo Car Corporation based on static, dynamic and thermal contributions

---

Adrian Aune
William Andersson

Supervisor: Simon Schütte
Examiner: Jonas Detterfelt

Linköping University
SE-581 83 Linköping, Sweden
+46 13–28 10 00 | www.liu.se

Abstract

A nominal setup at Volvo Cars Corporation is the placement determination for two adjacent exterior parts on the car. To place the parts in optimal positions, nominal values for gaps and flushes are determined. When a nominal setup becomes more complex, VSA (Vehicle System Architect) is summoned. These appearing situations regard the involvement of several attributes and the need for a combination of various contributions. There are static, dynamic (overslam or dynamic movement) and thermal contributions that are combined into nominal values of gap and flush distances. The determination process of a nominal setup contains both calculation for each contribution, as well as the combination method which takes place at the VSA meetings. This Master Thesis project consists of the development of an improved determination process for nominal setups.

The current determination process has a low level of transparency within the different group's methods. Another issue is the insecurity of the probability estimations made when combining the contributions. Therefore, the focus of the project was to infuse a greater understanding of the contribution derivations, and greater insight into the probability of the taken risks. To achieve that, the project was divided into three parts; mapping of the determination process, individual contribution improvements and finally, improvements to the combination method. In contemplation of improving a process, plenty of knowledge needs to be gathered, regarding methods, simulations and possibilities. This was executed by interviewing experts within specific areas at the different groups at VCC. Development of the improvements was done by interviews and various studies.

It was shown that the mapping of the determination process increased the transparency between the groups as it increased the understanding of individual groups' work. Contribution improvements lead to more realistic load cases used for dimensioning. A performed overslam clinic, where closing velocity data of a tailgate were collected, lead to a greater statistical base for which load case should be used. For dynamic movement, another method is proposed that considers relative movement instead of applied accelerations. For the thermal contribution, the approach of geographically gathered temperature data was proposed. The improved combination method generates combinations with regard to three input values instead of one, from each contribution, to create different combination scenarios. The probabilities of the scenario occurrences are estimated which gave VCC a greater understanding of what risks that are taken. Furthermore, the combination method also educates the VSA meeting attendees by exhibiting the derivations and bases for each contribution.

Sammanfattning

En nominell setup på Volvo Cars Corporation är placeringsbestämningen för en del på bilen med hänsyn till angränsande delar. För att placera delarna i optimala positioner bestäms nominella värden för spel- och stegdistanser. När en nominell setup blir mer komplex kallas VSA (Vehicle System Architect) in. De uppträdande situationerna avser flera attributs medverkan och behovet av att kombinera flera olika bidrag. Det finns det statiska, dynamiska ("overslam" eller dynamisk rörelse) och det termiska bidraget, som kombineras till nominella värden för spel- och stegrelationer. Bestämningsprocessen för en nominella setup innehåller både beräkning av vardera bidrag, liksom kombinationsmetoden som används under VSA-möten. Detta examensarbete omfattar utvecklingen av en förbättrad beslutsprocess för nominella setuper.

Problemen med den nuvarande bestämningsprocessen är den låga transparensnivån som existerar mellan de olika grupperna, gällande de metoder som används för att ta fram respektive bidrag. Det existerar även en osäkerhet i sannolikhetsberäkningarna som gjorts vid kombination av bidragen. Projektets fokus var därför att få djupare förståelse för bidragshärledningarna och större insikt i sannolikheten att bidragens lastfall inträffar. För att uppnå detta delades projektet upp i tre delar; kartläggning av bestämningsprocessen, förbättring av de individuella bidragen och slutligen förbättring av kombinationsmetoden. För att förbättra en process måste kunskap samlas in om metoder, simuleringar och möjliga förbättringar. Detta genomfördes genom att intervjua experter,på VCC, inom specifika områden. Förbättringsarbetet baserades bland annat på intervjuer och olika studier.

Kartläggningen av bestämningsprocessen visade sig öka transparensen mellan de olika grupperna eftersom det ökade förståelsen för andra gruppers arbete. Bidragsförbättringar leder till mer realistiska belastningsfall som används för dimensionering. En utförd "Overslam"-klinik, där stängningshastighetsdata för en baklucka samlades in, ledde till en större statistisk bas för hur sannolikt det är att lastfall inträffar. För dynamisk rörelse föreslås en alternativ metod som tar hänsyn till relativ rörelse istället för tillämpade accelerationer. För det termiska bidraget föreslogs metoden att geografiskt insamla temperaturdata. Den förbättrade kombinationsmetoden genererar kombinationer med avseende på tre ingångsvärden istället för ett, från vardera bidrag, för att skapa olika kombinationsscenarier. Sannolikheterna för scenariohändelserna estimeras, vilket gav VCC en större förståelse för vilka risker som tas. Dessutom utbildar kombinationsmetoden VSA-mötesdeltagarna genom att visa härledningarna och grunderna för vardera bidrag.

Acknowledgements

This master thesis was conducted on behalf of Volvo Cars Corporation, VCC, in Torslanda, Gothenburg during the spring semester of 2020.

The authors would like to thank everyone that has been involved in this master thesis and has helped us to succeed. It would have been impossible to finish this master thesis without your help and input. We would wish to express our sincere appreciation to our industrial supervisors, David Brinkby & Magnus Ahl, who have convincingly guided and encouraged us to be professional and keep our spirits high. A special thank is given to Mårten Karlsson, without your shrewdly wit and supportive manners the project outcome wouldn't have been the same.

In addition, we wish to express our gratitude to our academic supervisor, Simon Schütte and examiner Jonas Detterfelt of the Department of Management and Engineering at Linköping University, who has helped us during the course of this master thesis.

An extra thanks to our opponents Daniel Berglund & Jon Eklund Olsson that helped us during the course of this master thesis with constructive criticism.

We wish to express our sincere thanks to Axel Jyrkäs, Casper Christiansen, Gustav Ljungquist, Harish Santhosh Kumar & Viktor Alkelin for your great company during our VCC lunches and your continuous support during the project.

We must express our very profound gratitude to our families for providing us with unfailing support and continuous encouragement throughout our years of study and through the process of researching and writing this thesis. They supported us with the right words when we needed to hear them the most. We will give back to you, once our mountain of student debts are gone, with interest!

Gothenburg, June 2020.

Adrian Aune

William Koo Andersson

Abbreviations and acronyms

CAD Computer Aided Design

CAE Computer Aided Engineering

CAT Computer Aided Tolerancing

GSU Geometrisystemutvecklare (Eng. Geometry System Developer)

LSL Lower Specification Limit

PCI Process Capability Index

POT Power Operated Tailgate

PQ Product Quality

RD&T Robust Design & Tolerancing

RSS Root Sum Square

USL Upper Specification Limit

VCC Volvo Car Corporation

VSA Vehicle System Architect

Hällered VCC's proving ground outside Gothenburg

Contents

List of Figures

List of Tables

Chapter 1

Introduction

The first chapter, Introduction, starts with the background of the project, followed by the problem description, purpose, objectives and ultimately the delimitations.

1.1 Background

The aim of the background is to provide the reader with the information needed to understand the problem and purpose of the project.

1.1.1 Volvo Car Corporation

Volvo Car Corporation, from now referred to as VCC, is a global automotive manufacturer, founded in 1927 in Gothenburg, Sweden as a part of Volvo Group AB. Nowadays, VCC is a separate company from Volvo Group AB and owned by a Chinese automotive company called Geely. (Volvo, 2020)

The world is changing rapidly, especially in the automotive industry, the standard of today will be outdated tomorrow. The level of quality is constantly increasing to meet the demands of tomorrow. VCC was acquired by Geely in 2010 and has since then been in a phase of transformation where they have renewed their portfolio of cars and moved up to the premium segment of car manufactures. (Volvo, 2020)

For a vehicle to be perceived as premium, the build quality is a necessary factor. The process to obtain a high level of build quality, consists of several steps and the work of different groups at VCC. The Robust Design & Tolerancing group who ordered the thesis project, at VCC's Research & Development department are working with factors connected to vehicle quality. Two examples of these factors are geometry robustness and tolerancing to verify and improve the build quality. The Robust Design & Tolerancing group was formerly called GSU and will from now be referred to as GSU to avoid confusion between the group and the software program called RD&T. The other relevant groups in this project will be presented shortly.

1.1.2 Gap and flush

GSU are specialists within tolerances and alignment between different parts of the virtual car. Gap and flush distances are commonly used to define fit and alignment between two parts. The gap is the clearance between two parts while the flush is the step difference. See Figure 1.1 for an illustration of a gap and flush distance connected to a split-line between the hood and a fender. Along a split-line, most often there are multiple split-line sections with individual gap and/or flush relations that determine the position of a part.

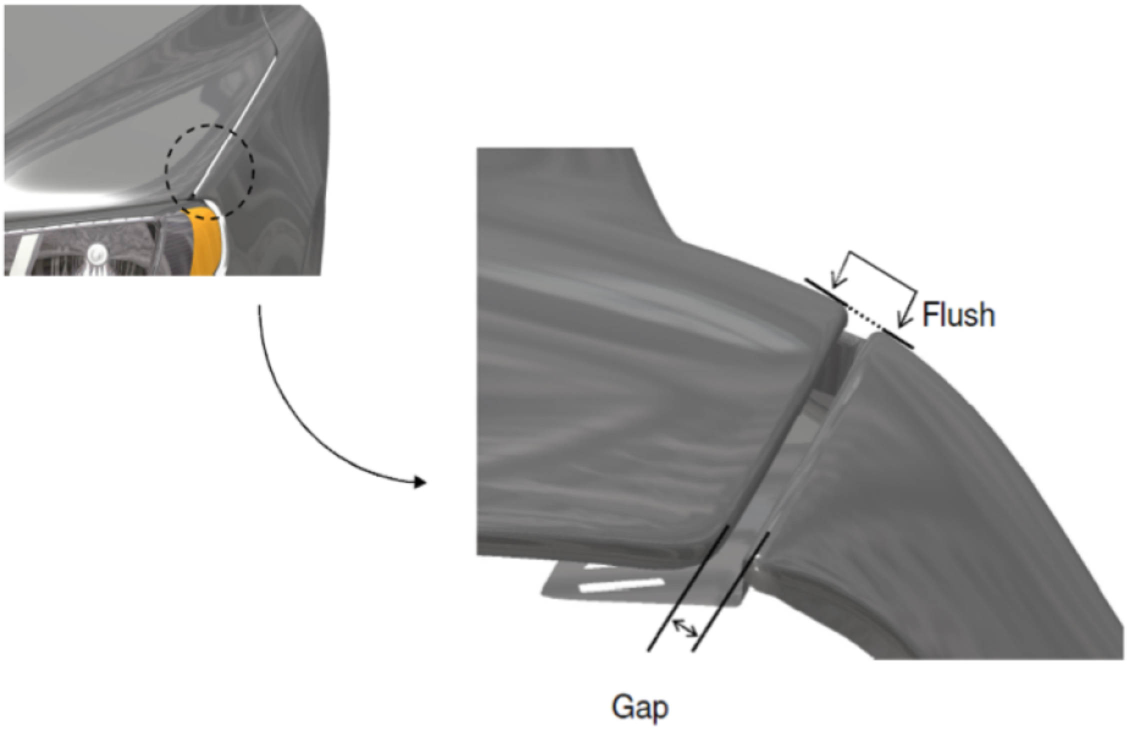


Figure (1.1): *Gap and flush distances between two parts. (Wagersten, 2011)*

Gap and flush distances between exterior parts have impacts on the perceived quality as well as the functionality of the car. Too wide distances can result in unaesthetic appearance of the car, and thereby decrease the perceived quality or affect the functionality of a part. Whilst too narrow there's a risk of collision between the exterior parts, which consequently could lead to damaged parts and expensive repairs. Furthermore, there are different contributions that cause gap and flush reductions. Meaning that the distance is decreased due to constant or instantaneous contributing factors, which will be further explained in upcoming sections. The dimensioned values of these gap and flush distances are called nominal values.

1.1.3 Nominal setup

In a virtual environment, a nominal car is designed. The nominal car does only exist in a virtual environment, all physically produced cars are non-nominal since it's not possible to mass-produce a car without experiencing dimensions and shapes diverging from the digital version of the car.

Each part of the digital representation of the car has a nominal shape, measurements and placement. This placement, combined with distance relations to surrounding parts, is called the nominal setup.

The nominal setup is built up by multiple nominal values and represent where the best function of a product is obtained. In a nominal setup, the nominal values for both gap and flush distances are determined. The nominal values with related tolerances are assumed to cover measurement, precision and shape deviations that might occur during manufacturing and product usage.

1.1.4 Determination process of nominal setup

A department called Mechanical Integration is in charge of the nominal setup of parts. They are responsible for dimensioning gap and flush distances. However, in complex areas on the car, they are getting help with the dimensioning of gap and flush relations by engineers from the VSA (Vehicle System Architect) group. The rear end is one of these areas since it contains around eight different sub-systems. Each system has an individual owner with different responsibilities and demands to meet. The VSA assists by suggesting an overall solution that is assumed to be good from a project perspective and satisfy all sub-systems.

The nominal values for complex nominal setups are determined on a VSA meeting. The VSA group coordinate the meeting and make sure that the nominal setup for each specific dimensioning case is carried out. There are representatives from different groups and departments at VCC attending these VSA-meetings since there are several contributions that can ultimately lead to a gap and flush reduction. The following list presents the different groups that are part of the determination process and those who attend the VSA meetings.

- VSA - Holds meeting
- GSU - Static contribution
- Durability - Overslam contribution
- Solidity - Dynamic movement contribution
- Material Centre - Thermal contribution
- PQ (Product Quality) - Aesthetic design demands

There are static, dynamic and thermal contributions that are considered in the determination process. In short, the different groups derive their contributions to the meeting, for where they are combined to meet PQ's demands. A schematic figure, see Figure 1.2, is added to illustrate the determination process.

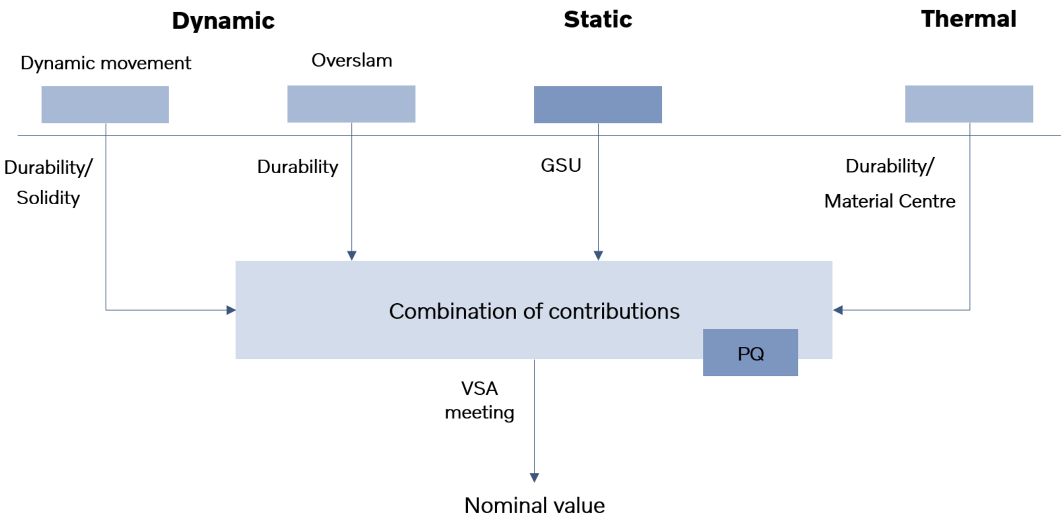


Figure (1.2): *Schematic overview of the determination process of nominal setup.*

1.1.5 Static contribution

The static contribution regards the originating geometric variation between mass-produced cars. GSU are responsible for this contribution and uses statistical measurement data to estimate the number of cars that will be produced within the range of acceptance. The contribution is constant since the geometric variation of the gap and flush distances are constant for a specific car. However, the other contributions are instantaneous, since they are not existing all the time and vary due to the user's behaviour as well as the geographic position.

1.1.6 Dynamic contribution

The dynamic contribution is divided into two. The overslam part and dynamic movement. The dynamic contribution that regards overslam, which will be referred to as the overslam contribution, occurs when the user is closing their tailgate, hood or doors (this report will solely regard tailgate). Therefore, the contribution is instantaneous. The magnitude of the dynamic contribution depends on the user's over-closing technique and applied force to the tailgate while closing it. When over-closing a tailgate, the applied force to the tailgate will reach a level that's larger than needed. The effect of this will be that the tailgate will instantaneous elastically deform when then tailgate's lock mechanism hit the striker and result in a gap reduction. The Durability group at the Strength & Endurance department at VCC is responsible for the overslam contribution. Durability performs simulations, with predetermined over-closing velocities, to calculate the gap or flush reductions in different nominal setups.

The other dynamic contribution, which from now on will be referred to as the dynamic movement contribution, appears during rough dynamic driving. If the car is driven recklessly, adjacent parts risk colliding into each other. Dynamic movement is an instantaneous dynamic contribution since it only appears during driving and increases proportionally to the driver's recklessness.

1.1.7 Thermal contribution

The last contribution is the thermal contribution. It regards the thermal expansion of parts which leads to gap and flush reductions. This contribution is also instantaneous and increases with rising temperature. The load cases, the temperatures used in simulations, are predetermined by Material Centre at VCC. However, the simulations performed are done by CAE engineers at the Durability group.

1.1.8 Combination of contributions

The final step of the determination process is to combine these different contributions into a resulting nominal value that still satisfies the aesthetic demands set by PQ. PQ's desire is small gap and flush relations. Small distances between exterior parts provides a more premium perception of the car's design (Stylidis et al., 2019). All the different groups present their contributing values at the VSA meeting and explain the resulting consequences if that value was to be reduced. The margin of safety concerning all contributions, as well as the aesthetic design demands, are discussed and combined into a nominal value of a specific gap or flush distance. Lastly, a mutual risk estimation is subtracted to the calculated nominal value. The existing combination method of how to combine the contribution values into a nominal has been changed over time. A consistent combination method that is based on well-documented theory has been missing.

1.2 Problem description

Today, there is a lack of transparency within VCC's determination process of the nominal setup. Each group has a vague insight and understanding regarding how the different contributions and demands are determined. To increase this, VCC require a mapping of the current determination process.

VCC has a plausible basis for the static contribution and great understanding of its consequences for the nominal setup. However, the bases of dynamic and thermal contribution are not as defensible. It is problematic to estimate these instantaneous contributions since they occur during given situations, for example,when the car is exposed to thermal heat or a hard closing of a tailgate. The instantaneous contribution values have not been determined with regards to dimensions, which is not optimal.

The combination method of contributions is also a problem. The method today works, however it is not as consistent as one would like it to be. Also, VCC believes that the combinations might lead to over-dimensioned gap and flush distances.

1.3 Purpose

The purpose of this project is to develop an improved determination process for the nominal setup. Since the determination process occurs in several steps it is important to oversee all. Therefore, obtained insights and implemented investigations were applied not only to the individual instantaneous contributions, but also the combination method.

The other purpose of the project is to conduct a master thesis that meets the criteria of a master's degree of mechanical engineering.

1.4 Research questions

One of the goals of this project was to answer these following research questions.

1. Is it possible to develop an improved method for combination of contributions, in the determination process of nominal setup, for VCC? If so, what would it look like?
2. Are there better testing methods that determine the dynamic contribution in the determination process of the nominal setup? If so, what would these test methods be? If not, what improvements to the current one can be done?

1.5 Deliverables

The other goal of the project was to deliver the following deliverables listed down below.

- Master thesis report that meet the all academic demands from Linköping University.
- Improved determination process of nominal setup for VCC containing:
  - Analysis of current determination process of nominal setup that regards both individual contributions and the combination method.
  - Improved dynamic test methods.
  - Improved combination method of contributions.
- Evaluation of obtained determination process and comparison to the current one.

1.6 Delimitations

The amount of improvement work for the determination process is limited to the time given for the project and the resources available. Desired tests and simulations that are not carried out due to lack of time will instead be investigated and then be presented as future work.

Regarding the execution of tests, they were solely focused on dynamic tests. The thermal tests, providing the current value of the thermal contribution, was deemed to be adequate enough. Even though thermal tests weren't executed, an examination of possible improved testing methods regarding the contribution was performed. The dynamic movement tests and simulations were not performed due to lack of time and resources.

The determination process presented in this report was adapted for the rear end of the car. The practical tests were therefore performed on the rear end, more specifically the tailgate's relation to adjacent surfaces. Due to this delimitation, the project was focused on a determination process adapted for gaps only, since gap relations are more collision critical in the rear end of the car than the flush relations. However, a future desire is to derive a determination process for general cases.

Being a master thesis, the project will be limited to 800 hours / student, resulting in a total of 1600 hours distributed even among two students.

1.7 State of the art

Geometry assurance has its effects on aesthetics and functions on manufactured products. That makes it an important factor of quality assurance, especially in the automotive industry. A case study shows good conformance between actual results and simulated results in RD&T. This considering a new robustness value in Computer Aided Tolerancing (CAT) that considers that the complexity of the assembly influences geometrical quality, not only the sensitivity to variation. (Rosenqvist, Falck, and Söderberg, 2016)

Walter, Spruegel and Wartzack (2015) state that performed statistical tolerance analyses evaluates appearing deviations that affect the functional key characteristics. These deviations are classified into random deviations (manufacturing-caused variation) and time-deviant (deformation, thermal expansion, mobility of parts and wear) deviations. The authors present a methodology for the least cost tolerance allocation of systems with time-variant deviations. The demonstrator was a crank mechanism and the optimization algorithm used was particle swarm optimization. (M. S. J. Walter et al., 2015)

Walter, Spruegel and Wartzack (2013) say, in another article, that there are "possible interactions between the different deviations and resulting effects on themselves as well as on the functional key characteristics". (M. Walter et al., 2013) They represent the appearing interactions by metamodels (response surface methodology and artificial neural networks) and prove that the functionality of a product (in their case a crank mechanism) depends of these interactions of deviations. The methodology they presented show that in extent of variation caused by random deviations and a mean shift caused by the functional key characteristics there is a additional variation due to interactions between deviations. (M. Walter et al., 2013)

The articles of M. Walter et al. were inspiring to the thesis work. However, the reasons their methodologies cannot be applied in this project are due to the crank mechanism which is a repetitive cycle mechanism. Their methodologies are thereby not applicable to the dynamic contributions presented in this report. The mobility strictly simulates specific dynamic movements, which doesn't suit the project. Furthermore, the dynamic and thermal contributions can't be described as time-variant deviations in that manner.

Thermal stress causes different materials to expand, which could lead to that products do not fulfill their aesthetic and functional demands. This is considered during the development phase by designing locating schemes that allow the product to be exposed by varying temperatures. Although, it may not be sufficient to calculate the results from the geometrical variation simulations and thermal expansion simulations separately, especially for products including plastic parts. In an article, Lorin et al. (2012) propose a method where thermal expansion is considered in combination with the variation simulation in RD&T. Since they cannot simply be super-positioned to one another, according to the authors. (Lorin et al., 2012)

Chapter 2

Theoretical background

2.1 Perceived quality

According to Stylidis et al. (2019), obtaining an ideal perceived quality, within a certain boundary, is assumed to be one of the most challenging tasks in today's product development process. Examples of these boundaries are available technology, manufacturing capabilities and financial limitations. The ability to control perceived quality during the product development process has a major impact on the product's success on the market. The authors mean that it is essential that designers focus on product attributes that communicate quality to the customers. They call these attributes for perceived quality attributes. The perceived quality attributes are defined as characteristics that convey the functional and psychosocial benefits of a product to the customer. The purpose of these attributes is to increase the customers´ will to pay more for a product due to its perceived as a premium quality product.

2.1.1 Perceived quality attributes

Regarding measurable perceived quality attributes, three attributes appear to have a substantial impact on a product's visual quality: gap, flush and parallelism. All three attributes form a spatial relationship between the mating parts in an assembled product, also known as a split-line, see Figure 2.1. The split-line creates visual cues that enable the customer to notify manufacturing variation of a product. These types of variations appear to lower the sense of a product's premium quality. (Stylidis et al., 2019) (Wickman, 2007)

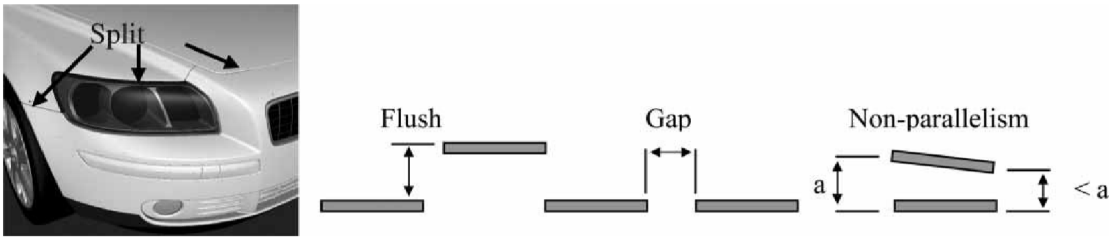


Figure (2.1): *Split-line and perceived quality attributes. (Wickman, 2007)*

The split-line's influence on customers perception of quality have been addressed in multiple studies. The outcome seems to be that misaligned or improperly spaced split-lines do often lead to a negative impact on customers perception of products. The importance of split-lines in perceived quality assessment can't thereby be underestimated. (Stylidis et al., 2019)

2.2 Car geometry coordinate system

All existing car models at VCC are using a common coordinate system to describe the position of parts within the design space. It is illustrated in Figure 2.2, where the origin is positioned in front of the vehicle. The x-axis travel along the length of the car and the z-axis is perpendicular to the "ground" whilst the positive y-axis is perpendicular to the xz-plane that divide the car in a right and left side. (VCC, 2016)

Figure (2.2): *The coordinate system used at VCC. (Composited figure, background picture was taken from VCC, 2020)*

2.3 Robust design

Geometry assurance are the engineering activities that ensure that all geometrical requirements for a product are fulfilled.(Rosenqvist, Falck, Lindkvist, et al., 2014) In the product development processes, different geometry assurance activities must be performed in order to enable a stable geometrical quality. A basic principle within geometry assurance is the concept of robust design. (Rosenqvist, Falck, and Söderberg, 2016)

Robust design means that the design is insensitive to disturbance and variation. By increasing robustness in a design, the manufacturing costs can be lowered, since the main source of variation is considered to be manufacturing variations. The robustness of a design can be increased by shifting the nominal value of an input parameter since it thereby decreases the output characteristic variation, see Figure 2.3. (Morse et al., 2018)

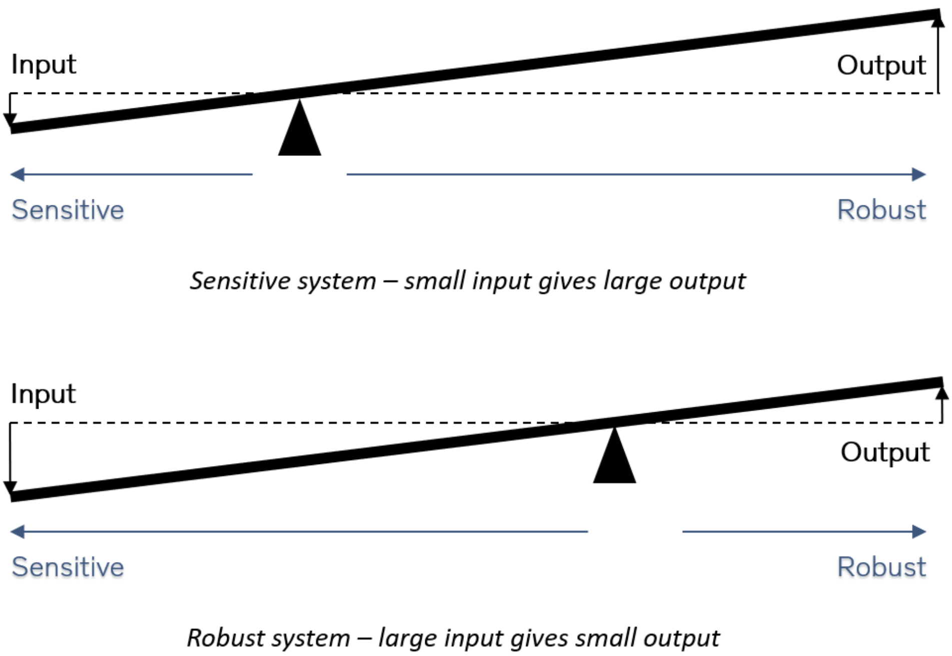


Figure (2.3): *Simple examples of sensitive and robust designs.*

There are different activities that increase the robustness of a design, such as place locators in certain ways to minimize the amplification of variations or set tighter tolerances on input parameters (Morse et al., 2018).

In the automotive industry, locators (points that establish and maintain the position of a part in a jig or fixture) are used to control the stability of a system. The placement of these locators has a large impact on the geometrical robustness of a product due to their influence on how variation propagates through the system.(Rosenqvist, Falck, Lindkvist, et al., 2014)

2.3.1 Tolerances

All Wickman (2007), Stylidis et al. (2019) and Morse et al. (2018) claim that geometrical variations between different copies of a product are unavoidable during manufacturing and assembly processes when a product is mass-produced. Each copy will more or less be affected by geometrical variation. Stylidis et al. (2019) also describes that all products will receive some type of error, the importance is to reduce the impact of these errors. Large errors may lead to difficulties during the assembly process of a product or even result in malfunctioning products. Sometimes they might not have any functional impact but impact on the aesthetic characteristics of a product and thereby affect the perceived quality of the product.

To create space for geometrical variations, see Figure 2.4, that occur while producing a part, tolerances are used. Fischer (2004) describes a tolerance as the specified amount a feature is allowed to vary from the nominal design, often a virtual version (3D CAD model), of the actual part or product. This may include the form, size, orientation or location of the feature as applicable. According to Morse et al. (2018) tolerancing is a set of activities that allow designers to manage geometrical variations, due to manufacturing process, already in the product development process.

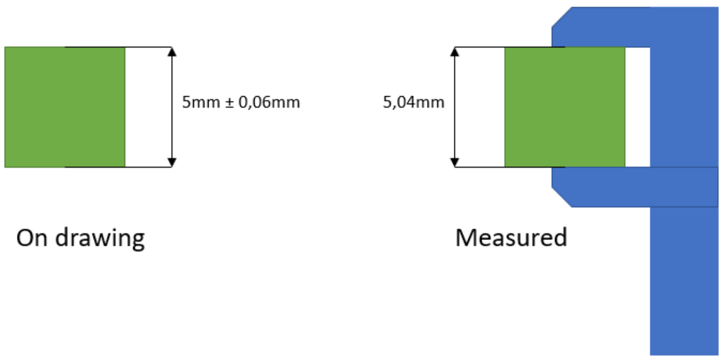


Figure (2.4): *Comparison between measurement on drawing and on physical object. (Figure inspired by Fischer, 2004).*

2.4 Statistics

This section will provide the reader with the theoretical framework of statistics needed for this project. Statistics are used by engineers to describe and understand variability where statistical framework and methods can help solving engineering problems. (Montgomery and Runger, 2011)

2.4.1 Probability density functions

Density functions are commonly used to describe physical systems in engineering. A probability density function describe the probability distribution of a continuous random variable, a random variable with real numbers for both interval and range. The most common distribution used is the normal distribution. The theoretical basis of a normal distribution is mentioned to justify the somewhat complex form of the probability density function. With appropriate choices of the center and the width of a normal distribution curve, random variables with means and variances can by modeled by normal probability density functions, see Figure 2.5. The value of μ is the mean, and the value of σ is the standard deviation. (Montgomery and Runger, 2011)

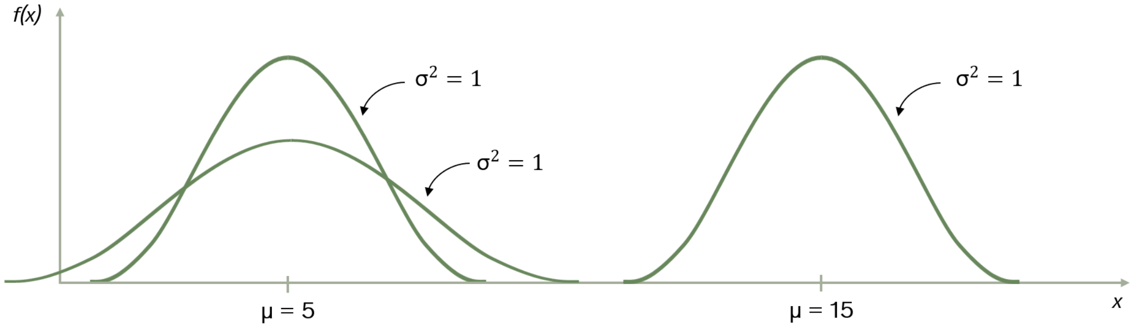


Figure (2.5): *Normal probability density functions with means and variances. (Figure inspired by Montgomery and Runger, 2011)*

Underneath the normal probability density function, 0,9973 of the probability is within an interval of 6σ. The area outside of the interval is deemed to be quite small. More about these intervals and corresponding probabilities will further explained in *Six-sigma process*. In Figure 2.6 an illustration of the probability density function with different probabilities related to sigma intervals is presented. (Montgomery and Runger, 2011)

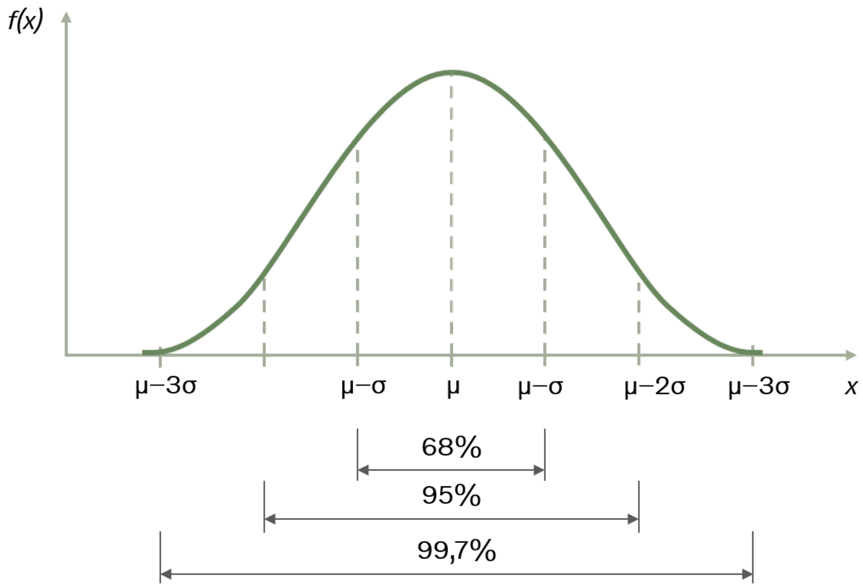


Figure (2.6): *Corresponding probabilities to sigma intervals. (Figure inspired by Montgomery and Runger, 2011)*

2.4.2 Process capability indices

The performance of the process, when it operates in control, is called process capability. There are different ways to assess the process capability, where one of the tools are process capability indices. (Montgomery and Runger, 2011)

A process capability index is a non-dimensional parameter that is used to evaluate the machining process in mass production and prevent machining errors.

$$C_p = \frac{(U - L)}{3\sigma} \qquad C_{pk} = min\left(\frac{(\mu - L)}{3\sigma}, \frac{(U - \mu)}{3\sigma}\right) \tag{2.4.1}$$

Inequalities between the process capability indices and design parameters control that the process maintains within its capability. L stands for lower specification limit and U for upper specification limit. (Otsuka and Nagata, 2018) In this report LSL and USL will be used instead of L and U

The C_p assumes that the distribution is centered at the nominal dimension. If the process is placed off-center the C_p will indicate higher value than the actual capability represents. For this reason, the C_{pk} ratio is proven to be useful. The index is calculated relative to the specification limit nearest to the process mean. Both indices, C_p and C_{pk} are shown in equation 2.4.1.

2.4.3 Six-sigma process

If the C_{pk} is set to a value of 2, when assuming normal distribution, the distance between the process's mean and closest specification limit is six standard deviations. A process like this is called a six-sigma process. (Montgomery and Runger, 2011)

Six-sigma is a quality philosophy where the "sigma" regards standard deviation. The property that the standard deviation, or variance σ^2, is the dispersion around the mean can be used to measure the performance variability.

In Figure 2.7 the LSL is set to -3σ and USL to 3σ. The areas under the normal distribution shift depending on what σ-level range that is chosen. That range is the performance variation and can be characterized as a number of standard deviations from the mean. (Koch et al., 2004)

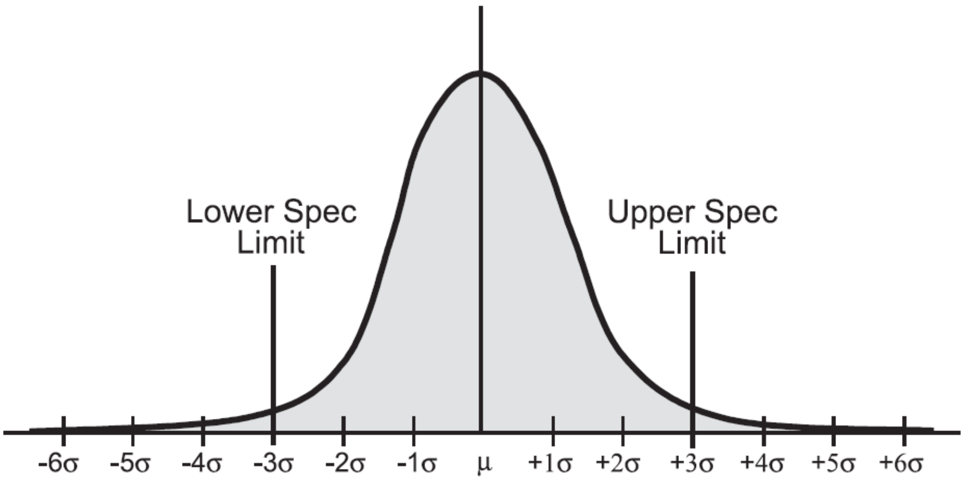


Figure (2.7): *Example of a 3σ-process. (Koch et al., 2004)*

For instance, a performance variation of $\pm 1\sigma$ would represent a probability of 68,26%. The different performance variations with corresponding probabilities is shown in table 2.1. (Koch et al., 2004)

Table (2.1): *Sigma level as performance variation and corresponding percent variation.*

Sigma level	Percent variation
$\pm 1\sigma$	68,26
$\pm 2\sigma$	95,46
$\pm 3\sigma$	99,73
$\pm 4\sigma$	99,9937
$\pm 5\sigma$	99,999943
$\pm 6\sigma$	99,9999998

In many cases $\pm 3\sigma$ would've be deemed "fine", but the quality of the mass-produced products cannot be ensured unless the sigma level, performance variation, is increased. A process of $\pm 6\sigma$ which covers a range of 12σ, equal to a probability of 99,9999998%, is called a six-sigma process. (Koch et al., 2004)

2.5 Tolerance analysis

A common tolerance analysis situation is where tolerances of several parts are accumulated into the tolerance of a product consisting of the parts assembled, see Figure 2.8. (Morse et al., 2018)

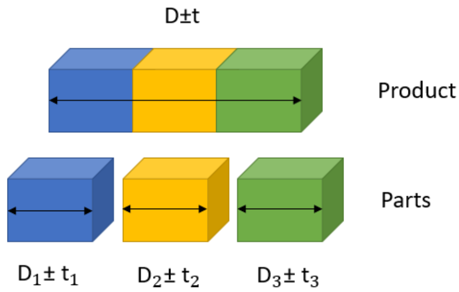


Figure (2.8): *Illustration of multiple part tolerances' contribution to the total product tolerance. (Figure inspired by Morse et al., 2018).*

Morse et al. (2018) mention that tolerance analysis most often are using two types of methods while merging tolerances from parts to a combined product tolerance. These methods appear to either be *Worst-case tolerancing* or *Statistical tolerancing*:

- **Worst-case tolerancing**

  Worst-case tolerancing is the most popular method to use for simple tolerance stacking (Judic, 2016). Morse et al. (2018) mean that by applying the worst case method, the designer will consider the worst possible combination of individual tolerances and examines the functional characteristics. As a result, the method may lead to excessively tight part tolerances as well as high production cost. Regarding application areas of the approach, Van Hoecke (2016) & Judic (2016) are presenting a few areas, for example:

  - It is applicable in situations where no assumptions can be made.
  - Situations where the supplier or manufacturer only can guarantee a certain limit within which their product will meet.
  - Situations were statistical computation resources are unavailable.
  - If you want to be 100% sure that a relation between two parts is safe.

- **Statistical tolerancing**

  According to Judic (2016), the worst-case approach is both "old" and often assumed to be too pessimistic. This is due to that the probability that all contributors from a stack are maximum off-centered on the same side of their nominal value is tremendously low. Morse et al. (2018) present statistical tolerancing as a more practical as well as economical way of setting tolerances than the worst-case approach. Statistical tolerances are probability density functions that represent factors connected to a manufacturing process.

By using functions and statistical process capability indices, statistical tolerance analysis computes the probability that a product will be producible, possible to assemble and will function under given individual tolerances. The method admits the small probability that some copies of the assembly do not assemble or fail to function as planned. (Morse et al., 2018)

The Root Sum Squared (RSS) method is a statistical tolerance analysis method that can be used to analyse assembly tolerance distribution. It assume that the dimension distribution of manufactured parts can be described as a normal distribution. Then the mean value of the dimension distribution shares the same value as the tolerance mean value. Also, the dimension distribution range is equal to the tolerance range. By assuming this the tolerance of an assembly including multiple parts may be calculated. (Lin et al., 1997)

In cases where the part tolerance distribution might not be a normal distribution but instead be expressed as another type of distribution, for instance, a Weibull or Triangle distribution. The tolerance range will not be equal to the dimension distribution in these cases. The method can then be modified to handle these types of distributions.(Lin et al., 1997)

2.6 Monte Carlo simulation

Monte Carlo simulation is a powerful tool and one of the most commonly used methods regarding statistical tolerance analysis of mechanical assemblies due to its nonlinear capability and accuracy (Gao et al., 1999)(K. Chase and Parkinson, 1991). The tool works well for nonlinear assembly functions as well as non-normal distributions (K. Chase and Parkinson, 1991).

Otsuka and Nagata (2018) present Monte Carlo simulation as a probabilistic method, its level of accuracy appears to depend on the number of trails of the simulation. Since it's probability-based, the simulation output will have an approximation error built-in in its solution. According to K. Chase and Parkinson (1991) Monte Carlo is based on a random number generator to simulate the effects of manufacturing variations on assemblies. Glancy and K. W. Chase (1999) describes that, via input in terms of a small data set of dimension measurements with slight variations from a manufacturing process, the natural process variation of a part or assembly may be estimated. Also, Gao et al. (1999) claim that the accuracy of the method is connected to the sample size, the larger the sample size is, the lower approximation error and higher accuracy will be obtained.

K. Chase and Parkinson (1991) mention that the largest disadvantage of the Monte Carlo method is the need of a large sample size in order to achieve reasonable accuracy. The authors claims that the number of simulated assemblies must reach numbers around 100 000 to 400 000 in order to predict the small percentage rejects of modern manufacturing processes. This is due to it is assumed to be pretty time consuming to run around 100 000 simulations to obtain an optimum design and designers might not have that type of patience.

2.7 RD&T

A large part of virtual geometry assurance performed today is done by computers in Computer Aided Tolerancing (CAT) tools. It was Taguchi (1986) who introduced the principles and ideas behind geometry assurance. Nowadays, they play an important part in what we today call geometry assurance. Söderberg and Lindkvist implemented those ideas and principles into a CAT software program called RD&T. (Rosenqvist, Falck, Lindkvist, et al., 2014)

RD&T is a "Monte Carlo-based CAT simulation software" that is specially developed to support the geometry assurance process (Rosenqvist, Falck, Lindkvist, et al., 2014). RD&T has been used within automotive industry for over 15 years, it simulates and visualize the effect of manufacturing and assembly deviations in a virtual environment. This enables different design concepts to be analyzed and compared without the need of a physical prototype. (RD&T, 2020)

Morse et al. (2018) mention that RD&T is a CAT tool that supports the development process and bridge the gap between tolerancing and product development.

Chapter 3

Method

In this section the method used to carry out the project is presented. The project's desired outcome was broken into smaller activities and sorted in a chronological order. That resulted in a method that would help answer both research questions. In order to enable improvements to the determination process, knowledge about the existing process was acquired. The determination process could be divided into two phases.

- Determination of each contribution at respective group
- The combination of contributions at the VSA meeting

Which means that greater understanding of each contribution as well as the combination method is key to understand the whole determination process. Further on, it is important to overview the available resources of the project and gather necessary empirical data. Suggested improvements could then be presented to VCC. With these things in mind, the following project method was developed, see Figure 3.1. The five steps of the method, which will be described further in this chapter, are used to sectionize the method part of the thesis, and also help to structure the implementation part.

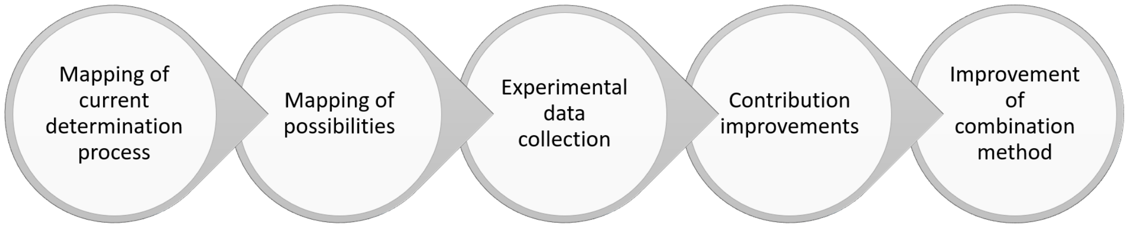


Figure (3.1): *The project's method.*

3.1 Mapping of current determination process

The first step in the method was to map the entire determination process. The mapping of every contribution was performed mainly by interviews with experts at the respective group, but also by studying corporate documents. The GSU group assisted with interviews, presentations and possible actions in RD&T. Engineers at the Durability group and Material Centre assisted the mapping of the dynamic and thermal contribution, by contributing in interviews and with study material. Lastly, the interviews regarding the combination method was performed with engineers from the GSU and VSA group.

The interview process was an iterative one, since the more knowledge about the contributions achieved, the more questions appeared. The purpose of the approach, of meeting a lot of different people at different groups, was to achieve a nuanced picture of all contributions and the combination method. A thorough mapping of the current determination process is important because it is the basis for the entire development process.

3.2 Mapping of possibilities

The next step in the process was to identify and map the possibilities to improvements, both for the contributions individually and the combination method. By investigating possibilities and hurdle factors, a more solid knowledge foundation was obtained, from which decisions can be drawn.

With the mapping of the current determination process, different problems throughout that process were identified. Potential solutions and approaches for these problems were then mapped. It was done by further interviews with VCC employees and workshops between the authors and the supervisor.

This mapping of possibilities was executed especially for the instantaneous contributions (dynamic and thermal) and the combination method. GSU claims that the static contribution is well mapped and verified to be considered confiding.

3.3 Experimental data collection

Once the possibilities were mapped, certain viable approaches were followed-up with experimental data collection. They were conducted within areas where resources existed and within the project's delimitations. Performed empirical studies, that resulted in experimental data collection, regarded the overslam part of the dynamic contribution. First, the purposes and goals of the studies were identified, then planned and finally executed. The studies performed were an observation study and an overslam clinic, which both will be described in the implementation part of the report.

3.4 Contribution improvements

The next step in the method process was to propose particular contribution improvements. This step was executed by realisation of certain potential possibilities mapped in the second step of the process. Which possibilities that went further on to contribution improvements depended on accessible resources and the project's scope.

Improvement suggestions were independently developed for each instantaneous contribution. Desired data collection were gathered for all contributions. However, the underlying calculations and simulations were done by VCC engineers. The overslam contribution improvements were developed based on the experimental data collection from the performed studies.

3.5 Improvement of combination method

The last step in the project process was to suggest improvements for the combination method. By identifying flaws with the current method during the mapping process, multiple combination method concepts were developed and compared. The ones that were the most promising were then further developed to suit the data representing each contribution.

Finally, a tool was developed containing the improved combination. It is supposed to be used at the VSA-meetings to assist the combination of contributions and reach more realistic nominal distances for gaps and flushes.

Chapter 4

Implementation

This chapter covers the implementation part of the project, where the project method was carried out for the different areas. In order to bestow structure to the chapter, consisting of an elaborate implementation process, it was sectionized by the individual contribution and ended with the combination method. In each section all information and knowledge gatherings, from every method step, are presented. Additionally, an initial section where an overview of the entire determination process is presented in the beginning.

4.1 Overview of determination process

In order to clarify the determination process, Figure 4.1 was designed to illustrate an overview.

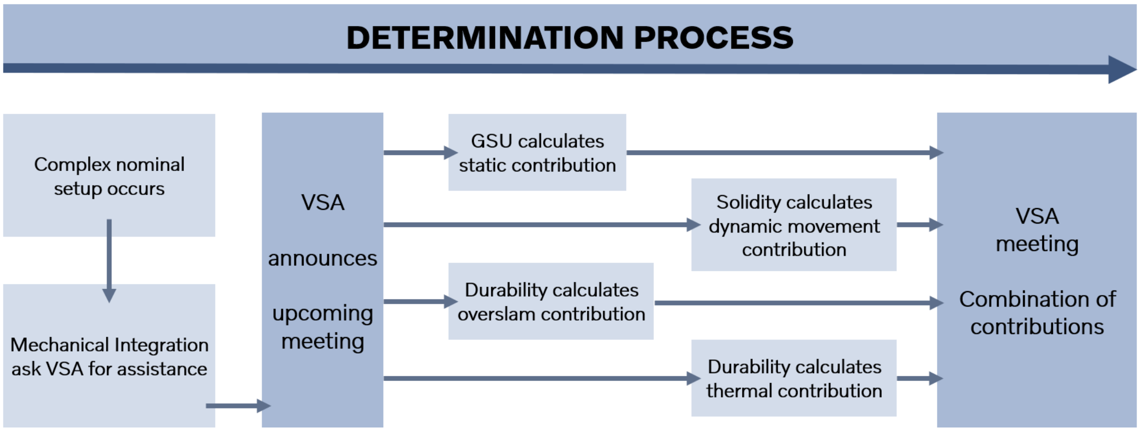


Figure (4.1): *Overview of determination process.*

The Mechanical Integration department is in charge of the nominal setup of parts. Their role is to make sure that different systems and parts of the car don't collide. Therefore, they're responsible for that nominal gap and flush distances are dimensioned. Normally, it's quite straight forward to determine these distances. Though, within some areas it's extra complex, which means that all gap and flush relations won't be achieved due to different circumstances such as design solutions and shapes. Instead, multiple gap and flush relations must be weighted towards each other, and attributes such as overslam and thermal expansion need to be taken into consideration, in order to achieve the best overall solution possible. To do this, people from Mechanical Integration are seeking assistance from VSA. VSA are working with weighting different demands to each other and suggest an overall solution by performing compromises within areas where the negative impact are lowest in an overall perspective. To achieve this, the VSA engineers are setting up meetings (VSA meetings) with people responsible for the affected systems on the car. At the meeting, the combination of contributions take place, so each responsible group have to calculate and predetermine input values regarding their respective contribution. (Brinkby, 2020)

4.2 Static contribution

The implementation part for the static contribution was executed with the help of the GSU group. The supervisor for the thesis project at VCC, a Robust Design Engineer, was the main contact regarding the static contribution and assisted to a great extent with interviews and discussions. In order to gain more practical insight, another Robust Design Engineer held a guided factory tour. Furthermore, insights were also gained from discussions with a Senior Robust Design Engineer as well as the Senior Manager for Robust Design & Tolerancing group.

4.2.1 Mapping of current static contribution

The static contribution of distance relation between two mating parts is calculated by the GSU group. The contribution aims to cover geometric variations that originates from supplied parts and VCC processes. This is done through an iterative process where the contribution is presented as a specified tolerance which copies of the final product will vary within. (Brinkby, 2020) A simplified version of the iterative process is illustrated in Figure 4.2.

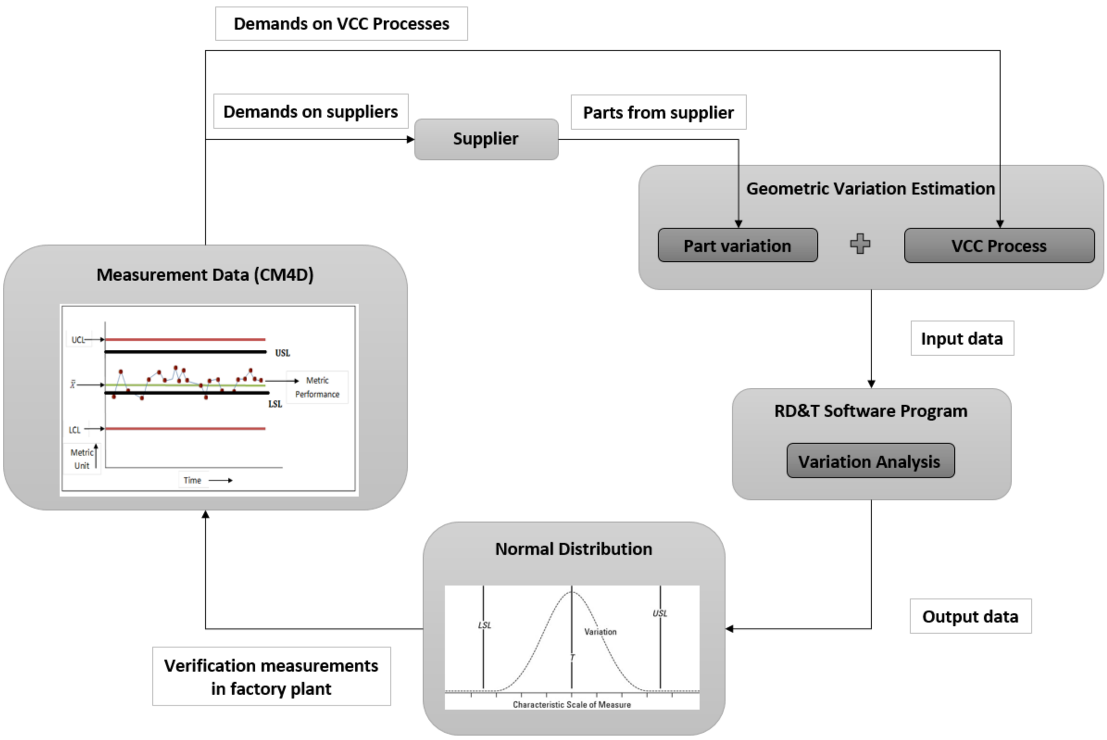


Figure (4.2): *Simplified iterative process used at GSU.*

Once the nominal setup of a part is about to be determined, the static contribution act as a central and important factor. To determine the static contribution of a new part, the GSU engineers initiate the process by analyzing measurement data from similar parts used in previous VCC projects of similar type. From this, data the engineers receive an indication of how much a part from a supplier most probably will variate within regarding size and shape. VCC will, based on measurement data from old similar parts, state supplier demands which the supplier's parts must meet. With analyze measurement data from vehicles rolling off the assembly line, the engineers also obtain an indication of how much the VCC precision processes will affect the total geometric variation. Based on these factors the engineers estimate the total geometrical variation connected to a part that is about to be implemented. The geometrical variation data are then used as input in a variation analysis made in the RD&T software program. As an output from RD&T, the engineers are provided with a normal distribution of how the building precision from, for instance, 100 000 produced cars are estimated to look like. In addition to the normal distribution, RD&T provides the engineers with an upper as well as lower specification limit, LSL and USL, which the produced cars are assumed to end up within. These limits are used as the most narrow tolerance span which GSU engineers can guarantee that VCC's factories can manage to meet with today's processes and suppliers. (Brinkby, 2020)

To validate that the suppliers and VCC factory processes fulfil GSU's tolerance requirements, both supplied parts and produced cars are measured to see that they meet the requirements. If supplied parts or complete vehicles fail to meet the requirements, actions are made to allocate the main source and fix the issue. The result might be that an operation station needs to be re-calibrated or that the tolerance span has to be changed due to precision limitations in today's manufacturing processes. (Brinkby, 2020)

4.2.2 Mapping of possibilities

A possible weakness of today's procedures connected to the method would be if a new part is introduced in a new project and that doesn't emulate any previously used part in terms of size or required processes. The method of today works fine as long as the output is verified through for instance measurement activities of produced cars in the factory. The more you measure in the factory, the larger amount of data GSU will have access to. However, each measurement station cost money, space and increase total production time of a car. It is nearly impossible to measure all relations on each vehicle on the factory line today since it would take a lot of time to complete, therefore only sections assumed to be important or critical are measured today. (Brinkby, 2020)

4.2.3 Static contribution improvements

The static contribution is an area where VCC feel that they have good control over due to that the result is based on data and experiences from previous projects and that GSU's simulations are continuously being validated. Although, an improvement recommendation in the factory was identified. It is to optimize the choice of measurements rather than quantitatively collecting measurements. Meaning that the measurements which differ the most should be measured more often throughout the different manufacturing processes.

4.3 Overslam contribution

The implementation part for the overslam contribution was executed with help of the CAE Interior, Exterior & Closures group, commonly known as Durability, at the Craftsmanship & Durability department. The main contact was a CAE Durability Engineer who assisted the project with interviews and performed simulations. Guidance and assistance regarding the overslam clinic and corresponding test equipment were thanks to a Testing Body Analysis Engineer. Finally, the knowledge gained about past overslam clinics and load cases were received from interviews with one of the Attribute Leaders at Strength & Endurance.

4.3.1 Mapping of current overslam contribution

In the overslam load case requirement of a tailgate, the tailgate is closed with a certain speed which forces the tailgate to deform and thereby obtain a different shape for a shorter period of time.

When a tailgate (or boot lid if it's a sedan car) is closed, contact between the tailgate and adjacent parts should be avoided. The rear lamp for instance is very sensitive to unwanted contact since it might break and it's an expensive part. Neither scratches nor dents are wanted on sheet metal surfaces. (Karlsson, 2020)

When buying a car, the customer shall be able to close a tailgate without damaging the car even when closing it harshly. To prevent this from occurring, the CAE department are performing overslam simulations. In their simulations, CAE engineers are applying a load at the tailgate so that it reaches a certain velocity just before it get in contact with the rest of the car. The velocity is estimated to cover the closing behaviour of the 90th percentile customer regardless of their mood. (Karlsson, 2020)

When simulating an overslam load case, the tailgate of a nominal car is closed with a certain velocity which forces the tailgate to elastically deform and impact the distance between e.g. tailgate and rear lamp. This is done in a virtual environment in NASTRAN simulation software. The behaviour analysis of the part is quite the same as in the dynamic movement situation. The distance in a specific section between two mating parts is evaluated over a certain time span. The distance difference between the most extreme position of the tailgate in relation to its nominal position in a specific section of the car is assumed to be the dynamic contribution. The value is a result of the overslam load case in the specific section. (Karlsson, 2020)

4.3.2 Mapping of possibilities

The input data, velocity of a heavily closed tailgate, for the overslam simulation model is based on estimations made by CAE engineers. These estimations are based on statistically based surveys where a smaller amount of VCC employees have been asked to manually close a tailgate with a force that they think is high but reasonable. The combination of a low number of participants in combination with that the participants were VCC employees makes the it easy to perceive the statistical base as vague. (Karlsson, 2020)

The input data, closing velocity, should be based on statistical empirical data. By performing an empirical study where a large number of people are asked to close the tailgate of a car with a velocity that they think is high but reasonable. By doing so, it might be possible to obtain a normal distribution over customer behaviour.

4.3.3 Experimental data collection

Based on information from interviews and discussions with VCC employees, it was determined that the existing overslam simulation method and validation test methods were well designed. However, it's doubtable whether the size of the existing load case (closing velocity of the tailgate) should be used for dimensioning the car. A study was decided to be performed, in order to investigate if today's load case is realistic or not and if it is possible to express the possible closing velocities of a tailgate as a normal distribution. Today, engineers are working with a few different closing velocities depending on car configuration, these are determined based on smaller empirical studies and has been changed over the years depending based on in-house experience due to the lack of large statistical data collection. Also, it seems to be unclear how much the overslam closing velocity on an “open car” (all side doors open) will differentiate to a “closed car” (all side doors closed). The difference in air pressure between an open and closed car, when closing a tailgate, might have an impact on the closing velocity.

4.3.3.1 Supporting research

No external previously conducted research within this area were found. This case is automotive specific and the test method isn’t a universal standardized test method. The reason for this might be that automotive companies classifies the result from these types of tests as confidential and do not release them in public. However, interviews have been performed with VCC employees connected to overslam tests, including the owner of the load case requirement. This study was designed based on obtained information from those interviews.

4.3.3.2 Observation study

In order to develop more realistic test methods for the clinics, an observation study was conducted. The purpose of the observation study was to produce a collection of data that can be used as a statistical base for dimensioning of the overslam load case.

To obtain this, an observation method was developed where the people’s closing behavior of tailgates was observed from a distance at parking lots outside shopping malls and super markets. The purpose of keeping a distance to the people who closed their tailgates and not get in contact were to not influence their closing behavior.

The main objective of the observation study was to investigate whether people are using manual closing technique or a power-operated tailgate to close the tailgate. Also, it was of big interest to investigate whether people are most frequently using one or two hands when closing a tailgate manually.

Four different parking lot areas around Gothenburg was selected as observation spots. Observations were conducted on the following locations in Gothenburg, Sweden.

- Köpcentrum 421, Högsbo
- Backaplan
- Bäckebol Köpcenter/IKEA Bäckebol
- Frölunda Torg

Observations were performed from a distance to avoid interfering of the car owners "personal space".

During the study, three types of aspects were about to be observed.

- **Closing technique**

  The closing techniques were categorised into three different categories; one hand closing, two hand closing and power-operated tailgate (POT).

  - The 1 hand closing category covered all closing techniques where one hand at the time are placed on the tailgate during the closing motion.
  - The 2 hand closing category covered all closing techniques where both hands were placed on the tailgate at the same time during the closing motion.
  - The POT category covered all non-manual tailgate closings where an automatic closing function was used to close the tailgate.

- **Grip alternative**

  Three different grip alternatives were observed, these were the outside grip, the middle grip and the inside grip.

  - The outside grip category referred to tailgate closings where the hand grip was placed on the outside of the tailgate.
  - Some cars have a handle placed underneath the tailgate, the middle grip category referred to tailgate closings where this handle was used.
  - The inside grip category referred to tailgate closings amongst which a grip or strap, placed on the inside of the tailgate, were used to close the tailgate.

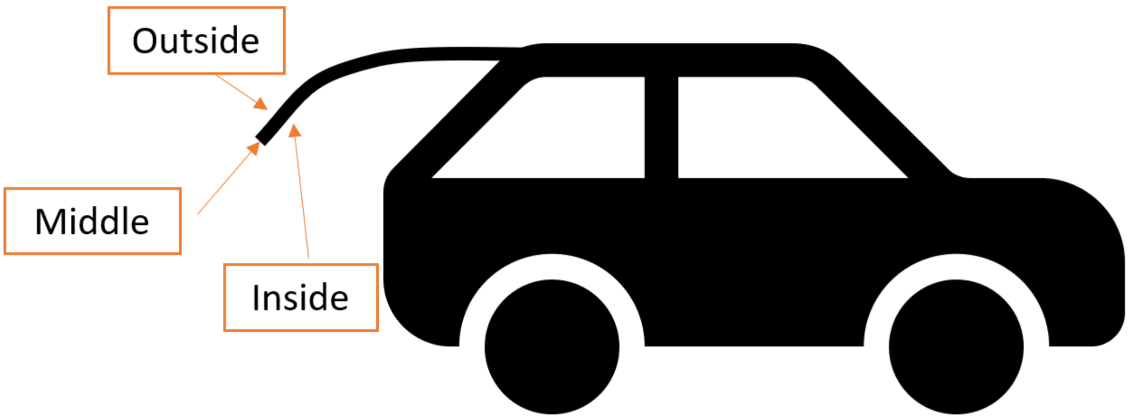


Figure (4.3): *Illustration of the grip alternatives' positions on the tailgate.*

- **Closed or opened**

  Another aspect that was studied was whether side doors were closed or opened during the closing motion of the tailgate. A closed car referred to a car where all side doors were closed during the closing motion of the tailgate. An opened car referred to a car with one ore more side doors open during closing motion of the tailgate.

4.3.3.3 Overslam clinics

The clinic's design was influenced by the outcome of the observation study analyses. The empirical overslam clinic study consisted of two clinics, one main clinic and a side clinic. The main clinic investigated the difference between closing the tailgate with one hand vs. two hands. In the clinic, the participants closed the tailgate both in a normal and a hard manner. The side clinic examined the difference between a closing a tailgate with the side doors closed and closing it with the side doors open.

Four different types of hypotheses were developed for the overslam clinic.

- By conducting an overslam clinic where multiple people are asked to close a tailgate with different types of pre-defined closing techniques it is possible to express the result as a normal distribution.
- There is some difference between the mean tailgate closing velocities depending on whether the car is closed or open.
- By placing your grip on the outside of the tailgate, you are enabled to reach the highest closing velocity of the tailgate.
- The majority of the car owners are closing the tailgate using a one-hand closing technique. Due to this reason, the VCC cars with a tailgate could be dimensioned based on the result from a one-hand closing technique.

The goals of this study were to either confirm or deny the hypotheses of the project. All tests were performed in a lab facility on a Volvo estate car called V60, with a manual operated tailgate. The car was suited with one inside grip on the right side but lacked a middle grip.

4.3.3.3.1 Test method & equipment

The test execution, method and used equipment were the same for both clinics. When the tailgate was closed by the participant in an assigned manner, the closing velocity right before impact was measured. The test equipment was mounted on the left rear end side of the car, placing the two speed sensors close to the impact position of the tailgate, see Figure 4.4

Figure (4.4): *Test equipment placement.*

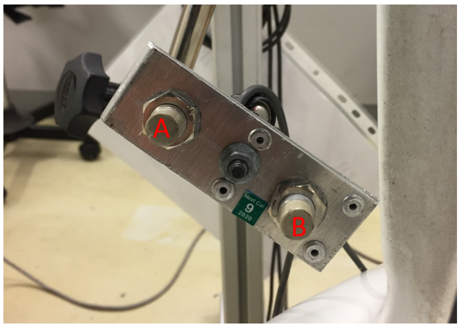


Figure (4.5): *Test equipment sensors.*

The test equipment calculated the mean velocity between sensor A and B in Figure 4.5 by register the time for each sensor when the tailgate passes by and the known distance between the sensors. The velocity shown on the test equipment's display was noted in an Excel sheet.

4.3.3.3.2 Main clinic

The main clinic was based on results from the two first ones as well as the pre-study's outcome. The goal of this clinic is to collect a larger amount of data that can be used as a base when dimensioning the size of the overslam load case which affect the car's design.

This clinic was performed on 105 participants. Each person was asked to close the tailgate five times but in different ways. The test procedure for one participant followed like this.

1. The participant was asked to close the tailgate with normal force in a normal manner using 1 hand.
2. The participant was asked to close the tailgate with normal force i a normal manner using 2 hands.
3. The participant was asked to close the tailgate hard with 1 hand and outside grip. The participant was asked to use a force that they thought a car should be able to withstand.
4. The participant was asked to close the tailgate hard with 2 hands and outside grip. The participant was asked to use a force that they thought a car should be able to withstand.
5. The participant was asked to close the tailgate hard with 1 hand and inside grip. The participant was asked to use a force that the thought a car should be able to withstand.

4.3.3.3.3 Side clinic

In the side clinic, the difference in possible closing velocity between an open car and a closed car was examined. A closed car means that the side doors are open when the tailgate is being closed, whilst an open car means that the side doors are left open.

To obtain as equal conditions as possible in terms of applied work to the tailgate closing, it was decided to let the tailgate fall free without any application of external forces. The tailgate was exposed to two different scenarios. In both scenarios the tailgate was first closed a few times with all side doors closed. Thereafter, the tailgate was closed a few times but this time with all side doors open.

In the first scenario the tailgate, supported by two gas dampers, was released right below its balance position. The balance position is the position where the tailgate can stand still due to that the pulling forces from the gas dampers are equal to the force of gravity. The point from which the tailgate was released was located 710 mm above the ground, see Figure 4.6.

In the second scenario, one gas damper was removed to increase the closing velocity and allowing a higher release point of the tailgate. The new release point was instead located 1300 mm above the ground, see Figure 4.6.

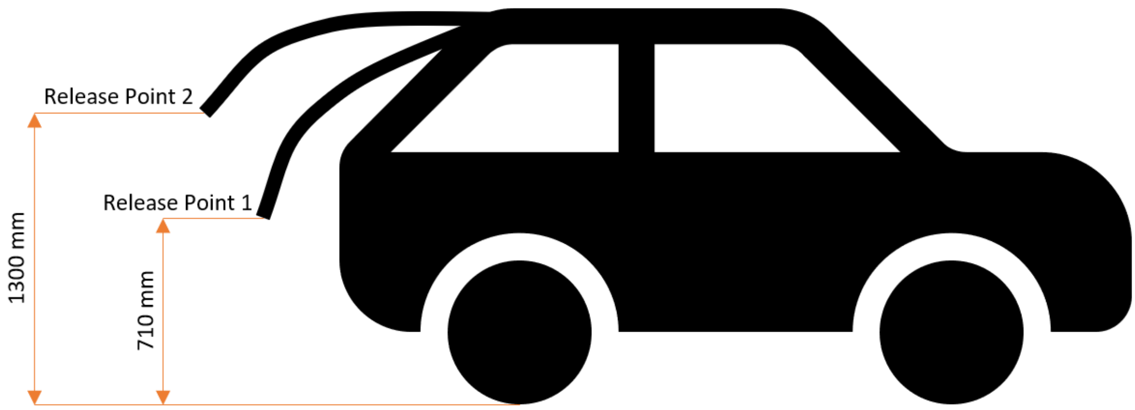


Figure (4.6): *Illustration of the two release points used in the side clinic.*

4.3.4 Overslam contribution improvements

Both the observation study and the overslam clinic were performed to achieve a better statistical foundation enabling more realistic overslam contribution. By combining data from the observation study and the overslam clinic it became became possible to estimate the probability that a person will close with a specific velocity and use a certain closing technique.

To investigate if the value distributions from the overslam clinic could be converted from velocity distributions to gap reduction distributions, virtual overslam simulations were conducted at VCC with different closing velocities. These simulations were performed on a virtual Volvo V60 model by an CAE engineer specialist at the

Durability group. In the simulations, the relative gap reduction for pre-defined closing velocities, based on the overslam clinic's results, were analysed for five different split-line sections between the tailgate and the body.

The simulations showed that a linearity relation exists between the tailgate's closing velocity and gap reduction in different gap relations between the tailgate and surrounding parts. By simulating an overslam motion for two different velocities within the span where linearity relation occurs, it is possible to calculate how an arbitrary velocity will result in a gap reduction.

4.4 Dynamic movement contribution

The implementation part for the dynamic movement contribution was executed with help of the Solidity group at Craftsmanship & Durability department. However, the same CAE Durability Engineer, who contributed in the overslam part, explained and clarified the dynamic movement contribution part. For further overview and guidance, a Principal Solidity Engineer and one of the Attribute Leaders of the Solidity group, assisted. Finally, the understanding of the Solidity method are thanks to a CAE Engineer and a Senior CAE Engineer at the Solidity group who helped out with interviews and information distribution.

4.4.1 Mapping of current dynamic movement contribution

When driving a car, the car will experience different types of forces depending on if it is accelerating, braking, turning, hitting a bump etc. In all these situations, the vehicle will experience loads that are distributed throughout the whole vehicle. These loads will force parts on the vehicle to move in relation to each other which impact split-lines and the distance between mating parts. By simplifying it, it can be seen as following; the higher the load is, the larger will the movement of part be and thereby affect the split-line relation more in a negative way. If the estimated dynamic movement is large, VCC will have to have a large distance between two mating parts to prevent visual and functional damages. (Karlsson, 2020)

To estimate how much two parts on a car might move in relation to each other, CAE engineers at VCC use simulations. They perform these simulations that estimate how much parts might move during heavy driving right before it goes over to become reckless driving. (Karlsson, 2020)

Different parts of the vehicle will experience different levels of loads. Today, the CAE engineers are using acceleration factors in x,y and z-direction, a hypothetical load case could be 2g in z-direction and 4g in x-direction. The acceleration factors derive from load cases obtained at a test track designed for accelerating fatigue analysis. From now on this method will be referred as "Applied Accelerations method" (Karlsson, 2020)

To simulate the dynamic movement, CAE engineers are applying acceleration factors (g-force), in x,y, and/or z-direction on a specific part in a simulation software program. The acceleration will force the part to move and affect the split-line relationship between mating parts. Hence, the distance between two parts is evaluated over a certain period of time, the closest relationship between two parts are then measured and compared to their nominal position. The difference between the most extreme position and the nominal position is used as the dynamic contribution in the specific section of the car that's being evaluated. The Applied Accelerations method is assumed to be heavily simplified and not necessarily provide a faithful result. (Karlsson, 2020)

The Durability track, that will from now on be referred as the Durability track, is designed with very harsh road bumps to accelerate the fatigue process. According to engineers from GSU, VSA and CAE, the track might not be suitable for dynamic movement simulations of a car that is designed for normal use and not heavy conditions and loads. The track isn't designed for analysing tolerances between mating parts. By using the potential unnecessarily high load cases from the Durability test track, the engineers assume that they might are using more extreme load cases than needed and thereby obtain an unreasonable high dynamic contribution. (Karlsson, 2020)

4.4.2 Mapping of possibilities

There is a group, called Solidity, at VCC's Craftsmanship & Durability department that is working with squeak & rattle (S&R) simulations on vehicles. The engineers at this group are analysing how and when sound occurs due to contact and motions between mating parts(Karlsson, 2020). Solidity are using a different simulation method to the Applied Accelerations method, that the Durability group uses. Instead of applying accelerations to a part that forces it to depart from its nominal position, Solidity are able to simulate relative movement between two surfaces. That allows them to simulate how two parts, on the vehicle, moves in relation to each other when the car driving on a virtual road. (Puhasmägi et al., 2020) From here on out this method will be referred as the Solidity method.

At VCC's testing ground at Hällered, there are several types of test tracks with differentiating purposes. Solidity are using tracks that are designed to mimic normal customer usage. The Solidity tracks have recently been scanned and virtual representations of them have been recreated which will enable VCC to perform a full vehicle dynamic movement analyzes on these tracks with faithful results in future projects. (Puhasmägi et al., 2020)

The load cases derived from the Solidity tracks are more gentle compared to ones that derives from the Durability track. Engineers at both GSU and CAE thinks that use of load cases from the Solidity track might be a better option for simulating dynamic movement. While the Durability track may appear to achieve too harsh load cases for dimensioning gap values, the Solidity tracks might be too gentle which would create gap in between i terms of load case severity. (Karlsson, 2020) (Puhasmägi et al., 2020)

4.4.3 Dynamic movement contribution improvements

The suggested improvement regarding dynamic movement is to change the method used when determining the contribution. The Solidity method is more realistic than the Applied Accelerations method for several reasons. The Solidity method considers relative movement between parts, scenarios that occur during actual driving. Whilst the Applied Accelerations method causes two adjacent parts to move in the same direction. It's not untruthful, since that scenario might occur, the problem is all the other scenarios it doesn't consider. Which the Solidity method covers in a wider sense. It manage aspects such as frequency vibrations due to uneven track surfaces, parts' eigenfrequency and relative movement of two parts. Also, the Solidity simulation are using an entire vehicle in their simulation which provides realistic scenario. The Applied Accelerations method cannot depict the gap reduction that occurs on the Durability track, including different track segments that are already scanned in. Which the Solidity method today can.

When simulations are performed on the recently scanned Solidity tracks, even more scenarios can be evaluated from simulations than what's possible today, this will provide VCC with a greater base of driving scenarios from which the dynamic movement can be determined from. By switching from the Applied Accelerations method to the Solidity method, VCC will be able to take more aspects into consideration and obtain more realistic test results. The simulated gap reductions could be complemented with statistical data regarding the probability that a car will experience a specific load case/track. By doing so, the probability that different driving scenarious would occur may be estimated. A study would need to be performed in order to enable this.

4.5 Thermal contribution

The implementation part for the thermal contribution was executed with help of the Craftsmanship & Durability department, in particular with Material Centre in terms of load cases. But first, the base knowledge of the thermal contribution, was given from the same CAE Durability Engineer who helped out in the overslam and dynamic movement contribution. Nevertheless, it was a Polymer Materials Body & Trim Technical Specialist who distributed necessary data and contributed by attending interviews and discussions.

4.5.1 Mapping of current thermal contribution

The gap reduction due to the thermal contribution is virtually simulated by engineers at the Durability group at VCC. They are virtually simulating the thermal expansion of parts that will occur due to temperature variations. The computerised simulation method of parts' thermal expansion, that's used today, is assumed to be quite straight forward. The load case temperatures that are used as input in the simulations are derived from physical measurements conducted on parked VCC cars around the globe. The temperature value, used as input for the virtual simulations is determined to be a temperature that VCC cars are assumed to be able to handle at the hottest pre-defined market.

The thermal expansion is validated through physical heat tests performed in a closed and controlled environment at the same temperature that's used as input to the virtual simulations. During the execution of the test, the car is exposed to a temperature that's evenly distributed and results in that the car obtains a homogeneous temperature. The test allows VCC to understand how parts expand and how the material creeps on a physical car. To express the thermal contribution of today, Volvo are exclusively using a single value when expressing the gap reduction that occur due to thermal expansion for the pre-determined top temperature. (Karlsson, 2020)

4.5.2 Mapping of possibilities

VCC has since a few years back a new improved facility were they are able to physical simulate the ambient conditions for a parked car at different markets. Also, VCC are developing a simulation method that makes it possible to perform virtual simulations on a parked car at different locations around the world. Once the method has been implemented and fine-tuned, it will be possible to estimate the temperatures, more exact, of which car components will reach on different markets. In the future, VCC aims to perform virtual simulations of a parked car that are considering aspects such as position of the sun and wind. These simulations would enable a move from virtual simulating the thermal expansion of parts on a car with a homogeneous temperature to simulating a vehicle with varying temperature gradients at different parts of the vehicle. The improved simulation method would reflect a real case scenario in a more exact way and result in more realistic values representing the thermal contribution. (Mattsson, 2020)

Cars that are sold at different markets will experience different temperatures, thereby it might be interesting to see what type of temperatures VCC cars assumes to be exposed to depending on different markets. The Material centre have performed multiple physical measuring events on VCC cars at different markets, where ambient temperatures have been measured as well as temperatures of different components on the car. By combining the max average ambient temperature to component temperature relation with sales numbers, a probability estimation of temperature exposure may be developed. (Mattsson, 2020)

The current physical testing method is equivalent to place the car in an oven. The Durability department deems it a tad unnecessary to simulate a car with a homogeneous temperature, since the car most likely won't be exposed to that load case (Karlsson, 2020). Material centre are currently developing a new and more realistic physical testing method, where lamps simulates the sun. Different parts of the car will be exposed differently because the method considers factors like wind, location, duration, outside temperature and position of the sun. (Mattsson, 2020)

4.5.3 Thermal contribution improvements

VCC have conducted temperature experiments on different markets around the world where the ambient temperature was measured along with temperatures on different parts on the vehicle. These experiments provides VCC with an indication over what level of temperatures of different parts of the car may reach on different markets. Due to confidentially reasons, detailed description of these experiments and data were excluded from the report.

The experiment data combined with climate statistics and VCC sale numbers would enable probability estimations to be made regarding what temperatures VCC cars risk to experience. Also, by combining those factors the probability that a car will reach specific temperatures and gap reduction will be possible to be estimated to some extent.

4.6 Combination method

The implementation part of the combination method was executed with help of the VSA (Vehicle System Architect). Two Rear End Vehicle System Architects in the Closures group help out with the understanding of the combination method and mapping of the different attributes. Also, the supervisor and the CAE Durability Engineer assisted by filling knowledge gaps regarding the combination of contributions.

4.6.1 Mapping of current combination method

Today, VCC are using a worst case tolerancing method when determining the nominal setup of a part. The static, dynamic and thermodynamic contributions are combined in an Excel document to build up the nominal setup. The Excel document contains the different contributions for all sections where the nominal setup shall be determined. A new document is created for each individual determination process, which could lead to incoherence between different determination processes.

The dynamic contribution may either be represented by the outcome from an overslam or dynamic movement at the rear end of the vehicle. The CAE engineers base their contribution estimation on the most extreme outcome out of the two simulations. The engineers at VCC that are involved in the determination process of nominal setup on the vehicle's rear end are convinced that the existing method is too pessimistic. They state that the method is providing an unnecessarily large value of the nominal distance between parts. They base their statement on that it is extremely unlikely for all the contributions to provide their worst case scenario at the same time. For instance, a car with maximum allowed geometric variation, that is extremely hot and exposed to large forces from heavily driving or a heavily closed tailgate, at the same time. Due to this, they are most often reducing the nominal value before the initiating production starts. The level of reduction is made via long discussions and based on the involved people's experiences and qualified guesses. This is something they want to move away from since it is time consuming and unknown how big the risk is that a car will experience a scenario where damage will occur if they select a certain value. (Leijonborg and Furunger, 2020) (Brinkby, 2020)(Karlsson, 2020)

4.6.2 Mapping of possibilities

There are several potential improvements to the combination method. A possible improvement is to design a template, which shall be used every determination process. That would create coherence between all determination processes and a clear approach of how the contributions shall be combined. The template may be structured to fit rear end cases, but with the potential to be further developed for general cases. The template could include calculated probabilities of the different load cases occurrences, to ease the discussions and support arguments during VSA-meetings.

A clarification regarding the groups responsibilities of different operations during the determination process would improve the whole process. That is done due to the mapping process. However, an improvement that would help structure the process is that VSA ensures that needed input values are delivered before the meeting.

One possible solution to the problem might be to use a statistical tolerancing method instead of worst case method. If all contributions could be described as normal distributions, they could combine to one single normal distribution by using a statistical combination method, for instance *Root Sum Square* (RSS). The static contribution is already today based on a normal distribution, the largest issue at the moment is assumed to be that it's unknown whether the other contributions are possible to be expressed as normal distribution in practise or not. (Brinkby, 2020)

4.6.3 Improvement of combination method

The main focus when developing the improved combination method was to provide both insight of the contribution derivation and the probability of different scenario occurrences. An improved Excel template was developed in order to ensure that the combination method consisted of knowledge insight and probabilities. The idea was that this template should be used during the VSA-meetings for the combination of contributions. The Excel document contains of several sheets where the one named *Main* will be the most used. In Figure 4.7 zoomed part of *Main* is shown.

	PROJECT XXX REAR END	ISSUE: 2020						
	INPUTS	Part & Process - GSU (σ-level)			Overslam - Durability (m/s)			Own input:
	Filled in by respective group	G1	G2	G3	DO1	DO2	DO3	DOX
GAP #	Between which components	Level 1	Level 2	Level 3	Velocity 1	Velocity 2	Velocity 3	Velocity X
Section 1	Part A - Part B							
Section 2	Part C - Part D							
Section 3	Part E - Part F							
Section 4	Part G - Part H							
Section 5	Part I - Part J							
Section 6	Part K - Part L							
Section 7	Part M - Part N							
Section 8	Part O - Part P							
Section 9	Part Q - Part R							
Section 10	Part S - Part T							
					POT ratio:	Yes/No/Both	Closing force	
					50%	Both	Hard	
	PROBABILITIES	G1	G2	G3	DO1	DO2	DO3	DOX
	Probability of number of cars that will be out of spec.	%	%	%	%	%	%	%
	Number of cars:	-	-	-	-	-	-	-
	100000							

Figure (4.7): *Part of Main sheet of the improved combination method.*

The complete part of *Main*, among the other sheets of the document, are shown in Appendix A. The different steps of the combination method will now be described. The presented parts of the combination method are generalized for the report.

Step 1 - Preparatory work

Each group fill in their contribution input values, in the empty cells seen in Figure 4.7, that they receive from respective simulation and calculation. Instead of just one contribution for each section, like in the old method, there are now three contribution values that each group shall deliver. The idea was that the input part of the sheet shall be filled in before the meeting in order to increase effectiveness during the meetings.

Step 2 - Explanation and derivation of contributions

As said before, a focus in the improved method was to provide insight for the meeting attendees. Therefore, explanation of how each contribution has been derived was included in the combination method. Each contribution has its own sheet in the Excel document, where not only probability calculations take place, but also descriptions of the contribution derivation. For instance, in the dynamic movement sheet the different tracks used to simulate driving conditions were explained with help of images. The reason of this was to reduce the knowledge gaps between the groups and to gain greater insight of what risk will be taken in the end, since one could know more what conditions have been taken into consideration.

Step 3 - Calculation of probabilities

The other focus of the improved method was to provide the probability of how many cars that will end up outside specification regarding certain load cases. For static contribution the probability was calculated with related confidence interval. The overslam part is the one where the most focus has been. The derivation of the probability of certain gap distances, related to closing velocities, could be done due to the performed observation study and overslam clinic. The user choose the POT ratio, normal or hard closing and Yes/No/Both which answers the question:

"Have you ever closed a tailgate this hard before?". That question was asked, to the clinic's participants, to give the authors a general indication of how many of the hard closings that were unrealistic. The chosen input parameters calculates the probability of number of cars that will end up outside of specification in the *Overslam* sheet, and return those values to *Main*.

The calculation of the dynamic movement probabilities still awaits for the execution of a study. A study where the Solidity and Durability tracks are mapped together with driving scenarios that VCC cars tend to experience. The study will be further explained in Chapter 7, Future Work. For the thermal contribution the load cases are temperatures registered at different locations. The probability is calculated by the number of days certain temperatures are obtained divided by the total number of days during a year.

Step 4 - Combination into scenarios
In the old method the contributions were added, then a mutual risk estimation was subtracted from the calculated nominal value. The new method containing three values of each contributions, plenty more of different combinations, or scenarios as they will be referred as, can be calculated. The three different values associate to three different load cases. For instance, what σ-level used or which track consideration for dynamic movement, see Figure 4.7. The improved combination method still uses worst case tolerancing, but with including probability of the number of cars that will end up outside specification, for that specific scenario. The individual probabilities for the load cases are combined into the resulting probability of the scenario where all load cases occur at the same time. So instead of one single resulted nominal gap distance, several will be presented in *Main* based on unique combined scenarios.

Step 5 - Determination
The last step in the combination process is to determine the nominal gap distances for each section. This step is similar to how it has been determined in the past, through discussion, reasoning and comparing with PQ demands. Although, now the meeting have greater understanding of the risk they're taking and how many cars that estimate to end up outside specification. The likelihood of different scenarios and their resulting gap distances together with the understanding of the load cases, more defensible nominal values can be reached at the VSA-meetings.

Chapter 5

Results

In this chapter the results of the project are presented, in the same chronological order as the implementation part.

5.1 Overslam contribution

This section presents the results of the studies performed regarding the overslam contribution. First the observation study results, then the results of the overslam clinics and ultimately the results drawn from the linearity analysis.

5.1.1 Observation study

As mentioned in the implementation chapter, three aspects were in focus during the observation study. The outcome of the observation study is presented in this section.

5.1.1.1 Closing techniques

A total of 550 observations, see Figure 5.1, were made of people closing their tailgate. The closing activity was divided into three different techniques, POT (Power Operated Tailgate), one hand manual closing and two-hand manual closing. The one hand closing technique was most commonly used before the POT technique and the two-hand closing technique was extremely rare.

Out of the 550 in total observations, in 70% of them the one hand technique was used, 29% were using a POT function and in 1% of the total observations the two-hand closing technique was used.

When comparing the two manual closing techniques, one will see that the one hand closing technique was used in 98.2% of the cases whilst the two-hand closing technique was used in 1.8 % of the cases.

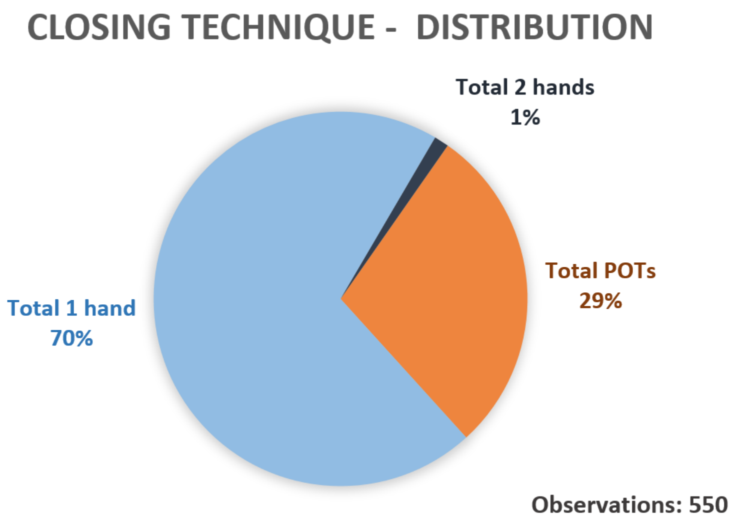


Figure (5.1): *The number of observations made where the POT, one-hand and two-hand closing technique were used, respectively.*

5.1.1.2 Grip alternatives

A total of 349 observations, see Figure 5.2, were made of people closing their tailgate manually using different grip alternatives. As the figure below shows, most people were using the outside grip, the inside grip was second most popular whilst the middle grip was the least popular grip alternative.

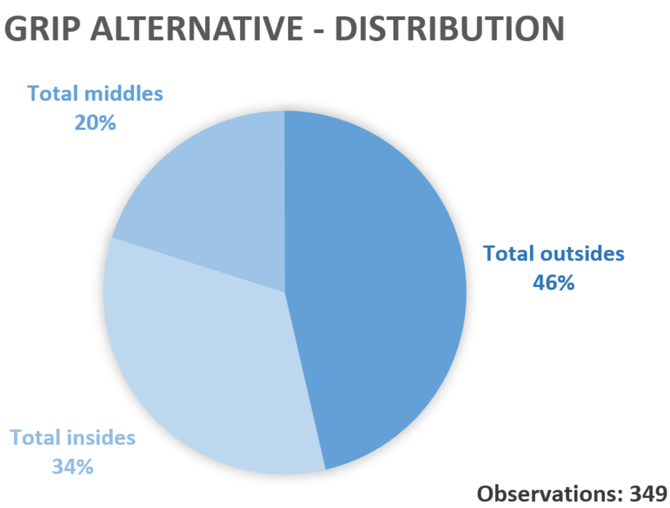


Figure (5.2): *The number of observations made where the outside, middle and inside grip were used, respectively.*

5.1.1.3 Closed or open

A total of 331 observations, see Figure 5.3, were made where people either closed their tailgate with the side doors closed or open. A car with one or more side doors open was registered as open. The majority of the observed closings, 87%, were performed on a closed car.

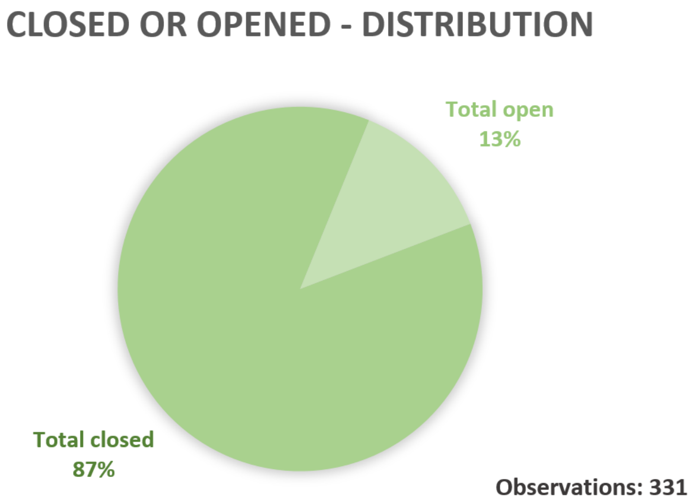


Figure (5.3): *The number of observations made where the car was either open or closed.*

5.1.2 Overslam clinics

The overslam clinic results are divided into the following subsections; participant demography, main clinic and side clinic, and are presented in that order.

5.1.2.1 Participant demography

In the overslam clinic, a total of 105 participants attended the clinic, all were VCC employees. 90 of these were males and 15 females which results in a proportion of 85,7% males to 14,3% females.

The age distribution of the participants are illustrated in Figure 5.4. The age distribution was quite spread out with the majority of participants belonging to the three middle categories.

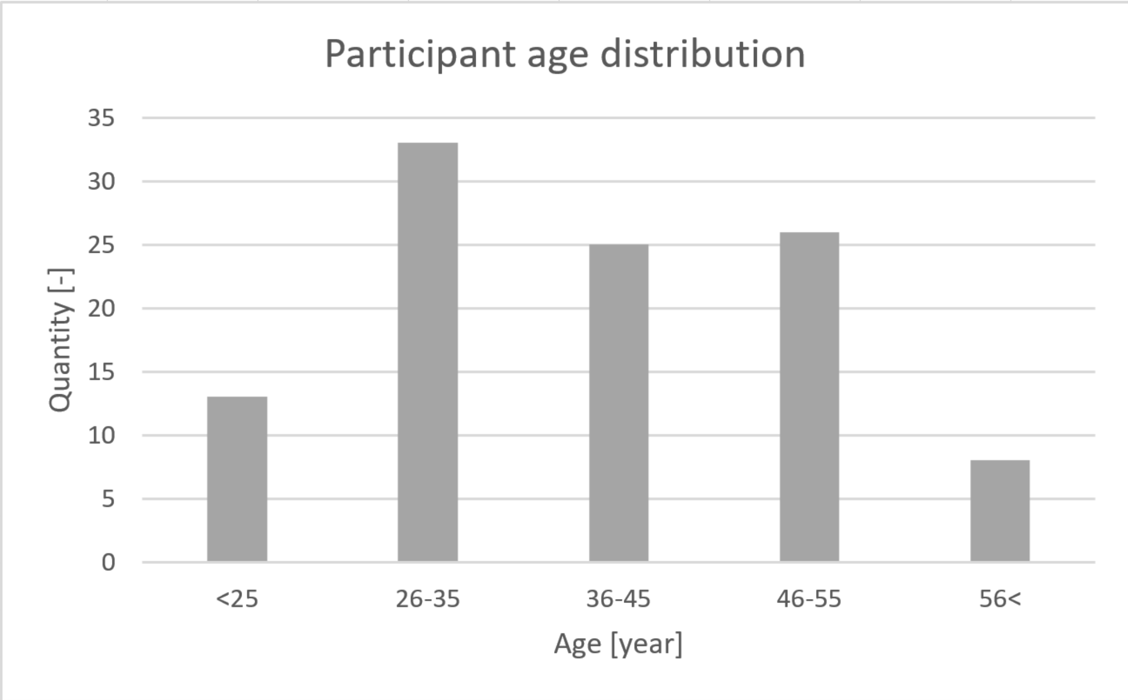


Figure (5.4): *Age distribution of the participants divided up into different age groups.*

The height distribution, see Figure 5.5, of the participants was much more concentrated than the age distribution. As the figure chart illustrates, the majority of the participants were between 171 cm and 190 cm tall. It does reflect the gender composition of 84,7% male participants.

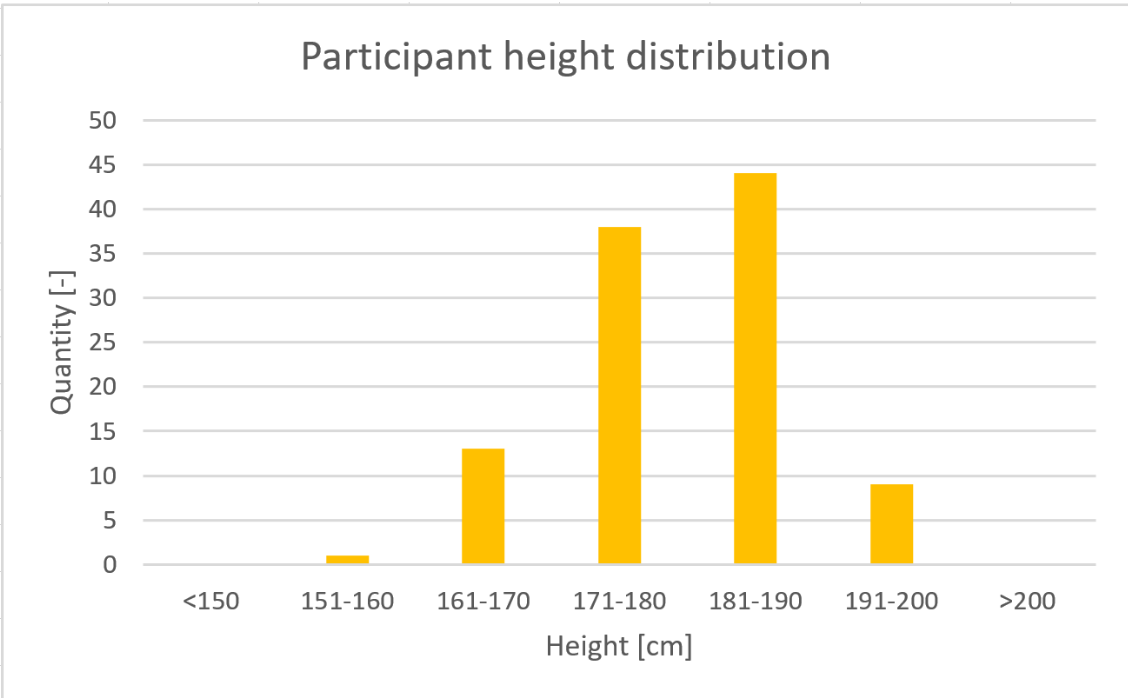


Figure (5.5): *Height distribution of the participants divided up into different height groups.*

5.1.2.2 Main clinic

All presented results are based on normalised data from the clinic. The values have been divided by the highest registered closing velocity, which was measured in m/s.

To ease the interpretation of the data collection from the overslam clinic, the velocities were rounded to single decimal values. Some participants closed the tailgate with a velocity that the measurement equipment was unable to detect due to that the tailgate traveled with a too high velocity. These attempts were registered as equal to the highest measured value but with an remark attached to the value.

The closing velocity distribution for closing the tailgate, with one or two hands, in a normal manner is shown in Figure 5.6, whilst the hard closings are shown in Figure 5.7.

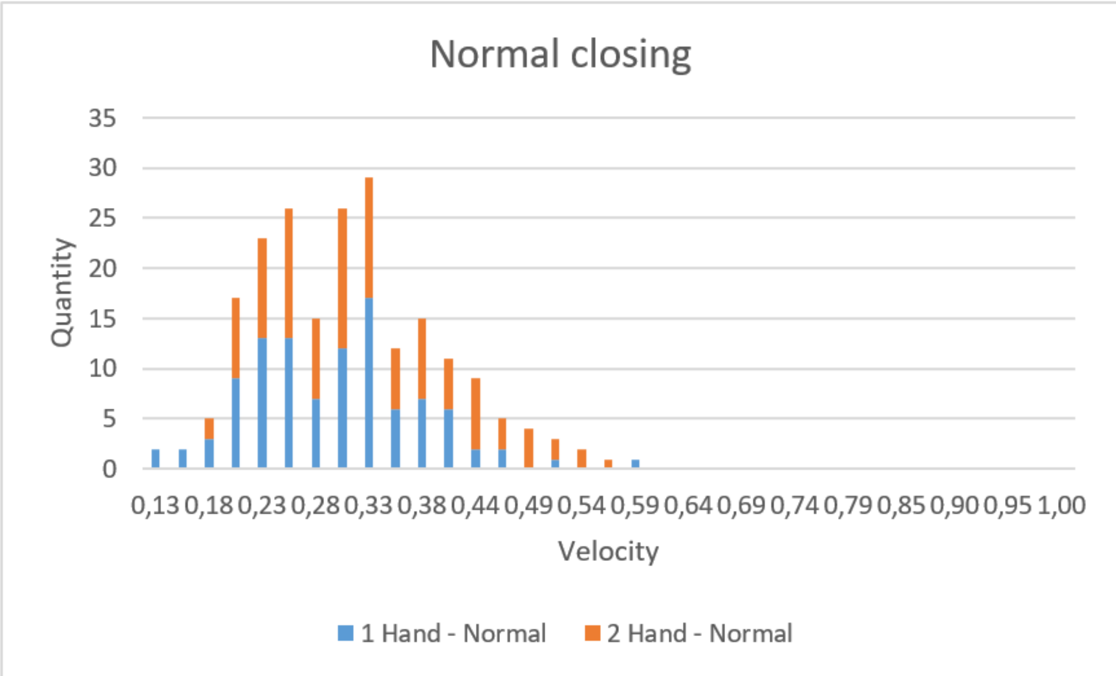


Figure (5.6): *Value distribution of normal closings.*

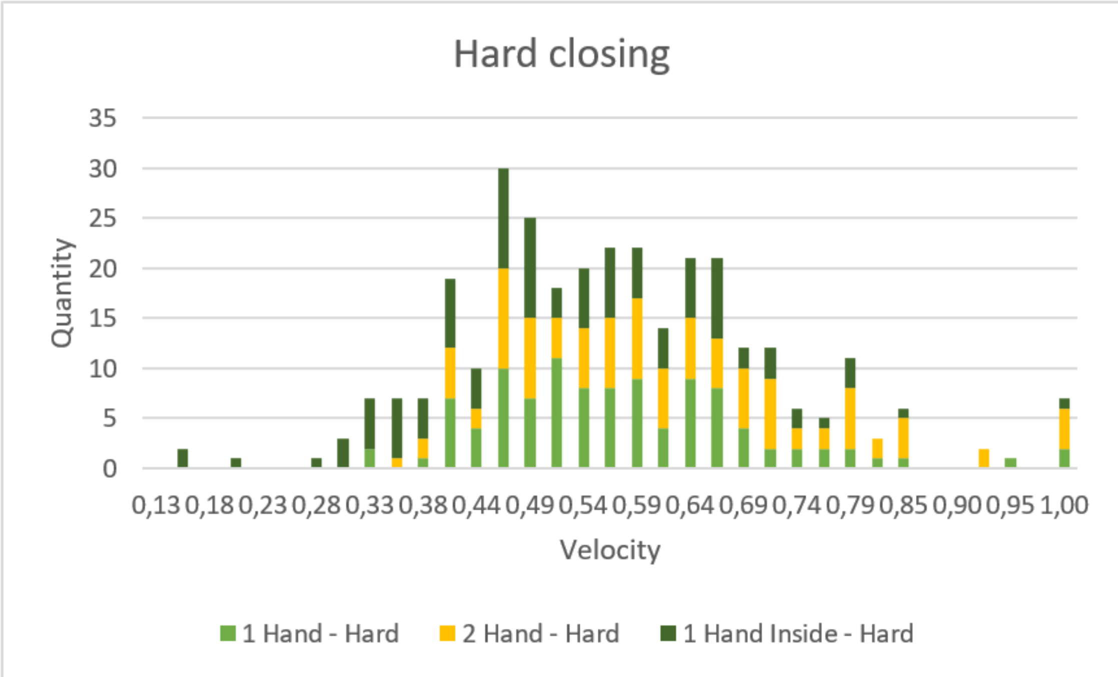


Figure (5.7): *Value distribution of hard closings.*

When removing the hard closing results from all participants who declared that they did not think that they realistically would reach the same velocity on their own car in any situation, the standard distribution became slightly different. The result from removing the "unrealistic" values is presented in Figure 5.8.

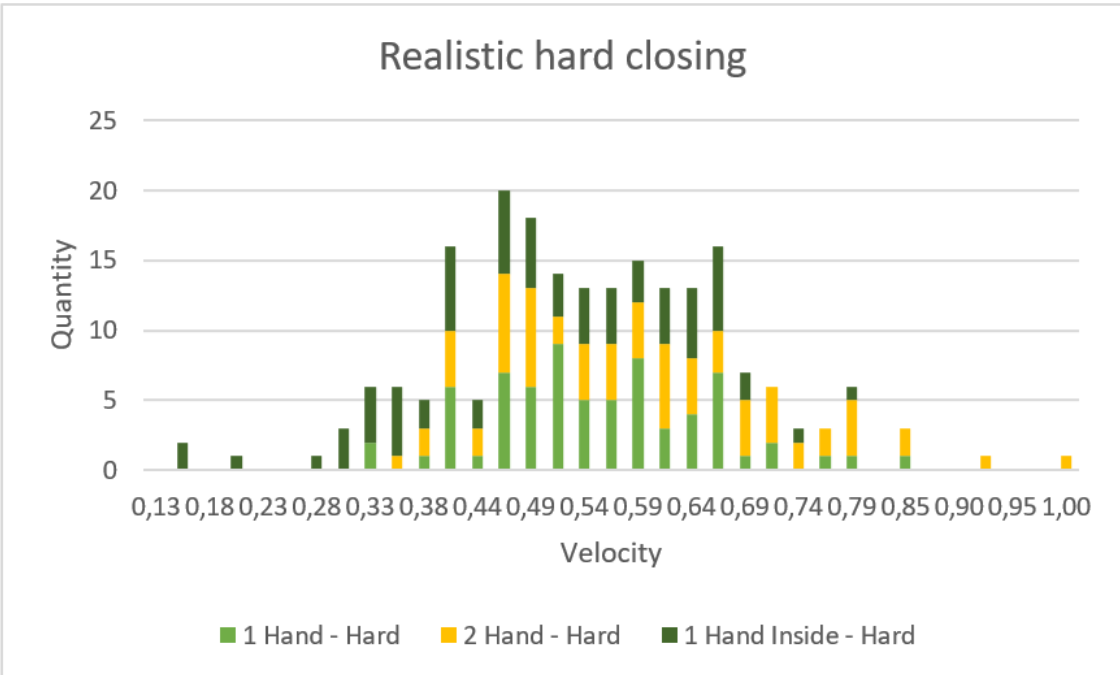


Figure (5.8): *Value distribution of realistic hard closings.*

5.1.2.3 Side clinic

The results of the side clinic, see Figure 5.9, is that an open car reaches a higher closing velocity than a closed one when they are exposed to the same test condition. The difference in average closing velocities for the two scenarios, release point 1- 2 dampers (710mm) and release point 2 - 1 damper (1300mm), are shown in Figure 5.9. Furthermore, the side clinic results also show that a higher closing velocity leads to a larger velocity difference.

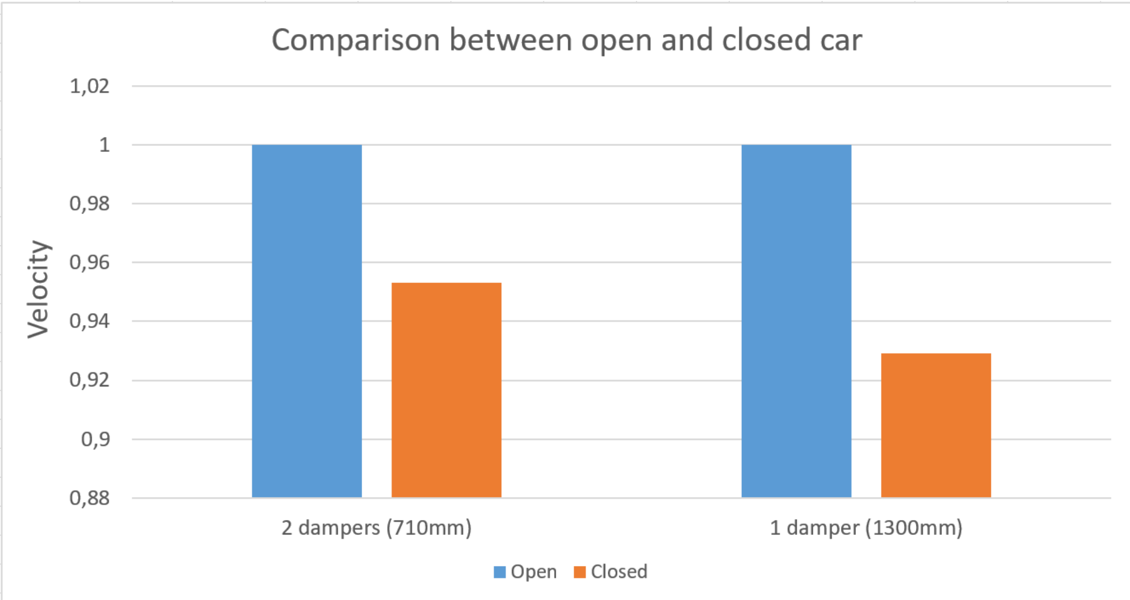


Figure (5.9): *Value distribution of realistic hard closings.*

5.1.3 Linearity analysis

The linearity analysis, see Figure 5.10, shows that there are a linear relation between closing velocity and gap reduction in different split-line sections. Each graph in the figure represent the correlation for a certain split-line section. The sections were four along the side, and one in the bottom, of the tailgate between its surroundings. The axes in the figure have been normalized to ease the comparison between the different section but also due to confidential reasons. The linearity is especially good within some specific velocities whilst it differentiates a little bit more outside the velocity span. The load cases VCC use for overslam contribution are inside that velocity interval, which is the reason it can be applied in the combination method later on to determine gap reductions for "any" closing velocities.

Figure (5.10): *Linearity analysis between closing velocity and gap reduction.*

To improve the overslam contribution, the current method to determine the contribution was mapped and evaluated. Based on the evaluation, possible improvements could be identified. The identification process resulted in improvements in how the contribution should be determined to suit the improved determination process. Also, experimental data collections were performed to enable necessary improvements to be implemented. The improvements to the determination process of the overslam contribution were the following.

- The number of load cases were increased from one to three to provide the VSA meetings with more gap reduction references from which combined nominal gap distances can be determined.
- The determination process of the contributions has been documented and illustrated to ease the understanding of where the load cases derive from.
- Due to the experimental data collection, it will be possible to estimate the probability that a car's tailgate will be closed with a certain velocity.
- All load cases have an estimated probability value which makes it possible to estimate the probability that a load case will occur.
- A linearity simulation was performed and it showed that a linear correlation exists between closing velocity and gap reduction. So, by performing two simulations on a split-line section when applying two different velocities, linear relation between these two values can be assumed to exist. With this in mind, the closing velocity with a correlating gap reduction may be easily adjusted within a predefined span, where linearity is assume to exist based on test results presented in this report.

5.2 Dynamic movement contribution

To improve the dynamic movement contribution, the current method to determine the contribution was mapped and evaluated. Based on the evaluation, possible improvements could be identified. The identification process resulted in improvements in how the contribution should be determined to suit the improved determination process. Also, simulation results of both methods for a specific case were compared. The improvements to the determination process of the dynamic movement contribution were the following.

- The number of load cases were increased from one to three to provide the VSA meetings with more gap reduction references from which combined nominal gap distances can be determined. Various vehicle types will be able to be dimensioned for different road types and driving scenarios.
- The determination process of the contribution has been documented and illustrated to ease the understanding of where the load cases derive from.
- All load cases shall have an estimated probability value which makes it possible to estimate probability that a load case will occur. However, a study needs to be performed in order to achieve trustful numbers. When implemented, it will benefit the combination method and give the employees greater understanding of the risk taken due to certain road type scenarios.
- The Solidity method provides much more realistic simulation results than the Applied Acceleration method, since it's more advanced and considers several more aspects.

5.3 Thermal contribution

To improve the thermal contribution, the current method to determine the contribution was mapped and evaluated. Based on the evaluation, possible improvements could be identified. The identification process resulted in improvements in how the contribution should be determined to suit the improved determination process. Also, temperature measurement data provided by VCC was analysed. The improvements to the determination process of the thermal contribution were the following.

- The number of load cases were increased from one to three to provide the VSA meetings with more gap reduction references from which combined nominal gap distances can be determined.
- The determination process of the contribution has been documented and illustrated to ease the understanding of where the load cases derive from.
- All load cases will have an estimated probability value which makes it possible to estimate probability that a load case will occur.

5.4 Improvement of combination method

An improved combination method has been developed and will act as a tool at the VSA meetings when determining nominal gap values for complex nominal setups. Some of the improvement aspects in comparison to the current method were the following.

- The new combination method includes information about the different contributions. Illustration, presented calculations, pictures and external documents describe where all load cases derive from. This will increase the level of transparency within the determination process and educate all involved groups, resulting in a greater understanding for each other's work.
- Three load cases will be presented for each contribution instead of one, as it is in the current method. This makes it possible to combine load cases with different level of severity. Multiple reference scenarios can be created and will most likely ease the determination of the nominal value.
- Each contribution load case will have an estimated probability value which makes it possible to estimate probability that an event will occur when all contributions' load case are active simultaneously. This provides VCC with an indication of how many cars there are that will experience a specific scenario. Hence, VCC will no longer only have a nominal value for a gap distance but also have a measure of how many cars there are that risk to experience contact between the adjacent surfaces.

Chapter 6

Discussion

In this chapter discussions and reflections regarding the project results, methods used and possible approaches will be presented. The chapter is sectionized according different topics that the authors found necessary.

6.1 General

A lot of focus has been on the mapping of processes in this project due to the lack of knowledge insights regarding the determination process between groups. The associated groups at VCC are experts in their field, although the awareness of other group's calculations and approaches has been inadequate. This is not necessarily bad for their respective work but it can cause issues in the determination process for nominal setup. The improved determination process that has been developed state clearly how the different contributions were derived and with which methods. Also, the combination method distributed to VCC contains descriptive explanations, images and derivations to help people understand the processes if the different groups.

If the project had been re-performed, less focus would have been put on the static contribution. The authors focused relatively much of learning the method and tools for calculation of the static contribution. It was useful information, however, with more thought, the focus should have been laid on the combination method or the overslam, dynamic movement and thermal contribution.

6.2 Obstacles

There is one factor that has affected the project the most, that is the Corona pandemic which erupted the spring of 2020. A lot of different companies had to layoff personnel in order to fight the virus, VCC included. The employees at VCC's Research & Development department has, since the middle of March, been working 60%. Since this thesis project is heavily dependent on contact with other groups within the company, the 60% work weeks have caused problems. Meetings have been postponed, desirable studies and simulations have been limited, delayed and cancelled. It's unfortunate indeed, however reasonable due to the most peculiar situation.

6.3 Work routines

An important factor for the determination process are the work routines. The authors' perception is that the process has been uniquely situation based. As the VSA group gets involved, due to the appearance of a complex nominal setup, the approach doesn't follow a clear structure. The consequences are returning discussions and questioning of the derivations of the contributions, which results in inefficient meetings. As the improved determination process gives clear structure to prevent same discussions of appearing, the work routines before the meetings are of great importance. A strong recommendation for VCC is that every group make sure to run their simulations and send in all three ranked contributing values before the VSA meeting. By applying this work routine the combination method will have all prerequisites, give better probability estimations and ultimately the meetings will be more efficient.

6.4 Overslam

The reason why the numbers presented in the result charts are normalised is because of corporate confidentiality, load cases are not to be distributed outside the company. The maximum reaching values on the x-axes are 1 in the clinic results (Figures 5.6 - 5.8) and the linearity analysis result (Figure 5.10). For the overslam clinic the maximum value was the highest velocity the test equipment could register. For the linearity analysis the maximum value for x was the highest velocity used in the simulation.

What is worth of mentioning is that both the overslam clinic and the linearity analysis are performed on specific car models, which should be considered when using the results for upcoming projects. However, the results give a good basis of theory to derive load case probabilities, that haven't been possible before.

There are few things to take into consideration regarding the interpretation and results of the observation study performed. The majority of cars appearing at parking lots, connected to supermarkets or shopping malls, are carrying 1-3 people. Therefore, it's unlikely that all doors are opened at the same time. Also, the observations were made in Gothenburg during the first half of April, when the outdoor temperature reached around 10-15 degrees Celsius. This means that the inside part of a parked car won't experience high temperatures, in comparison to the summer months. During the summer months a parked car may easily reach temperatures above 45 degrees Celsius. During the summer, people are more likely to open the car's side doors, in order to let out the hot air inside the car, before closing the tailgate and thereby reduce the resistance due to air pressure. Although, when the temperature is rising, the gas in the pneumatic dampers (that resist the closing of the tailgate) will expand and therefore might decrease the closing velocity.

A hypothesis when developing the observation study was that a closing with the outside grip would result in a higher closing velocity than an inside grip. That's why the grip observation was included in the study. However, the results of overslam clinic contradict that hypothesis since the difference of velocity regarding the different grips was not convincing. The small velocity difference is also the reason why the value distribution of hard closings, seen in Figure 5.7, consisted of all three data collections; 1 hand, 2 hand and 1 hand outside.

The initial overslam clinic was planned to cover around 500 participants. Furthermore, it was planned to be performed at three different locations; Volvo Torslanda, Nordstan in Gothenburg City and outside Chalmers Institute of Technology. This to increase the participant demography outside the walls of Volvo. It was noted that some employees during the performed clinic shut the tailgate incredibly hard. Hard enough for the authors to assess that no non-employee, that are not aware of the concepts of overslam clinics, would reach those closing velocities. Nevertheless, this planned overslam clinic had to be quite scaled down due to the Corona related recommendations from the Public Health Agency of Sweden.

In the linearity analysis, the graph for split-line section 2 in Figure 5.10 deviates from the other split-line sections. The reason for this is a tad unclear. Several more analyses have to be performed in order to answer this question definitely, which was not possible within the projects time frame. However, a hypothesis is that the adjacent parts in split-line section 2 alternates between an in phase and an out of phase relative movement.

In Figure 5.10 the measurement points for the lowest velocity indicates a negative gap reduction. The explanation for this is that the tailgate doesn't return to its nominal value, due to the very low velocity.

Lastly, the locations of the split-line sections have been left out of the report intentionally for the same reason different graphs have been normalized. Corporate information of that kind should not be shared outside the company.

6.5 Dynamic movement

In the beginning of the project the author's tried hard to turn all contributions into normal probability density functions, in order to combine them with statistical tolerancing. The dynamic movement contribution was the most difficult one to do that with. For overslam the population is the different closing velocities of different people, whilst for static it's the geometrical variation for each produced car. For dynamic movement that would be the driving behaviour of VCC customers. That factor was difficult to describe and even hard to measure. Pre-studies were commenced whether the safety department of VCC should be included, to help derive load cases or categories for certain driving behaviours. A PhD student's study regarding driver behaviour was briefly studied, but the approach was dropped due to time constraints.

Certain dynamic movement simulations were unfortunately postponed. They are still going to be executed, but unfortunately couldn't be a part of the results in this project. The simulations regard relative movement analyses on the scanned Solidity tracks. In other words, the exact simulations desired since it would compare the dynamic movement contribution between the Durability tracks and the Solidity tracks. The suggestion for VCC is to use these simulation results in the determination process to derive a more realistic dynamic movement contribution.

Another activity was cancelled, which was a visit to testing tracks in Hällered. The visit would give greater insights of the dynamic movement contribution to the authors. The ability to test drive on the tracks would have possibly lead to more opportunities for improvement and more descriptive explanations of the tracks that are used in the combination method.

6.6 Thermal

The calculated probability estimation for thermal contribution in the combination method, is based on the analysed measurement data provided by VCC. It was a small amount of data that was analysed, although still resulted in interesting conclusions. Which means that more analyses on a larger data collections could lead to a greater representation of the thermal contribution load cases, from different locations in the world.

Due to limited time, desired thermal simulations were omitted. It was thermal expansion simulations, with corresponding gap reductions, that would have been performed by the Durability group. The idea was to perform the simulation for the same split-line sections as the overslam linearity simulation, for comparison reasons. Hypothetically, the truly interesting scenario is to investigate simulations for all instantaneous contributions, with the same prerequisites. On the same car model and for exactly the same split-line sections. The persistent problem remains though, it still does not investigate the scenario where all contributions occur at the same time.

6.7 Combination method

With more thought, the development of the combination method should have started earlier in the project process. Instead of seeing it as the last thing to do, it could've been started in the middle of the project and simply be further developed. However, the combination fulfills its purpose since it estimates probabilities and contains instructive sheets.

A presentation will be held at VCC for the concerned groups, where the authors will thoroughly explain the combination method. The improved developed combination method is specifically developed for gap calculations for the rear end of the car. However, with minor modifications it can be redesigned to suit desired application, since it acts as an assisting tool during the VSA meetings.

Chapter 7

Future work

This project has started a philosophy transformation regarding how to determine nominal gap values on the rear end of the car. However, there is work left to do in the future to improve the determination process even more.

The overslam clinic results found in this report were a step in the right direction. However, the participant demography was quite homogeneous and the majority are working with research and development which may have resulted in bias participants and thereby untruthful data points. To obtain an even better statistical base for determination of the overslam probability, a suggestion to VCC is, therefore, to conduct another and even more comprehensive overslam study. Outside the company walls preferably, like the one intended from the beginning. By performing a more comprehensive clinic outside VCC, it would most likely result in a larger and more diverse participant demography, which would minimize the risk of bias participants.

Once the new Solidity method has been implemented into the determination process, a mapping study of the different tracks and physical tests would be profitable. The goal of this study would be to determine which of the available track sections to be used to represent different levels of harshness, but yet realistic driving scenarios. Also, it would be interesting to do a survey regarding how often people tend to experience a different type of driving scenarios. The outcome would be probability estimations of how often a VCC car would experience the different driving scenarios.

It would be very useful and beneficial to the determination process if visual aids were added to the combination method document. A suggestion is, therefore, to perform a project with the aim of producing visual aids connected to the different contributions. For instance, record physical tailgate closings at different velocities or how it looks like when performing a certain driving scenario at Solidity or Durability tracks at Hällered. If each track section would be thoroughly documented and illustrated, the people involved in the determination process would be able to relate more to the taken risks at the VSA meetings. This would also probably increase the transparency and understanding within the entire determination process.

The probability that VCC cars will experience different temperatures is based on statistical data. However, this data could be improved and become more detailed by combining detailed sales numbers with measured temperature data and global temperature statistics. Hence, a study where these aspects are meticulous evaluated would be a great contribution to the fidelity of the probability estimation, of that a VCC car is exposed to a certain temperature.

The ambient temperature will influence the functionality of gas dampers and thereby the closing velocity of the tailgate, hence, it would be an interesting aspect to study. If they are dependent on each other, some events could be ignored due to that it would be unlikely that they occur simultaneously. Another aspect, that wasn't studied in this project, but would be interesting to learn more about, is how the temperature on exterior parts will decrease due to convection while driving.

The determination process in this report focused specifically on the rear end of the car as well. However, the improved determination process is probably applicable to other parts of the car, for instance, front end, floor or sides. It would be interesting to conduct a study, with the aim of either confirm or deny, if it's true. If confirmed, the improvements derived in this project could be applied to other areas of the car were complex split-line sections exist.

Chapter 8

Conclusion

The thesis project had two research questions which were about to be answered. The first research question stated;

"*Is it possible to develop an improved method for combination of contributions,in the determination process of nominal setup, for VCC? If so, what would it look like?*".

During the thesis project, improvements to the existing determination process of nominal setup have been presented. The existing determination process for gap relations results in a nominal gap value. The improved process will also result in a probability estimation that a gap reduction will occur that is equal to or larger than the nominal value. By implementing the improvements, presented in this report, VCC will be able to estimate the probability that an event appear as a result of two or more contributions occurring simultaneously. A probability factor has been introduced to the process, where each contribution has an individually estimated probability value for each presented load case. This enables VCC to estimate the probability that an event, resulting in a specific gap reduction, will occur.

The second research question was formulated as follows;

"*Are there better testing methods that determine the dynamic contribution in the determination process of the nominal setup? If so, what would these test methods be? If not, what improvements to the current one can be done?*".

As previously mentioned, the dynamic contribution is either expressed by the overslam contribution or the dynamic movement contribution. Regarding the overslam contribution, an experimental data collection was conducted that enabled probability estimations to be made. The probability that a certain gap reduction would occur, due to closing the tailgate in with a specific velocity, became possible to estimate. The dynamic movement was mainly improved by switching over from the Applied Acceleration method to the more advanced Solidity method.

On the request from VCC, analysis of the existing determination process were conducted. This resulted in that all contribution that builds up the nominal value was mapped and analysed regarding possible improvements. Further on, the thermal contribution was improved to suit the new combination method. Also, here a probability factor was added to the gap reduction contribution.

To sum it up, improvements have been conducted to the overslam, dynamic movement and thermal contribution. Also, the combination method has been improved to better suit the needs of the existing determination process.

Appendix A

Combination method tool

In the appendix, screenshots of the developed combination method tool are presented. Firstly, the main sheet where the combination process takes place. The remaining figures in this section show the different included sheets explaining the calculations and load cases for the different contributions. Some parts in the sheets have been censored due to corporate confidentiality.

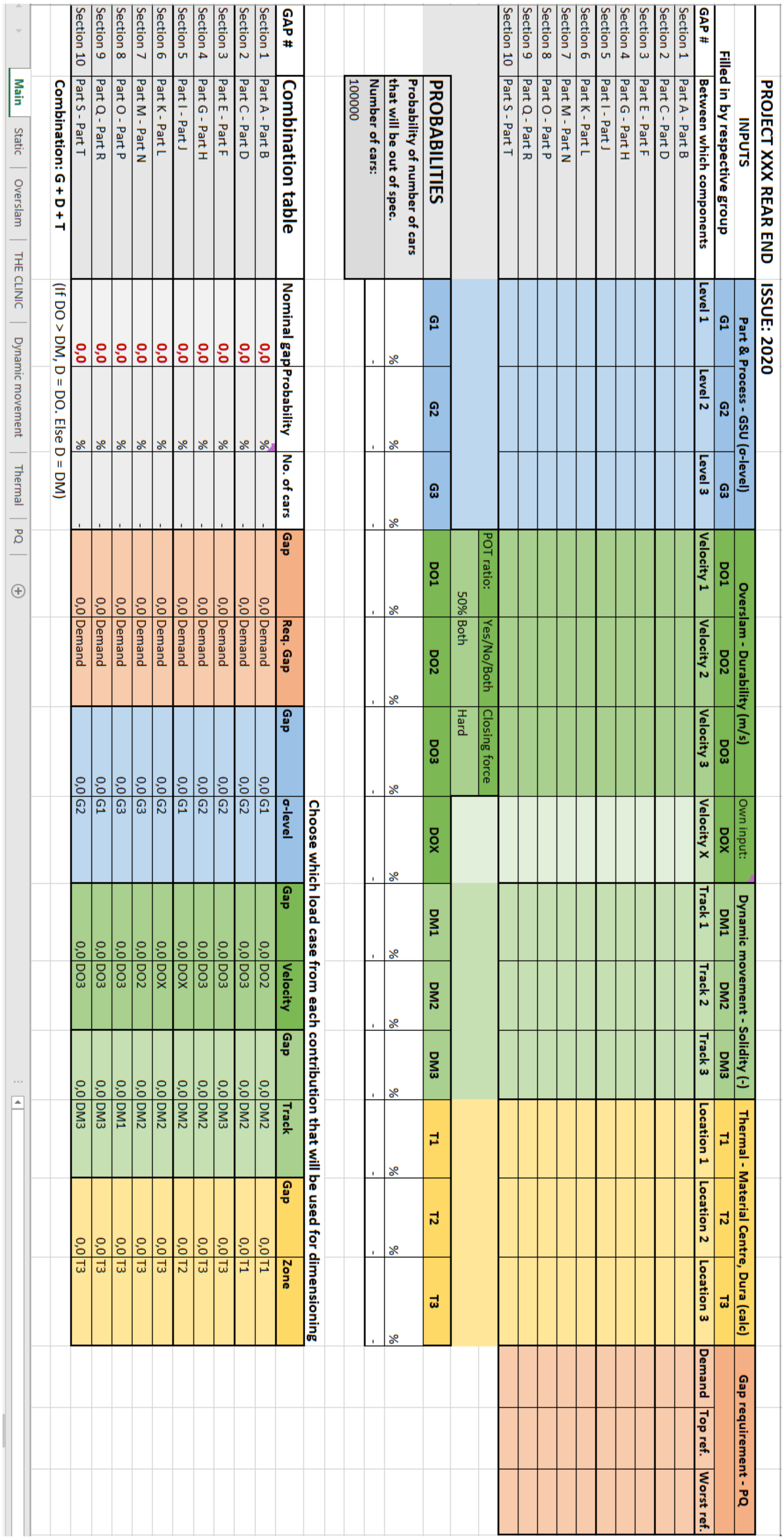


Figure (A.1): *Main sheet in combination method tool.*

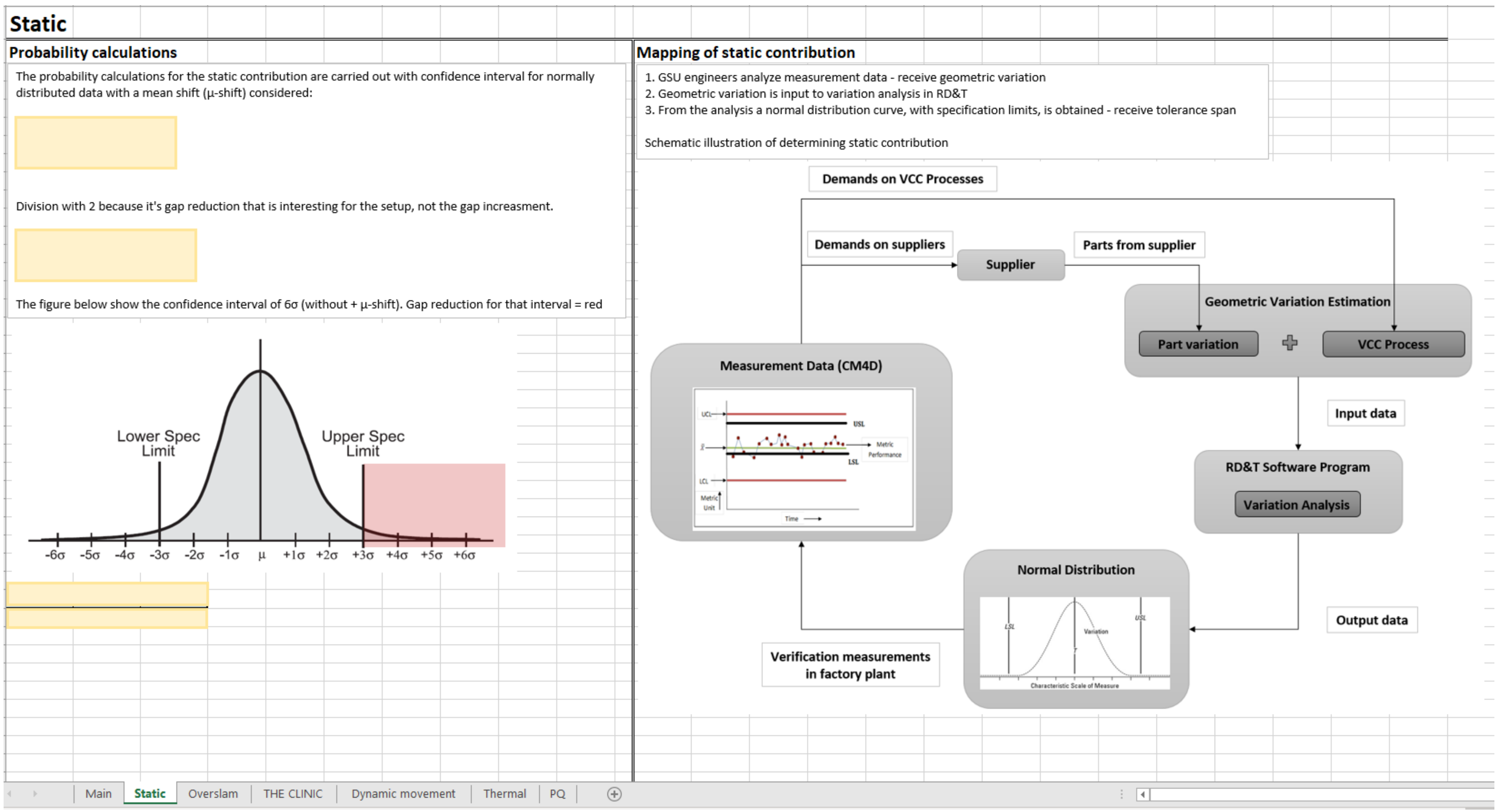


Figure (A.2): *Static sheet in combination method tool.*

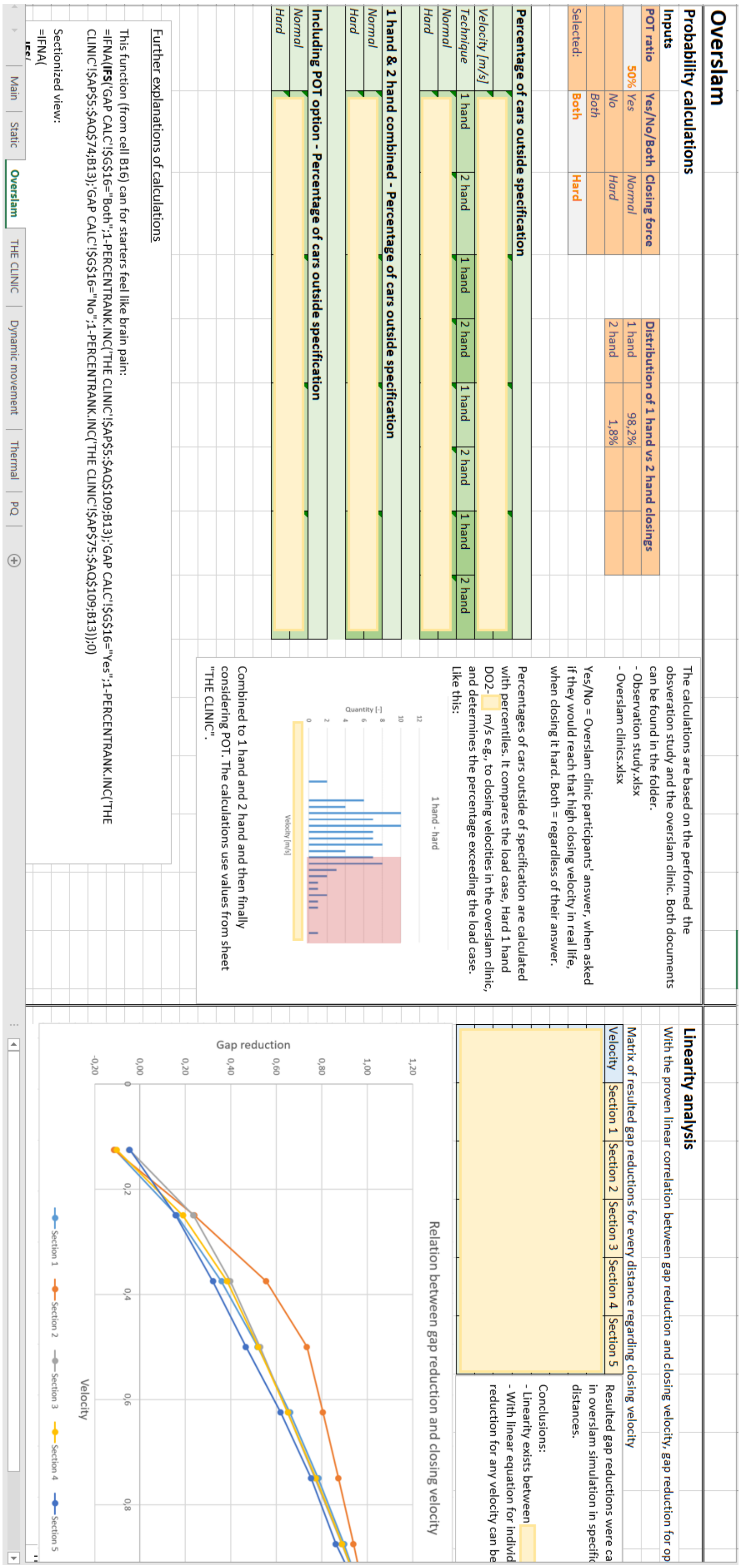
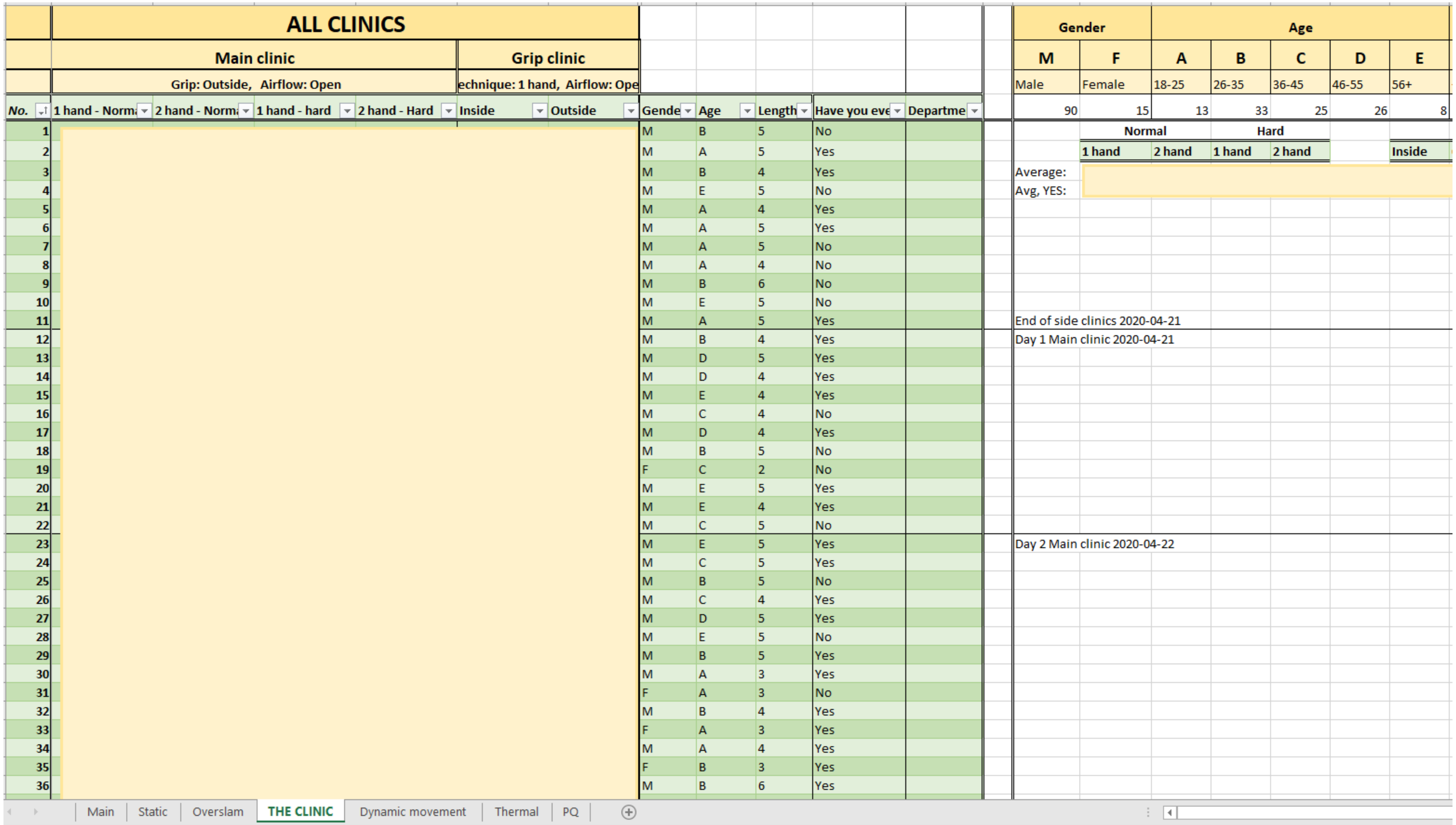


Figure (A.3): *Overslam sheet in combination method tool.*



ALL CLINICS

Main clinic — Grip: Outside, Airflow: Open | Grip clinic — echnique: 1 hand, Airflow: Ope

No.	1 hand - Norm	2 hand - Norm	1 hand - hard	2 hand - Hard	Inside	Outside	Gende	Age	Length	Have you eve	Departme
1							M	B	5	No	
2							M	A	5	Yes	
3							M	B	4	Yes	
4							M	E	5	No	
5							M	A	4	Yes	
6							M	A	5	Yes	
7							M	A	5	No	
8							M	A	4	No	
9							M	B	6	No	
10							M	E	5	No	
11							M	A	5	Yes	
12							M	B	4	Yes	
13							M	D	5	Yes	
14							M	D	4	Yes	
15							M	E	4	Yes	
16							M	C	4	No	
17							M	D	4	Yes	
18							M	B	5	No	
19							F	C	2	No	
20							M	E	5	Yes	
21							M	E	4	Yes	
22							M	C	5	No	
23							M	E	5	Yes	
24							M	C	5	Yes	
25							M	B	5	No	
26							M	C	4	Yes	
27							M	D	5	Yes	
28							M	E	5	No	
29							M	B	5	Yes	
30							M	A	3	Yes	
31							F	A	3	No	
32							M	B	4	Yes	
33							F	A	3	Yes	
34							M	A	4	Yes	
35							F	B	3	Yes	
36							M	B	6	Yes	

Gender		Age				
M	F	A	B	C	D	E
Male	Female	18-25	26-35	36-45	46-55	56+
90	15	13	33	25	26	8

Figure (A.4): *Overslam clinic sheet in combination method tool.*

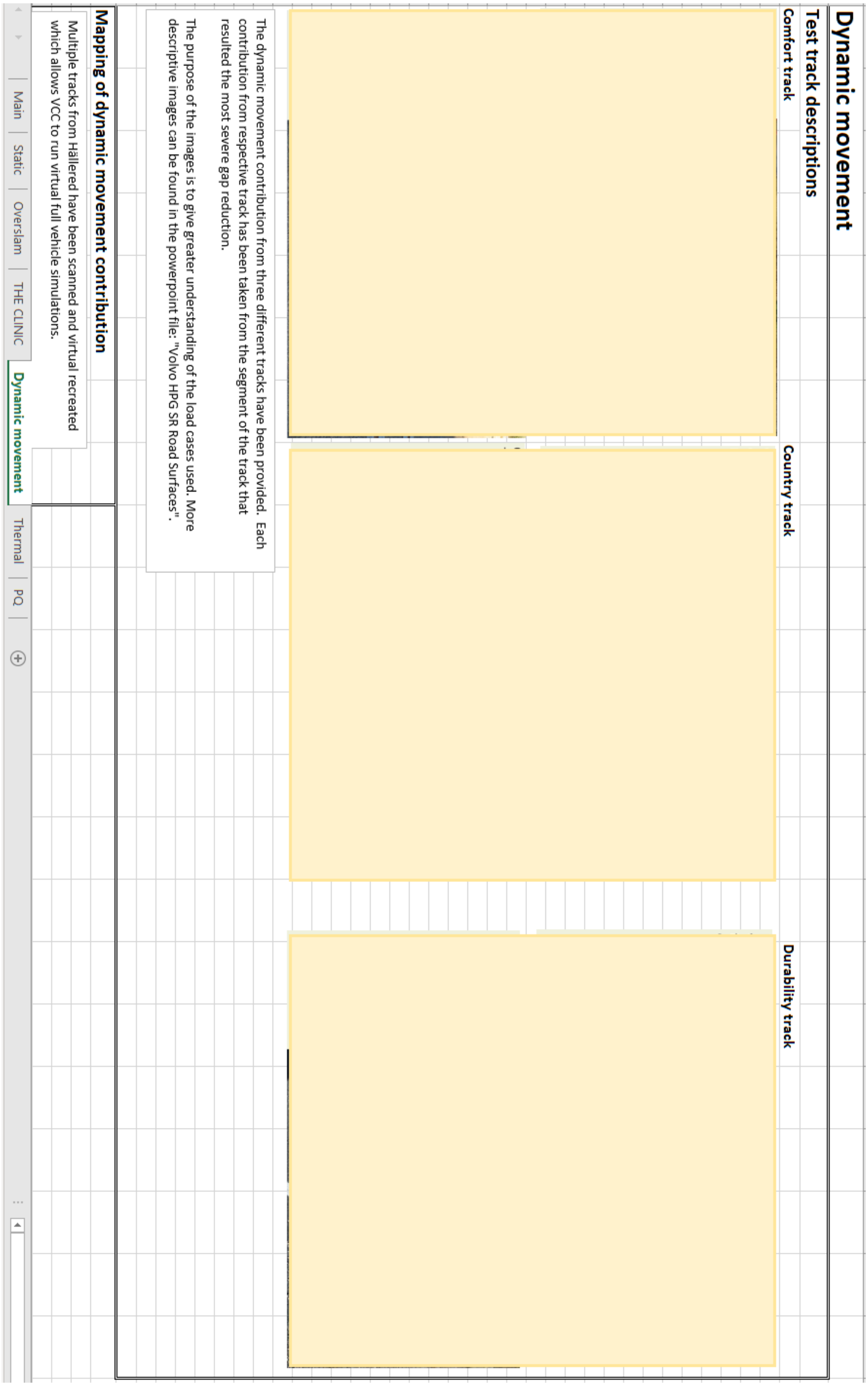


Figure (A.5): *Dynamic movement sheet in combination method tool.*

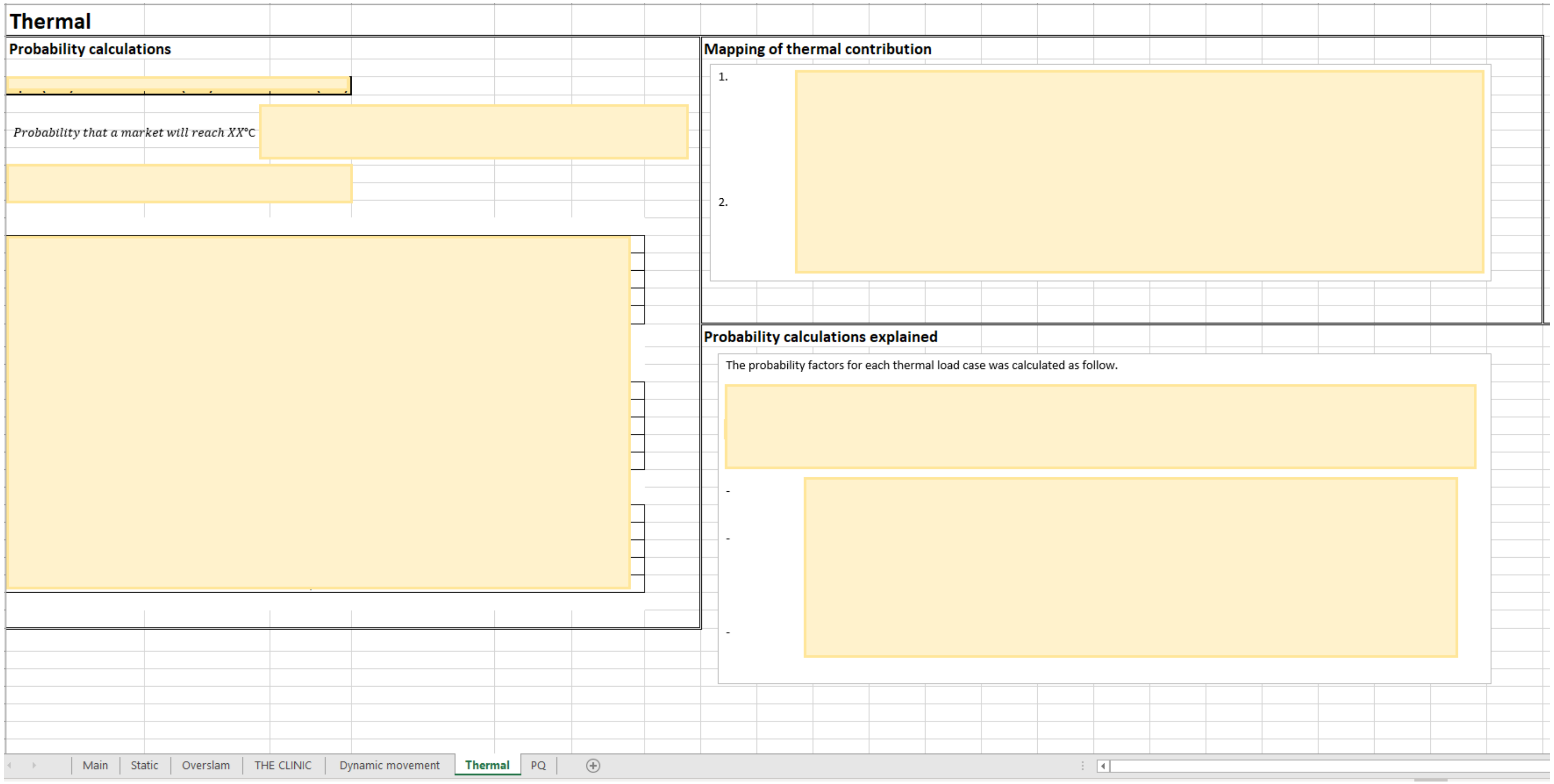


Figure (A.6): *Thermal sheet in combination method tool.*

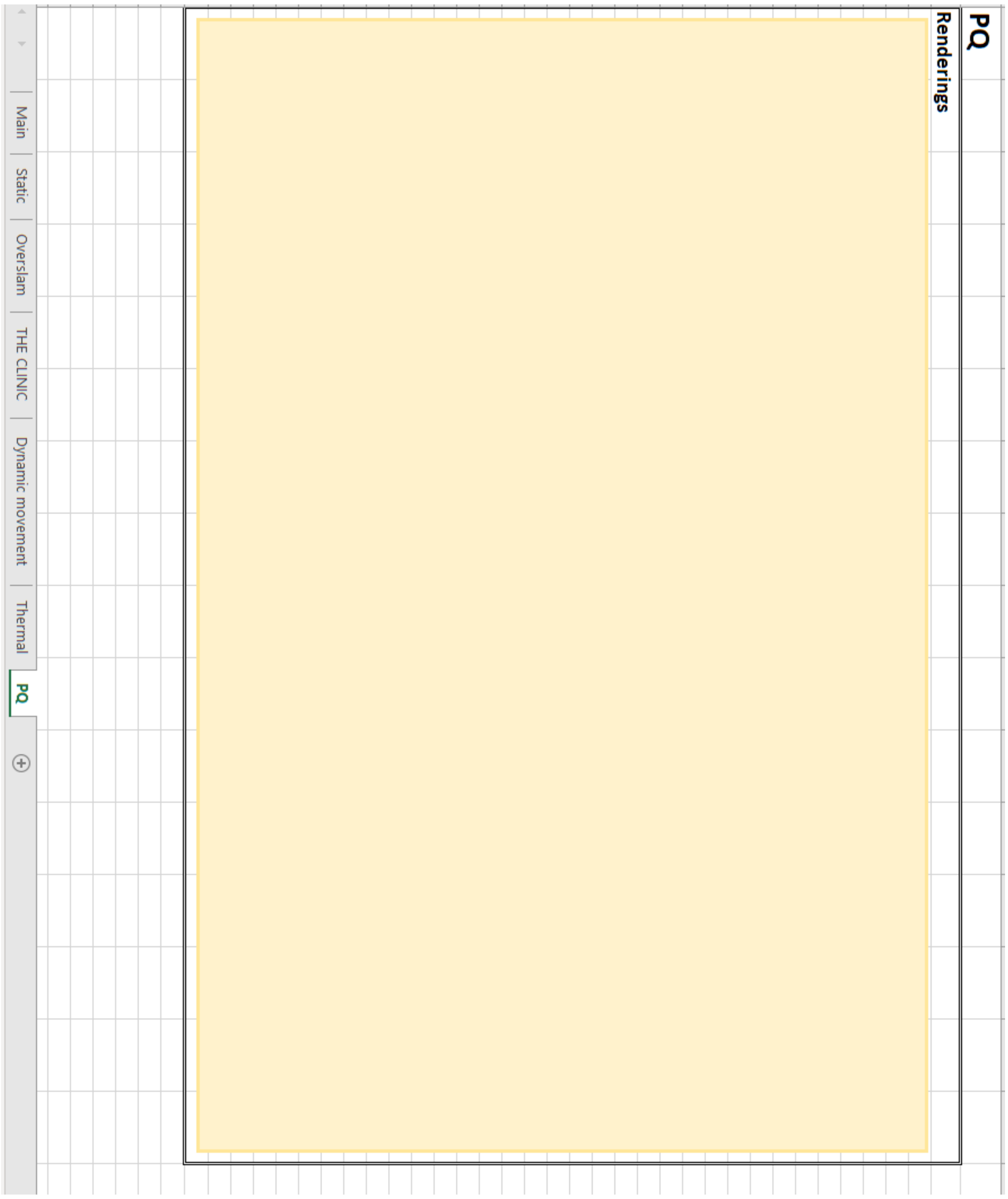


Figure (A.7): *PQ sheet in combination method tool.*

References

Brinkby, D. (2020). *Interview with a GSU engineer.*

Chase, K.W. and A.R. Parkinson (1991). "A survey of research in the application of tolerance analysis to the design of mechanical assemblies". In: *Research in Engineering Design* 3, pp. 23–37.

Fischer, B.R. (2004). *Mechanical Tolerance Stackup and Analysis.* Mechanical Engineering. CRC Press. ISBN: 9780203021194. URL: https://books.google.co.in/books?id=4ZlcaPdz-p8C.

Gao, J., K. Chase, and S. Magleby (Sept. 1999). "Comparison of Assembly Tolerance Analysis by the Direct Linearization and Modified Monte Carlo Simulation Methods". In: *21st Annual Design Automation Conference* 82, pp. 353–360.

Glancy, C. G. and K. W. Chase (1999). "A Second-Order Method For Assembly Tolerance Analysis". In:

Judic, J.-M. (2016). "Process Tolerancing: A New Approach to Better Integrate the Truth of the Processes in Tolerance Analysis and Synthesis". In: *Procedia CIRP* 43. 14th CIRP CAT 2016 - CIRP Conference on Computer Aided Tolerancing, pp. 244–249. ISSN: 2212-8271. DOI: https://doi.org/10.1016/j.procir.2016.02.024. URL: http://www.sciencedirect.com/science/article/pii/S2212827116002948.

Karlsson, M. (2020). *Interview with a CAE engineer.* CAE engineer at Durability, VCC.

Koch, P., R.-J. Yang, and L. Gu (Feb. 2004). "Design for six sigma through robust optimization". In: *Structural and Multidisciplinary Optimization* 26, pp. 235–248. DOI: 10.1007/s00158-003-0337-0.

Leijonborg, P. and R. Furunger (2020). *Interview with two VSA engineers.*

Lin, C.-Y., W.-H. Huang, M.-C. Jeng, and J.-L. Doong (1997). "Study of an assembly tolerance allocation model based on Monte Carlo simulation". In: *Journal of Materials Processing Technology* 70.1, pp. 9–16. ISSN: 0924-0136. DOI: https://doi.org/10.1016/S0924-0136(97)00034-4. URL: http://www.sciencedirect.com/science/article/pii/S0924013697000344.

Lorin, S., L. Lindkvist, R. Söderberg, and R. Sandboge (Aug. 2012). "Combining Variation Simulation With Thermal Expansion for Geometry Assurance". In: *Journal of Computing and Information Science in Engineering* 13. DOI: 10.1115/DETC2012-70646.

Mattsson, B. (2020). *Interview with technical specialist at VCC Material Centre.*

Montgomery, D.C. and G.C. Runger (2011). *Applied Statistics and Probability For Engineers.* John Wiley & Sons, Inc. ISBN: 978-0-470-05304-1. URL: www.wiley.com/college/montgomery.

Morse, E., J-Y. Dantan, N. Anwer, R. Söderberg, G. Moroni, A. J. Qureshi, X. Jiang, and L. Mathieu (July 2018). "Tolerancing: Managing uncertainty from conceptual design to final product". In: *CIRP Annals* 67 (2), pp. 695–717. DOI: 10.1016/j.cirp.2018.05.009.

Otsuka, A and F Nagata (Aug. 2018). "Quality Design Method using Process Capability Index based on Monte-Carlo Method and Real-Coded Genetic Algorithm". In: *International Journal of Production Economics* 204, pp. 358–364. DOI: 10.1016/j.ijpe.2018.08.016.

Puhasmägi, H., H. Viktorsson, and T. Larsson (2020). *Interview with Solidity engineers.*

RD&T (2020). *The tool RD&T.* URL: http://rdnt.se/tool.html (visited on 2020).

Rosenqvist, M., A-C. Falck, L. Lindkvist, and R. Söderberg (Dec. 2014). "Geometrical Robustness Analysis Considering Manual Assembly Complexity". In: *Procedia CIRP* 23, pp. 98–103. DOI: 10.1016/j.procir.2014.10.072.

Rosenqvist, M., A-C. Falck, and R. Söderberg (2016). "Including Measures of Assembly Complexity in Proactive Geometry Assurance, A Case Study". In: *Procedia CIRP* 44. 6th CIRP Conference on Assembly Technologies and Systems (CATS), pp. 151–156. ISSN: 2212-8271. DOI: https://doi.org/10.1016/j.procir.2016.01.194.

Stylidis, K., A. Dagman, H. Almius, L. Gong, and R. Söderberg (July 2019). "Perceived Quality Evaluation with the Use of Extended Reality". In: *Proceedings of the Design Society: International Conference on Engineering Design* 1, pp. 1993–2002. DOI: 10.1017/dsi.2019.205.

Taguchi, G (1986). *Introduction to Quality Engineering: Designing Quality into Products and Processes.* Quality Resources.

Wagersten, Ola S (2011). "Towards Efficient Evaluation of Impacts of Geometrical Variation on Perceived Quality in Early Phases". In: *Research series from Chalmers University of Technology, Department of Product and Production* 55.

Walter, M. S. J., T. C. Spruegel, and S. Wartzack (2015). "Least Cost Tolerance Allocation for Systems with time-variant Deviations". In: 27, pp. 1–9. DOI: doi.org/10.1016/j.procir.2015.04.035.

Walter, M., T. Sprügel, and S. Wartzack (Apr. 2013). "Tolerance analysis of systems in motion taking into account interactions between deviations". In: *Journal of Engineering Manufacture* 227, pp. 709–719. DOI: doi.org/10.1177/0954405412473719.

Van Hoecke, A. (2016). "Tool Risk Setting in Statistical Tolerancing and its Management in Verification, in Order to Optimize Customer's and Supplier's Risks". In: *Procedia CIRP* 43. 14th CIRP CAT 2016 - CIRP Conference on Computer Aided

Tolerancing, pp. 250–255. ISSN: 2212-8271. DOI: https://doi.org/10.1016/j.procir.2016.02.039. URL: http://www.sciencedirect.com/science/article/pii/S2212827116003188.

VCC (2016). *VCS 5026,4 Master location system*. Standard. Volvo Car Corporation.

— (2020). *Volvo Press Material*. URL: https://www.media.volvocars.com/image/low/259192/1_1/5 (visited on 2020).

Wickman C.and Söderberg, R. (Apr. 2007). "Perception of gap and flush in virtual environments". In: *Journal of Engineering Design* 18.2, pp. 175–193. DOI: 10.1080/09544820600751023.

Volvo (2020). *Volvo Car Group in short*. URL: www.media.volvocars.com/se/sv-se/corporate/this-is-volvo (visited on 2020).