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The Closure Challenge
Quality Improvement of Automotive Rear Door Closure Performance at Volvo Cars

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Idag är dagen då vi tackar Dag för dagarna som gått, då vi
dagligen uppdagat Dags alla alldagliga (namn)skämt.
Tack för reflektion och förvirring.
Emma

Gothenburg, May 2018

Abstract

This master thesis examines how to improve quality of automotive rear door closure performance by determining which factors critically affect closure performance, by using both qualitative and quantitative data. The research was conducted on the behalf of Volvo Cars to improve closure performance on automotive rear doors. However, the closure challenge is not limited by Volvo Cars only. The closure challenge, and how to achieve high quality closure performance, is examined by various car manufactures worldwide. Further, closure event is used as a term to describe the actual motion: when the rear door is set into motion to close. It is assumed that the door will result in total closure. However, the closure event can result in two different outcomes; either a successful closure event or an unsuccessful closure event. Hence, the closure event is evaluated by the term closure performance. Closure performance is measured by minimum closure speed (Y_1) and minimum closure energy (Y_2) required for total closure of the rear door: the door is secured into second lock mode.

Furthermore, a comprehensive interview study was performed at Volvo Cars, where employees at several departments related to rear doors were interviewed. It was realized during the interview study that the closure performance is not limited by one department. Hence, a system perspective should be adopted when examine the closure performance. Continuing, the interview data provided the base for the determination of which type of factors to examine further. Based on the interview study, a number of mechanical factors related to the rear door were selected to be included in a Design of Experiment. The purpose of the Design of Experiment was to find which factors critically affected closure performance, and to support the research by quantitative data. A model which describes the relationship between the mechanical factors and closure performance was developed based on the Design of Experiment, which can be used to improve quality of the closure performance at Volvo Cars. The outcome of the closure event can be understood in advance by applying the model. Hence, the arrangement of the mechanical factors can be examined in advanced, in order to understand what the optimal arrangement of the factors are to achieve high quality closure performance. The model is suited for Volvo Cars, however, a similar model can be derived for other car manufacturer by utilizing the same method as described in the report. The Design of Experiment method are emphasized within the report to facilitate for externals to reuse the findings. Practical considerations or issues when performing Design of Experiment within an industrial context are also emphasized, since Design of Experiment is often underestimated as a method and not well distributed within Swedish corporations.

Key words: variation, quality improvement, automotive rear door closure performance, Design of Experiment, D-optimal design, and split-plot design.

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Section 1
Introduction

The closure challenge refers to the closure performance of automotive rear doors. There are different issues related to the closure event of automotive side doors e.g. noise and door closing sound, isolation from contamination and weather conditions, sealing system etc. (Petniunas, Otto, Amman & Simpson, 1999; Jei, 2011). Which complicates the closure performance of automotive side doors. Currently, research regarding the closure event and closing efforts of automotive side doors have investigated how to achieve high quality closure performance (Nayak & Im, 2003; Jei, 2011; Ishida, Aoki, & Tooya, 2003; Wagner, Morman, Gur, & Koka, 1997). Various methods have been utilized in order to examine automotive closure performance, e.g. simulation models and numerical methods for closure behavior (Nayak & Im, 2003; Ishida, Aoki, & Tooya, 2003). However, this research investigates how to improve closure performance of rear doors by using Design of Experiments (DoE). First, a qualitative interview study was conducted, which were analyzed by using affinity diagram in order to determine which factors affected door closure performance. Based on the qualitative interview study, the factors which were assumed to critically affecting closure performance were selected to be included in a DoE. By using DoE, a model was developed which describes the relationship between the closure performance and factors. The model can be utilized to examine closure performance in advance, in order to achieve high quality closure performance.

1.1 Background

This master thesis was conducted on the behalf of Volvo Cars, and examines how to improve quality of automotive rear door closure performance. The rear door closure performance has been a matter of quality improvement for several years worldwide (Nayak & Im, 2003; Jei, 2011; Ishida, Aoki, & Tooya, 2003; Wagner, Morman, Gur, & Koka, 1997). There is variation within the closure event and in rear door closure performance. The closure event will result in successful closure performances in some cases, however, the closure event will result in poor closure performances in other cases. The cause for this variation is unknown. However, the closure event is dependent on various factors, e.g. mechanical or manufacturing related factors, which all can affect the closure performance. The various factors that affect closure performance should be weighted, in order to discern which factors affect closure performance the most. Further, quality improvement of rear door closure performance is also motivated by the high amount of customer complaints collected by Volvo Cars. Also, the quality of the closure performance is perceived differently between customers, e.g. what some customers perceive as poor closure performance is not noticed by others. This makes closure performance a complex issue; how to ensure satisfaction within closure performance if the issue cannot be concluded between different customers? The closure performance might also be perceived differently between Volvo Cars and customers. Hence, a common direction and objective of high quality closure performance must unify the various stakeholders. Otherwise, the closure performance might be sub optimized and not reach high quality performance. High quality closure performance should be described by quantitative data, in order to determine what is defined as high quality closure performance. Further, the need for quality improvement within closure performance is not limited to Volvo Cars only. As Jei (2011) mention, quality deviations within closure performance is a known challenge among car manufacturers worldwide. The research can therefore be applied by other car manufacturer and within other industrial contexts as well.

Continuing, the door closure event can be described as a system, where several factors are integrated which all affect closure performance (Jei, 2011). Hence, these factors are correlated and dependent on each other during the closure event. Thus, any internal issues or conflicts between the factors might result in poor closure performance. The closure event is not only a system of various mechanical factors, but also a system in terms of organizational structure, process related factors, requirement related factors etc. The organization of Volvo Cars consists of several departments where different expertise and responsibilities can be found regarding factors and mechanical functionalities of the rear door. High quality closure performance is considered as a system challenge, since it is affected by several factors including mechanical functionalities and organizational structures. Hence, the closure event must be seen as a system where various stakeholders are involved. To broader the system perspective even more, the closure performance is also a matter for processes related factors, e.g. in production, in product development etc. For instance, each factor of the door must be produced within the specific tolerances, in order to ensure perfect motion and total closure. Hence, it is therefore important to identify and eliminate causes of variations that affect closure performance in production, if high quality closure performance should be achieved (Bisgaard & Kulahci, 2000). The closure event might enable successful closure on drawings and in 3D models, however, the outcome in practice might be different. The closure event might result in unsuccessful closure in practice, even if successful closure were achieved in the 3D model. Hence, the gap between theory and practice is an important issue to consider as well, if high quality closure performance is wanted.

Lastly, the research will be conducted at the department of Robust Design and Tolerancing, which organizational belongs to the R&D section of Volvo Cars. The main objectives are to investigate which factors critically affect rear door closure performance, and to provide suggestions for quality improvements. DoE, as a statistical tool, will be utilized in order to examine the closure event and how to achieve high quality closure performance. Further, according to Tanco, Viles, Ilzarbe, & Alvarez (2009), literature regarding how to conduct DoE in practice within industry are rare. Also, DoE is often underestimated as a method, and not well distributed within Swedish corporations (Lundkvist, Bergquist & Vanhatalo, 2018). The originality and value of the research is the actual application of DoE in Swedish industry. Statistical tools as e.g. DoE is not well distributed in Swedish corporations, and the research provides unique insights in how to apply DoE in Swedish industry in order to improve quality. The originality of the research is also the insights that even if a certain DoE design (split-plot design) is advocated by literature when conducting a DoE with hard-to-adjust factors, the design might not be the superior one. Hence, this research suggest another type of design (D-optimal design) as superior, even if hard-to-adjust factors are included in the DoE. Also, this research aim to facilitate for externals to use DoE in similar context. Also, to advocate the excellence of DoE when examining quality improvement. The literatures highlight challenges to consider prior to conducting DoE. Therefore, the research will investigate how an organization as Volvo Cars can apply DoE in order to investigate rear door closure performance in practice. The purpose is to decrease the gap found in literature regarding performing DoE in practice. The actual project description and the closure challenge is further described in Section 1.2 below.

1.2 Project Description and The Closure Challenge

Closing a door appears as a fundamental task to most of us. However, achieving a high quality closure event can be quite complicated. The closure event and the kinematics of a door is complex, involving both static and dynamic aspects (Jei, 2011). The door is equipped with different functions which all interact during the closure event, e.g. hinges, springs, striker, latch, sealing systems etc. in order to ensure total closure of the door. Total closure of the rear door is defined to occur when closed into second lock mode. Closure event is used as a term to describe the actual motion when closing the door. The closure event can result in two different outcomes; either a successful or an unsuccessful closure. The closure event is evaluated by the term closure performance. Closure performance is measured by closure speed and energy.

Further, the definition of a successful closure event is when the door is secured into the second lock mode and total sealed at the maximum closure speed of 1.3 m/s. If the door does not seal properly at the speed of maximum 1.3 m/s, the closure performance is defined as unsuccessful. The closure performance should also be managed by adding minimum closure energy by the user. The closure energy is defined as total amount of energy that are required in order to successfully close the door into second lock mode. Currently, the required energy is not internally approved at Volvo Cars, and the closure event often results in re-closing efforts of the door. However, Volvo Cars plans to change measurement unit from speed [m/s] into energy [J]. Energy is therefore included as measurement of closure performance as well, within this research. Continuing, the purpose of this research is to identify which factors critically affect closure performance, by assessing closure speed and closure energy. The objective is to develop a model which describes the relationship between closure performance and the factors. The model can be utilized in order to improve quality of closure performance in advanced. However, it is important to ensure that the factors that critically affect closure performance can be discern. The various factors might interact during the closure event, which might aggravate the identification process. Also, some factors are assumed to be amplified during the presence of other factors, which might also aggravate the identification process as well.

Lastly, the closure challenge is not limited to mechanical factors only. For instance, some factors might be classified as 'soft factors' which affect the closure performance, e.g. opinions, organizational issues, silo structures, culture aspects etc. However, these type of factors are difficult to control because of the involvement of subjectivity and qualitative aspects, but they should not be neglected. Additionally, this research should also address the issue on a higher perspective, identifying possible gaps within the theoretical literature regarding variation within quality related aspects of automotive rear doors.

1.3 Purpose and Objective

First, the purpose of this research is to identify which factors critically affect closure performance of automotive rear doors, and thereby causing variations within the closure event. Based on the identified factors, a suggestion for quality improvement will be given by presenting measures for quality assurance and prediction possibilities.

Second, the objective is to develop a model, which describes the relationship between the factors and closure performance by using DoE. This model can be used in order to improve the quality of closure performance at Volvo Cars. The outcome of the closure event can be examined in advance by applying the model. Hence, the factors can be examined in advanced in order to understand which arrangement of factors results in high quality closure performance. Also, insensitivity to variation can be examined by using the model. The model will suite Volvo Cars, but similar models can be derived for other car manufacturer by utilizing the same method as described in this research.

1.4 Research Questions

The following research questions of the master thesis are presented below. The research questions are based on above discussed challengers related to closure performance.

RQ1. Which factors critically affect closure performance of automotive rear doors in terms of closure speed and closure energy?

RQ2. How can the identified critical factors be confirmed quantitatively for improving quality of automotive rear door closure performance?

1.5 Delimitations

Six Sigma is often addressed as a method related to robust design and applied for achieving high quality standard (Smętkowska & Mrugalska, 2018). Therefore, it could be considered as obvious to follow the method of Six Sigma through the research. However, the process steps of Six Sigma, DMAIC (define, measure, analyse, improve, and control), and the practices it includes will not be followed strictly nor emphasized in the research. In order to conduct a research, the problem must be defined (D), how to measure the problem must be defined (M), how to analyse the collected data must be decided (A), suggestions for improvements must be discussed (I), and how to control the suggested improvement could also be discussed (C). Hence, the DMAIC cycle will rather guide the research on a higher level, than to be followed strictly by the researchers. Hence, the chosen methods are inspired by the process steps of Six Sigma in order to assure a comprehensive research, but they are not emphasized within the report. The emphasis of the research is turning DoE into practice and to find which factors that critically affect closure performance, not necessarily by following a certain well-spoken methodology. Hence, the efficiency of the method used for achieving the results are not discussed.

1.6 Disposition of the Research

The disposition of the research is outlined in Table 1 below. In total, the master thesis is divided into seven sections: 'introduction', 'theoretical framework', 'methodology', 'analysis and results', 'discussion', 'conclusion', and 'limitations and recommendations'. Note, the research includes a combination of mixed methods research strategy, by using both qualitative and quantitative research approaches. The qualitative research approach is an interview study, and the quantitative research approach is a DoE. In 'methodology' section, both the methods used for conducting and analyzing the interview study, and the method used for conducting and analyzing the DoE are described. The analysis and results of the interview study and the DoE are later described in 'analysis and result' section.

Table 1. Disposition of the Research

Section 1	Introduction	This section provides an overview of the automotive rear door closure challenge. The project description is provided, which outline the scope of the research, followed by purpose and objectives. The research questions are also provided in this section which will guide the research. Lastly, delimitations for this research are proved in order to describe the boundaries of the research.
Section 2	Theoretical Framework	This section provides an overview of the theoretical frame work used for this research. It starts with describing variation and p-diagram, and how p-diagram can be utilized. Followed by theory regarding DoE, and what is important to consider when conducting a DoE, as well as what the challengers are related to DoE in practice within an industrial context.
Section 3	Methodology	This section provides an overview of the research strategy, methods, and tools used for investigating the research questions. The methodology sections are divided into a qualitative and a quantitative section. In the qualitative section, methods and tools used for conducing and analyzing the interview study is described. In the quantitative section, methods and tools used for conducting and analyzing the DoE is described. The theoretical framework supports the methods and tools which are utilized in order to conduct and analyze the DoE. Ethical considerations during the research are also described within the section.
Section 4	Analysis and Results	This section provides the analyses and results of the qualitative and quantitative research. It is structured by first analyzing the qualitative study and describing the result, followed by analyzing the quantitative study and describing the result. The theoretical framework supports the analyzing methods and tools which are utilized in order to analyze the DoE. Challengers within DoE related to the theory section are also analyzed.
Section 5	Discussion	This section provides an overview of the results. Discussing the qualitative and quantitative results. Also, the challenges related to DoE is discussed, emphasizing when practice interfere with theory.

Section 6	Conclusion	This section provides answers for the two research questions. The results of both the qualitative interview study and the quantitative DoE are provided in this section. Followed by main findings and deliveries of the research.
Section 7	Limitations and Recommendations	This section provides an overview of the limitations which influence recommendations for future work. In recommendations, it is suggested how to use the results from this research in further investigations.

Section 2
Theoretical Framework

The following section outline the theoretical framework used in this master thesis, which consists of literature regarding p-diagram, DoE cycle, and challenges related to DoE. This provides the general theory regarding required knowledge to perform a DoE of the rear door closure performance.

2.1 The Bittersweet Variation

The issues related to the closure challenge of automotive rear doors is variation in quality. Variation is incoherent, which makes it difficult to predict the performance of the closure event. Therefore, awareness of variation is important and to distinguish it from variety. This will support the research when investigating causes of unwanted variation (Bergman & Klefsjö, 2010). Additionally, variation can also be distinguished into signal factors, control factors, noise factors, and output factors (Enoch, Shuaib, & Hasbullah, 2015; Zang, Friswell, & Mottershead, 2003). This will support the choice of method to utilize for managing variation. For instance, variation classified as noise cannot be eliminated and should thereby be managed differently compared to control factors (Arvidsson & Gremyr, 2008; Tsui, 1992). The division into signal factors, control factors, noise factors, and output factors are further described below.

2.1.1 Signal Factors, Control Factors, Noise Factors, and Output Factors

To be able to manage variation, it is important to consider the origin of variation. Depending on where variation originated. Different methods and tools should be applied to mitigate negative effects caused by variation but in some cases, variation cannot be eliminated (Arvidsson & Gremyr, 2008; Tsui, 1992).

A p-diagram can be used for visualizing various types of factors affecting the system and their relationships, see Figure 1 below. The product can be seen as a system and be affected of factors, which can be divided into signal factors (X), control factors (C), noise factors (N), and output factors (Y). Where variation can be present within all these various factors. (Zang, Friswell, & Mottershead, 2003). Signal factors can be described as input for the system e.g. closure speed. The output factors as a respond from the system. Noise factors are described as factors which are difficult to control, e.g. differences in batch-to-batch (Park, Lee, Lee &

Hwang, 2006). Compared to control factors, which are described as factors which can be controlled, e.g. shape of the door. Both noise and control factors will influence the output factor (Y) (Enoch, Shuaib, & Hasbullah, 2015).

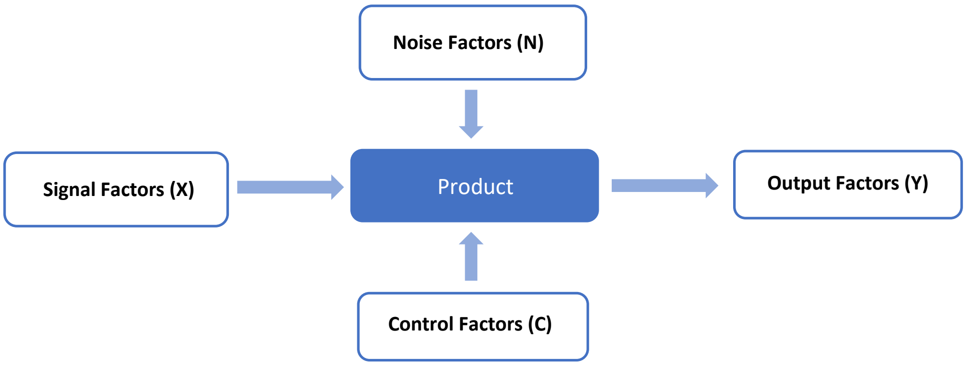

Figure 1. Schematic illustration of the p-diagram.

The signal factor transforms according to the function and results into a designed outcome. For instance, if the system is the rear door closure event where the function is the door when closing, then the signal factor is the energy provided by the user for closing the door. The energy transforms according to the function, the door mechanism, and make the door close. However, the system might be affected by noise factors, which will cause an outcome different from what the system was designed to deliver. For instance, the door might not close properly even though closure energy is provided by the user. Hence, the system will deliver an unsealed door due to noise factors affecting the closure function. Noise factors are usually classified into three different categories: external (e.g. human error, dust in environment, temperature), unit-to-unit (e.g. weight, dimension tolerance, differences in batch-to-batch), and internal (e.g. plastic creep, mileage of a car) (Park, Lee, Lee & Hwang, 2006). Noise factors are difficult, costly or even impossible to control (Arvidsson & Gremyr, 2008; Tsui, 1992). Hence, noise factors are the cause of variability within the system. Compared to control factors, which are factors that the designer can influence. The designer should create an optimal setting of the control factors invulnerable to noise factors (Zang, Friswell & Mottershead, 2003). The relationship between signal, control, noise, and output factors are mostly unknown. As long as the relationships are unknown, it will be difficult to create an optimal setting of the control factors for inhibit influences by noise factors. Thus, the relationships can be obtained through tests or experiments by using DoE (Tsui, 1992), which is further described below.

2.2 Design of Experiments

DoE was founded in 1925 by Fisher (Goh, 2002; Jones & Nachtsheim, 2009) as a tool for examine relationships between factors and response values. DoE requires less time and is resource effective compared to ordinary experiments where e.g. only one factor is changed at a time (Owen et al., 2003). If only changing one factor at a time, a large number of observations and tests are required to collect necessary data. Testing several factors at a time is more complex and often poorly understood. Therefore, DoE was established where factors and response values could be investigated in practice in an efficient and effective manners. Further, George Box is well-spoken within DoE, who developed the tool for suiting industrial issues and Hunter and Hunter whom brought DoE into practice (Goh, 2002). DoE is useful in several aspects since it emphasizes the importance of practical experiments for collect empirical data. DoE is often applied within improvement contexts, in order to improve e.g. operations of a process or a product to achieve high quality standard (Goh, 2002). Also, as mentioned by Simpson, Listak, & Hutto, (2013), "*DoE is the method for managing random variation uncertainty while learning the most from limited resources in which factors influence performance*". Goh (2002) discusses reasons why DoE can be useful. One of them is that DoE is supported by a mathematical foundation together that it is designed to require minimum of efforts for a certain amount of data. Hence, DoE is optimized to organize different experimental runs as the least number of runs needed for collecting the necessary data (Goh, 2002). These are mentioned as reasons to conduct a DoE where there exist different factors that have impact on the system. Likewise, a p-diagram is utilized to give knowledge of the factors that have impact on the challenges before a DoE is executed. Currently, there are several software programs for analyzing the collected data such as Minitab and JMP[1].

2.2.1 Design of Experiment Cycle

In this section is four phases of DoE cycle: planning phase, design phase, execution phase, and analyse phase are described in detail. The four phases constitute appropriate process-order to follow when conducting a DoE (Simpson, Listak & Hutto, 2013).

2.2.1.1 Planning Phase of the DoE

The first phase of the DoE cycle is planning. To apply a DoE successfully, a detailed and effective planning is required. In order to plan a successful experiment, all involved stakeholders should be allowed to contribute and provide their opinions (Simpson, Listak & Hutto, 2013). Thus, a positive attitude within the project is highly important to create commitment and support for the DoE. According to Simpson, Listak & Hutto (2013), successful experiments require commitment by all important stakeholders or key members. Hence, it is important to let stakeholders join when designing the experiment, take their opinions into consideration and ensure that they felt ownership of the experiment. Only then the experiment would gain support by key individuals whom will be in favor of the execution of the experiment. Further, a detailed description of what the DoE contains may include: risk of problems that might occur, desired outcomes and objectives, potential factors to be included, budget constraints etc. (Simpson, Listak & Hutto, 2013). The planning phase is the foundation for the later execution phase, which might include e.g. a process flow diagram of each step in the execution phase, to provide a system perspective among the involved team members of the DoE (Simpson, Listak & Hutto, 2013; Viles, Tanco, Ilzarbe & Alvarez, 2008). In order to reduce possibilities of biased experiments, the team should be encouraged by a diverse perspective by letting interested and knowledgeable persons participate (Coleman & Montgomery, 1993). It is important to create unified objectives that are accepted by the team members to direct the work effectively. This is facilitated by creating a common understanding

[1] *Note, JMP is used as the analyzing software in this research. However, the researchers do not emphasize how to used JMP. The researchers assume the reader to be experienced in JMP.*

of the project. The objectives might be decided after the process has been determined, in order to think in what way it can be measure or evaluated. This is known as a response according to Viles, Tanco, Ilzarbe & Alvarez (2008) where they define the response as "*the desired variable measured to evaluate the output of a process*". The selected response is recommended to consider a clear association with the problem to get accurately results.

The DoE might be difficult to conduct in practice if a large number of factors are included. Therefore, screening would be appropriate to enables minimum number of experimental runs with a large number of factors. This is done by identifying key factors affecting product quality and process performance. Hence, screening aim to identify these factors appropriate for further investigation (Antony, 2003; Meyer, Steinberg & Box, 1996). To reduce the possibilities of mistakes and affect validity of the result, detailed documentation is essential. It should be clearly and easy to understand to avoid misinterpretations (Costa, Pires & Ribeiro, 2006).

2.2.1.2 Design Phase of the DoE

The next phase of the DoE cycle is the design phase. Coleman & Montgomery (1993) quote Box, Hunter and others with "*attention to detail can determine the success or failure of the experiment*". Therefore, is an exemplary planning together with how well designed the experiment is, the most important success indicators. The design phase involves tasks as: formulating the strategy, determine number of test points and which combinations of factors to include. Furthermore, an understanding of the system is evident to reach in order to include the important factors. Where these factors need to be fully explored. It is not possible to combine all combinations that can be investigated due to constraints to other factors, time and resources. Therefore, knowledge regarding involved factors are important when the DoE is designed, and when the factors adjusted range selected (Simpson, Listak & Hutto, 2013). The focus in the design phase is to conduct strategies where each factor is given a range that should be realistic in order to adjust in the tests and related to the reality.

The appropriate numbers of levels should be examined, for instance if a linear relationship among factors and response values are assumed, a two level design should be applied. A three level design is appropriate if curvature is assumed. Curvature can also be examined by adding center points into a two level design. Center points are used in order to determine if relationship between factors and response value are linear or curvature. Center points are positioned in the middle of low and high level of factor range (Stone, Scibilia, Pammer, Steele & Kelle, 2016). The chosen levels of involved factors should be carefully determined. A factor level is used to give a specific value or setting to facilitate estimation in the experiment. Hence, if the experiment is expected to be a nonlinear function, levels of factors should be at three or more to assist in quantifying nonlinear (Antony, 2003). Also, the most important constraints should be examined when designing the DoE. The design should facilitate to overcome or mitigate the constraints (Simpson, Listak & Hutto, 2013). For instance, if factors are constrained by their possibility to be adjusted in practice the design should advocate a few factor adjustments as possible.

Furthermore, to improve efficiency of the DoE, Antony (2003) mention three principles of experimental design that can be utilized, but for this master thesis, only two are applicable. These principles are randomization and replication. These can be used in industrial experiments to improve experimental efficiency and reduce, or remove, experimental bias. Otherwise, large experimental bias may have impact on the result which lead to wrong optimal settings or it could hide the effect of significant factors. First is randomization described. Without randomization, the result would be meaningless and misleading. Therefore, the experimental team often rely on randomization in order to reduce effect of the experimental bias e.g. reduce the noise factors that may be present in the stated product. This increase the possibilities to ensure equal chance that all levels of a factor would be affected by noise. Second, replication will be described. As Antony (2003) states "*replication is a process of running the experimental trials in a random sequence*." This allow the experimenter to get an estimate regarding the experimental error and a more accurate estimate of the factor and interaction effects. If number of replicates are enough, satisfactory conclusions can be made regarding effect of factor and interactions. However, including replicates may result in increased time and cost to complete an experiment. This need to be considered before an experiment are executed (Antony, 2003). Followed by Viles, Tanco, Ilzarbe & Alvarez, 2008 whom mention it is important to conduct information regarding what the identified priority factors have for possible effects on the response before running the experiment. This may improve the selection of the design and levels of factors.

Different Designs within DoE

There exist several different types of experimental designs to choose from when conducting a DoE. For this research, there are two designs that are more suitable: The D-optimal design and split-plot design. As Simpson, Listak & Hutto (2013) states "*optimal designs certainly have a role in situations when no classical design well suits the needs of the problem".* Since the door closure performance have unknown factors and internal interactions, this master thesis has possible a non-standard design of experimental design.

D-optimal Design

D-optimal design is included in the Optimal Designs where there exist many forms such as A, D, G, or I-optimality (Simpson, Listak & Hutto, 2013). Hence, only D-optimal design will be provided because it fits better for this master thesis. 'D' in D-optimal designs stands for determinant and the design maximize the determinant of the information matrix (Goos & Jones, 2011). D-optimal designs are used when standard approaches cannot be used in experimentation tests and to select those factors that should be observed in an experiment because it provides an economic and efficient method (Kovach & Cho, 2009). Furthermore, it has an accurately estimation of factors effect and of the coefficients. This increase the possible to understand which factors effects are significant and which are insignificant (Kovach & Cho, 2009; JMP, 2018e; Goos & Jones, 2011). Another strength is that the D-optimal design can find the most beneficial design in order to maximize the information of the model that is of interest (Goos & Jones, 2011). By using D-optimal design, it provides benefits with an alternative method instead of inappropriately use of traditional design methods. By inappropriately means, traditional designs are forced to be used in non-standard experimental situation. Thus, the real issues in practice include restrictions or constraints. In the experimental plan, it is necessary to include possible restrictions of the system since the D-optimal design accurately describe the systems behavior (Kovach & Cho, 2009). According to Kovach & Cho (2009), when "*an alternative design is used, the resulting optimum parameter settings will likely produce larger deviations from the desired target values than in studies where traditional methods were used*". Additionally, the approach for D-optimal designs allows for adding any number of runs (Goos & Jones, 2011).

Split-plot Design

Split-plot design is emphasized when hard to adjust factors, HTA, are included in the DoE and where those effects are of interest (Jones & Nachtsheim, 2009; Simpson, Listak & Hutto, 2013). Also, when budget constraints might prevent use of total random order of the experimental runs. A split-plot design can be selected when lower number of experimental runs is required, less time consuming, and when HTA factors exists. The split-plot design consists of both easy to adjust, ETA, and hard to adjust, HTA, factors (Jones & Nachtsheim, 2009). Split-plot design is arranged by which factors have the lowest possibilities to be adjusted in practice, and therefore should be given the lowest number of adjustments. Usually, the chosen factors for the DoE are extremely difficult to randomize (Box & Jones, 1992). In industrial experiment, factors are selected with respect of how easily adjusted they are from experimental run to experimental run (Jones & Nachtsheim, 2009). Another aspect to consider from Jones & Goos (2009) is that it is preferable to design the HTA factors with few adjustments. According to Arnouts & Goos (2017), many industrial experimental designs involves HTA factors. Jones & Nachtsheim, (2009) have three reasons which they advocate for choosing a split-plot design: cost, efficiency, and validity. First, the cost of running a split-plot design are generally less than the cost of the same experiment but instead have the factors completely randomized. The main cost and time of a split-plot design occurs in the adjustments of HTA factors. Second, the design is often more efficient statistically and less expensive to run than an experiment that is completely randomized. The reduced amount of adjustments leads to increased accuracy in the estimates for all factor effects. Hence, it is of importance to recognize in what level the experiment follows the correct way of doing a split-plot experiment. Third, in order to validate the experiment, it is important to plan the execution to reduce mistakes and make wrong analysis of the result (Jones & Nachtsheim, 2009). According to Simpson, Listak & Hutto (2013), there exist drawbacks when using the split-plot design. The drawback is because of the lack of complete randomization which decrease the result of cause-and-effect relationship between the response and the HTA factor.

2.2.1.3 Execution Phase of the DoE

This is the third phase in the DoE cycle where the planned DoE are conducted. Important aspects are mentioned to consider when perform a DoE. Selection of location is of importance because of affection from external sources of noise (e.g. temperature, vibration) should be as minimum as possible. Before conducting the experiment, it is recommended to prepare the experimental design matrix or schedule, and make sure everyone involved is provided with the necessary information regarding roles and responsibilities during the experiment. Together with a time plan to reduce possibilities of noise in the experiment (Antony, 2003). As Tanco, Viles, Ilzarbe & Alvarez, (2009) mentioned, DoE requires use of statistics, planning and discipline and it might be difficult to make sure that all involved understand the importance of these aspects. Hence, by conducting a test pilot of the experimental runs, any misunderstandings could be reduced and prevent failure of the DoE (Costa, Pires & Ribeiro, 2006). To decrease interfere of noise during the actual DoE in practice, it should be the same persons whom has the same roles and perform the same tasks during the entire experiment (Antony, 2003). It is recommended to perform trials runs in order to test the proposed activities since many people probably have not done experiments such as DoE before. This will ensure function of documentation and data collection during the actual DoE. Lastly, in industrial environment it is of important to pay attention to experiments realization and its related activities. Additionally, it is important to record and analyse any experiment deviations or unusual occurrences during the performance of the DoE (Costa, Pires & Ribeiro, 2006).

2.2.1.4 Analyze Phase of the DoE

This is the last phase of the DoE cycle, where the result should be analyzed and interpreted. In the analysis should process variables be determined regarding how those affect the main response values and influence variability (Antony, 2003). Previous phases have a strong dependent relate to a successful analysis where this is a crucial phase (Costa, Pires & Ribeiro, 2006). The analysis conducts the interactions among factors which can be seen, and in which active level those are in the process. It requires technical skills in order to interpret the obtained results (Costa, Pires & Ribeiro, 2006). Before the final results are conducted, non-significant factors are removed in order to increase the quality of the experiment. The result of the analysis will be foundation for the next step. Simpson, Listak & Hutto (2013) recommend that the analysis consists of a model validation to ensure that the design reflects true system performance. Further, within the analyse phase, there exist several aspects to consider in order to conduct a complete analysis with a result from the experimental testes. Those aspects are parameters estimation, prediction profiler, prediction expression, and evaluation of the model. The data will be analyzed using the software program, JMP, where the analysis is provided in steps as a standard format. Therefore, this section is briefly described due to the standard procedure presented by JMP. The first step in the analysis is the parameters estimation. The parameter estimates report provides the p-value of each factor (JMP, 2018a; JMP, 2018b). The p-value determine for each factor whether it is significant or non-significant. The factors p-value should be lower than 0.05 to be significant. Factors that are non-significant should be considered removal from the model one-by-one to increase quality of the model. When only significant factors are remaining in the model, a prediction expression can be generated which describe the mathematical relationship between response values (Y_n) and included factors (X_m). Hence, the value of each factor is determined and investigated of which level of effect it has on the response values. Furthermore, the evaluation of the model is the following step where quality can be examined by investigate RSquare and RSquare Adj values which are included in the summary of fit report. These are used to evaluate if the model fits the data. Also, center points might be included to test if the model is linear or curvature. By adding center points, the linear assumption can be confirmed or rejected if there are significant or non-significant factors.

2.3 Challenges Related to Design of Experiments

According to Tanco, Viles, Ilzarbe & Alvarez (2009), there are a limited amount of literature available which describe the gap between theoretical development of DoE and its application for industrial use. 16 challenges related to DoE issues have been noticed by Tanco, Viles, Ilzarbe & Alvarez (2009). These are recommending considering and to discuss prior conducting a DoE. Below are these challenges further described in detail. However, not all mentioned challenges are described. Only challenges especially related to this context of research are emphasized below.

2.3.1 Business Challenges

Resistance to change is an important challenge to consider and is therefore included in the area of Business Challenges. This is considered as an important aspect during DoE and are significant because engineers often tend to perform experiments with one factor at a time. This is not the case when conducting DoE, since DoE involves experiments where several factors are included simultaneously. Hence, the new way of conducting experiments must be accepted by engineers if successfully implementing DoE in the organization. Thus, engineers need to be convinced that methods can be used to improve and change previous working process that has been performed in several years (Tanco, Viles, Ilzarbe & Alvarez, 2009). As Owen et al. (2003) states, "*resistance is an almost inevitable consequence of the introduction of a new technique*". Furthermore, creating engagement and commitment among engineers by applying DoE is important to successfully implementing DoE (Simpson, Listak & Hutto, 2013). Therefore, the level of resistance to change is one of the most important challenge to consider when investigating if DoE can be utilized successfully in an organization. The level of resistance to change within the organization should be examined, in order to anticipate and prevent DoE to become rejected by the organization. The often-unpopular statistician prevents DoE to be absorbed by people or engineers. The negative image of statistics is another challenge and reason why many engineers reject the idea of DoE. The challenge is that DoE requires use of statistics, planning and discipline. Hence, some engineers can relate to this as a method to compile data which may lead to a negative vision regarding statistics (Tanco, Viles, Ilzarbe & Alvarez, 2009).

2.3.2 Educational Challenges

Within the area of Educational Challenges, DoE is considered as often badly taught. Which is one challenge that is of importance for this research. In general, DoE is rather emphasized in theoretical aspects and not focused in how to apply for industrial use and for business related issues. The often lack of conducting actual experiments in practice when learning DoE is one reason why it is badly taught. DoE is a tool of practice where it should be learned by doing (Tanco, Viles, Ilzarbe & Alvarez, 2009). Since a DoE requires more resources than traditional methods, limited and insufficient resources is another challenge. This is because there are assumptions that includes more resources to conduct a DoE which are not correct since the resources are more or less equal for traditional and designed experiments (Owen et al., 2003).

2.3.3 Technical Challenges

Within the area of Technical Challenges, the absence of assisting theory how to solve real industrial issues is found as an important challenge to consider. This is often defined as a problem concerning how to turn theory into practice. For instance, the experimental runs must be conducted in random order to reduce noise (Antony, 2003). Where random order might not always be applicable within industrial contexts (Simpson, Kowalski & Landman, 2004). This can be impossible to find a solution to because of restrictions in factors (Tanco, Viles, Ilzarbe & Alvarez, 2009). Restrictions within factors may involve interaction when factors are included in a wider perspective than its main function. Which could have impact in an unknown aspect. Furthermore, within the area of Technical Challenges, DoE is limited in usage due to often high level of complexity. According to Tanco, Viles, Ilzarbe & Alvarez, (2009) Some engineers says that DoE is a difficult technique and if DoE has a low frequently use, or no use, in an organization it makes the decision to perform experiments difficult to develop and utilize in projects.

Section 3
Methodology

Below is a description of the chosen research design, research strategy and research methods for collecting, analyzing, and evaluate the data. Ethical principles have also been in consideration during the research, which are further explained below.

3.1 Ethics during the Research

This research involves qualitative aspects where data have been examined and analyzed through an interview study. When people are involved in a research for collecting data, ethical considerations should be noted. There are four main principles of ethics which have been considered during this research: avoid harm to participants, lack of informed consent, invasion of privacy, and deception (Bryman & Bell, 2015). First, to avoid harm to participant, none of the involved people of the research were exposed by stress or pressure which could damaging their self-esteem. Stress and pressure were avoided by inform the interviewee which type of questions to prepare for. To ensure that, answering a question was not requested if the question was perceived as inappropriate. Second, to avoid lack of informed consent during the research and the interview study, purpose and rights for the participants were clearly outlined and informed. The participants were also asked if they agreed to record the interview for analyzing purpose. All interviewed persons will be kept anonymously, and the collected raw data will not be distributed. Third, to avoid invasion of privacy the actions mentioned previously align with this principle regarding inappropriate question. However, it is difficult to outline what type of questions that might be perceived as inappropriate and invasion of privacy by the researchers. Additional, confidential agreements were signed by the researchers to not distribute sensitive information or data. To avoid deception, all gathered data during the interview study were approved by the interviewees. However, if disagreement how the data were used in a certain context, the data could be withdrawn by the interviewee (Bryman & Bell, 2015).

3.2 Case Study as Research Design

The following research is a case study in collaboration with Volvo Cars, to identify which factors critically affect rear door closure performance, and causing variation in quality outcome related to the closure performance. Based on the identified critical factors, a suggestion for quality improvement will be given by presenting measures for quality assurance and prediction possibilities to avoid poor closure performance in future. The focus is on the closure event, where the aim is to provide an in-depth research of the closure performance, which is why the research design should be considered as a case study (Bell & Bryman, 2015). The findings will be related to the context of Volvo Cars. However, a comprehensive case description is provided to enable transferability and generalization of findings, see Appendix 1 (Bell & Bryman, 2015). Variation within quality related to automotive rear door closure performance is by no means unique for Volvo Cars. The rear door closure performance has been a matter of quality issue for several years among car manufacturer (Nayak & Im, 2003; Jei, 2011; Ishida, Aoki, & Tooya, 2003; Wagner, Morman, Gur, & Koka, 1997). The findings can therefore be applied in a wider perspective, and utilized by externals to examine similar quality issues.

3.3 Research Strategy and Research Methods

This project covers both aspects of qualitative and quantitative methods for collect and analyze data. Qualitative and quantitative research approaches are often considered as opposites. However, it does not exclude a combination of them as mixed methods research strategy (Bell & Bryman, 2015). This research will cover a qualitative interview study, administered by interview sessions among employees at Volvo Cars. The interview study resulted in qualitative data, which allowed the researches to map and scope the closure challenge within the organization. Hence, orientation towards the most critical area regarding the closure challenge could thereby be determined. Further, in-depth research within the most critical area (mechanical factors), based on the interview study, was established by applying DoE to collect quantitative data. The different research approaches are further described below in Section 3.4 and Section 3.5.

Furthermore, to ensure trustworthiness of the qualitative data, four quality criteria are presented by Bell & Bryman (2015): credibility, transferability, dependability, and confirmability. For this research, only reliable literature sources were used in majority to support the theoretical framework or any statements. Information regarding the software JMP will only be derived from JMP or Minitab, and not by second order sources or references. This will ensure credibility. Thus, transferability is achieved through the provided case description, see Appendix 1. The steps in each method for collecting data will be described in detail in each section, to ensure that the context is captured and understood by the reader. Further, dependability is ensured by recording each step of the research. The procedure for analyzing the interview study is outlined and supported by a well-known method called Affinity-diagram (Lucero, 2015; Kendall, 1999). All decisions made in the DoE cycle for performing the DoE is described and motivated in detail as well. Also, different data collecting methods were used for increasing trustworthiness of the research; ensuring the same result and conclusion even if different methods was used. This is referred to triangulation (Bell & Bryman, 2015). Lastly, to ensure confirmability of the research, all researchers should act in good faith. The research is driven by commitment, curiosity, and engagement among the researchers, and no personal values or hidden agendas have interfered during the research. Additional, the quantitative data will be verified using the software program JMP.

3.3.1 Literature Study

The literature study has been an iterative process during the whole research to ensure that the framework was updated and relevant. This allowed new knowledge and information to be incorporated. The main purpose of the literature study was to understand various concepts and theories supporting the research e.g. DoE, variation, mechanics of a rear door etc. Both web-based and physical sources have been utilized. The literature study has been conducted to support both qualitative and quantitative methods. Below is a description of the different qualitative and quantitative techniques for collecting data.

3.4 Qualitative

Qualitative data is used for contextual understanding, and emphasizing words rather than quantifications. Qualitative strategies have an inductive approach towards the orientation to the role of theory in relation to research. A qualitative approach emphasizes in generation of theory rather than testing of theory. The epistemological orientation of qualitative research is interpretivism. Hence, qualitative research emphasizes how people interpret their surroundings or social worlds. The ontological orientation of qualitative research is constructionism. Hence, the social world is considered to be formed and constantly shifted by the people involved (Bell & Bryman, 2015). However, it is often difficult to assure credibility of qualitative research since qualitative data is mostly interpreted. To increase credibility and to assure validity of the interview study, the analysis method used for the interview data is described in detail below. How the interview sessions were conducted are also described, as well as what type of questions used, whom were interviewed, and in which department of the organization the interview session were conducted. This will also facilitate repeatability of the interview study by externals. The interview questions can be found in Appendix 2. However, all people interviewed are kept anonymous to sustain ethical obligations. In the following section, the qualitative interview sessions are described, as well as the analyzing method applied for the interview data.

3.4.1 Qualitative Interview Study

Qualitative interview sessions were conducted to collect data regarding closure performance of automotive rear doors. Different employees in different departments at different levels of the organization related to rear door closure performance were interviewed. The various roles and departments that were included in the interview study can be found in Appendix 3. A system perspective of the door closure performance was provided due to the large variety among employees interviewed. Also, bias is assumed to be reduced when collecting data from different departments and levels of the organization. Thus, the interviews are not limited to one department but are spread across several departments. The purpose of the wide distribution of interview sessions among employees were to map and scope the closure challenge within the organization. Hence, orientation towards the most critical area regarding the closure challenge could be determined, based on the interview study. An in-depth quantitative research was later performed in the most critical area, based on the interview study and further described in Section 3.5.

Further, the interview questions were in the form of semi-open ended. Semi-open-ended questions might reduce the risk of influence the interviewee and affect their choice of answer. Asking leading questions were avoided by the researchers during all interview sessions. All the interview questions can be found in Appendix 2. In the end of each interview, the interviewees were asked to suggest a suitable candidate to interview next. This was requested in order to ensure comprehensiveness and appropriate direction of the interview sessions, also advocated by Bell & Bryman (2015). The interview study ended when saturation was achieved: when the interviewees started to suggest people preferable to interview whom already had been included. The collected data were further analyzed using affinity diagrams to structure the large amount of qualitative data, similar to Lucero (2015). Respondent validation was applied if necessary, for ensuring correct interpretations of the collected data as mentioned by Bell & Bryman (2015). Factors affecting rear door closure performance was mapped based on the information derived from the interviews. The analysis method applied for the interview data is further explained below.

3.4.2 Methodology for Analyzing the Qualitative Interview Study

As mentioned above in Section 3.4.1, the interview questions were semi-open ended, which resulted in various different types of answers among the interviewees. The answers could take various forms and different directions based on the background, knowledge, and experiences possessed by the interviewee. However, the large spread among the type of answers were encouraged by the researchers, in order to capture differences in opinions among employees regarding rear door closure performance. The large spread among the type of answers required an analyzing method that enabled high-quality grouping of the various answers, in order to make sense of the data. The chosen method to analyze the interview data was affinity diagram. In general, affinity diagram is used for sorting data into groups, by clustering data based on commonalities. It is possible to sort larger groups into subgroups to facilitate the analysis. After completing the grouping sessions, the affinity diagram can be used for creating cause and effect diagrams in order to show relationships between groups (Lucero, 2015; Kendall, 1999). One of the reason to use affinity diagram as analyzing method was to ensure that the data was analyzed in structured manners, and to increase repeatability of the research. The analyzing process is described below in Section 3.4.2.1.

3.4.2.1 Transcription

All interviews were recorded and transcribed by the researchers. The transcription process was conducted immediately after the interview session, in order to reduce risk of misunderstanding or incorrect interpretations of the interview. The interview data were further analyzed using affinity diagrams as a framework for grouping decisions. Overall, three grouping sessions were conducted in order to categorize the transcripts. Before the grouping sessions, all the answers and comments provided by the interviewees were rewritten as key sentences. The key sentences described the essential meaning of the answer.

3.4.2.2 Key Sentences

In each key sentence, the essential content of the interviewee's comment or answer were summarized shortly. Key sentences were a convenient format of the interview data, and enabled the interview data to be well-overviewed. The key sentences were constructed prior the grouping sessions. Hence, the initial step was to extract the most important data from the interviews and rewrite it into shortly expressed sentences, without impair or twist the meaning of the comment. Rewriting into key sentences were made independently between the researchers, in order to reduce the risk of bias. Also, to check whether the researchers had come to the same conclusion of what is a fair key sentence to represent the comment. The key sentences were later compared. If the two key sentences, provided by each researcher, expressed similar meanings, they were compiled into one key sentence used for the analysis. The key sentences were written on post-it notes and placed on a wall to create an overview of the analysis. Post-it notes was used in order to create flexibility within the grouping sessions. Hence, the post-it notes could easily be repositioned by the researchers when forming various groups. In total, 500 post-it notes was created. When the interview data had been rewritten into key sentences, a grouping session was performed which is further described in Section 3.4.2.3.

3.4.2.3 Grouping Sessions

In total, three grouping sessions were conducted where all key sentences were divided into different sub levels based on commonalities. The first grouping session was division into segments, the second grouping session was division into categories, and the third grouping session was division into sub categories. The hierarchy order of the three sub levels[2] is visualized in Figure 2 below. During the grouping sessions, the division process (at all sub levels: segmentation, categorization, and sub categorization) was made iterative. The three grouping sessions were conducted in similar ways as described by Harboe & Huang (2015) and Kendall (1999).

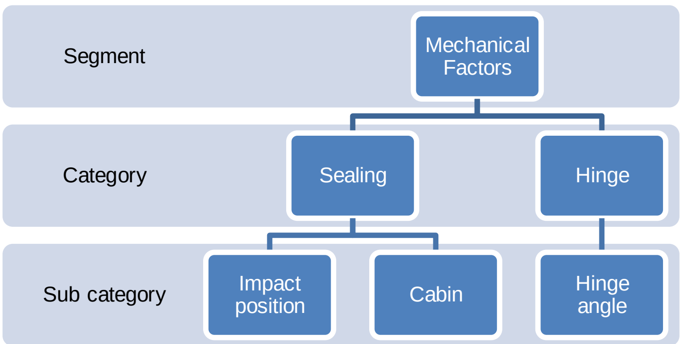

Figure 2. Schematic illustration of the hierarchy order of the three sub levels (segmentation, categorization, and sub categorization).

First Grouping Session: Segmentation

The first grouping session where to divide key sentences into six segments, shown in Table 2 below. The segments represented common themes on a higher level, which affected rear door

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[2] *Note, although divisions into sub levels were made among the key sentences, the overall objective were to identify factors affecting rear door closure performance. Hence, the divisions into sub levels did not distinguish certain key sentences that affect closure performance from other key sentences that do not affect closure performance. All divisions represented factors or key sentences which affected closure performance, but in different aspects.*

closure performance. The choice of division into a certain segment were based on commonalities that represented that segment. For instance, the segment: 'mechanical factors' included all key sentences related to the mechanics of the rear door e.g. sealing and hinge.

Table 2. First grouping session into segments.

	Grouping Sessions					
Segment	Mechanical Factors	Process Factors	Soft Factors	Requirement	Car Models	Others
Description of Segment	All factors included related to the mechanics of the rear door, e.g. sealing, hinge, striker etc.	All factors included related to different types of processes, e.g. production process, measurement process, CAD modeling etc.	All factors included related to different types of soft factors, e.g. subjectivity, organizational structure, communication etc.	All factors included related to requirements regarding rear door performance, e.g. closure definition, speed limit, energy limit etc..	All factors included related to car models, e.g. division between car models into high quality of closure performance and less quality of closure performance etc.	All factors remaining which were difficult to group, e.g. facts regarding rear door performance etc.

Second Grouping Session: Categorization

The second grouping session where to divide key sentences into categories within each segment. Hence, all segments were examined for commonalities representing a category on a lower level which affected rear door closure performance. The categories are shown in Table 3 below. Each word beneath the segment describes a separate category, e.g. 'sealing' is a separate category consisting of various key sentences which all share commonalities with that specific category. Just as 'hinge' is a separate category etc.

Table 3. Second grouping session into categories.

	Grouping Sessions					
Segment	Mechanical Factors	Process Factors	Soft Factors	Requirement	Car Models	Others
Category*	sealing, hinge speed, air evacuation, aerodynamics, door lock, door check, door shape	construction, audit, CATIA, non-robust system, good looking, sequence & time process, reality vs plan, same, information, door position, geometry, compensated door frame, measurement, robot, tolerances	customer, weighted factors, silo, non-silo, bad boss	wrong requirement, definition of close, individual requirements, 1.3 m/s, 1.1 m/s, energy requirement, requirement vs requirement, subjectivity, people afraid of changing requirements	high quality of closure performance, less quality of closure performance	larger problems with underwrap, opening angle, noise, force in overslam, energy input = energy output, higher closure force for rear doors, many investigations but no compilations, position front and rear door, dynamic compensation

**Each word beneath the segment describes a separate category, e.g. 'sealing' is a separate category consisting of key sentences which share commonalities with that category. Just as 'hinge' is a separate category etc.*

Third Grouping Session: Subcategorization

The third grouping session where to divide key sentences into sub categories within each category. Hence, all categories were examined for commonalities representing a sub category on a lower level which affected rear door closure performance. The sub categories are shown in Table 4 below. Note, if no sub category could be determined, the previous category from the second grouping was used as a sub category as well. For instance, 'construction' is a category beneath the 'process factors' (segment). However, no sub category could be determined for the key sentences beneath 'construction'. Therefore, 'construction' was also kept as a sub category in the third grouping session. Unlike the category of 'tolerances' beneath the 'process factors' (segment). 'Tolerances' could be divided into the following five sub categories: 'removed tolerance', 'non-robust system', 'tolerance chain', 'big tolerances', and 'relation between articles'. Further, each word beneath the category describes a different sub category, e.g. 'impact position' is a separate sub category consisting of various key sentences which all share commonalities with that specific sub category. Just as 'cabin' is a separate sub category etc. Further, any post-it notes that described similar key sentences were placed above each other. Each sub category was later summarized into one headline, representing the sub category. See Appendix 4 for the translation table of each sub category into one headline.

Table 4. Third grouping session into sub categories.

	Grouping Sessions					
Segment	Mechanical Factors	Process Factors	Soft Factors	Requirement	Car Models	Others
Category*	sealing, hinge speed, air evacuation, aerodynamics, door lock, door check, door shape	construction, audit, CATIA, non-robust system, good looking, sequence & time process, reality vs plan, same, information, door position, geometry, compensated door frame, measurement, robot, tolerances	customer, weighted factors, silo, non-silo, bad boss	wrong requirement, definition close, individual requirements, 1.3 m/s, 1.1 m/s, energy requirement, requirement vs requirement, subjectivity	high quality of closure performance, less quality of closure performance	larger problems with underwrap, opening angle, noise, force in overslam, energy input = energy output, higher closure force for rear doors, many investigations but no compilations, position front and rear door, dynamic compensation
Sub category**	(***sealing***) impact position, cabin, soft, primary, different cuts, aerodynamics, size, position, stiffness, door frame, seal gap, characteristics , force-energy curve, capacity of sealing (***hinge***) hinge angle,	construction, audit, CATIA, non-robust system, good looking, sequence & time process, reality vs plan, same, information, door position, geometry, compensated door frame, measurement, robot ***(tolerances)*** removed tolerance, non-	***(customer)*** internal customer, subjectivity assessment, non-customer facts, non-standardizatio n, customer do not know ***(weighted factors)*** balance solution, weighted factors	wrong requirement, definition of close, individual requirements, 1.3 m/s, 1.1 m/s, energy requirement, requirement vs requirement, subjectivity, people afraid of changing requirements	*(high quality of closure performance)* *** *(less quality of closure performance)* ***	larger problems with underwrap, opening angle, noise, force in overslam, energy input = energy output, higher closure force for rear doors, many investigations but no compilations, position front and rear door, dynamic compensation

	spread, hingeline, hinge friction, hinge line position, hinge slope **(*Speed*)** speed & pressure, speed & air resistance **(*air evacuation*)** cabin, air inside sealing, air between sealing, door shape, speed **(*aero-dynamics)*** door frame, non-aerodynamics **(*door lock)*** striker position, latch position, bump energy loss, stiffness, non-lock, energy loss **(*door check)*** inertial area, friction door check, shape, spring energy, spring speed, door stop **(*door shape)*** thickness, center of gravity position, door weight, door pocket, door design	robust system, tolerance chain, big tolerances, relation between articles	silo, non-silo, bad boss

** Each word beneath the segment describes a separate category, e.g. 'sealing' is a separate category consisting of key sentences which share commonalities with that category. Just as 'hinge' is a separate category etc.*
*** Each word beneath the category (the word within parentheses) describes a different sub category, e.g. 'impact position' is a separate sub category, just as 'cabin' etc.*
**** It was decided not to outline which car model belongs to which sub category due to confidential issues.*

3.4.2.4 Axial Coding

After the three grouping session, axial coding was applied where connections between the headlines of each sub category were made; exploring the data by making new connections (Harboe & Huang, 2015; Kendall, 1999). The aim was to reduce the number of various headlines or factors, in order to discern which of the headlines or factors that might be considered critically affecting the rear door closure performance. The focus was to map the relationships between the headlines or factors and to explore how they were integrated. This is summarized into a relationship-map and can be found in Appendix 5. Explanations to the various numbers in the relationship-map can be found in Appendix 4, which complements the relationship-map. Based on the axial coding and the relationship-map, a group of important factors affecting rear door closure performance were found interesting. These factors were considered as not consequences but potential causes which most likely resulted in poor closure performance. These factors are further analyzed and discussed in Section 4.1.

Further, it was decided to close the investigation of the remaining factors in the relationship-map: process related factors, soft related factors, and requirement related factors. This project will therefore be limited to mainly investigate mechanical related factors affecting closure performance. Since mechanical related factors were the largest group that affected closure performance, see Table 4 above. This indicates a high interest from the interviewees as well. How the mechanical related factors affected the response values, the rear door closure performance in terms of speed and energy, could then be examined using DoE. The DoE would be based on quantitative data, which support which factors that critically affect closure performance. The DoE plan is described in detail within Section 3.5.1.

3.5 Quantitative

Quantitative data is where the results are measurable and quantifiable. In general, quantitative researchers employ measurement, compared to qualitative researchers whom do not. Quantitative strategies have a deductive approach towards the orientation to the role of theory in relation to research. A quantitative approach emphasizes in testing rather than generation of theory. The epistemological orientation of quantitative research is positivism and natural science models. The ontological orientation of quantitative research is objectivism. Hence, quantitative researchers view the social world as objective. Mostly, quantitative data is considered to involve a high level of reliability (Bell & Bryman, 2015). Therefore, an in-depth research of the most critical area regarding factors which affect closure performance, based on the qualitative interview study, was conducted in the research by using DoE. Based on the interview study, the most critical area to examine was the mechanical related factors. Therefore, mechanical factors were selected to be included in the DoE. DoE is a quantitative tool to collect data regarding closure performance. In Section 3.5.1 below, the methodology of the DoE is described sequentially by following the DoE cycle: plan, design, execute, and analyze.

3.5.1 DoE Cycle

The performed DoE at Volvo Cars is context related for suiting the circumstances of this project. However, the detailed description of the performed DoE in this section emphasizing on the methodology, and assists in understanding the context of the DoE to enable a simplified generalization of the findings as mentioned by Bell & Bryman (2015). The DoE methodology can therefore be used by externals in similar industrial contexts. Appendix 7 summarizes the most important findings of the DoE methodology, and can be used as a simplified checklist. However, the underlying assumptions and motivations that support Appendix 7 are explained in this section. The section is organized according to the sequence of the DoE cycle: planning phase, design phase, and execution phase. The analysis phase can be read in Section 4.2.

3.5.1.1 Planning Phase of the DoE

The first phase of the DoE cycle is planning phase. In this section, all necessary planning prior the design phase, execution phase, and analysis phase of the DoE are described. The section involves: creating commitment, problem description and objectives of the DoE, and limitations during the DoE.

Creating Commitment

The first step in order to perform the DoE was consultation with key people. The purpose was to gain general knowledge regarding the circumstances to consider when performing the DoE. For instance, what factors are difficult to adjust in practice, are there any internal relationships between factors that must be considered when adjusting them, how to use the measurement device EZSlam to measure the closure performance etc. As mentioned in Section 2.2.1.1, successful experiments require commitment by key people and stakeholders (Simpson, Listak & Hutto, 2013). Therefore, it was important to let key people join during discussions and meetings in order to create support for the DoE. However, DoE was often questioned if suitable by key people, stakeholders, and team members. Therefore, the excellence of DoE when conducting factorial tests were motivated by the researchers, in order to convince key people, stakeholder, and team members to use DoE.

Problem Description and Objectives of the DoE

This DoE was performed on behalf of Volvo Cars, aiming to create a deeper understanding on how mechanical factors affect rear door closure performance in practice. The purpose is to weight the various factors in order to understand what factor, or combination of factors, that have the largest negative effect on the closure event and results in poor closure performance. The objective is to develop a model, which explains the relationship between the factors and closure performance. The model can be used to improve quality of closure performance at Volvo Cars. If the relationship between factors and closure performance is known, the closure performance can be calculated in advanced by applying the model, and appropriate adjustments of the factors can be made to avoid poor closure performance. Hence, the arrangement of the mechanical factors can be examined in advanced, in order to understand what the optimal arrangement of the factors are to achieve high quality closure performance.

Further, closure performance is measured by closure speed (Y_1) and closure energy (Y_2), which is also referred to as response values[3]. Least amount of closure speed and closure energy should be applied for making a successful closure of the rear door. As defined by Volvo Cars, the maximum closure speed for approval is 1.3 m/s, and the closure event is defined as successful if total secured into second lock mode when closing at the speed of maximum 1.3 m/s. The closure event is defined as unsuccessful if not closed into second lock mode at the speed of maximum 1.3 m/s. Currently, closure speed is the main measurement when assessing closure performance at Volvo Cars. However, Volvo Cars plans to change measurement unit into

[3] *Note, the reason for two response values is that Volvo Cars, in the near future, are planning to go from measuring closure performance in closure speed to energy.*

closure energy (J). For that reason is also closure energy included as response value in the research when examine closure performance.

Limitations during the DoE

There are several limitations to consider when conducting the DoE in practice. Below are the main limitations discussed which are: the unknown measurement device EZSlam and customer car.

The Unknown Measurement Device EZSlam

All response values were measured using the measurement device EZSlam. For additional information about EZSlam, see Appendix 8. EZSlam is a recently purchased measurement device, and there are only a handful of people within the organization whom operates the device. Hence, the knowledge of the measurement device is limited to these people. However, it was possible to measure both the closure speed and closure energy by using EZSlam[4]. EZSlam was therefore selected as the appropriate measurement device to use for the DoE. The accuracy of EZSlam is claimed to be within 5%, according to EZSlam (2018). Any measurement devices should have an accuracy of less than 10% for approval (Hammersberg, 2017a). However, a MSA (measurement system analysis) were not found that could support the claim of accuracy level of EZSlam, neither the level of precision. Hence, the measurement device might affect the results of the DoE, due to the unknown level of accuracy and precision. As an attempt to reduce any noise caused by the measurement system, all measurements were performed by the same operator.

Customer Car

The DoE will be carried out on a customer car, and no damage on the car must not occur. Hence, when making the factor adjustments on the car, they must be adjusted gently to not damage the car. This require an execution planning of how to adjust the factors in the most sensible way, to ensure minimum risk of damage. Therefore, how to adjust the factors are limited by the assurance of returning the car undamaged.

3.5.1.2 Design Phase of the DoE

The second phase of the DoE cycle is design phase. It is highly important to select an appropriate design suitable for the circumstances, limitations, and conditions of the DoE. Selecting the most appropriate design for the situation would facilitate the execution of the DoE, and increase the chances of conducting the DoE successfully. Additionally, it is also important to consider which resources are available and what are the time constraints when choosing the design. In this section, all motivations which support the chosen design are discussed.

[4] Other measurement devices at Volvo Cars were incapable of measuring both closure speed and closure energy, except from EZSlam. Also, the measurement device currently used to measure closure speed is considered as imprecise, and there are no other measurement devices available to measure closure energy except from EZSlam.

The Choice of Number of Factors to Include and their Characteristics

Based on the analysis of the interview study, see Section 4.1.6, five mechanical factors: X_1, X_2, X_3, X_4, and X_5 were selected to be included in the DoE and can be found in Table 5 below. These factors were considered as interesting to include by people interviewed. There was also uncertainty how these factors affected closure performance in practice, which made them interesting to examine. Also, the five factors were chosen based on their simplicity to be adjusted in practice. It was desirable to include more factors, but the number of factors were restricted by the simplicity to adjust them in practice. The number of factors were also constrained by time limitations. Therefore, the number of factors were kept low, to fulfill the specified time limitations. It was important to ensure total completion of the DoE, otherwise it would be unusable for the research and for Volvo Cars.

Table 5. The five factors included in the DoE and the characteristics of the factors.

#	Factor	Units	Range	Adjust: ETA, HTA	Design Range
X_1	Sealing Ingress	mm	-2.5 mm to +2.5 mm	ETA	-1 mm to +1 mm
X_2	Striker Alignment	mm	- 1 mm to +1 mm	ETA	-1 mm to +1 mm
X_3	Door Frame	mm	-1 mm to +1mm	ETA	-1 mm to +1 mm
X_4	Cabin Air Evacuation	Categorial	Covered to uncovered	ETA	Covered to uncovered
X_5	Sealing Stiffness	Categorial	Higher stiffness to lower stiffness	ETA	Higher stiffness to lower stiffness

In Table 5 above, the different characteristics of the factors are outlined. All factors, except from X_4, are continuous variables and measured in the unit millimeter (mm). X_4 is a categorical variable and measured as covered or uncovered. The ranges of the factors are the physical possible operating ranges of the factors in practice (Simpson, Listak, & Hutto, 2013). Compared to the design ranges of the factors, which are the chosen adjustment intervals. The ranking scale: ETA (easy to adjust) and HTA (hard to adjust), ranks how easily the factors can be adjusted in practice. All the factors are ranked as ETA, since the selection of factors to include in the DoE were based on their simplicity to be adjusted in practice.

The Dilemma of Semi-HTA Factors

Based on the analysis of the interview study, see Section 4.1.6, only ETA factors were selected to be included in the DoE. ETA factors are defined as easy to adjust in practice. However, the chosen factors *still* implies difficulties to be adjusted in practice in terms of contextual constraints. For instance, small design range (intervals of only 2 mm), risk of material fatigue and crack initiation in the area where the factors are mounted if adjusted too many times, risk of decrease in height of the rear door due to gravity when adjustments are made in the hinges, risk of internal relationship (confounding[5]) among the factors which might affect the result if not managed etc. The factors can therefore also be defined as HTA factors. The factors are defined as ETA, since they are feasible to adjust in practice. However, there are contextual constraints which oppose the factors to be adjusted many times, *even* if they are defined as ETA. In that sense, the factors could be described as semi-HTA.

[5] The effect on Y_n cannot be confirmed to be caused by X_m, if X_m is confounded with X_p. Hence, there are internal relationships between factors if they are said to be confounded. A low level of confounding in the design is to prefer when conducting DoE.

Additional, if the chosen design (different designs enable different functionalities) allows the factors to be ranked as either ETA or HTA in the software program JMP, then different numbers of factor adjustments will be generated. The definition of ETA and HTA by JMP are: easy to adjust and hard to adjust, which only refers to the *actual feasibility of adjusting* the factors. If the factor is defined as HTA in JMP, JMP will generate a design where the HTA factor will be adjusted as few times as possible. Compared to, if the factor is defined as ETA in JMP, JMP will generate a design where the ETA factor is not adjusted as few times as possible. However, the factors included in the DoE for this project can be defined as ETA, since they are feasible to adjust in practice, but they are also constrained by their context which oppose a high number of factor adjustments. This is referred as the dilemma of semi-HTA factors by the researchers, and will affect the choice of design for the DoE.

The Most Important Constraints to Consider when Choosing the Design

The most important constraints to adapt the design are summarized in Table 6 below. The chosen design should be applicable to the following conditions: the dilemma of semi-HTA factors, time limitations, and confounding.

Table 6. The most important constraints to consider when choosing the design for the DoE.

Constraint	Consideration	Comment
The Dilemma of Semi-HTA factors	Reduce the number of factor adjustments	The dilemma of semi-HTA factors will also be supported if the number of experimental runs are reduced as well
Time constraint	Reduce the number of experimental runs	The time constraint will also be supported if the number of factor adjustments are reduced as well
Confounding	Evaluate the confounding of the design by using in-built function in JMP	Color map on correlation is an in-built function by JMP, which can be used to examine the confounding level

The Constraint of the Dilemma of Semi-HTA Factors

An important constrain to consider is the dilemma of semi-HTA factors. Hence, the factors are defined as ETA, but it is at the same time difficult to adjust the factors in practice in terms of contextual constraints, as explained above. Hence, even if the factors are defined as ETA, they *still* imply difficulties to be adjusted in practice in terms of contextual constraints e.g. risk of crack initiation in the material where the factor is mounted if adjusted too many times. The choice of design should therefore advocate a small number of factor adjustments, even if the factors are defined as ETA. However, a design which do not generate the smallest number of factor adjustments could also be chosen, since it is feasible to adjust the factors in practice. However, that choice involves a risk of various context related implications, which could be devastating for the DoE.

Continuing, the dilemma of the semi-HTA factors, which imposes them to be adjusted as few times as possible even if they are defined as ETA, also complicate the importance of conducting the experimental runs in random order (Minitab, 2018c; Sanders & Coleman 2003). Random order of the runs would increase the number of factor adjustments. Therefore, conducting the experiment using non-random order was considered. After consultations with experts, it was decided to adopt the design of the DoE for suiting the situation which involves the dilemma of semi-HTA factors. In other words, treat the factors as HTA and conduct the runs in random order. The choice of design should allow HTA factors to be placed in positions where the number of adjustments were reduced. If non-random order would have been chosen instead, the level of noise in the DoE could be jeopardized. It is not known if noise caused by the mechanic due to random order (random order will require a high number of adjustments of factors which are HTA, resulting in an increased risk of placing factors in incorrect positions) can be assumed to be larger than the noise present do to non-random order. Therefore, it was decided to adopt the design for suiting the situation instead of just conducting the experiment using non-random order.

Time Constraint

An important constraint to consider were the specified time limitations. The choice of design should support completion of the DoE within the specified time. Therefore, the design should generate lowest possible number of experimental runs. The DoE would be useless if not completed within the specified time limitations.

Confounding Constraint

Some of the chosen factors have internal relationships with other factors. For instance, when adjusting the rear door in y-direction, the striker must be adjusted by the same distance in y-direction to remain the distance constant between the rear door and the striker. (Striker adjustment in y-direction is not included as a factor, only striker adjustments in z-direction, see Section 3.5.1.3). If not repositioning the striker by the same distance in y-direction, a changed distance between the rear door and the striker would occur, which would affect the result negatively since the DoE is no longer measured by the same basis and premises. These internal relationships are considered as an important constraint to consider as well, when choosing the most appropriate design for the DoE.

Pilot Test

It was important to examine the constraints in practice in order to understand how the DoE should be executed, and which factor adjustments that could be performed. The pilot test was also utilized in order to understand appropriate design ranges for the factors. When all ranges (which is defined as the physical possible operating range) for the factors were to be determined, some factors were constrained by other factors, which limited the choice of design range (which is defined as the chosen adjustment intervals for the DoE). How to adjust the factors in practice can be read in Section 3.5.1.3.

The Choice of Appropriate Design Ranges for Factor Adjustments

As mentioned above, the design range is the chosen interval of adjustments of each factor for the DoE, e.g. the design range is - 1 mm to + 1 mm for X_1, see Table 7 below (Simpson, Listak, & Hutto, 2013). The design range begins and ends by the low and high levels for the factors.

The design range were determined during consultation with key people and during the pilot test, mentioned above. The pilot test was conducted prior the actual DoE. Where the adjustments of each factor were examined in practice. Time duration for the adjustments were noted as well during the pilot test. This provided information regarding the ranges of the factors, which in turn could be used as information when deciding appropriate design ranges. For the DoE, it is wise to choose large design ranges as possible. This will ensure a wider collection of data, compared to a small design range. However, the large range of a certain factor might be constrained by the small range of another factor. The choice of design range for each factor must be decided jointly. As mentioned above, due to internal relationships or confounding among some of the chosen factors, it was important to adjust the factors in certain manners in order to eliminate or reduce the effect of these internal relationships. These internal relationships were examined during the pilot test as well. It was understood which factors were constrained by others, and maximum ranges were also noted. The following ranges and design ranges of the factors were decided as follow, see Table 7 below. The ranges assume a measured reference point, and the minus and plus signs indicates the direction of the adjustments from the reference point.

Table 7. The ranges and the chosen design ranges for the four factors included in the DoE.

#	Factor	Units	Range	Adjust: ETA, HTA	Design Range
X_1	Sealing Ingress	mm	-2.5 mm to +2.5 mm	ETA	-1 mm to +1 mm
X_2	Striker Alignment	mm	- 1 mm to +1 mm	ETA	-1 mm to +1 mm
X_3	Door Frame	mm	-1 mm to +1 mm	ETA	-1 mm to +1 mm
X_4	Cabin Air Evacuation	categorial	covered to uncovered	ETA	covered to uncovered

First, the range of X_1 was determined to - 2.5 mm to + 2.5 mm. As mentioned above, the striker must be repositioned by the same distances in y-direction when adjusting X_1, to eliminate internal relationships between X_1 and striker in y-direction. The physical possible operating range of the striker was - 1 mm to + 1 mm, which is a smaller range compared to X_1. Hence, X_1 is constrained by the striker, which impose the design range of - 1 mm to + 1 mm for X_1. Second, there were a risk of material fatigue and crack initiation in the area where X_2 is mounted if adjusted too many times. Therefore, the design range of - 1 mm to + 1 mm was decided as suitable for X_2. Third, the design range for X_3 were constrained by the relation of X_1 and has to be determined jointly as well. The relation between X_1 and X_3 were examined during the pilot test, where X_1 and X_3 were adjusted jointly to determine the range in order to set the appropriate design range. The appropriate design range should allow the door to be tilted for X_3, and at the same time allow adjustments of X_1 in y-directions. The design range for X_3 was determined to + 0.5 mm to + 1 mm. Fourth, after consultation with key people from the department of climate involved air evacuation issues. The design range was chosen as covered and uncovered for the car body mounted air evacuation vents, X_4. The choice of design range for X_4 were based on facts from simulation data indicating that only a small area of the air evacuation vents was utilized when the air was transported from the cabin. Therefore, it would be no difference by choosing a smaller area to cover as design range for X_4.

Finally, for X_5, which is the sealing stiffness factor, it was decided to remove this factor from the DoE, although the interest for this factor was high. The level of adjustments for X_5 were to adjust the sealing into high and low level of stiffness by removing the sealings completely from the car body and replace it with new ones. However, there were uncertainties how to arrange the DoE for suiting X_5 to minimize the influence of noise. It was unclear how to assure the same level of stiffness of the sealings when adjusted. For instance, when adjusting X_5, there should be a waiting time before the next experimental run, to ensure that the sealing have reach the same level of stiffness. Hence, the specified time limits of the DoE would have been exceeded if adding the waiting time between each factor adjustment of X_5. The DoE would then not be completed within the specified time limits. No appropriate solution was found regarding the stiffness issues and the long waiting time, X_5 was therefore removed from the DoE. Further explanation of X_5 can be found in Appendix 9.

The Choice of Number of Levels, Type of Effects, Center points, and Replicates to Include

First, a two-level design was chosen due to linear assumptions. The only model possible to fit between two levels is a linear relationship. The decision of a two-level design was also influenced by the previously discussed dilemma of semi-HTA factors. For instance, a three-level design would require a higher number of factor adjustments, which is not advocated by the researchers. Hence, it was important to sustain a low number of factor adjustments for the DoE.

Second, only main effects (X_m) were included in the design. Except from sustaining a low number of factor adjustments and meet the time specified limitations, a low number of experimental runs were advocated as well. If main effects were not the only ones included, but also interactions (X_mX_n) and quadratic terms (X_m^2), the number of experimental runs would increase. Also, any interactions between factors were assumed as low, which was supported by the color map on correlations when the confounding level were examined, see below. In general, interactions and quadratic terms are rare (Hammersberg, 2017b). This motivates why only main effects were included in the DoE. However, the linear assumptions should be tested by using center points, and a quadratic term must therefore be added.

Third, two center points and two replicates were included in the design, to test for curvature and to estimate noise. When testing for curvature, a quadratic term can be required in JMP. After removal of non-significant factors, data can be utilized to estimate curvature.

Comparison of Three Different Designs and the Choice of most Appropriate Design for the DoE

As mentioned in Section 2.2.1.2, the most suitable choices of design, based on the conditions and constraints of the DoE, are either a split-plot design or a D-optimal design. A split-plot design is suitable since it enables efficiency of the DoE and practical feasibility by the option to rank the factors (ETA or HTA). A D-optimal design is suitable since it enables efficiency of the DoE and allows center points and replications to be included in the design. Both the split-plot and D-optimal designs can be customized in the software program JMP, for suiting the specific conditions and constraints of the DoE in this research. Therefore, three different customized designs were compared, in order to evaluate which, the most appropriate design for the DoE was. The three different designs: D_1, D_2, and D_3 are summarized in Table 8 below. The superior choice, based on the assessment categories, of design was D_1, even if D_1 did not enabled ranking of the various factors (ETA and HTA). D_1 was the superior design in terms of: numbers of center points, number of replicates, estimation efficiency, and level of confounding. However, D_1 was not superior in terms of: number of experimental runs and number of factor adjustments. Sustaining a low number of experimental runs and a low number of factor adjustments were advocated for the DoE due to the dilemma of semi-HTA factors. Hence, the choice of design should advocate a small number of factor adjustments, even if the factors were defined as ETA. However, a design which do not generate the smallest number of factor adjustments could still be chosen, since it is feasible to adjust the factors in practice. However, that choice involves a risk of various context related implications. A D-optimal design (D_1) could therefore be applied, but it is not just preferred to adjust the factors too many times due to the risk of various context related implications.

Furthermore, the choice of appropriate design could also be motivated as either D_2 or D_3, since they provided the feature of ranking the factors (ETA and HTA) in order to sustain a low number of factor adjustments. However, the design should also include center points, in order to test for curvature. Including center points were requested by Volvo Cars, and should not be neglected. However, center points cannot be included in split-plot designs (D_2 or D_3). As explained by Volker Kraft, JMP Sr. Academic Ambassador: "*regarding center points in split-plot designs: split-plot designs use so-called whole-plots where you keep the HTA factors fixed. Plots are then split into sub-plots to vary the ETA factors. Because of the different whole-plots, there is no common center, and therefore no option for adding center points*" (Jones, & Nachtsheim, 2009). D_2 and D_3 are therefore less appealing as designs compared to D_1, where center points could be added. Further, a low level of confounding in the designs were requested as well. Hence, it is impossible to discern whether the effect on the response value is caused by X_1 or X_2 if they are confounded. The purpose of the DoE is to find which critical factors affect closure performance. Therefore, the factors must be distinguished in order to understand which factor that caused the effect on the response value, otherwise the research would fail to fulfill the purpose. Hence, the result of the DoE will be of no use if the design involves a high level of confounding.

Furthermore, the assessment categories were based on the previously mentioned constraints to adapt the design to: the dilemma of semi-HTA factors, time constraint, and confounding constraint. First, when assessing the time limitation constraint, number of experimental runs and number of factor adjustments were examined where lower is better. Second, when assessing the semi-HTA constraint, number of factor adjustments were examined where lower is better. Also, the possibility to rank the factors were examined, where it is better if it is possible to rank factors. Third, when assessing the confounding constraint, the color map on correlations were examined, where a low level of confounding was advocated. However, the design should enable test for curvature and to include replications in order to estimate noise. Therefore, number of center points and number of replicates were included as assessment categories where a high number of center points is better. Lastly, estimation efficiency is an in-built assessment category by JMP, which assess the fractional increase in confidence interval (CI) length and the relative standard (std) error of estimate for each term estimate in the model (JMP, 2018h). Where lower is better for both the fractional increase in CI length and the relative std error, further explained below.

Table 8. Comparison of three different designs for evaluation of most appropriate design for the DoE.

Assessment Category	D_1	D_2	D_3	**The Superior Choice**
Type of design	D-Optimal	Split-plot	Split-plot	-
Type of effects included in the design	Main effects only: X_1, X_2, X_3, and X_4	Main effects only: X_1, X_2, X_3, and X_4	Main effects only: X_1, X_2, X_3, and X_4	-
# of levels (min. 3)	2	2	3	D_3
Changes: ETA and HTA* (if possible to rank the factors the better)	X_1: ETA X_2: ETA X_3: ETA X_4: ETA	X_1: HTA X_2: HTA X_3: ETA X_4: ETA	X_1: HTA X_2: HTA X_3: ETA X_4: ETA	D_2 D_3
# of center points (the higher the better)	2	Not possible to include center points**	Not possible to include center points**. However, the 3-level design corresponds to center points, since it enables testing for curvature	D_1 D_3
# of replicates (the higher the better)	2	Not possible to include replicates	Not possible to include replicates	D_1
# of experimental runs (the lower the better)	9	6	9	D_2
# of factor adjustments of the HTA factors (the lower the better)* **	6****	4	6	D_2
Estimation efficiency* **	Fractional Increase in CI Length: [0.090 - 0.323] Relative Std Error Estimate: [0.363 - 0.441]	Fractional Increase in CI Length: [0.225 - 0.581] Relative Std Error Estimate: [0.500 - 0.645]	Fractional Increase in CI Length: [0.247 - 0.960] Relative Std Error Estimate: [0.416 - 0.653]	D_1
Confounding**** (assessed by color map correlations, the lower the better)**	Lowest	Average	Highest	D_1
SUMMARY***** **	4	3	3	

** ETA = easy to adjust and HTA = hard to adjust*
*** Center points cannot be included in a Split-plot design.*
**** See Section Number of Factor Adjustments of the HTA Factors below, for the motivation behind the decision.*
***** None of the factors were chosen as HTA for D_1, however the number of factor adjustments were counted for X_1 and X_2 just as for D_2 and D_3, since they were chosen as HTA.*
****** See Section Estimation Efficiency below, for the motivation behind the decision.*
******* See Section Confounding below, for the motivation behind the decision.*
******** The number of times a certain design was selected as the superior choice (the last column).*

Number of Factor Adjustments of the HTA Factors

Three different experimental run plans of the three different designs, D_1, D_2, and D_3, are provided below, see Table 9, Table 10, and Table 11. The tables can be used to examine which of the designs have the lowest number of factor adjustments of the HTA factors. A factor adjustment appears when a factor is adjusted between low level (-1 or uncovered), middle level (0 or half covered), and high level (1 or covered). For instance, a factor adjustment appears in D_1 between the first row and second row when X_1 is adjusted from -1 into 1, see Table 9. The number of factor adjustments are only counted for the HTA factors, X_1 and X_2. It is important to sustain a low number of adjustments for these factors since they are defined as HTA. None of the factors were defined as HTA for D_1, in order to include center points and replications. However, the number of factor adjustments are counted for X_1 and X_2 in D_1 as well, to make an equal assessment. Additional, the first row in each design is counted as an adjustment as well. Because the first row in each design do not represent the reference position (X_1=0, X_2=0, X_3=0, and X_4=uncovered). Hence, an adjustment had to be made between the reference position and the first row in order to set the factors into their levels. The first row is therefore counted as an adjustment as well. In Table 9, Table 10, and Table 11 below, the number of factor adjustments of the HTA factors X_1 and X_2 can be counted for each design. First, the highest number of factor adjustments of D_1 are six times. Second, the highest number of factor adjustments of D_2 are three times. Third, the highest number of factor adjustments of D_3 are six times. Hence, D_2 has the lowest number of factor adjustments, and are therefore the superior choice of design when comparing number of factor adjustments.

Table 9. The number of factor adjustments for D_1.

Run	X_1 Sealing Ingress (Y)	X_2 Striker Alignment (Z)	X_3 Door Frame	X_4 Cabin Air Evacuation	Y_1 Closure Speed [mm/s]	Y_2 Closure Energy [J]
1	1	-1	-1	Uncovered		
2	1	1	1	Uncovered		
3	0	0	0	Covered		
4	0	0	0	Covered		
5	-1	-1	1	Uncovered		
6	1	-1	1	Covered		
7	-1	1	-1	Covered		
8	1	1	1	Uncovered		
9	1	-1	-1	Uncovered		

Table 10. The number of factor adjustments for D_2.

Run	Whole Plots	X_1 Sealing Ingress (Y)	X_2 Striker Alignment (Z)	X_3 Door Frame	X_4 Cabin Air Evacuation	Y_1 Closure Speed [mm/s]	Y_2 Closure Energy [J]
1	1	-1	-1	-1	Uncovered		
2	1	-1	-1	1	Covered		
3	2	1	-1	-1	Covered		
4	3	-1	-1	1	Uncovered		
5	4	-1	1	-1	Covered		
6	5	1	1	1	Uncovered		

Table 11. The number of factor adjustments for D_3.

Run	Whole Plots	X_1 Sealing Ingress (Y)	X_2 Striker Alignment (Z)	X_3 Door Frame	X_4 Cabin Air Evacuation	Y_1 Closure Speed [mm/s]	Y_2 Closure Energy [J]
1	1	1	1	0	Half covered		
2	1	1	1	1	Covered		
3	2	0	-1	0	Uncovered		
4	2	0	-1	-1	Covered		
5	3	1	0	-1	Uncovered		
6	4	-1	0	0	Covered		
7	5	-1	1	-1	Uncovered		
8	6	0	0	1	Half covered		
9	7	-1	-1	1	Half covered		

Estimation Efficiency

The estimation efficiency reports of the three different design, D_1, D_2, and D_3, are provided below in Table 12. The estimation efficiency report provides the fractional increase in CI length and the relative std error of estimate for each factor (JMP, 2018h). The estimation efficiency report is used for assessing which of the designs that are the most appropriate to use for the DoE. The design with lowest value of both fractional increase in CI length and relative std error of estimate is the superior choice for the DoE (JMP, 2018h). First, when examining the three different estimation efficiency reports in Table 12 below, the fractional increase in CI length is within the range of [0.090 - 0.323] and the relative std error of estimate is within the range of [0.363 - 0.441] for D_1. Second, the fractional increase in CI length is within the range of [0.225 - 0.581] and the relative std error of estimate is within the range of [0.500 - 0.645] for D_2. Third, the fractional increase in CI length is within the range of [0.247 - 0.960] and the relative std error of estimate is within the range of [0.416 - 0.653] for D_3. Hence, D_1 has the lowest value of both the fractional increase in CI length and the relative std error, and is therefore the superior choice of design when comparing estimation efficiency.

Table 12. Estimation Efficiency of D_1 (upper left corner), D_2 (upper right corner), and D_3 (lower left corner).

Estimation Efficiency

Term	Fractional Increase in CI Length	Relative Std Error of Estimate
Intercept	0,09	0,363
X1 Sealing Ingress (Y)	0,323	0,441
X2 Striker Alignment (Z)	0,173	0,391
X3 Door Frame	0,173	0,391
X4 Cabin Air Evacuation	0,09	0,363

Estimation Efficiency

Term	Fractional Increase in CI Length	Relative Std Error of Estimate
Intercept	0,581	0,645
X1 Sealing Ingress (Y)	0,581	0,645
X2 Striker Alignment (Z)	0,581	0,645
X3 Door Frame	0,225	0,5
X4 Cabin Air Evacuation	0,225	0,5

Estimation Efficiency

Term	Fractional Increase in CI Length	Relative Std Error of Estimate
Intercept	0,563	0,521
X1 Sealing Ingress (Y) 1	0,621	0,54
X1 Sealing Ingress (Y) 2	0,854	0,618
X2 Striker Alignment (Z) 1	0,96	0,653
X2 Striker Alignment (Z) 2	0,491	0,497
X3 Door Frame 1	0,47	0,49
X3 Door Frame 2	0,247	0,416
X4 Cabin Air Evacuation 1	0,306	0,435
X4 Cabin Air Evacuation 2	0,417	0,472

Confounding

The color map on correlations reports of the three different design, D_1, D_2, and D_3, are provided below in in Figure 3. The color map on correlations report provides the level of confounding in the design (JMP, 2018i). The color map on correlations reports are used for assessing which the appropriate choice of design is for the DoE. The level of confounding is evaluated by the blue to red color scale, where blue indicates no confounding and red indicates high level of confounding in the design. When the different color maps are examined, see Figure 3 below, it can be determined that the lowest level of confounding is found in D_1. Where the area is covered by a higher number of bluish colored squares compared to D_2 and D_3. D_1 is therefore the superior choice of design. Note, only main effects are included in the design: X_1, X_2, X_3, and X_4. Hence, only main effects should be examined in the color map when assessing the level of confounding. The main effects are positioned in the upper left corner of each color map on correlations.

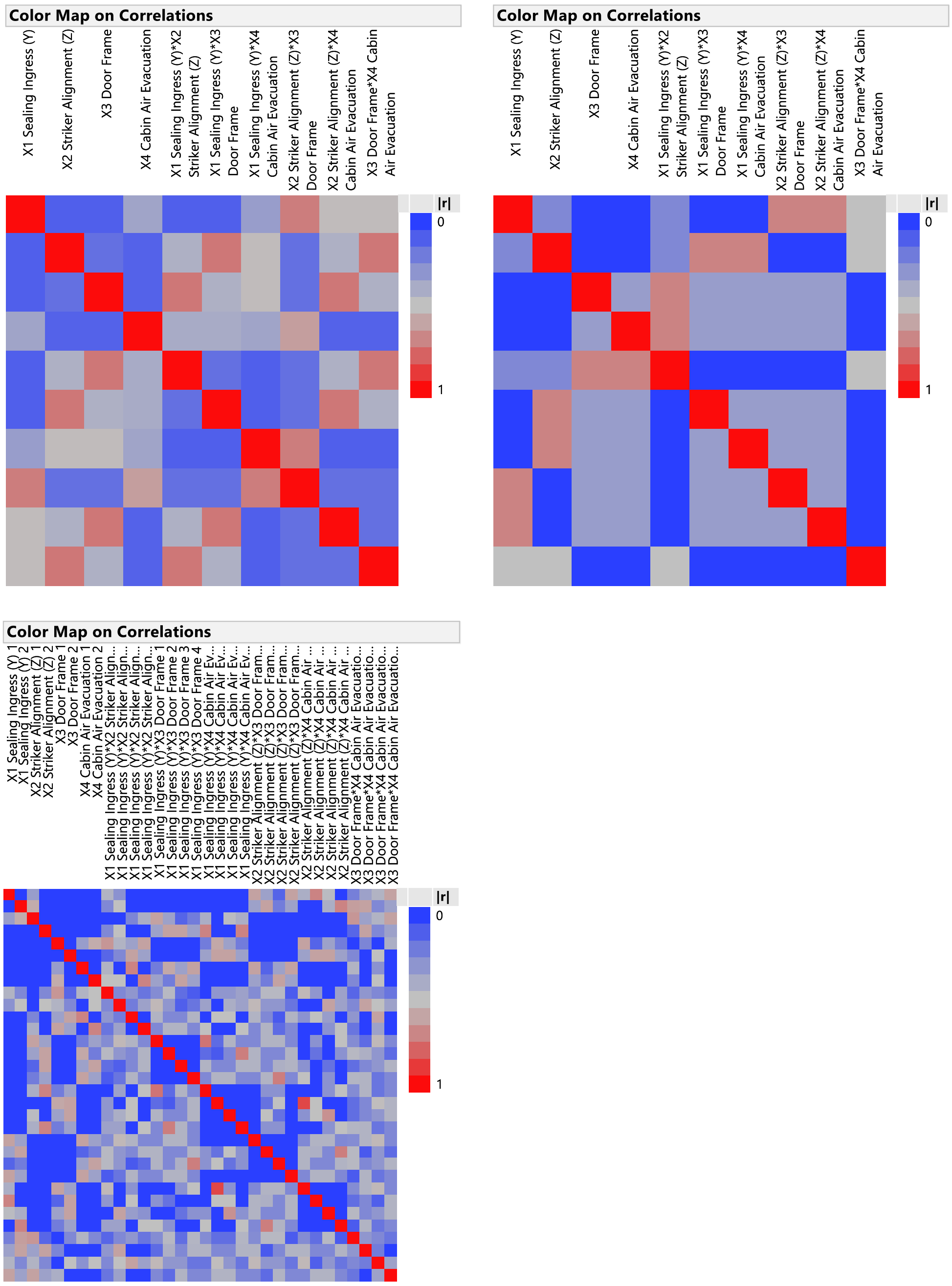

Figure 3. Color map on correlations for assessing confounding of D_1 (upper left corner), D_2 (upper right corner), and D_3 (lower left corner).

3.5.1.3 Execution Phase of the DoE

The third phase of the DoE cycle is execution phase. The following section describes the actual execution phase of the DoE, which includes: roles and responsibilities, set up for all the experimental runs, how the factors will be adjusted in practice, the experimental run plan generated by JMP, and EZSlam management during the DoE.

Roles and Responsibilities during the DoE

Roles and responsibilities during the execution of the DoE are provided in Table 13. Note, the table only involves persons present during the actual execution. There are more people involved in the actual planning and analysis of the DoE. People involved except from the researchers are kept anonymous to sustain ethical obligations.

Table 13. Roles and responsibilities during the experiment.

Name	Role	Responsibility
A*	Mechanic of the factor adjustments for X_1, X_2, X_3, and X_4	Making all the adjustments of the involved mechanical factors during the DoE execution
B*	Operator of the measurement device that measures the response values Y_1 and Y_2	Making all the measurements with EZSlam during the DoE execution
Emma Remgård	Project leader of the DoE	Plan the DoE and lead the execution, as well as analyse the results
Emma Wendelin	Project leader of the DoE	Plan the DoE and lead the execution, as well as analyse the results

**The involved mechanic and operator are kept anonymous to sustain ethical obligations.*

Setup for All the Experimental Runs

Below are an explanation of the setup for all experimental runs. It is important to conduct the experimental runs by the same conditions, in order to reduce experimental noise and variation. Hence, noise and variation between experimental runs might affect the result negatively.

First, all experimental runs will be carried out on the same car model, in the same location. The choice of location was based on the terms of the measurement device EZSlam, to reduce levels of disturbances. The most important conditions are to ensure constant temperature, low noise level, and low level of vibrations that might affect the measurement device. Further, the experiments will be conducted on the left side rear door only. All windows and other doors of the car will remain closed during the experiment to avoid impact of air evacuation. At each experimental run, the left side rear door will open and close from an angle of maximum open door. At each experimental run, the door will open and close according to the measurement procedure of the EZSlam software to ensure proper registration of the response values. All measurements of the response values will be carried out by the same operator using EZSlam, and adjusted by the same mechanic in order to reduce noise. Before each experimental run, the measurement device EZSlam is calibrated.

Second, a measurement tool is used to confirm the high and low level of the factor adjustments by the mechanic. The acceptable level of error when adjusting factors are 10% (Hammersberg, 2017a). All factors will be adjusted relative to a reference point. The reference points of all factors are noted as: X_1 = (0), X_2 = (0), X_3 = (0), and X_4 = (uncovered). In Figure 4 below, the reference positions for X_1, X_2, and X_3 are outlined. X_1 will be adjusted in the reference positions: 1, 2, and 3. X_2 will be adjusted in the reference position: 3. X_3 will be adjusted in the reference position: 2. X_4 will be adjusted by covering the cabin air evacuation using tape. The reference position of X_4 is: uncovered air evacuation vents.

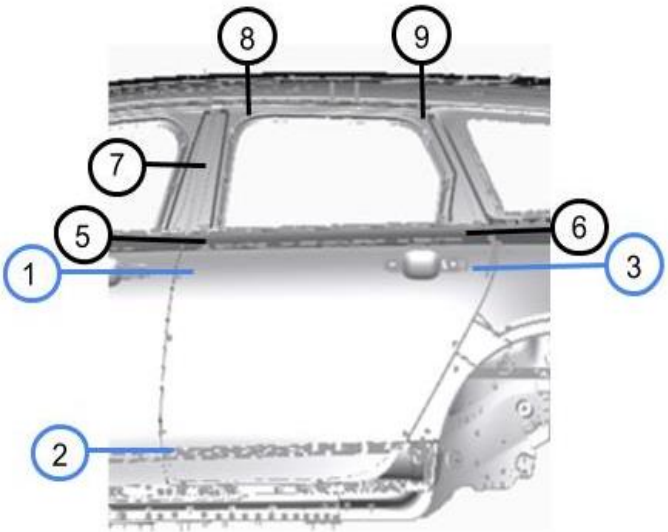

Figure 4. The positions of the reference points for the factor adjustments of X_1, X_2, and X_3.

How the Factors will be Adjusted in Practice

The following section describes in detail how the four factors will be adjusted into their high and low levels. The selected factors to be included in the DoE are shown in Figure 5.

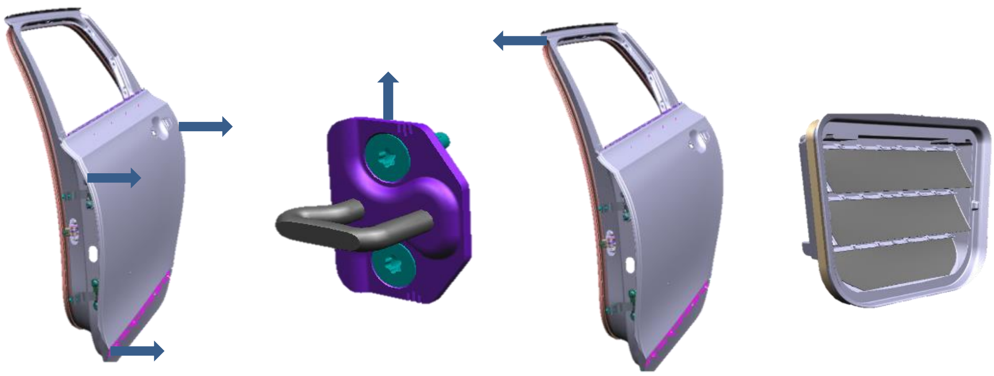

Figure 5. The four factors included in the DoE. The arrows shows the direction of the adjustment. From left to right: X_1, X_2, X_3, and X_4.

Factor X_1 Sealing Ingress in Y-Direction

Table 14 provides the adjustment explanation for X_1. A more detailed description of the adjustment is provided after the table.

Table 14. The adjustments explanation for X1 Sealing Ingress.

Factor	Adjustment	Notice	Time to Adjust
X_1 Sealing Ingress	Unscrew one hinge at a time for keeping the rear door in place. Adjust rear door position in y-direction: low level = - 1 mm towards car body, high level = + 1 mm outwards car body, in position 1, 2, and 3. Secure the door in the position by screw in hinges.	Reposition the striker alignment in y-direction by the same distance in position 3, to remain the distance between the rear door position and striker position constant.	~ 15 min

The sealing system of the rear door is constructed by two different sealings: a body mounted sealing and a door mounted sealing. The sealings should be treated as a system. In order to adjust sealing ingress between body and door when closing the rear door, the sealings should be repositioned in distance. Sealing ingress is determined by the positions of the sealings. If both the sealings are positioned closed to each other, a greater ingress will occur when closing the door. If both the sealings are positioned far away from each other, a smaller ingress will occur when closing the door. Hence, reposition of sealings will create different distances between them, and sealing ingress can be tested. Both the door and body mounted sealings are considered as difficult to adjust in practice, but it is feasible to adjust them. The door mounted sealing is fastened by glue. The body mounted sealing is clamped by a flange. The type of fastening makes adjustments of the sealings difficult. Also, once the sealings are removed, they are consumed and cannot be reused. Therefore, new sealings must be used in each adjustment when conducting the experimental runs. This increase the costs of the experiments. Also, the sealings are made by rubber which is a material characterized by a change of stiffness over time. Sealings characterized by less stiffness will reduce resistance between the door and body mounted sealing when closing the door. The ingress between the sealings will appear smoother and provide total closure of the door. Hence, adjusting the positions of the sealings by removing them and add new ones, will require a waiting-time between each substitution to ensure that the new sealings have reached the same level of stiffness before proceeding with the experimental runs. Therefore, the stiffness of sealings should not be changed, it has to remain constant during all experimental runs. Otherwise it will affect the result of the experiment. This waiting time is estimated to 12-20 h. Which will affect the experiment by not be completed within the specified time.

Due to the difficulties involved when adjusting sealing ingress, it was determined to adjust sealing ingress without removing and reposition the sealings themselves. To be able to adjust the sealing ingress, it was decided to adjust the position of the rear door in y-direction. Adjusting the position of the rear door will correspond to the same reposition of sealings as discussed above. Adjusting the door position in y-direction requires less efforts than removing the sealings and add new ones. It will also decrease costs, time, and risk of uneven stiffness levels of the sealings. The adjustment of the rear door can be seen in Figure 6 below. The rear door will be adjusted within the interval of -1 mm to + 1 mm in y-direction from the reference point (1, 2, and 3). The high level will be +1 mm relative the reference point, the direction is outwards the car body. The low level will be -1 mm relative the reference point, the direction is towards the car body.

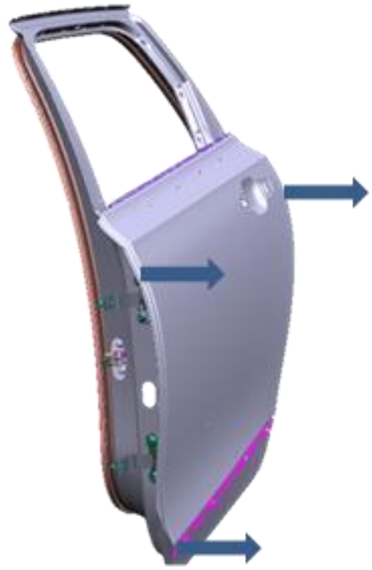

Figure 6. The adjustment of X_1 Sealing Ingress.
The arrows show the direction of the adjustment.

When adjusting the rear door back and forth in y-direction, the striker position in y-direction must be repositioned by the same adjustment as the rear door. This must be made in order to remain the relation in y-direction constant between rear door position and striker position. Otherwise it will affect the result of the experiment if not remaining the relationship constant. Also, there is a risk of a change in height for the rear door due to gravity when disassembling rear door from hinges.

Factor X_2: Striker Alignment in Z-Direction

Table 15 provides the adjustment explanation for X_2. A more detailed description of the adjustment is provided after the table.

Table 15. The adjustments explanation for X_2 Striker Alignment.

Factor	Adjustment	Notice	Time to Adjust
X_2 Striker Alignment	Hit the striker for adjust in position. Adjust striker position in z-direction: low level = -1 mm towards the car ground, high level = +1 mm upwards the car ground.	Caution when adjusting the striker. The area where the striker is mounted might be damaged due to material fatigue or crack initial when adjusting.	~ 15 min

Striker alignment is considered as an easy factor to adjust in practice. The striker is mounted on the car body and will be adjusted by the mechanic using a tool to hit the striker into the high and low levels. This will allow the striker to move from the reference position (3). There is a risk of material fatigue or crack initiation in the area where the striker is mounted when adjusting. Even if the striker is considered as easy to adjust, the number of times for adjustments should be kept low. The adjustment of the striker can be seen in Figure 7 below and will only be adjusted in z-direction. The striker will be adjusted within the interval of -1 mm to +1 mm. The high level will be +1 mm relative the reference position (3), the direction is upwards the car ground. The low level will be -1 mm relative the reference position (3), the direction is towards the car ground. As mentioned above, the striker position in y-direction is related to the door position in y-direction. Hence, this relationship is important to sustain during the experiment. Otherwise it will affect the result.

Figure 7. The adjustment of X_2 Striker Alignment.
The arrow shows the direction of the adjustment.

Factor X_3: Door Frame Position

Table 16 provides the adjustment explanation for X_3. A more detailed description of the adjustment is provided after the table.

Table 16. The adjustments explanation for X_3 Door Frame Position.

Factor	Adjustment	Notice	Time to Adjust
X_3 Door Frame Position	As low level, the door will be tilted 0.5 mm towards the car body in position 2, creating an ingress between the sealings. As high level, the door will be tilted 1 mm towards the car body in position 2, creating an ingress between the sealings	Keep the same position in reference points 1 and 3 in order to tilt the door in a correct way.	~ 15 min

The door frame is considered as difficult to adjust in practice, but it is feasible to adjust. The door frame is tilted as the nominal value when constructing the door frame. The construction of the door frame is tilted by bending the upper section of the door towards the car body to create an increased ingress between the sealings. Where the door frame does not follow the nominal car body profile. The increased ingress between the sealings will sustain a total sealed door when affected by aerodynamic when driving, which imposes the door frame to move outwards from the car body. When adjusting X_3, it is important to reconstruct a situation which corresponds to that sealing ingress when bending the door frame. In order to reconstruct a situation corresponding to the same sealing ingress at the upper section of the door, the rear door will be repositioned in y-direction at the lower section of the door by adjusting the position outwards the car body. This will allow the upper section of the rear door to be tilted towards the car body. When tilting the rear door towards the car body, an ingress between the sealings will occur, which will correspond to the same ingress when bending the door frame in production. In Figure 8, the adjustment of the door frame for the experiment is shown.

Figure 8. The adjustment of X_3 door frame.
The arrow shows the direction of the adjustment.

As low level, the door will be tilted 0.5 mm towards the car body. As high level, the door will be tilted 1 mm towards the car body. It is easier to ensure an ingress between the sealings by adjusting door position in lower section of the door and then tilt the door towards the car body, instead of bending the door frame. When bending the door frame, inner tensions have to be overcome in order to achieve the wanted sealing ingress. It might also be difficult to remain the sealing ingress due to the inner tensions forcing the door frame to swing back. Additional, it is important to consider the above-mentioned factor X_1 when adjusting X_3. Because X_1 will be adjusted in y-direction as well, which indicates that there are internal relationships between X_1 and X_3. When adjusting the door frame by first changing position in y-direction to allow space to tilt the door, current position of the door in y-direction due to X_1 must be taken into consideration. Whether if X_1 is set into the high or low level, X_3 should be adjusted 0.5 mm towards the car body from the reference position of X_3 (2) when adjusting into low level of X_3.

Factor X_4: Cabin Air Evacuation

Table 17 provides the adjustment explanation for X_4. A more detailed description of the adjustment is provided after the table.

Table 17. The adjustments explanation for X_4 Cabin Air Evacuation.

Factor	Adjustment	Notice	Time to Adjust
X_4 Cabin Air Evacuation	For the body mounted air evacuation area: as low level, the air evacuation area will be total covered using tape. As high level, the air evacuation area will be uncovered.		~ 5 min

The body mounted air evacuation area is considered as easy to adjust in practice. When closing the door, air within the cabin will be confined and thereby hinder the door to result in total closure. If the confined cabin air is not removed, the air pressure peak occurring when closing will oppose the closure. The body mounted air evacuation tunnel is used to remove and transport air from the cabin and thereby facilitate closure. The air evacuation tunnel starts from the cabin and continues to the rear section of the car body. Here is where the vent is placed, releasing air from the cabin. Further, as low level, the air evacuation vent will be total covered using tape. As high level, the air evacuation area will be total uncovered. In order to access the air evacuation vents, the bumper must to be demounted. The bumper will be mounted again after conducting all the experimental runs. The air evacuation vets are shown in Figure 9 below. As mentioned above, after expert consultation with the Department of Climate at Volvo Cars, it was decided to set the low and high levels to total covered and uncovered. This was decided due to air evacuation simulations demonstrating how cabin air was removed and transported through the air evacuation vents. The simulations showed that only a small part of the whole vent was utilized by the air for transportation. Hence, only covering a small part of the air evacuation vent, for example only cover half of the area would be indifferent.

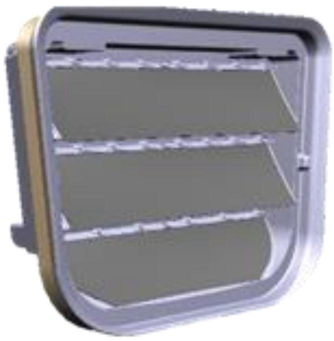

Figure 9. Air evacuation vents which will be covered by tape for the adjustments of X_4 Cabin Air Evacuation.

The Plan of the Experimental Runs Generated by JMP

Table 18 below provides the experimental runs of the DoE. For each run will all factors be adjusted into its high and low level. The plan is generated by the software program JMP. The execution schedule of the DoE can be found in Appendix 6.

Table 18. The Experimental run plan for the DoE generated by JMP.

Run	X_1 Sealing Ingress (Y)	X_2 Striker Alignment (Z)	X_3 Door Frame	X_4 Cabin Air Evacuation	Y_1 Closure Speed [mm/s]	Y_2 Closure Energy [J]
1	1	-1	-1	Uncovered		
2	1	1	1	Uncovered		
3	0	0	0	Covered		
4	0	0	0	Covered		
5	-1	-1	1	Uncovered		
6	1	-1	1	Covered		
7	-1	1	-1	Covered		
8	1	1	1	Uncovered		
9	1	-1	-1	Uncovered		

EZSlam Management during the DoE

Table 19 provides the management of EZSlam during the DoE. A more detailed description of the management is provided after the table.

Table 19. The management of EZSlam during the DoE.

Device	Installation	Notice	Time to Adjust
EZSlam	EZSlam will be mounted on the left rear door (the test door) using suction cups.	EZSlam should be managed by the operator only. Measurement instructions for EZSlam for collecting the closure speed and energy data is provided by a software program and must not be ignored. Each step of the instructions must be approved before continuing.	~ 10 min

Between each experimental run, the measurement device EZSlam is used to measure the response values, closure speed (Y_1) and closure energy (Y_2). EZSlam will be used by one operator who makes all the measurements, to reduce noise. EZSlam will be mounted on the left side rear door using suction cups. If possible, the measurement device should be kept in assembly position and not be removed during the DoE. If the factors cannot be adjusted without removing EZSlam, the position of the mounted EZSlam should be noted prior removal to ensure the same assembly position when remounting the device. EZSlam is programmed to follow a software program, which provides instructions on how to conduct the measurement tests. The software program should not be ignored, and each step of the program must be approved before continuing.

3.5.2 Methodology for Analyzing the Design of Experiments

The last phase of the DoE cycle is analyzing phase. The following section provides the method and key measures used for analyzing the DoE after completing all experimental runs. The section includes: parameter estimates, prediction profiler, prediction expression, and evaluation of the model. The summary of the section can be found in Appendix 7.

3.5.2.1 Parameter Estimates

The parameter estimates report provides the p-value of each factor (JMP, 2018a; JMP, 2018b). The p-value determines whether the factor is significant or non-significant. If the p-value is below 0.05, the factor is considered as significant and should thereby be remained as a term in the model (the prediction expression mentioned below). If the p-value is above 0.05, the factor is considered as non-significant and should thereby be removed from the model (JMP, 2012). When removing non-significant factors, they should be removed one-by-one using the software JMP, starting with the least significant factor.

3.5.2.2 Prediction Profiler

The prediction profiler provides graphs which visualizes how the various factors are changing when adjusted from high and low levels. Hence, the relationship between the response value Y_n and the factor X_m can be examined by changing X_m into high and low level meanwhile noting the response value Y_n.

3.5.2.3 Prediction Expression

When completing all the runs in accordance with the DoE plan generated by JMP, the prediction expression is as follow, see Equation 3.1 below. Where Y_n = the response value, a_m = the coefficient, X_m = the factor, and together the $a_m * X_m$ is the prediction term. The prediction expression is the mathematical explanation of the model which describes the relationship between response value Y_n, and factors X_m based on the experiment (JMP, 2018g). However, when completing all experimental runs, JMP might generate a prediction expression that involves many terms, including non-significant factors. The aim is to reduce the expression by removal of non-significant factors. If the factor is significant, the factor has a high effect on the response values and should be kept. However, factors must be removed without decreasing the quality of the model. RSquare and RSquare Adj can be examined when removing non-significant factors to confirm quality of the model, see Section 3.5.2.4 below for explanation (Minitab, 2018a). The prediction expression can be used for calculating what specific values the factors should have, in order to reach a certain response value. For instance, the values of the factors can be calculated for reaching a certain critical value of the response. Hence, the prediction expression can be used to improve quality of the closure performance. The outcome of the closure event can be understood in advance by applying the prediction expression. The arrangement of the mechanical factors can be examined in advanced, in order to understand what the optimal arrangement of the factors are to achieve high quality closure performance.

$$Y_n = a_1 * X_1 + a_2 * X_2 + a_3 * X_3 + a_4 * X_4 + \cdots + a_m * X_m \qquad (3.1)$$

3.5.2.4 Evaluation of the Model

The quality of the model can be examined in JMP. Different measures can be applied for increasing the quality of the model. For the analysis, the model is assumed to have high quality if the model is improved by the measure. The model is assumed to have poor quality if the model is not improved by the measure. The quality of the model will be assessed by examining RSquare and RSquare Adj values. Also, since linear assumptions are assumed for the model, the linear assumption will be tested by using center points. If the linear assumptions are confirmed by the test, the quality of the model are assumed as high. The following sections are discussed below: summary of fit report and center points (JMP, 2018d; JMP, 2009).

Summary of Fit

The summary of fit report provides the RSquare and RSquare Adj values. First, according to Minitab (2018a): *"RSquare is the percentage of variation in the response that is explained by the model"*. Where the RSquare value is utilized for determine how well the model fits the data. The level of approval is assumed to minimum 50%. A higher value of RSquare indicates a better fit between the model and the data (Minitab, 2018a). However, the RSquare value will always increase when adding predicting terms (factors) to the model, even if the model was not improved by the additional term. The same reasoning applies for the reverse; the RSquare value will always decrease when removing predicting terms from the model, regardless whether the model was improved or not by the removal. Therefore, it is important to pay attention to the RSquare Adj value as well when examine the RSquare value. According to

Minitab (2018b): *"RSquare Adj is the percentage of the variation in the response that is explained by the model, adjusted for the number of predictors in the model relative to the number of observations"*. Where the RSquare Adj value is utilized when comparing models constructed by different numbers of predicting terms. If the RSquare Adj value was decreased after adding a prediction term to the model, the quality of the model was not improved. The level of approval is assumed to minimum 50%. Hence, just adding prediction terms in the model to increase the RSquare value will not always improve the quality of the model, even if the RSquare value increase and are above 50%. The RSquare Adj value should therefore be examined as well.

Center points

Since the design is a two-level design, a linear model relationship between the response values and factors is assumed. Center points can be added in the design, in order to test the linear assumptions (JMP, 2018f). If a factor is assumed to have nonlinear effect on the response, a quadratic term X_m^2 for the model can be requested in JMP. The quadratic term can then be tested for significance by examining the term in the parameter estimates report. If the quadratic term is non-significant (p-value above 0.05) the linear model assumptions can be confirmed. If the quadratic term is significant (p-value below 0.05) the linear model assumptions can be rejected. This indicates that the relationship between the response value and factors consists of curvature. If the linear model assumptions are rejected, the design has to be augmented. Augmented design is when additional experimental runs are added to the current experiment in order to examine e.g. curvatures (JMP, 2018c; JMP, 2018d).

Section 4
Analysis and Results

In following section, both the analysis of the qualitative and quantitative study are provided. The analyzes are based on above mentioned analytical methodologies, see Section 3.4.2 and Section 3.5.2.

4.1 Analysis of the Qualitative Interview Study

This analysis is based on the qualitative study that was described in Section 3.4, which resulted in the relationship map that can be found in Appendix 5. The relationship map resulted in a broader system perspective of the closure challenge, and visualizes the high level of complexity regarding the construction of automotive rear doors and the closure performance in practice. The closure performance of the rear door is a complex function, dependent on various factors. Both related to mechanical constructions of the rear door, but also related to organizational issues, cultural aspects, process related factors e.g. processes applied when building car models in CATIA, and processes applied when tolerancing etc. Also, the complexity involves difficulties in terms of how to understand how various factors affect closure performance e.g. which of the factors are main contributors for affecting closure performance negatively. The relationship map provides a wide foundation for fundamental understanding of the system perspective, due to the various aspects involved e.g. mechanical factors, process factors, soft factors, and requirement factors. Therefore, the continued analysis of the interview study will mainly be based on the relationship map. Important to remember, axial coding as a tool for analyzing the interview study was based on the researchers' own analyzing ability result in logical sequential reasoning of consequences. Hence, the various relationships between 'headlines' in the relationship map are estimations, and cannot be supported by science. The analysis is organized by division into sections based on segmentations: 'mechanical factors', 'process factors', 'soft factors', and 'requirement factors'. Note, both segmentations: 'car models' and 'other' are excluded from the analysis.

4.1.1 Mechanical Factors

The following section describe the analysis of the segment: 'mechanical factors'. Mechanical factors are fundamental to rear door closure performance. However, there are different opinions regarding which mechanical factor affect closure performance the most: *"the sealing system is* *one of the main contributors affecting closure performance"* or *"the large spread within tolerances resulting in a changed geometry affect closure performance"*. Compared to: *"geometry is not the main cause of poor closure performance"* or *"the air evacuation is the biggest problem affecting closure performance"*. There is a large spread in opinions between departments and functions: *"all have different perspective of what affects closure performance"*. The sealing system have been mentioned by many functions as one of the main contributors affecting closure performance. For instance, the different characteristics of sealings e.g. level of stiffness, ability to evacuate air, ability to deliver total seal etc., are important to take into consideration in order to ensure high performing door closure event. The sealings are constructed to seal well by high stiffness, however, it may result in harder to close. Further, related to sealings are the door frame. When the car is in motion, aerodynamic forces imposes the door frame to move outwards from the car body. Sealings must be able to seal in these conditions as well, by ensuring a larger ingress between sealing and door frame. A large ingress will be difficult to assure if the sealing is characterized by a high stiffness. Furthermore, to control the door swing and to assure a stationary open door, a door stop is required. The door stop opposes door closure since it should assure a stationary open door, and thereby affect the closure performance negatively. Also, the door stop is equipped with springs where friction might appear, which also affect closure performance. Another factor affecting closure performance is the striker. The latch and the striker (which constitutes the door lock) need to have proper alignment for total closure. Hence, just by mention a few, it can be understood that these different requirements among the mechanical factors do not easily comply.

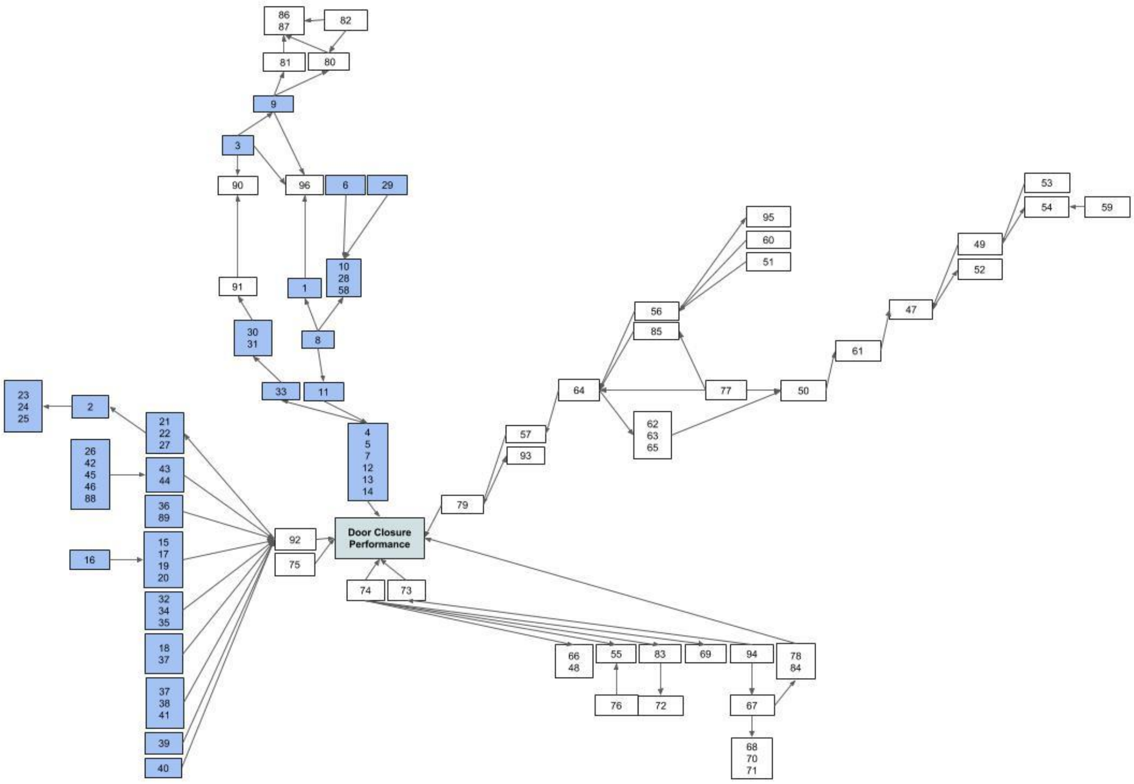

Figure 10. A group of mechanical related factors, colored as blue in the relationship map.

All mechanical related factors affecting door closure performance is outlined in the relationship map, see Figure 10 above. These are (1-46), see Appendix 5 and Appendix 4 for translation of each number in the relationship map. However, even in the relationship-map it is difficult to distinguish which of these mechanical factors have the largest impact on door closure performance. They are all related to (92) or to (13, 7, 14, 5, 4, 12) which all affects the closure performance. However, there is a longer derived relationship branch for (13, 7, 14, 5, 4, 12), relating to (33, 11, 30, 31, 1, 10, 28, 58, 6, 29, 3, 9) see Figure 11 below.

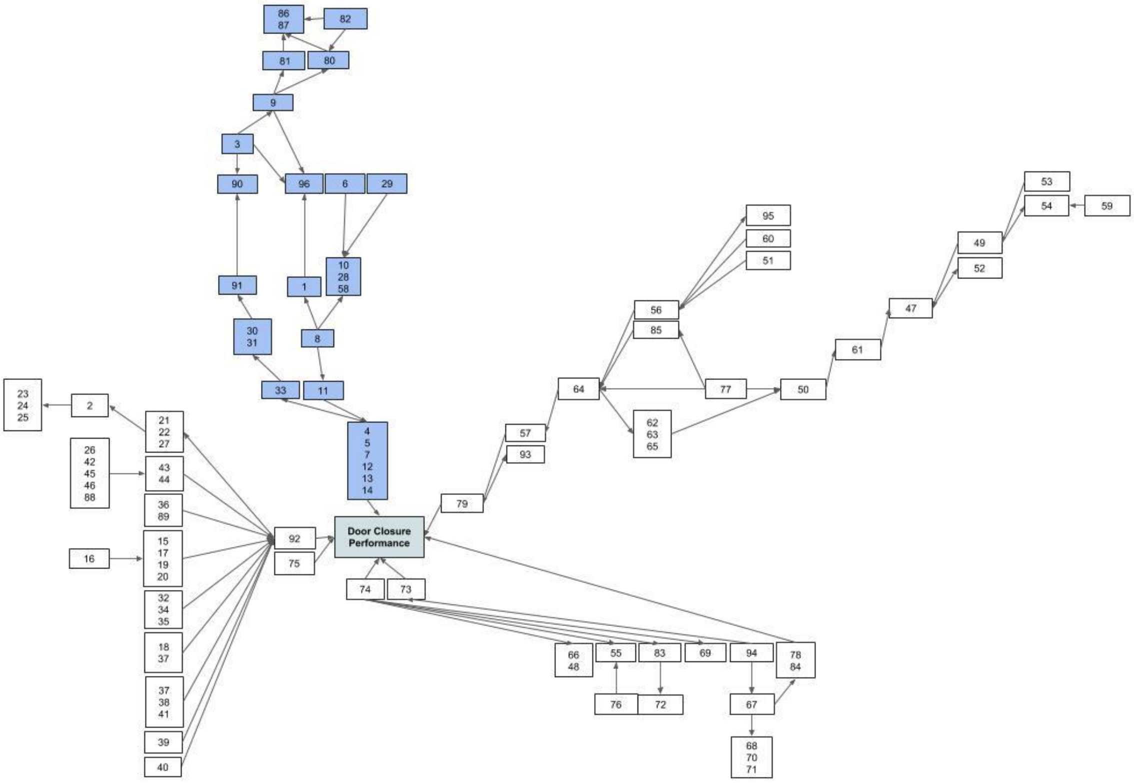

Figure 11. A longer derived relationship.

The factors within this branch are in majority related to sealings or to door lock issues. Which indicates that further investigations should include sealings and door lock as important contributors affecting closure performance. As mentioned above, it is difficult to distinguish which of these mechanical factors have the largest impact on door closure performance. The factors are not summarized into one branch, resulting in one end-point indicating that this factor could be a possible cause of poor closure performance. Instead, the mechanical factors are spread, creating a network of different branches in the relationship-map. The challenge is to weight these different factors, compare them to each other, in order to understand which, affect closure performance the most. This issue was also included as a factor in the relationship-map, weighted factors (73), and mentioned by many interviewees as well, comment that the difficulties is how to weight the factors: *"we are well aware of all different factors affecting closure performance. However, the difficulties are how to determine which affect the most"*.

The overview of the relationship-map cannot derive which mechanical factor affects the closure performance most. The mechanical factors must be weighed and compared to each other, to determine which affect the most. Also, the comparison should be based on quantitative data. It is difficult to rank and analyze the different mechanical factors in order to understand which affect the most by only using qualitative data based on the interview study. The qualitative data can be used to understand how they affect, and for contextual understanding (Bryman & Bell, 2015). However, the qualitative data should be supported by quantitative data, providing facts of which mechanical factors have the largest impact on closure performance.

4.1.2 Process Factors

The following section describe the analysis of the segment: ‘process factors’. Based on the interviews, different process related factors affecting closure performance as well. Process related factors include the way from construction to production and those situations the door follow through the production process. Currently, there are no simulation of the door closure event. In the relationship-map, the process related factors affecting door closure performance are outlined, see Figure 12 below. These are (47-65), see Appendix 5 and Appendix 4 for translation of each number in the relationship map.

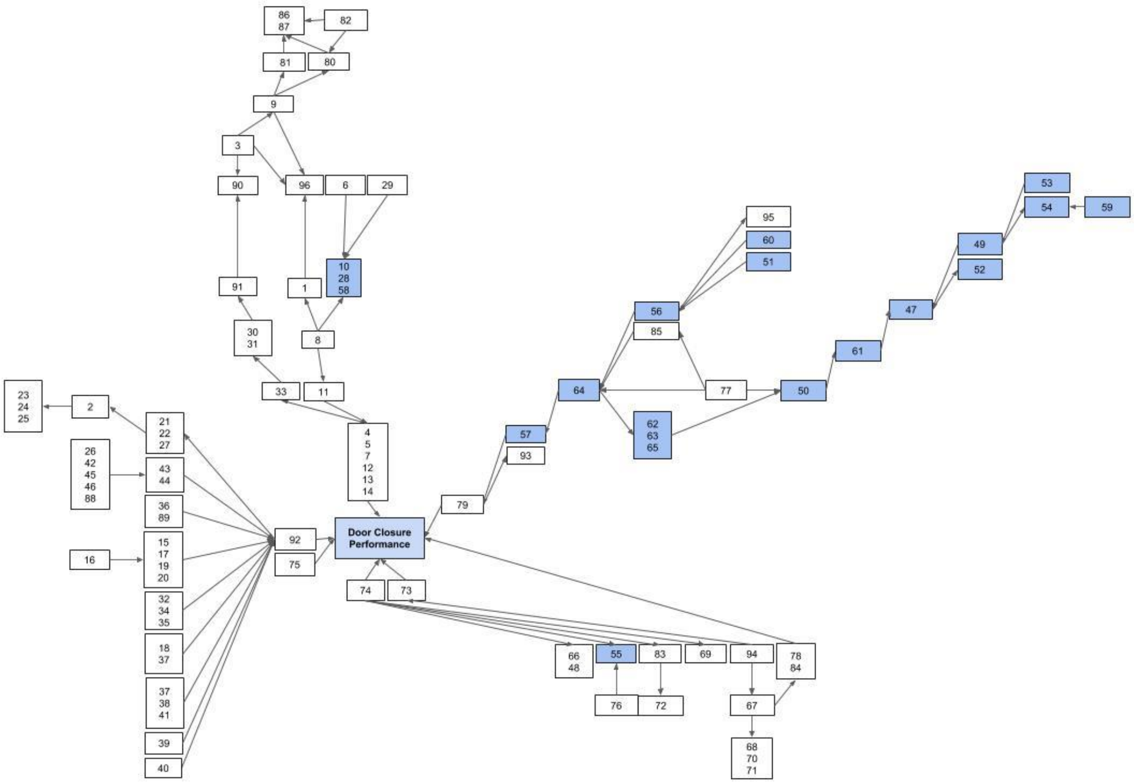

Figure 12. A group of process related factors, colored as blue in the relationship map.

Compared to the mechanical related factors, these factors are arranged into a longer branch. Hence, there is a longer derived relationship branch for the process related factors, indicating a sequence of factors affecting each other. The start-point of the branch is (79), and the end-points of the branch are (59). The total branch encompasses following factors: (79, 93, 57, 64, 62, 63, 65, 56, 85, 77, 95, 60, 51, 50, 61, 47, 49, 52, 53, 54, 59). Where the factors within this branch are in majority related to geometry, tolerance, and requirement issues. When analyzing the branch, the main issues can be summarized into that the lack of appropriate measurement management (59). This results in changed tolerances for suiting the situation (61), which both affects geometry of the construction (57) and when building CAD models in the software program CATIA (49). The branch is ended in measurement (54), which include the non-use of measurement data from production, also the possible variation within the measurement device. Comment as: *"the measurement system should be questioned since there is variation within the measurement data. One day the sample indicates good results, but the other day the sample indicates the opposite"*. This is assumed to influence the variation within the door process in production as well, and resulting in poor closure performance. No measurement data can be trusted if the measurement system involves variation. Also, if not utilizing measurement data from production as basic facts when designing, there will be a gap between the actual outcome in production and the designed outcome. Hence, the poor closure performance could be an issue due to the non-use of measurement data from production, providing unreliable data as the base for the CAD model. The CAD model then constitutes the base for the further developed construction to be built on. It is important to build the CAD model on reliable data: the data from the actual outcome from production, and not build the CAD model based on 'previous data', as mentioned: *"the tolerances and reference systems are based on previous data from earlier projects"*. However, during the interviews, it was also mentioned that there is an unwillingness within the organization for changing tolerances in the model: *"the tolerances should be smaller. However, people are often afraid of changes and prefer not to"*, also included as (64, 85) in the relationship-map affecting (57). This could be a possible reason for not utilizing measurement data from production when designing. This would refer to culture and organizational issues affecting closure performance. However, it is difficult to know whether the variation within the door process in production is due to the non-use of measurement data from production when building models, or due to the process applied when building models in CATIA mentioned during the interviews: *"there are differences in how to build models in CATIA. There is no common routine for the process applied when building models in CATIA, everyone draws the model differently and there are different directions how much allowed to differ from the tolerances"*.

Further, the comments of the too large tolerances (64): *"currently, the tolerances are too big. For instance, the tolerances of the position for sealings are ± 2.5 mm. However, problems will already occur if the sealings ends within ± 1 mm which is within the allowed area"*, could be a possible reason for the non-robust tolerance system (62): *"the tolerance system is too sensitive"*. Also comment as: *"the tolerances do not add up. The tolerance chain calculations are a weak system, there is always gap or flush issues"*. Hence, the too big tolerances (64) could cause cascade effects affecting the tolerance chain (63) as outlined in the relationship-map. Currently, if utilizing worst case scenario of the tolerance: the maximum tolerance allowed for the article, if repeated for all articles the added tolerances would not be approved, as comment: *"all the variation within the different articles will affect, the tolerances is a chain reaction. The tolerances do not add up"*. Which affects the whole system of robustness regarding tolerances. For instance, the door positioning in production (56) would be affected by this. However, it is difficult to state why the too big tolerances (64) currently exist within the organization. Of course, big tolerances are beneficial within manufacturing since it allows a larger area of production approval for the article. Also, as mentioned above, this could refer to the unwillingness of changing tolerances due to cultural and organizational aspects as well. However, just reduce the tolerances will not solve the issue of variation in production: *“just changing the tolerances do not really solve the problem. The system should be able to manage variation, but the system is too sensitive”*.

4.1.3 Soft Factors

The following section describe the analysis of the segment: ‘soft factors’. In the relationship-map, the soft related factors affecting door closure performance are outlined, see Figure 13 below. These are (66-76), see Appendix 5 and Appendix 4 for translation of each number in the relationship map.

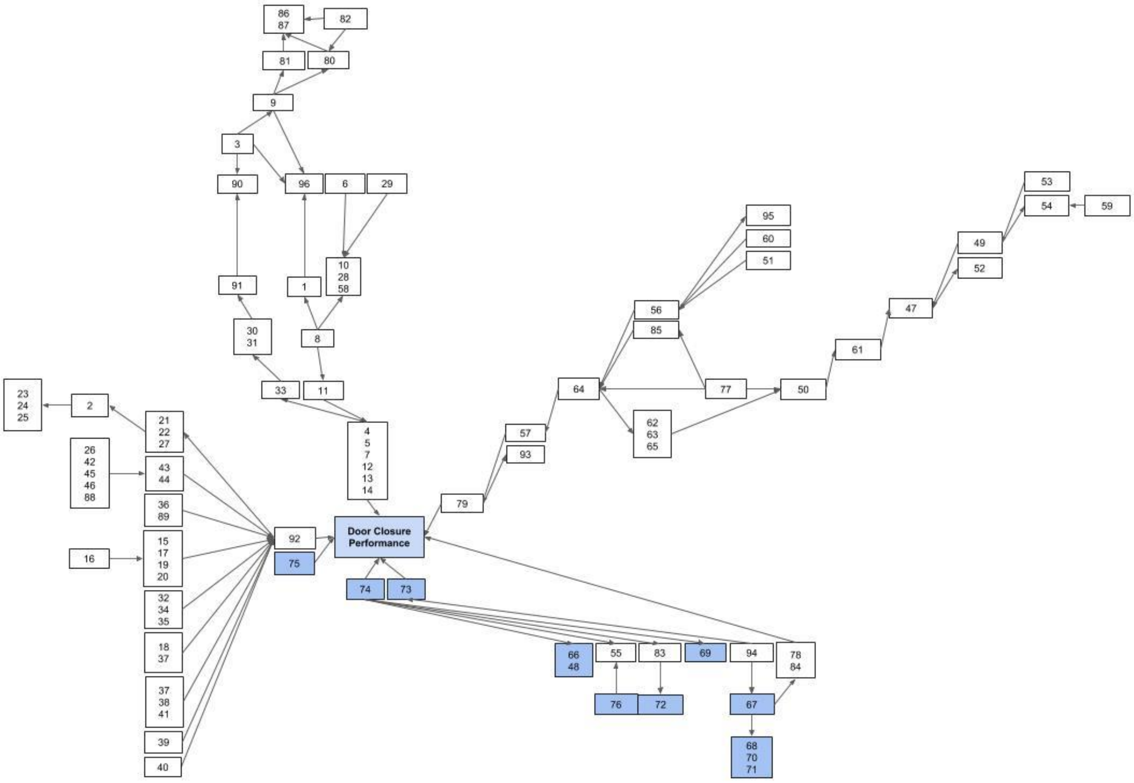

Figure 13. A group of soft related factors, colored as blue in the relationship map.

Soft factors are not distributed as one branch, as for the process related factors mentioned above. Instead, they are spread into a network similar to the mechanical related factors. This indicates that it is difficult to weight which of the soft related factors affect closure performance the most. Hence, the factors are not summarized into one branch, resulting in one end-point which could be a possible cause of poor closure performance. However, silo (74) relate to (66, 48, 55, 83, 69, 76, 72), which indicate that the current existing silo culture or structure affect the possibility of distributing customer facts, there is an internal customer focus (48, 66), as well as the flow of information is limited (55). There is an internal conflict between different functions regarding requirements (83), comment as: *“it is difficult when the problems lies within the interfaces between different functions, whom is responsible then?”*. Hence, there might be a silo culture and organizational structure which inhibit functions from determine requirements appropriate for the system perspective, instead of just be beneficial for the function alone *"design department have main focus on the esthetics regarding rear doors, we do not focus on functionality or poor closure performance. It is not our problem"*. For instance, the door should seal properly to block noise. However, the door will be harder to close when sealings are used. Which relate to the need of finding a balanced solution (72) among the different functions' requirements for the closure performance, enabling a successful closure justified by all functions involved of the closure performance. Also, it affects the possibility of creating a unified picture of what are the most important requirements from a customer perspective (69) if no information can be distributed efficiently nor accepted as important by the different functions. Additionally, as mentioned during the interviews: *"there are many investigations regarding poor closure performance of rear doors, providing information of the issue. However, there a no compilation among the functions which unites and direct the work for solving the issue"*. Which indicates that there are many investigations and projects regarding closure performance. However, there are no common compilations summarizing the different investigations (94), which affect the possibility of weight the different factors affecting closure performance correctly (73). The lack of a common compilation of investigations could be a possible situation caused by the silo and function culture within the organization. Which might inhibit findings of investigations to be distributed among other functions. Further, the difficulties in providing a common definition of a proper closure performance (78), and due to the existing subjectivity how people interpret 'good closure' (84), affect the closure performance in terms of how to direct the work for creating a high performing closure event. Hence, the actual closure event consists of feelings; the closure should 'feel robust', providing a high-quality feeling: *"attractiveness is important for reaching premium feeling among the customers. It is important that the closure feels good"*. The closure should also sound good: *"it is important that the closure sounds good, the closure should be experienced as high quality. However, it is very difficult to measure sound and to determine whether it sounds good or bad. How do you measure music?"*. The closure event should also ensure a proper sealed door within the specified speed and energy requirements. All of these conditions of a successful closure event involve subjectivity and are difficult to measure. Also, as comment: *"the customer might also think differently. They notice some things but do not care about other things. However, this could be totally different compared to what Volvo believes is the most important issues to put focus on"*. Further, the present of subjectivity when assessing the closure performance also affect the difficulties in providing a total standardized customer complaint report (68, 70).

4.1.4 Requirement Factors

The following section describe the analysis of the segment: 'requirement factors'. In the relationship-map, the requirement related factors affecting door closure performance are outlined, see Figure 14 below. These are (77-85), see Appendix 5 and Appendix 4 for translation of each number in the relationship map.

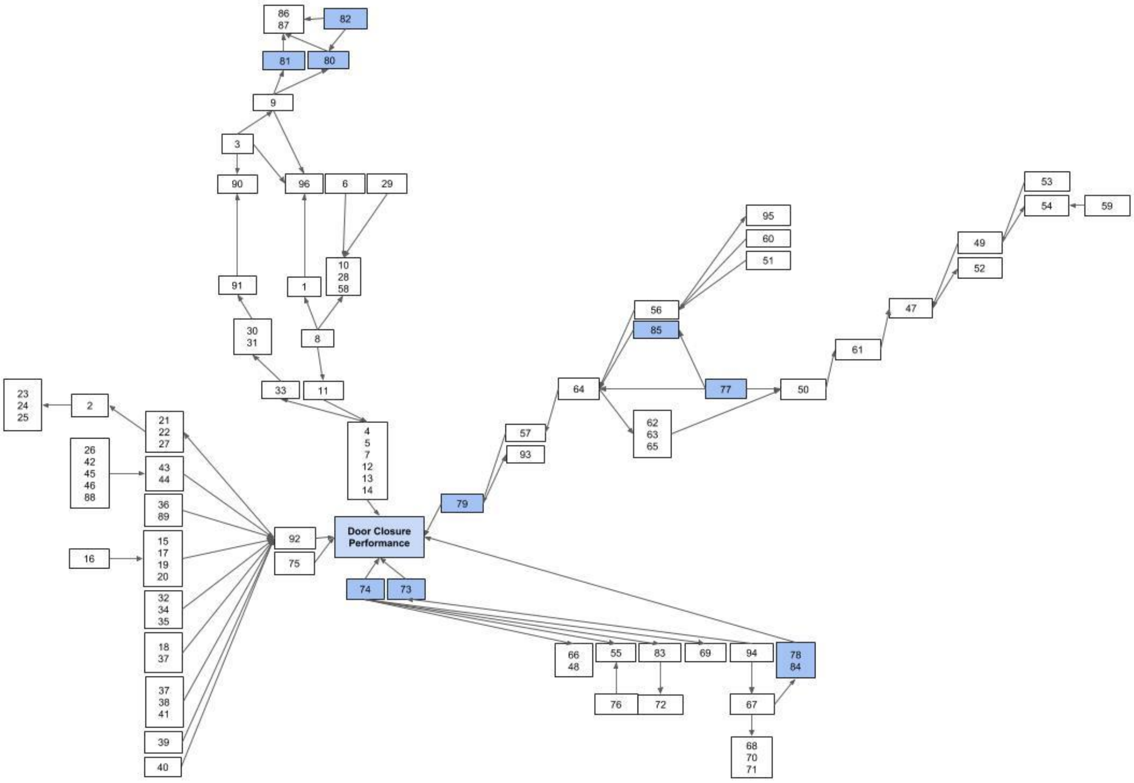

Figure 14. A group of requirement related factors, colored as blue in the relationship map.

These factors are spread out in the relationship-map. Hence, the factors are not summarized into one branch, resulting in one end-point which could be a possible cause of poor closure performance. However, if analyzing the relationship-map, the majority of the requirement related factors are positioned either in the beginning of a branch or in the end of a branch. This could be interpreted as that the requirement related factors have a fundamental impact of closure performance. However, important to notice is that (80, 81 82) are the current speed and energy requirements for the rear door closure performance. They are not causing variation within the closure performance, but they affect in that sense that they limit the area of approval for the other factors affecting closure performance. For instance, if the speed requirement is 1.3 m/s (75), this affect e.g. sealing stiffness (9), to be set into a certain level of stiffness for approving that requirement. Hence, all the other factors are affected by the requirement related factors since they determine the allowed speed and energy limit for closure approval. Not passing the requirements will result in closure failure. Therefore, the requirement related factors have a fundamental impact of the closure performance in that aspect. The requirement related factors are also fundamental since it is important that they are explicitly expressed and understood by the organization. If the requirements are not understood or motivated, they will be even harder to fulfill. As comment: *"different departments or functions have different objectives and goals. For instance, the design function has specific requirements which are difficult to fulfill for the construction function"*. Hence, there might be internal conflicts between different functions and their deliveries, due to different objectives. The requirement related factor (73, 74) indicates that there are difficulties in distributing information and objectives between different functions. Likewise, that it is difficult to weight the different factors affecting closure performance as discussed above in Section 4.1.1. Hence, if the e.g. organizational culture or structure not facilitate and encourage information sharing between functions, the requirements will be difficult to understand if not adopted by every function. There will be a lack of system perspective due to each function focus on their internal requirements and objectives, and there might be a risk of optimizing the function's own objectives at the expense of the total objectives of the organizational. Also, (79) indicates that the same requirements are used for all different car models, which is possible since they do not differ in terms of e.g. door structure, function, mechanical factors etc. However, according to: *"even if the cars should be the same, we see that they differ"* indicates that the different car models do differ, and should be adopted to different individual requirements. Lastly, (77) indicates that the requirements for a project might be based on previous projects and not on measurement data. The situation is neither benefiting from that people are afraid of changing requirements (85). Hence, the cultural and organizational aspects might be important factors influencing the situation regarding requirement related factors.

4.1.5 P-diagram of the Factors Concerning the DoE

The analysis of the relationship map resulted in increased knowledge regarding which factors affect closure performance. The analysis also resulted in increased understanding of the difficulties to decide which factors are the most critical factors to examine further. However, mechanical factors were selected as main contributors of closure performance, and were selected to be examined further. All mechanical factors that affect the door closure performance are divided in noise factors, control factors, signal factors, and output factors, see Figure 5 below. Signal factors are both 'closure speed' and 'closure energy', which also are the two output factors of the rear door closure performance. Noise factors are assumed as 'unknown' within this research. Control factors are the following: 'sealing', 'hinge', 'door shape', 'striker', 'door check', and 'air evacuation'. Each control factor involves various sub factors which affect closure performance as well. Hence, the sub factors explain more in detail how the control factor affect closure performance. These are selected because they had a high frequency of answer from the qualitative study, and because those have a high possibility to be investigated and included in a DoE.

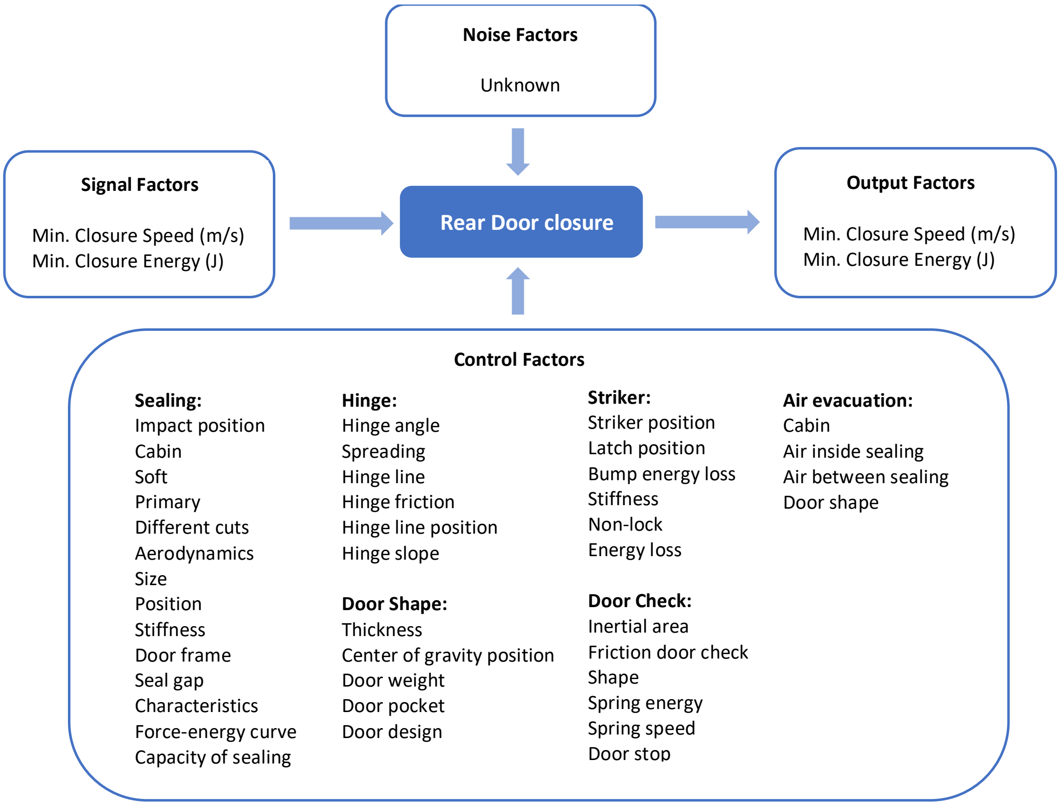

Figure 15. An illustration of the p-diagram which visualizes factors to evaluate when conducting the DoE.

4.1.6 The Analysis of the Interview Study Constitutes the Input Data for the DoE

Based on the relationship map, see Appendix 5, and the p-diagram, see Figure 15 above, a group of mechanical relating factors which affect rear door closure performance were selected. After the analysis, it was found that there were knowledge missing on *how* these mechanical related factors affected closure performance. For instance, which factor affected closure performance the most. It was decided to investigate the mechanical related factors by including them in a DoE. After consultation with technical and mechanical experts, and based on information from the interviews, it was understood that some of the factors were considered as difficult to adjust in practice. To minimize the number of experimental runs and thereby the extent of the DoE, some of the mechanical factors were determined to not be included. Thus, the exclusion of mechanical factors were based on the factor's simplicity and feasibility to be adjusted in practice. The mechanical factors selected to be included in a DoE are marked as 'include' and can be found in Table 20 below. Appendix 10 provide detail information regarding these selected factors.

Table 20. Selection of which mechanical factors to include in a DoE.

Mechanical Factor	ETA or HTA*	Selection
Air Between Sealings	HTA	
Air Inside Sealings	HTA	
Bumpstop	HTA	
Cabin Air Evacuation	ETA	Include
Capacity of Sealing	HTA	
Different cuts in Sealing	HTA	
Door Stop	HTA	
Compensated Door Frame	ETA	Include
Force-Energy Curve in Sealing	ETA	Include
Friction Door Check	HTA	
Hinge Angle	HTA	
Hingeline	HTA	
Hinge Line Position	HTA	
Hinge Slope	HTA	
Hinge Friction	HTA	
Center of gravity position	HTA	
Latch Position	HTA	
Lock Stiffness	HTA	
Door Lock	HTA	
Size of Sealing	HTA	
Spring Speed	HTA	
Spring Energy	HTA	
Seal Gap	ETA	Include
Shape Door Check	HTA	
Striker Position	ETA	Include

**ETA = easy to adjust and HTA = hard to adjust.*

4.2 Analysis of the Design of Experiments

Below is the experimental run plan generated by JMP, and the measured response values of Y_1 and Y_2 for each run, see Table 21. Y_1 is the minimum closure speed required for a successful closure performance. The interval of Y_1 was determined to -0.3 m/s to 3.0 m/s. Y_2 is the total closure energy required for a successful closure performance. The interval of Y_2 was determined to -30 J to 100 J. However, Y_2 is a summary of the following energy parts: closing energy provided by user, closing energy provided by gravity, closing energy provided by spring, closing energy loss to drag, closing energy loss to air bind, closing energy loss to static compression, closing energy loss from gravity, closing energy loss to check (friction), and closing energy loss from spring. It was decided to not treat the different energy parts separately when analyzing the data in JMP. The total amount of energy required for a successful closure performance was of interest to analyze, in order to understand the magnitude of closure energy required. Further, the order of the experimental runs is randomly distributed, and two center points were added, run 3 and run 4, see Table 21 below, as well as two replicates were conducted.

Table 21. The experimental run plan and the response values.

Run	X_1 Sealing Ingress (Y)	X_2 Striker Alignment (Z)	X_3 Door Frame	X_4 Cabin Air Evacuation	Y_1 Closure Speed [mm/s]	Y_2 Closure Energy [J]
1	1	-1	-1	Uncovered	790	14,91
2	1	1	1	Uncovered	1042	17,74
3	0	0	0	Covered	1218	25,29
4	0	0	0	Covered	1076	21,03
5	-1	-1	1	Uncovered	1150	19,28
6	1	-1	1	Covered	983	16,65
7	-1	1	-1	Covered	1388	22,46
8	1	1	1	Uncovered	855	15,19
9	1	-1	-1	Uncovered	747	13,91

4.2.1 Parameter Estimates

The objective of the DoE was to determine which factors critically affected closure performance. The critical factors are the factors which affect the response values the most when changed into high and low level. If the adjustment of the factor into high and low level resulted in a large change in the response value, the factor is assumed to affect the closure performance critically. In the parameter estimates report, the factors' effect on the response values are outlined; significant and non-significant. In Table 22 below, the parameter estimates report is provided for Y_1. The significant factor is X_1 since the p-value is $0.0125 < 0.05$. The p-value for X_4 is 0.0852, which is close to the significance level of 0.05. Factors close to the significance limit are all interesting factors. All experiments are affected by noise, which might affect the result negatively. Hence, it is illogical to make the precise selection of significant factors based on the specific limit of 0.05. Therefore, X_4 is included as significant as well. The non-significant factors were removed from the model of Y_1, which were X_2 and X_3 where the p-values are $0.1319 > 0.05$ and $0.4838 > 0.05$ respectively. It can be discussed whether X_2 should be included as significant or not, since the p-value is 0.1319, and might be considered as close to the significance limit of 0.05. If all factors are compared, X_3 is the only factor which deviates to a large extent compared to the rest of the factors.

Table 22. The parameter estimates report of Y_1.

Parameter Estimates				
Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	1094,7083	31,44362	34,81	<,0001 *
X1 Sealing Ingress (Y)	-164,6667	38,1711	-4,31	0,0125 *
X2 Striker Alignment (Z)	63,916667	33,83507	1,89	0,1319
X3 Door Frame	26,083333	33,83507	0,77	0,4838
X4 Cabin Air Evacuation[Covered]	71,541667	31,44362	2,28	0,0852

Further, in Table 23 below, the parameter estimates report is provided for Y_2. There are no significant factors for Y_2 since all p-values are above 0.05. However, the p-value for X_1 is 0.1151 and the p-value for X_4 is 0.1176, which are close to the significance limit of 0.05. Hence, it can be discussed whether X_1 and X_4 should be included as significant factors or not. For the continuing analysis, X_1 and X_4 are included as significant. The non-significant factors were removed from the model of Y_2, which were X_2 and X_3, where the p-values are $0.444 > 0.05$ and $0.8607 > 0.05$ respectively. Thus, the quality of the model will be evaluated below, to assess whether the model of Y_2 fits the data well or not.

Table 23. The parameter estimates report of Y_2.

Parameter Estimates				
Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	19,522083	0,922896	21,15	<,0001 *
X1 Sealing Ingress (Y)	-2,249167	1,120353	-2,01	0,1151
X2 Striker Alignment (Z)	0,8416667	0,993087	0,85	0,4444
X3 Door Frame	0,1858333	0,993087	0,19	0,8607
X4 Cabin Air Evacuation[Covered]	1,8354167	0,922896	1,99	0,1176

4.2.2 Prediction Profiler

In this following section, the prediction profiler is provided. Below, Figure 16 provides the prediction profiler for all factors included for Y_1 and Y_2. As mentioned previously, the factor is assumed to affect the response value critically if the factor is significant *and* results in a large change in the response value when adjusted into high and low level. In the first graph from left; X_1 affecting Y_1 and Y_2 will decrease drastically when moving towards the high value (1) of X_1 due to the large angle of the slopes. In the second graph from left; X_2 affecting Y_1 and Y_2 will increase subtly when moving towards the high value (1) of X_2 due to the small angle of the slopes. In the third graph from left; X_3 will have no effect on the response values Y_1 and Y_2 independent of the level of X_3. Hence, the values of Y_1 and Y_2 will remain constant whether X_3 is in the low level or in the high level, due to the non- sloping flat line in the graph. In the fourth graph from left; X_4 affecting Y_1 and Y_2 will decrease drastically when moving towards the high value (uncovered) of X_4 due to the large angle of the slopes. These relationships between the response values of Y_1 and Y_2 and the factors, X_1, X_2, X_3, and X_4 can be utilized to understand which factor affect the response values critically if changed into high and low level. Remember, X_2 and X_3 are non-significant factors, and were removed from the model. Hence, the prediction profiler for only significant factors is further described below.

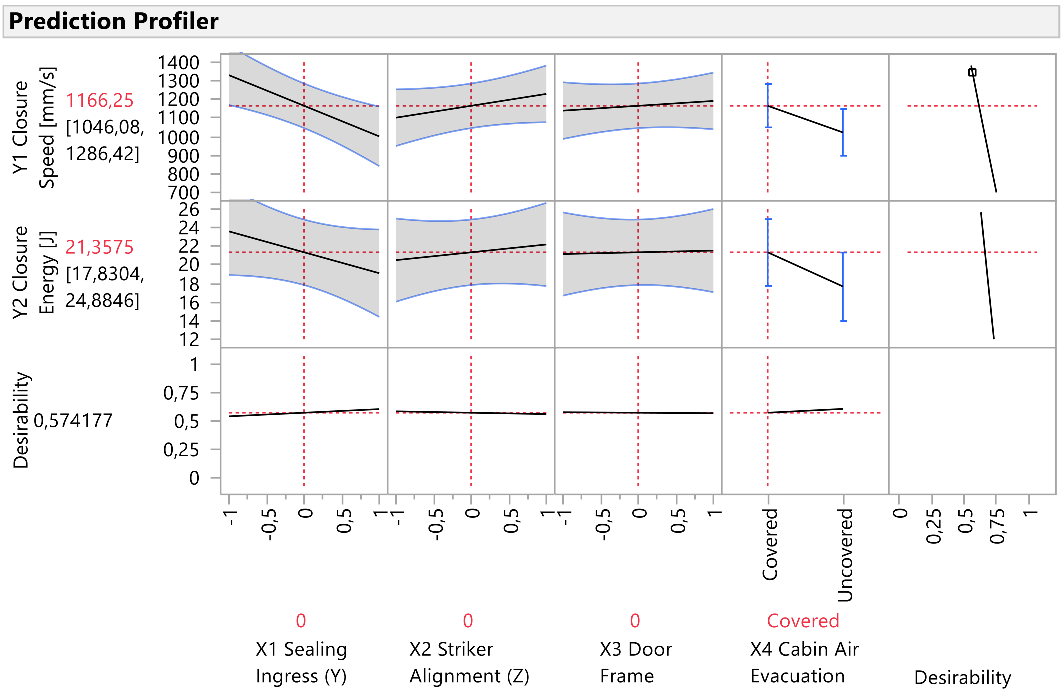

Figure 16. The prediction profiler for Y_1 and Y_2.

Continuing, Figure 17 below provides the prediction profiler for all factors except from the non-significant factors, X_2 and X_3. The prediction profiler is describing similar relationships among the response values and the factors as mentioned previously. Hence, the same reasoning applies for this situation as for above.

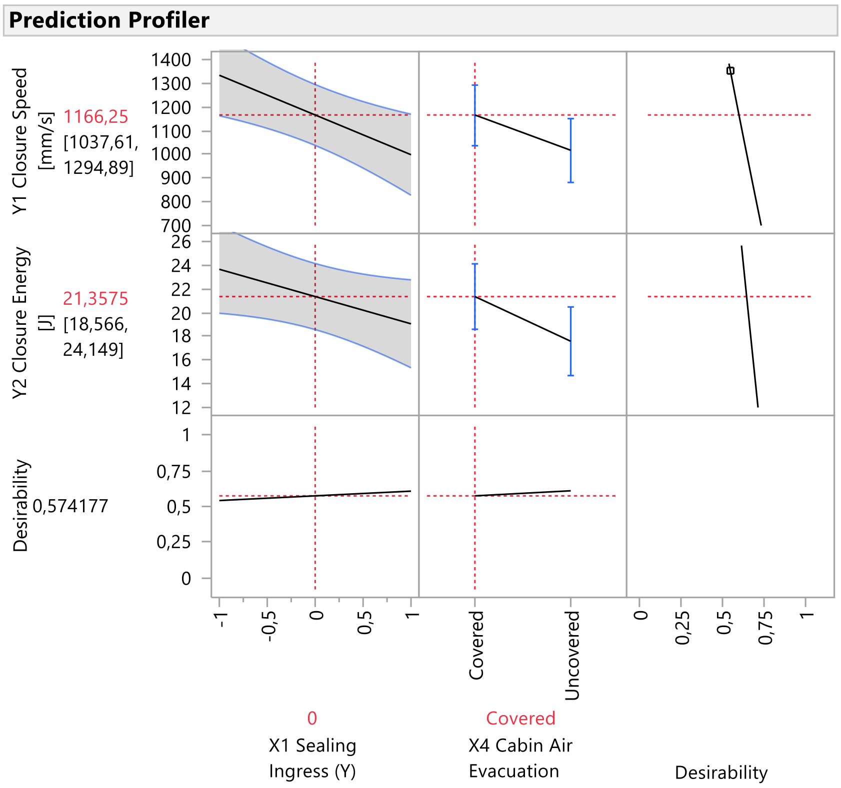

Figure 17. The prediction profiler for Y_1 and Y_2, after removing non-significant factors, X_2 and X_3.

4.2.3 Prediction Expression

In the following section, the prediction expression is provided based on the DoE. The prediction expression is the mathematical expression of the model generated by JMP, based on the data (JMP, 2018g). The prediction expression can be used e.g. for calculating the values of the factors, X_m, for achieving a certain response value, Y_n. For instance, if the closure speed should not pass 1.3 m/s, the values of the factors can be determined for achieving that outcome. Hence, the arrangement of the mechanical factors can be examined in advanced, in order to understand what the optimal arrangement of the factors are to achieve high quality closure performance. Below, Equation 4.1 describes the prediction expression for Y_1 after removing non-significant factors. Equation 4.2 describes the prediction expression for Y_2 after removing non-significant factors.

$$Y_1 = 1091.80 - 167.58 * x_1 + x_4 * \begin{cases} covered \rightarrow 74.45 \\ uncovered \rightarrow \ -74.45 \end{cases} \tag{4.1}$$

$$Y_2 = 19.47 - 2.30 * x_1 + x_4 * \begin{cases} covered \rightarrow 1.89 \\ uncovered \rightarrow \ -1.89 \end{cases} \tag{4.2}$$

4.2.4 Evaluation of the Model

The following section evaluates the above-mentioned models for Y_1 and Y_2, by assessments based on key measures. These key measures are as follow: the summary of fit report to examine

RSquare and RSquare Adj values, and center points to determine if the model approves for the linear relationships assumptions.

4.2.4.1 Summary of Fit

The summary of fit reports for Y_1 are provided in Table 24 below. For the response value Y_1, the RSquare value is 0.9145 when all factors are included in the model as predicting terms. The RSquare Adj value is 0.8290 for the same situation. The level of approval for RSquare and RSquare Adj is assumed to 0.50. Hence, these values are above 0.50 and high, which indicate that the model fits the data well. Below are the level of RSquare and RSquare Adj examined after removal of two non-significant factors X_2 and X_3 for Y_1. Non-significant factors are removed in order to improve quality of the model. All changes in RSquare and RSquare Adj when removing non-significant factors for Y_1 are summarized in Table 24 below.

First, after removal of non-significant factor X_3 for improving quality of the model, RSquare value was decreased by 0.0127 units (0.9145 - 0.9018 = 0.0127) to 0.9018. This is a rather small decrease. RSquare value should decrease after removal of predicting terms, as mentioned in Section 3.5.2.4 above. Further, to examine whether the quality of the model was improved or not, RSquare Adj value should be examined (Minitab, 2018a). RSquare Adj value was increased by 0.0139 units (0.8429 - 0.8290 = 0.0139) to 0.84 after removal of non-significant factor X_3. Which is a rather small increase as well. This indicates that quality of the model was improved by removal of X_3.

Second, after removal of another non-significant factor X_2, RSquare value was decreased by 0.091 units (0.9018 - 0.8108 = 0.091) to 0.8108 which corresponds to the same reasoning as above. However, the RSquare Adj value was decreased by 0.0951 units (0.8429 - 0.7478 = 0.0951) to 0.7478 after removal of X_3. This indicates that quality of the model was not improved by removal of X_2. Hence, only X_3 should be considered for removal in order to improve quality of the model.

Table 24. The changes in RSquare and RSquare Adj when removing non-significant factors for Y_1.

Y_1 Closure Speed Factors Included in the Model	RSquare	RSquare Adj
X_1, X_2, X_3, and X_4	0.9145	0.8290
X_1, X_2, and X_4	0.9018	0.8429
X_1, and X_4	0.8108	0.7476

Furthermore, for response value Y_2 is RSquare value 0.7806 when all factors are included in the model as predicting terms. RSquare Adj value is 0.5613 for the same situation. RSquare and RSquare Adj values are smaller compared to the values of Y_1. However, the RSquare and RSquare Adj values are high (above 0.50), which indicate that there is a well fit between model and data. Below are the level of RSquare and RSquare Adj examined after removal of two non-significant factors X_2 and X_3 for Y_2. Non-significant factors are removed in order to improve quality of the model. All changes in RSquare and RSquare Adj when removing non-significant factors for Y_2 are summarized in Table 25 below.

First, after removal of non-significant factor X_3 for improving quality of the model, RSquare value was decreased by 0.0109 units (0.7806 - 0.7787 = 0.0109) to 0.7787. Which is a rather small decrease. RSquare value should decrease after removal of predicting terms. Further, RSquare Adj value was increased by 0.0846 units (0.6459 - 0.5613 = 0.0846) to 0.6459 after removal of non-significant factor, X_3. Which is a rather small increase as well. This indicates that quality of the model was improved by removal of X_3.

Second, after removal of another non-significant factor X_2, RSquare value was decreased by 0.0441 units (0.7787 - 0.7346 = 0.0441) to 0.7346 which corresponds to the same reasoning above. However, RSquare Adj value was decreased by 0.0013 units (0.6459 - 0.6446 = 0.0013) to 0.64 after removal of non-significant factor X_2. RSquare Adj value could be assumed as constant when removing X_2 due to the small decrease of 0.0013 units. This indicates that quality of the model was equally improved by removal of X_2 as for removal of X_3. There was no notable change in RSquare Adj value after removal of X_2.

Table 25. The changes in RSquare and RSquare Adj when removing non-significant factors for Y_2.

Y_2 Closure Energy Factors Included in the Model	RSquare	RSquare Adj
X_1, X_2, X_3, and X_4	0.7806	0.5613
X_1, X_2, and X_4	0.7787	0.6459
X_1, and X_4	0.7346	0.6461

To conclude, both models of Y_1 and Y_2 were improved by removal of X_3, according to the summary of fit reports. However, Y_1 was not improved by removal of X_2. This is interesting to discuss, since X_2 was not significant when examined the parameter estimates report in Section 4.2.1 above. It was arguing whether to include X_2 or not as significant, since the p-value of X_2 was close to the significant limit of 0.05. Based on RSquare and RSquare Adj values, X_2 might be included in model of Y_1 even if not passing the significance limit of 0.05 since the model was not improved by removal of X_2. Further, both the RSquare and RSquare Adj values of Y_2 were rather low. Also, none of the factors were significant in the parameter estimates report of Y_2, see Section 4.2.1 above. Y_1 is therefore the model of interest.

4.2.4.2 Center Points

Since the experiment was a two-level design, the only relationship that can fit is a linear relationship between response value and factors. Linear model assumptions are only tested for Y_1 because none of the factors were significant for Y_2. After examining RSquare and RSquare Adj values of Y_2, both were above 0.50 which is assumed as the limit of approval. However, the values were rather low compared to Y_1, and the model might not fit the data well due to the low level of RSquare and RSquare Adj. Linear model assumptions will only be tested for Y_1. Further, X_1 were significant for Y_1 and a test for curvature are therefore of interest, to determine whether to reject or accept the linear model assumptions. Hence, X_1 may have non-linear effect on Y_1. A quadratic term X_1^2 is requested in JMP to test for curvature. In Table 26 below, the additional quadratic term X_1^2 has a p-value of 0.6932 which is above the significance limit of 0.05. The quadratic term X_1^2 is therefore not significant, and linear model assumptions for Y_1 are justified by the center point added.

Table 26. Testing curvature for Y_1 by requesting the quadratic term X_1^2

Parameter Estimates				
Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	1068,2045	75,55838	14,14	0,0001 *
X1 Sealing Ingress (Y)	-162,2955	39,88799	-4,07	0,0152 *
X2 Striker Alignment (Z)	68,659091	34,88104	1,97	0,1204
X4 Cabin Air Evacuation[Covered]	78,795455	39,88799	1,98	0,1194
X1 Sealing Ingress (Y)*X1 Sealing Ingress (Y)	38,5	90,7526	0,42	0,6932

4.2.4 Variation within the Measurement System

An interesting notice during the experiment was variation in response values between two identical reference runs: run 3 and run 4 can, see Table 27 below. These were center runs or reference runs, and no factor adjustments were adjusted between the runs. Run 4 was conducted immediately after run 3, and there are variation between the measured response values.

Table 27. Variation between the response values for two identical runs which are marked, run 3 and run 4.

Run	X_1 Sealing Ingress (Y)	X_2 Striker Alignment (Z)	X_3 Door Frame	X_4 Cabin Air Evacuation	Y_1 Closure Speed [mm/s]	Y_2 Closure Energy [J]
1	1	-1	-1	Uncovered	790	14,91
2	1	1	1	Uncovered	1042	17,74
3	0	0	0	Covered	1218	25,29
4	0	0	0	Covered	1076	21,03
5	-1	-1	1	Uncovered	1150	19,28
6	1	-1	1	Covered	983	16,65
7	-1	1	-1	Covered	1388	22,46
8	1	1	1	Uncovered	855	15,19
9	1	-1	-1	Uncovered	747	13,91

The response value Y_1 is 1 218 mm/s for run 3, compared to 1 076 mm/s for run 4. Which is a reduce of speed by 11.66%. The response value Y_2 is 25.29 J for run 3, compared to 21.03 J for run 4. Which is a reduce of energy by 16.83%, see Table 28 below for calculations. The approved variation within measurement is 10% (Hammersberg, 2017a). It can be discussed whether variation should be considered as significant or not, since the measured variation do not deviates in larger extent from the approved range of variation of 10%. It is important to understand that all factor adjustments were within ranges of 2 mm. Where only 1 mm of adjustment affected closure performance largely. Therefore, even the smallest changes will affect closure performance, and it might be of interest to examine the variation within the measurement system. Since the two runs 3 and 4 are identical and performed by the same operator who followed an instruction program of the measurement process, it might be of interest to consider if variation within the measurement device, EZSlam, are present. However, variation might not be caused by the measurement device only. Variation might be caused by the operator or by the measurement procedure. Therefore, a MSA (measurement system analysis) should be conducted in order to analyze variation within the measurement system if the above noted variation for run 3 and runt 4 are considered as important. Thereby, the performance of the measurement system could be examined in terms of accuracy and precision.

Table 28. The variation in percent between two identical runs, run 3 and run 4.

Response Value	Run 3	Run 4	Difference	%
Y_1	1 218 mm/s	1 076 mm/s	1 218 - 1 076 = 142 mm/s	(142 / 1 218) * 100 = 11.66% reduce of closure speed
Y_2	25.29 J	21.03 J	25.29 - 21.03 = 4.26 J	(4.26 / 25.29) * 100= 16.38% reduce of closure energy

4.2.5 Analysis of the Challenges Related to DoE

Currently, there are limited amount of literature regarding how to conduct a DoE in practice for industrial application (Tanco, Viles, Ilzarbe & Alvarez, 2009). Below are the identified challengers related to DoE in practice, mentioned in Section 2.3, and analyzed based on the executed DoE at Volvo Cars.

4.2.5.1 Business Challenges

According to Tanco, Viles, Ilzarbe & Alvarez (2009), the new way of conducting experiments by using several factors at a time and not one factor at a time, must be accepted by engineers if successfully implementing DoE within organizations. This was very well noticed during the planning phase of the DoE, since DoE as a method was often misunderstood by engineers, project leaders, and team members during discussions. The purpose of DoE was not clearly understood, nor the actual concept of DoE among the engineers, project leaders, and team members. DoE was often opposed to prevalent methods used by the engineers when conducting tests by one factor at a time. However, the engineers and project leaders should not be accused of not understanding the purpose and concept of DoE. The project leaders of the DoE should take full responsibility for explaining the purpose and concept of DoE, and motivate why it is to prefer in this situation. As mentioned by Tanco, Viles, Ilzarbe & Alvarez (2009) in Section 2.3.1, engineers should be convinced that methods as DoE can be used to improve previous working processes. DoE should be advocated by project leaders of the DoE to convince engineers of its excellence. A level of resistance within the organization was noticed due to the not well explanation and motivation of DoE within the planning phase. The level of resistance affected how the DoE was interpreted and disposed by engineers and project leaders. DoE cannot be incorporated successfully by the organization if any resistance is ignored. However, even if the concept and purpose of DoE was motivated and explained by the project leaders, there were still difficulties among engineers and project leaders to fully understand DoE. According to the researchers, DoE was not badly taught, but the *choice* of method for teaching DoE was insufficient, further explained in Section 4.2.5.2 below.

Furthermore, creating engagement and commitment are important in order to successfully implementing DoE within an organization, as mentioned in Section 2.3.1 (Simpson, Listak & Hutto, 2013). It was therefore emphasized within the planning phase of the DoE to create commitment by involving engineers, project leaders, mechanics, operators, and other stakeholders within discussions and decision making and ask for their opinions. Make sure that commitment for the DoE was created through engagement and involvement in discussions and decision making. However, engagement and commitment by various people were difficult to assure when there was a level of resistance to change the old way of performing tests within the organization. Hence, the level of resistance within the organization should be reduced by convincing people of the excellence of DoE and explaining the concept and purpose of DoE. However, during the DoE cycle, it was understood by the researchers that it might be a mutual process of converting into DoE. The level of resistance might not be reduced if people are not involved and committed in the different phases, especially within the planning phase. During the research, it was noticed that level of resistance was gradually reduced by creating engagement of DoE and by simultaneously teaching, motivating, and convincing the concept, purpose, and excellence of DoE.

4.2.5.2 Educational Challenges

As previously mentioned in Section 4.2.5.1, the purpose and concept of DoE was not proper understood by engineers and project leaders. In order to conduct a successful DoE, it is required to have a team where everyone have understanding of processes and steps to be performed (Simpson, Listak & Hutto, 2013). The excellence of DoE should be explained by the project leaders of DoE, whom should motivate other engineers and project leaders why DoE is to prefer. DoE was explained by the project leaders during the DoE cycle, especially during the planning phase. However, DoE was still not understood by all people involved. As mentioned in Section 2.3.2, DoE is a tool of practice and should be learned by doing (Tanco, Viles, Ilzarbe & Alvarez, 2009). DoE is about performing the experiments in practice, which require practical skills. Just teaching DoE by theoretical means and by explaining the purpose and concept through written documents or through verbal explanations is not enough. DoE must be taught by doing, since practical skills are required. Learning by doing should always be applied when teaching DoE. As described by Tanco, Viles, Ilzarbe & Alvarez (2009) in Section 2.3.2, lack of conducting actual experiments in practice when learning DoE is often one reason why it is badly taught. Hence, even if the purpose and concept of DoE were explained by the project leaders of the DoE, it was not sufficient. To improve the learning process of understanding DoE, all involved people in the DoE project should perform a smaller DoE in practice, to grasp all vital parts. Since learning by doing is advocated when one has to understand DoE.

Additional, DoE is rather emphasized in theoretical aspects than focuses in how to apply for industrial use and for business related issues (Tanco, Viles, Ilzarbe & Alvarez, 2009). This was experienced by the researchers during DoE as well, since it was difficult to understand how the included factors could be adjusted in practice. The adjustments should correspond to what was supposed to be tested e.g. how a bending door frame affected the response values, or how sealing ingress affected the response values. Creative solutions were therefore required, in order to manage all factors adjustments e.g. it was not possible to bend the door frame, but instead the door could be repositioned in y-direction and tilted, which corresponded to the same situation as if bending the door frame (X_3). Also, level of sealing ingress was to be tested as well (X_1) by changing the position of sealing. However, this required the sealing to be removed and repositioned from the car body and car door. Once the sealing was removed, the sealing could not be reused which was problematic for the DoE. However, the door was instead repositioned in y-direction, which corresponded to test different levels of sealing ingress. As explained above, only ETA factors were included in the DoE. However, even if the factors were defined as ETA and feasible to adjust in practice, they were *still* difficult to adjust in terms of contextual constraints e.g. risk of crack initiation if adjusted too many times. Therefore, the chosen factors were also HTA factors, and introduced as the dilemma of semi-HTA factors. Hence, this is when practice interfere with theory. In theory, easy means ‘easy’. In practice, easy means ‘complicated’. It was not that simple to decide whether the factors should be defined as ETA or HTA when the factors had characteristics of both. It was also important to define whether the factors were ETA or HTA since the choice of design was dependent on the definition.

Furthermore, it was difficult to determine appropriate design ranges for all factors. It was mostly argued by the engineers, whom were very experienced in the technical details of the chosen factors, that the design range should reflect the reality. A wider design range of the factors is to prefer since a wider range of data can then be collected. This opposed the engineers’ opinions, whom were afraid that adjusting the factors widely would not reflect reality, and the DoE might therefore generate unrealistic data. Additional, the choice of appropriate design ranges were also constrained by internal relationships among factors. Hence, wide ranges of a certain factor might be constrained by small ranges of another factor, due to internal relationships between these factors. For instance, the striker must be repositioned by the same distance as X_1 in y-direction, as described in Section 3.5.1.3. Even if X_1 has a range of ± 2.5 mm, X_1 can only be adjusted ± 1 mm since the striker can only be adjusted ± 1 mm. Hence, the design range of X_1 is constrained by the design range of the striker, since the striker must be repositioned by the same distance as X_1. In total, in order to realize and understand all previously mentioned practical constraints, DoE must be experienced by doing. Many of the practical issues e.g. how to adjust semi-HTA factors, and how to decide appropriate design ranges for the factors, were understood when performing a pilot test prior the actual DoE. Hence, pilot tests are advocated by the researchers in order to improve learning of DoE and to experience the gap between theory and practice.

4.2.5.3 Technical Challenges

As mentioned in Section 2.3.3, the absence of assisting theory how to solve real industrial and technical issues in practice is an important challenge to consider. As described above, some of the practical issues in the DoE e.g. how to adjust semi-HTA factors, and how to select appropriate design ranges for the factors, could not be found in literature how to be managed. Technical challenges were discussed among experienced engineers and mechanics during the research, supporting how to adjust the factors and what should be the appropriate design ranges. High technical skills, experiences within mechanic and industry, and to be creative were required in order to overcome the challenge. Technical challenges were also managed during the pilot test. The success of DoE, and to understand the technical details of the factors, were highly dependent on the pilot test where practical constraints were understood. Also, previously read technical explanations of various mechanical factors during the literature study aid in understanding the technical details of the factors. Furthermore, as described in Section 2.3.3, DoE is limited in usage among industries due to the often high level of complexity. This were also the case when conducting the DoE which affected the DoE. Initially, an additional factor was supposed to be included in the DoE as well, X_5. However, due to the high level of complexity and uncertainty how to adjust X_5, X_5 were decided to not be included in the DoE. The DoE would have been more comprehensive if X_5 were included.

To summarize Section 4.2.5, all three areas of challenges related to DoE described in the theoretical framework, see Section 2.3, were experienced by the researchers during the DoE. Aspects of business, educational, and technical challenges were experienced in terms of: importance of creating commitment, reduce level of resistance, importance of learning by doing when explaining DoE, importance of conducting a pilot test to understand technical and practical aspects of all factors, etc. All important considerations for managing the challenges.

Section 5
Discussion

Below are the qualitative interview study and the DoE shortly discussed, where main issues of the research are highlighted. Key learnings when practice interfere with theory regarding DoE are also discussed.

5.1 Qualitative Interview Study

A qualitative study in general broader and more difficult to conduct compare to a quantitative study because persons perceive quality different and it is hard to measure. Thus, it generated a broad knowledge regarding the rear door closure performance. However, axial coding, as a tool for analyzing the interview study, was based on the researchers' own analyzing ability, as mentioned in Section 4.1. Hence, the various relationships between 'headlines' in the relationship map are estimations and cannot be supported by science. The relationships are based on common sense and on logical sequential reasoning of consequences. The qualitative interview study provided the foundation for further investigation and was therefore an important step in the research when investigating closure performance. It was important to collect options from various departments in order to understand the holistic view of the closure event within the organization. The result from the interview study was to investigate mechanical factors in order to include them in a DoE. The group of mechanical factors was selected because it was the largest group and had possible factors to include in a DoE. Also, information and experts were easier to reach when it comes to understand the doors mechanisms and functions.

5.2 Design of Experiments

How to improve closure performance of automotive rear doors were investigated by using DoE. Closure performance is measured by minimum closure speed (Y_1) and minimum closure energy (Y_2) that are required for total closure of the rear door. Energy is included because there are investigations whether it should be the new measuring unit in the requirement for the door closure event. Therefore, is energy included for better understanding of its effects on the included factors in the DoE. These factors were: sealing ingress (X_1), striker alignment (X_2), door frame (X_3), and cabin air evacuation (X_4). Four factors were selected due to time restrictions and resources where it is important to conduct the all runs of the DoE. Otherwise, would the results have low usage since there are not enough data. Therefore, were the selection of the design for the DoE important in order to decide numbers of runs that could be manage within the mentioned restrictions. In the restrictions is the feasibility to adjust the factors in practice included.

As a result, from the DoE, a model explaining the relationship between the factors and the response values were generated by JMP, see Section 4.2.3. Based on the model, the critical factors that affected closure performance the most were sealing ingress (X_1), followed by cabin air evacuation (X_4) for the model of closure speed (Y_1). The result, where the sealing ingress has the largest effect, was no surprise, but it gave confirmation of what the experts suspected. The result of the cabin air evacuation showed that the factor affects more than the experts thought. This indicates that it should be included in further investigations to optimize the air escape from the cabin and affect the door closure performance. The model of closure energy (Y_2) could not be supported by quantitative data since none of the factors were found significant and were therefore dismissed. This indicates that the energy is more complex, and not linear as the model of speed, and something to consist by determining the requirement for energy.

5.3 When Practice Interfere with Theory

One of the major emphasizes of the research were to plan a DoE by following the steps of the DoE cycle. During the execution, practical issues were experienced which reflected the challenges mentioned in theory in terms of business, educational, and technical challenges related to DoE. The most important challenges found during the research were the educational and technical challenges. To understand the importance of deliver a proper education of DoE to others, and how to proper plan the DoE. During the research, it was understood that both can be managed using: *learning by doing*. There is no literature describing how to adjust the factors in practice. The gap between theory and practice regarding DoE affected the research when DoE was to be applied in practice at Volvo Cars. Mainly, the factor adjustments required technical skills, experiences, and creativity in order to adjust them successfully. No factor adjustment in the report could be determined by literature supporting how to make a proper adjustment. Instead, technical skills, experience, and creativity were needed in order to make appropriate factor adjustments. This was something that would have been done different after reflection of the process of the DoE. A pilot test should have been conducted included all involved persons, engineers and experts, to increase the understanding of the experiment. Since the real knowledge regarding adjustments of the selected factors came from this research conducted pilot test. This would improve the cooperation in the planning phase were all persons have the same understanding and knowledge regarding the process of the DoE.

Section 6
Conclusion

The research was conducted on the behalf of Volvo Cars, and examined how to improve quality of automotive rear door closure performance by determine which factors critically affected closure performance, by using both qualitative and quantitative data. Closure event is used as a term to describe the actual motion: when the door is set into motion to close. However, the closure event can result in two different outcomes; successful or unsuccessful closure event. Hence, the closure event is evaluated by the term closure performance. Closure performance is measured by minimum closure speed (Y_1) and minimum closure energy (Y_2) required for total closure of the rear door. The closure event is defined as unsuccessful if not closed into second lock mode at the speed of maximum 1.3 m/s. The closure energy is defined as total amount of energy required to successfully close the door into second lock mode. Currently, the required energy is not internally approved at Volvo Cars, and the closure event often results in a required re-closing of the door. However, Volvo Cars plans to change measurement unit from speed (m/s) to energy (J). Energy is therefore included as a measurement of closure performance within the research.

Furthermore, various factors and areas that affected closure performance were identified during a qualitative interview study. The purpose of the interview study was to identify various factors that affected closure performance, in order to understand the system boundary of the research. It was understood that the closure performance should be viewed in a wider perspective, affected by various factors and not only limited to mechanical factors, further described in Section 6.1. However, the various factors identified during the interview study should be supported by quantitative data, in order to determine which factors critically affected closure performance. Quantitative data supporting the critical factors that affected closure performance were collected during a DoE. A model was developed based on the empirical data from the DoE. The model describes the relationship between the response value and the factors, which can be utilized in order to calculate the closure performance in advanced, further described in Section 6.2.

Additional, practical challenges regarding DoE were experienced and noted during the research as well, emphasizing the importance of *learning by doing* when conducting DoE. Below, are the research questions answered, based on the analysis of the interview study and the analysis of the DoE. Followed by main findings and deliveries of the research.

6.1 The First Research Question

RQ1. Which factors critically affect closure performance of automotive rear doors in terms of closure speed and closure energy?

Based on the analysis of the interview study, the following areas were considered as affecting closure performance: 'mechanical factors', 'process factors', 'soft factors', and 'requirement factors'. Hence, it was discussed that variation within closure performance could not be limited to mechanical factors only. The closure performance should be viewed as a system, where different sub systems affect the closure performance. For instance, the processes related to construction of the rear doors, and the organizational aspects both affected closure performance. However, based on the analysis of the interview study, the difficulties to weight the various mechanical factors' effect on closure performance were considered as the most critical factor that negatively affected closure performance. Therefore, four factors within the area of mechanical factors were assumed as critical factors which all might affected closure performance. These factors were the following: X_1, X_2, X_3, and X_4. Note, the total number of mechanical factors that affected closure performance were far more than four. The four factors previously mentioned were selected based on their feasibility to be adjusted in practice in a DoE.

6.2 The Second Research Question

RQ2. How can the identified critical factors be confirmed quantitatively for improving quality of automotive rear door closure performance?

When answering the first research question above, the assumed critical factors that affected closure performance were X_1, X_2, X_3, and X_4. However, the factors should be supported by quantitative data in order to determine whether they were critical or not. All four factors were therefore included in a DoE, to investigate how they affected closure performance. The result of the DoE were based on quantitative data, and the factors could therefore be weighted and supported by quantitative data. Based on the DoE, a model was developed which described the relationship between the response values and factors. Based on the mode, the critical factors that affected closure performance the most were sealing ingress (X_1), followed by cabin air evacuation (X_4) for the model of closure speed (Y_1), see Equation 6.1 below. However, the model of closure energy (Y_2) could not be supported by quantitative data, since none of the factors were found significant. The model of closure energy (Y_2) were therefore dismissed.

$$Y_1 = 1091.80 - 167.58 * x_1 + x_4 * \begin{cases} covered \rightarrow 74.45 \\ uncovered \rightarrow \; -74.45 \end{cases} \tag{6.1}$$

Further, the quality of the model of closure speed (Y_1) were assumed as high, if examined the RSquare and RSquare Adj values. The model of closure speed (Y_1) were also described as linear, using center points to support the linear assumptions. The model can be used to improve quality of the closure performance at Volvo Cars. The outcome of the closure event can be understood in advance by applying the model. Hence, the arrangement of the mechanical factors can be examined in advanced, in order to understand what the optimal arrangement of the factors are to achieve high quality closure performance. Further, the DoE method used for this project followed the sequence of the DoE cycle and can be reused by externals, see Appendix 7.

6.3 Main Findings and Deliveries of the Research

First, the main findings and deliveries from the interview study are the relationship map and the complemented translation of the numbers in the relationship map, see Appendix 4 and Appendix 5. Note, the relationships between the various factors (‘headlines’) in the relationship map cannot be supported by science. The relationships were determined by common sense. Appendix 5 provides the identified various factors which affected closure performance, based on the interview study. Appendix 4 should be used in further closing effort investigations, in order to examine how the remaining factors affect closure performance.

Second, the main findings and deliveries from the DoE is the model that describes the relationship between the response value Y_1 and the factors X_1 and X_4. The model can be used to improve quality of the closure performance at Volvo Cars. The outcome of the closure event can be understood in advance by applying the model. Also, the DoE method can be reused by externals in similar industrial contexts, using Appendix 7 as main guideline. Hence, a similar model can therefore be developed in other industrial contexts in order to improve quality. The main findings and deliveries are further discussed in Section 7 below, as future recommendations.

Section 7
Limitations and Recommendations

7.1 Limitations

In the research, front doors were not of main interest since they do not cause variations within closure performance to the same extent as rear doors. The challenges within automotive rear door closure performance are not limited to Volvo Cars only, variations within closure performance are mentioned by other car manufacturers worldwide. However, this research focus mainly on the internal challenges relates to the context of Volvo Cars. The performed DoE is context related for suiting the circumstances of the project. Hence, the research is limited to Volvo Cars and to one specific car model. Based on the research a model was generated, which describes the relationship between the mechanical factors and the closure performance. By applying the model, the outcome of the closure event can be understood in advance. Hence, the arrangement of the mechanical factors can be examined in advanced, in order to understand which, the optimal arrangement of the factors is in order to achieve high quality closure performance. The model is suited for Volvo Cars only, however, a similar model can be derived for other car manufacturer by utilizing the same method as described in this research. The DoE method are emphasized within the report to facilitate for externals to reuse the findings in similar industrial contexts. Additional, the research is limited to mainly include mechanical factors to be investigated, even if the closure performance should be viewed as a system perspective including several areas e.g. organizational issues, silo structures, or culture aspects etc.

7.2 Recommendations

Based on the main findings and deliveries, mentioned in Section 6.2 above, the relationship map and the complementary Appendix 4 should be reused in further investigations by Volvo Cars. Both the relationship map and the complementary Appendix 5 provides a system view of the closure challenge, and the various factors affecting closure performance of automotive rear doors. The relationship map and the complementary Appendix 4 guides what other specific areas to investigate further, in order to examine the closure performance. For instance, there are several additional mechanical factors outlined which could be interesting to include in another DoE. If conducting an additional DoE, the material provided in the report, e.g. Appendix 7, can be used as guidelines in order to successfully plan and execute the DoE. More specific, the mechanical factor sealing stiffness (X_5), which were dismissed due to time limitations, could be of interest to include in an additional DoE. There is already information provided how to adjust the factor, suitable design range, time to adjust etc. for the factor X_5, see Appendix 9. Further, the process related factors outlined in the relationship map and the complementary Appendix 4 could also be of interest to investigate further. Also, a qualitative study could be conducted where the soft related factors e.g. the organizational aspects, culture, and silo structures etc. could be examined in order to understand how the soft related factors affect closure performance.

Furthermore, the model provided in the report, which describes the relation between the response value closure speed (Y_1) and the two critical factors affecting closure performance: sealing ingress (X_1) and cabin air evacuation (X_4), can be used in further investigations by Volvo Cars. For instance, the model can be used to examine insensitiveness to variation, factor sensitivity analysis, and robustness in the model by applying e.g. Monte Carlo-method (Cho, Shin, Kolch & Wolkenhauer, 2003; Paxton, Curran, Bollen, Kirby & Chen, 2001). For instance, the factors, X_1 and X_4, can be modified by adding noise distribution curves to them which allows them to vary. If the factors vary according to noise distribution curves, the variation in the response value Y_1 due to the variation in X_1 and X_4 can be examined. Hence, a factor sensitivity analysis can be performed to examine the robustness. Finally, the model provided in the report can also be used in simulation developments. Currently, there are no software program which simulates the actual closure event at Volvo Cars. The model provided in the report is built on empirical data, which can be used as fundamental information when building simulation models of the closure event, in order to evaluate the closure performance. If the closure event can be simulated, the closure performance can be managed in advanced and in prevention purposes. Where proactive measures prior the actual production of rear door can be applied. Hence, a computer aid tool for simulating the closure performance can be developed based on the empirical data found in this project. The simulation tool could be used for quality improvement by enable proactive work of closure performance. A computer aid simulation tool would also go beyond the practical constraints when investigating closure performance using e.g. DoE. A corporation for developing a computer aid simulation tool were initiated during the project by the researchers. The corporation were between Volvo Cars and Fraunhofer-Chalmers Centre (FCC), discussing simulation opportunities, see Appendix 12.

Lastly, there are endless of opportunities of future work to examine door closure performance, a few of them mentioned above. One just has to open the right door.

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Appendices

Appendix 1: Case Description of the Closure Challenge

The purpose of the master thesis is to improve the quality of closure performance by determine which factors affect closure performance on rear doors, by using both qualitative and quantitative data. The research was conducted on the behalf of Volvo Cars as a case, for investigating which factors affect closure performance. A door consists of several mechanical factors e.g. striker, hinges, sealings etc., which all have their functionality and purpose for enabling proper door closure and opening. The rear doors of cars might differ in design, functionality, mechanics etc., between different car suppliers, car models, and car manufacturers. However, basic mechanical functions of rear doors could be considered as generalizable among different car suppliers, car models, and car manufacturers. The chosen factors to investigate for this case is within the area of mechanical factors: sealing, striker, door frame, and cabin air evacuation vents. The project can therefore be reused in similar industrial context for determine which of the sealing, striker, door frame, or cabin air evacuation vents affect the closure performance critically. Also, the methodology used for determining which are the critical factors affecting closure performance can be adopted for other contexts as well. DoE was emphasized in the project as main method utilized for examine which mechanical factors critically affect closure performance. The DoE method are outlined in detailed in the report, of course relating to the very context of the case. However, the main findings from the DoE method and DoE execution in practice are summarized and could be reused in other contexts. A checklist of the DoE method is provided, which can be used by other externals whom shall conduct a DoE. Important reflections and discussions regarding the difficulties of performing a DoE in practice are provided as well.

Furthermore, the closure performance can be seen as a system of different factors affecting the closure performance. Depending on the context, the system might include different factors e.g. process related factors, measurement related factors, organizational aspects etc. Hence, the system might differ in other contexts. However, this case represents an industrial context; car manufacturer, and the project is of course most easily reused in similar industrial context involving the same type of system interactions. The system context should be considered when investigating which factors affect closure performance, since it was found important during the research. The door is a complex product aimed to please many different stakeholders, functions, and departments. Except from just enable entry and exit from the car, the door has other functions as well. For instance, the sealings on the door should prevent from noise and contamination, the door frame should enable total closure even if affected by aerodynamic forces imposing the door outwards when driving. Also, the door lock, constructed by striker and latch, should result in total closure as well as the door stop should allow the door to be stationary open. Hence, there are many different functions to fulfill when designing and construction a car door. Therefore, many different functions and departments are involved in the door process: designing and producing. Considering that, a system perspective should be adopted when investigating factors affecting closure performance. The system might differ depending on context, which should be noted if reusing the finding from this research. However, as mentioned previously, the main focus in this project were to examine mechanical factors, which were considered as generalizable among different car suppliers, car models, and car manufacturers.

Appendix 2: Interview Questions for the Interview Study

Date:
Department:
Role:
Topic:

Definition of Closure Performance

1. How do you define a good performing door?

2. How do you define a poor performing door?

Factors Affecting Closure Performance

3. Which factors do you consider to be related to closure performance of rear doors?

4. How are the factors related to the closure performance of rear doors?

5. Why are these factors important for closure performance?

6. In your opinion, which are the critical factors causing poor closure performance?

Actions to Avoid Poor Closure Performance

7. What actions are done today to prevent poor closure performance?

System Boundary of the Closure Performance

8. Could the closure performance relate to other departments and functions?

9. Do you experience any conflicts between objectives or requirements for the closure performance between different departments and functions?

10. Do you know if there are earlier or ongoing investigations regarding closure performance?

Customer Complaints

11. Do you have access to customer complaints of the rear door closure performance?

Others

12. Can you refer to other persons whom possesses expertise within this area?

Appendix 3: Roles and Departments Included for the Interview Study

AE-leader (Advanced Engineering) Virtual Optimization at Knowledge Based Engineering

Analysis Engineer at Testing body, Closures, Interior & Exterior

Attribute Leader at Ergonomics at Ergonomics

CAE (Computer Aided Engineering) Engineer, Durability at CAE (Computer Aided Engineering) Interior, Exterior & Closure

Concept Leader Pained Body & Closures at Strategy, Concept & Advanced Engineering

Geometry Assurance Engineer at Geometry Assurance Program

Group Design Leader at Closures

RCC (Resource & Competence Center) Technical Consulting at Technical Consulting

Robust Design Engineer at Robust Design and Tolerancing

SA (System Responsible) Door cpl at Door Trim

SA (System Responsible) Sealing System at Sealing & Closure Project Office

Senior Concept Leader Door Structure at VSA (Volvo Small Architecture) Door Complete, Closures

Senior Mechanical Integration Engineer at Block Door & Side

Senior Manager CMQ (Current Model Quality) Vehicle Hardware at Current Model Quality

Senior Quality Engineer at Forward Quality

Studio Engineer - Exterior Design at Exterior Studio Engineers

System Responsible Door Structure, Hinges & Check arm at Closures

Technical Expert Operational Sound Quality at Vehicle NVH (Noise Vibration Harshness) & Dynamics CAE (Computer Aided Engineering)

Traction Battery Analysis Engineer at Analysis & Validation

VRT (Variability Reduction Team) Leader Painted body & Closures, VCT (Volvo Cars Torslanda plant) at PPE (Pre Production Engineer), Interior/Exterior

Appendix 4: Translation of each Subcategory into Headline

The translation of each subcategory into one headline is provided in Table A below. The headlines are used in the relationship-map for the axial coding.

Table A. The translation of each subcategory into one headline used in the relationship-map for axial coding.

		The Translation: subcategory into headline		
Segment	**Category**	**Subcategory**	**Headline**	**#**
Mechanical Factors *All factors included related to the mechanics of the rear door*	Sealing	Impact position	Energy peak in sealing when closing the door. The door generates different impact position.	1
		Cabin	Too tight in cabin due to sealings which makes it difficult to close.	2
		Soft	Stiffness is affecting by time due to change of stiffness over time and the sealing becomes less stiff after time.	3
		Primary	Most important sealing and positioned at the door.	4
		Different cuts	Different cross sections on the sealing affect different amount of force.	5
		Aerodynamics	Sealing is same around the door but different impact by aerodynamic.	6
		Size	If bigger cross section in sealing, harder to close.	7
		Position	Seal gap position - Important for door closure. Affect impact position.	8
		Stiffness	Static resistance in sealing. Sealing damper. Stiffness, not important, only positively	9
		Door frame	Impact position during door closure. Sealing press door frame into nominal construction.	10
		Seal gap	The distance between primary and secondary sealing, the door will be difficult to close if bigger seal gap.	11
		Characteristics	Spreading in the design.	12
		Force-energy curve	Exponential power curve in sealing. Energy loss in sealing.	13
		Capacity of sealing	Spreading in basic design.	14
	Hinge	Hinge angle	The hinges are leaning and are important in self-closing aspects.	15
		Spread	Spread in impact of door closure.	16
		Hinge line	Give energy in door closure. Both hinges build a line in relation.	17
		Hinge friction	Small impact in energy loss.	18
		Hinge line position	Difficult to control. Give energy.	19

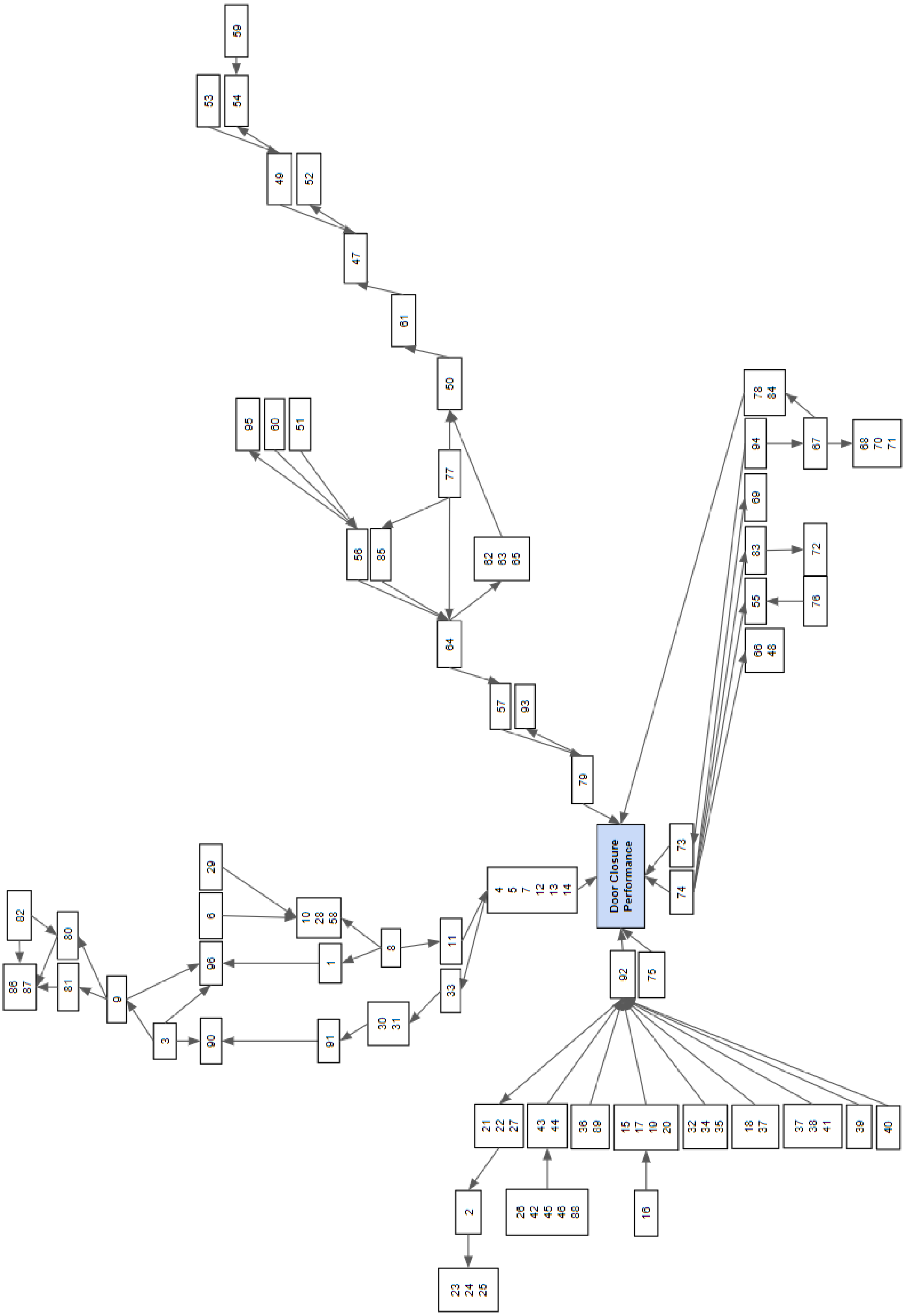
	Hinge slope	Leaning the door towards the body and backwards to use the gravity in the closing event.	20
Speed	Speed & pressure	Unknown relation and effect.	21
	Speed & air resistance	Relation to door closure. Higher speed gives greater resistance.	22
Air evacuation	Cabin	High impact on door closure. Energy loss. Difficult to evacuate air.	23
	Air inside sealing	Compresses during door closure. Constructed with holes for evacuation, low knowledge of impact e.g. placement of holes, amount.	24
	Air between sealing	Affect door closure. More entrenched air gives harder door closure.	25
	Door shape	Affect the amount of air in cabin.	26
	Speed	Higher speed gives easier door closure.	27
Aerodynamics	Door frame	Force door frame outwards. Should seal during drive.	28
	Non-aerodynamics	No effect on door closure.	29
Door lock	Striker position	Affect door closure.	30
	Latch position	Affect door closure.	31
	Bump energy loss	Affect due to energy loss.	32
	Stiffness	Internal stiffness is important. Stiffness in relation between lock and striker.	33
	Non-lock	No effect on door closure.	34
	Energy loss	All mechanical factors within the lock.	35
Door check	Inertial area	Exist between first and last lock mode.	36
	Friction door check	Check mechanism affects the door closure.	37
	Shape	Builds energy and affect the door closure.	38
	Spring energy	Give energy.	39
	Spring speed	Affect the door closure speed.	40
	Door stop	Affect door closure due to its design. Builds energy.	41
Door shape	Thickness	Spreading into the material.	42
	Center of gravity position	Position of the center affect the door closure.	43
	Door weight	Higher weight requires higher energy input.	44
	Door pocket	Size of pocket affect the size and weight of the door.	45

		Door design	Effect on door weight and door closure.	46
Process Factors *All factors included related to different types of processes*	Construction	Construction	Probably spread in construction. Much to consider during construction. Always construct in nominal values.	47
	Audit	Audit	Few remarks on door closure. Approve cars that maybe not are fully approved.	48
	CATIA	CATIA	Unclear guidelines regarding tolerances. Spread within measurement of same construction.	49
	Non-robust system	Non-robust system	Sensitive system. Instable processes in production.	50
	Good looking	Good looking	Priority exterior. No focus on function.	51
	Sequence & time process	Sequence & time process	Late measurement on door closure in production. Late detection of problem.	52
	Reality vs plan	Reality vs plan	No comparison between construction and reality. Construction and production outcomes differ.	53
	Same	Same	Same basic construction and platforms result in different outcomes on cars.	54
	Information	Info	Loss of information between construction to production.	55
	Door position	Door positioning	Unclear adjustment of rear door in production. Sensitive system.	56
	Geometry	Geometry	Split views if geometry affect or not. “Chain effect”, articles around affect door closure.	57
	Compensated door frame	Compensated door frame	Compensate toward car body. Affect sealing. Spreading in production.	58
	Measurement	Measurement	Question regarding accuracy and spreading in the measurement process in production.	59
	Robot	Robot	Affect door position. Little knowledge regarding accuracy and its effect on the closure performance.	60
	Tolerances	Removed tolerance	Change tolerance in construction process. Difficult to find information about the basic tolerances.	61
		Non-robust system	Sensitive system. Small tolerances impact in large outcomes.	62
		Tolerance chain	Spreading. Important to manage worst case scenario.	63
		Big tolerances	Large impact on problems. Spreading in tolerance chain.	64
		Relation between articles	Affect door closure. Chain effect. Small articles lack tolerances.	65
Soft Factors	Customer	Internal customer	Exist internal clinic that act customer. Focus on the production.	66

All factors included related to different types of soft factors		Subjectivity	Each person perceives feeling and force differently regarding the door closure.	67
		Assessment	Difficult to evaluate customers complaints.	68
		Non-customer facts	*No customer info* - Lack of information regarding customers complaints. Difficult to perceive customers complaints.	69
		Non-standardization	Difficult to interpret answers in questionnaires.	70
		Customer do not know	Difficult to perceive customers complaints.	71
	Weighted Factors	Balance solution	System that works for all requirements.	72
		Weighted Factors	Difficult to decide the most important factor. Lack of understanding how factors interacts in system.	73
	Silo	Silo	Own interests and lack of a holistic approach. Difficult to decide responsibilities between interfaces. Requirements conflicts.	74
	Non-silo	Non-silo	Great communication. Holistic approach.	75
	Bad boss	Bad boss	Lack of detailed knowledge.	76
Requirement	Wrong requirement	Wrong requirement	Requirements are transmitted from previous project. Too large tolerances.	77
All factors included related to requirements regarding rear door performance.	Definition of close	Definition of close	In second locking position.	78
	Individual requirements	Individual requirements	Difficult to have same requirements for all car models.	79
	1.3 m/s	1.3 m/s	Measurement of maximal closure speed direct after production and under two weeks.	80
	1.1 m/s	1.1 m/s	Measurement after two weeks of maximal closure speed.	81
	Energy requirement	Energy requirement	Want to measure in energy instead of speed. Today ergonomic requirement is 1,75 joules.	82
	Requirement vs requirement	Requirement vs requirement	Conflict between requirements.	83
	Subjectivity	Subjectivity	Difficulty to perceive some requirements regarding the closure performance.	84
	People are afraid of changing requirements	People are afraid of changing requirements	People are afraid of changing requirements.	85
Car Models	High quality of closure performance	High quality of closure performance	Car models with better quality of door closure performance.	86
All factors included related to car models	Less quality of closure performance	Less quality of closure performance	Car models with lower quality of door closure performance.	87
Others	Larger problems with underwrap doors	Larger problems with underwrap doors	Sealing impact position. More air between primary and secondary sealing.	88

All factors remaining which were difficult to group	Opening angle	Opening angle	Fully open and half open. Depending on door check. Larger angle gives easier door closure.	89
	Noise	Noise	Requirements affecting noise e.g. wind noise and locking noise. Quality perceives.	90
	Force in overslam	Force in overslam	Lack of knowledge in the door closure performance.	91
	Energy input = energy output	Energy input = energy output	Energy balance in door closure performance.	92
	Higher closure force for rear doors	Higher closure force for rear doors	Door properties.	93
	Many investigations but no compilations	Many investigations but no compilations	Many investigation and tests but no compilations.	94
	Position front- and rear door	Position front- and rear door	Rear door is affected by the front door position	95
	Dynamic compensation	Dynamic compensation	Properties within material that has impact on the door closure performance.	96

Appendix 5: Relationship map



Appendix 6: The Execution Schedule of the DoE

Below in Table B is the execution schedule of the DoE. The sequence of the activities is based on the experimental run plan, including time estimation for factor adjustments and usage of EZSlam. The adjustment time were estimated based on the pilot test. The usage time of EZSlam were estimated based on consultation with the EZSlam expert. Tuesday is the pilot test day for assuring the involved activities during Wednesday and Thursday. Also, during Tuesday all factors involved will be rechecked for adjustment in practice. In the end of the pilot test, the bumper will be adjusted to prepare for the first day run execution. Further, during Wednesday and Thursday, the actual DoE will be conducted. After all runs were conducted, the car needed to be restored as its basic setup e.g. adjust all factors to basis position and restore bumper, before it could be returned.

Table B. The execution schedule of the DoE.

Time	Tuesday 24/4	Wednesday 25/4	Thursday 26/4
8:00		**EZSlam test** Operator	**RUN 7** (15 min) Mechanic **RUN 7 EZSlam** (30 min) Operator
9.00	**PICK UP CAR** **Emma & Emma**	**RUN 1** (15 min) Mechanic **RUN 1 EZSlam** (30 min) Operator	**RUN 8** (15 min) Mechanic **RUN 8 EZSlam** (30 min) Operator
10:00	**EZSlam test** Operator	**RUN 2** (15 min) Mechanic **RUN 2 EZSlam** (30 min) Operator	**RUN 9** (15 min) Mechanic **RUN 9 EZSlam** (30 min) Operator
11:00	LUNCH (60 min)	LUNCH (60 min)	LUNCH (60 min)
12:00		**RUN 3** (15 min) Mechanic **RUN 3 EZSlam** (30 min) Operator	
13:00	**Factor Adjustment test** Mechanic	**RUN 4** (0 min) Mechanic **RUN 4 EZSlam** (30 min) Operator	**RESTORE CAR (30 min)** **Mechanic**
14:00	**Factor Adjustment test** Mechanic	**RUN 5** (15 min) Mechanic **RUN 5 EZSlam** (30 min) Operator	Restore Bumper Mechanic
15:00	**Remove bumper** Mechanic	**RUN 6** (15 min) Mechanic **RUN 6 EZSlam** (30 min) Operator	**BRING BACK CAR** **Emma & Emma**
16:00			

Appendix 7: Checklist of the DoE

Below are the most important findings summarized into a checklist. The checklist can be utilized by externals in similar industrial contexts when conducting a DoE.

The Planning Phase of the DoE

- ❑ **Creating commitment**
  DoE should be clearly understood by all participants
  Involve stakeholders and other participants in discussions and ask for their opinions

- ❑ **Problem description and the objectives of the DoE**
  Scope the DoE
  Outline the purpose of the DoE
  Define the objectives of the DoE
  Important deliveries

- ❑ **Limitations during the DoE**
  e.g. MSA of the measurement device used for recording response value
  e.g. budget limitations
  e.g. time limitations
  e.g. risk of failure

The Design Phase of the DoE

- ❑ **The choice of number of factors to include and their characteristics**
  Define the number of factors and motivate the choice
  Describe the characteristics of the factors

- ❑ **The most important constraints to consider when choosing the design**
  e.g. HTA factors
  e.g. time constraints
  e.g. confounding constraints

- ❑ **The choice of appropriate design ranges for factor adjustments**
  Examine internal relationships among factors affecting the design range
  Do the design range reflect reality
  Wide enough design ranges for examine how the factors affect response value

- ❑ **The choice of number of levels, type of effects, center points, and replicates to include**
  e.g. 3 levels to test for curvature
  e.g. only main effects
  Include center points to test for curvature
  Include replicates to estimate noise

- ❑ **Pilot test**
  Test feasibility of all factor adjustments in practice
  Test for internal relationships among factors in practice
  Test maximum range of factors
  Test for contextual constraints related to the factor adjustments in practice

Note the adjustment time in practice
Test the measurement device used for recording response value in practice

- ❑ **Comparison of three different designs and the choice of most appropriate design for the DoE**
  Base the assessment categories on the objective for the DoE
  Base the assessment categories on DoE limitation and constraints

The Execution Phase of the DoE

- ❑ **Roles and responsibilities during the DoE**
  e.g. project leaders of the DoE execution
  e.g. mechanic of the factor adjustments
  e.g. operator of measurement device
  e.g. recording response values

- ❑ **Setup for all the experimental runs**
  Ensure the same conditions for all factors when adjusted to reduce noise

- ❑ **How the factors will be adjusted in practice**
  Explain how to adjust the factors and what is important to consider

- ❑ **The plan of the experimental runs generated by e.g. JMP or Minitab**
  The experimental plan
  The execution schedule of the DoE

- ❑ **Management of the measurement device for recording the response value**
  Operator of measurement device
  Procedure or process for the measurements
  Backup recorder
  Reduce noise caused by measurement system

The Analysis Phase of the DoE

- ❑ **Parameter Estimates**
  Which factors are significant

- ❑ **Prediction Profiler**
  Visualizing how changes in factors' levels affect response value

- ❑ **Prediction Expression**
  Mathematical model of the relation between factors and response value

- ❑ **Evaluation of the model**
  Examine the quality of the model
  Summary of fit: RSquare and RSquare Adj
  Center points: require a quadratic term

Appendix 8: EZSlam Fact

EZSlam is a complex closure measurement system that are used to measure all statistic and dynamic characteristics of doors complete closing data and translate subjective impressions into objective numbers (EZSlam, 2018). This make it possible to measure all key metrics of a door easily with the approach, "all-in-one" measurement. EZSlam consists of a body-, door-, cabin- and base-unit (i.e. wireless communication), see Figure A below.

Figure A. EZSlam mounted on the cars' rear door

The body- and door-unit are mounted on the outside of the car with suction cups and the cabin-unit are placed inside the car near the door that should be tested. EZSlam are used because it can collect large amount of data that are extracted from different motions during the measurement, see Table C below (EZ Slam, 2018).

Table C. EZSlam measurement options

Slam Tests	The door is closed several times at different speeds to capture all its dynamics aspects.
Push Tests	The door is closed in a quasi-static motion.
Wiggle Tests	The door is moved back and forth to determine basic characteristics.
Tailgates	Swing Tailgate to a close and determine basic dynamics.
Pop Test	Latch door popping open.

EZSlam motions that are conducted of interest for this research are slam-, push- and wiggle-test. This gave information regarding door closure speed and required total closure energy. Hence, the kinematics of a door is complex. This can be characterized by a set of key metrics where one metric is optimized, might another metric be degraded as well. The metrics need to be controlled, studied and adjusted at the same time. Therefore, the technology uses a Combined Integrated Model (CIM) to combine information from several tests into one database to minimize the number of tests, increase used independent and correlations (i.e. minimum the closure performance) in order to determine key characteristics (EZ Slam, 2018). Further, a sample of key metrics that can be identified by using EZSlam are shown in Table D below (EZ Slam, 2018).

Table D. A sample of EZSlams key metrics

Trajectory	**Design**	**Dynamics**
Typical over slam	Hinge tip around X	Minimum Closing speed
Striker Alignment	Hinge tip around Y	Minimum Input Pulse energy
Latch Point	Hem radius	Kinetic closing energy
Door Rise	Swing Radius	Door Check Linearity
Open Position Angle	Inertia	Door Check Slope
Initial speed	Weight	Speed Curve
Force	**Pressure**	
Static Latch energy	Cabin pressure peak	
Static Latch Force	Pressure rise time	
Check Force Outbound	Pressure drop time	
Check Force Inbound	Temperature	
Closing force		

Appendix 9: Sealing Stiffness

Table E provides the adjustment explanation for X_5. A more detailed description of the adjustment is provided after the table.

Table E. The adjustments explanation for X_5 Sealing Stiffness.

Factor	Adjustment	Notice	Time to Adjust
X_5 Sealing Stiffness	As low level, a sealing with lower stiffness is used. As high level, a sealing with higher stiffness is used. Both the body mounted and the door mounted sealings will be adjusted. The body mounted sealing will be adjusted by removing the sealing from the car body and mount the new sealing by clamping it to the flange. The door mounted sealing shall be fasten by glue.	Prior the experimental run and at each adjustment into high and low value, the sealings shall be replaced by new ones to avoid impact of plasticization.	60 min

The sealing stiffness is considered as hard to adjust in practice, but it is feasible to adjust. The door mounted sealing is fastening by glue and the body mounted sealing is clamped on a flange. Once the sealings have been removed, they cannot be reused and must therefore be rejected. The sealings are made by rubber which is characterized by a plasticization curve (CLD curve). Hence, the rubber in the sealing will plasticize and the stiffness will change by time, this noticing must be considered.

Therefore, the experiment should be designed to reduce the number of times the sealings have to be adjusted and replaced. Hence, the experimental design is chosen so that factor X_5 only has to be adjusted two times into the high and low value. This is possible when using a split-plot design. During the first section of experimental runs, the low-level sealing is used (this sealing characterized by a lower stiffness) where all the runs are carried out and the other factors are adjusted according to the DoE plan. The low level of factor X_5 is held constant during this section of experimental runs. Then, factor X_5 is adjusted into high level (this sealing is characterized by a higher stiffness). Just as before, all the runs are carried out and the other factors are adjusted according to the DoE plan. The high level of factor X_5 is held constant during this section of experimental runs. The body mounted sealing will be adjusted by removing the sealing from the car body and add the new sealing by clamping it to the flange. The door mounted sealing shall be fastening by glue. This split-plot design will reduce the number of times the sealings have to be adjusted and replaced. The cost of the experiment will also be reduced due to the lower number of spent sealings.

Additional, during the experiment it is important to avoid impact of plasticizing, as mentioned above. Therefore, when adjusting the sealing stiffness into high and low value, all sealings will be replaced by new ones for ensure same level of plasticizing. It is desirable to conduct the experiment using sealings which have reached the same level of plasticizing as in commercial cars. This level of plasticizing is reached after 12-20 h. According to the DoE plan, the experiment will run for two days. The adjustment of sealing stiffness will appear between the days. Hence, during the first day, the low value sealing will be used for the experimental runs. The car will be prepared the day before by replacing the sealings into low level. The door will be held closed to rush the plasticizing for reaching the same level as used within commercial cars, and the experimental runs will start within 16 h, the next day. After conducting all the experimental runs using the low level sealing, the car will be prepared by adjusting and replacing the sealings into high value. The door will be held closed to rush the plasticizing for reaching the same level as used within commercial cars, and the experimental runs will start within 16 h, the next day. This process will ensure the same plasticizing level for the sealings used for high and low value. It is important to use sealings which have reached the wanted level of plasticizing. If stiffer sealings are used, the result might be bias. A sealing with high stiffness might worsening total closure of the door: hence, a higher closure force is needed for create the necessary sealing ingress for total closure. Therefore, the result might indicate sealing stiffness as a high influencing factor affecting the response value than it actually does due to faulty level of stiffness. Hence, it is important to use the same level of plasticizing which is actually used in commercial cars where the poor closure performance of rear doors occur.

Appendix 10: Mechanical Factors Affecting Closure Performance

The following appendix provide a detailed description of the different mechanical factors involved of the DoE. Initially, the door closure performance can be viewed as a balance of energy. To create motion, the door need energy. Sources of input energy are e.g. energy provided by user etc. Hence, to enable motion, the door is constructed by different mechanical factors e.g. hinges, door-check, and springs etc. Except from just enable motion, the door have other properties to fulfill as well e.g. contamination and water repellent, allow the door to be stationary open, soundproofing, resist aerodynamic forces imposing the door frame outwards when driving etc. However, these factors also consume energy. Hence, sources of output energy are: friction, air resistance etc., where the energy are consumed. Total closure of the rear door appears when the input energy is above or equal to the output energy, see Equation A below.

$$\sum input\ energy = \sum output\ energy \qquad \text{(A)}$$

Hence, this is the fundamental equation to enable total closure of the rear door. If the input energy is less than the consumed energy, the door will not result in total closure. However, energy provided by user is required to be low; it should not be difficult for the user to close the door. This requires that the other factors of the door mechanism must be designed to provide energy which can be utilized for closing the door. Energy should be built in to the mechanical factors, which can be released and utilized for door closure. For instance, potential energy is stored when opening the door due to the angle of the hinge line, which makes the door increase in height. When closing the door, the stored potential energy will be released as motion energy which increases the input energy and assist the door to close. However, even if the stored potential energy will facilitate the door to close, it will obstruct the door to open which is not wanted either. Therefore, there must be a balance of the involved factors for achieving high quality closure of the rear door.

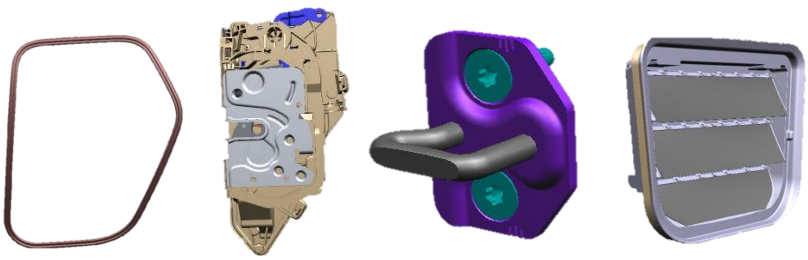


Figure B. The different main mechanical factors at the rear door.
From left to right: sealing, door lock, striker and cabin air evacuation.

As mentioned, the door is constructed by several mechanical factors, which all have a specific function to deliver in order to open and close the door, see Figure B above. The door mechanism can be viewed as a system, where all factors must operate together in order to provide high quality performance in door motion and closure. Below are the main mechanical factors involved of the closure performance described shortly. These mechanical factors are: sealing, air evacuation inside and between sealing, lock, hinges, check-links, and air evacuation in cabin.

Sealing

The sealing is one important factor that are of importance for a car because it has the function to seal e.g. isolate from water, reducing wind noise and contamination from various substances. The sealing system is divided into door mounted sealing as primary, and body mounted sealing as secondary, where the door mounted sealing is the more important one. Hence, there is a challenge of gathering knowledge regarding the sealing system due to change of stiffness over time. During time, the stiffness will decrease but the amount is difficult to measure. Also, the sealing is depending on the angle of attack of the door regarding how the effect of the damping will be in the closing mode (Nayak & Im, 2003). Since the car have two sealings, one mounted on the door and one on the body, makes a gap in between. When the door close, air builds up in between the sealings so called a seal gap. The sealings are produced with holes with an even distance in order to increase the air evacuation during compression from the door closing performance to increase the damping effect.

Door Lock and Striker

The lock consists of two parts, latch and striker. The latch is mounted on the door with the function of holding the door in a locked position. To lock the door, the latch need to hook into the striker which is mounted on the car body in a position that match the latch position. The lock is designed to let the door be hold in a first and second locking mode. Hence, the first locking mode are constructed in safety. In the second locking mode is the door completely locked. This is due to different expect of force to close the door e.g. is a child need to close the door but has not the full force that are required to let the door be locked in the second locking mode.

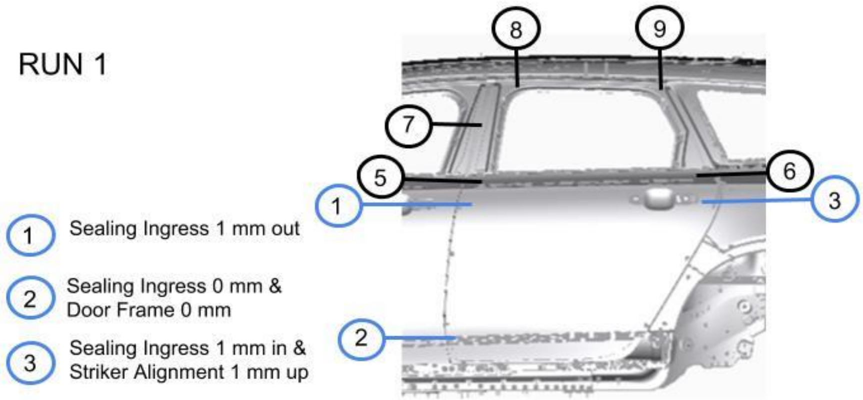
Air Evacuation in Cabin

Air evacuation in the cabin are needed when the door reaches the end of the closing motion. In that moment, air is being pushed inside the vehicle and creates a pressure inside the cabin. Thus, if all doors and windows are closed i.e. exit areas for the air, then the pressure inside the vehicle rises. This increases the air pressure in the closing motion of the door and offers resistance (Nayak & Im, 2003).

Appendix 11: Reference Points for Factor Adjustments

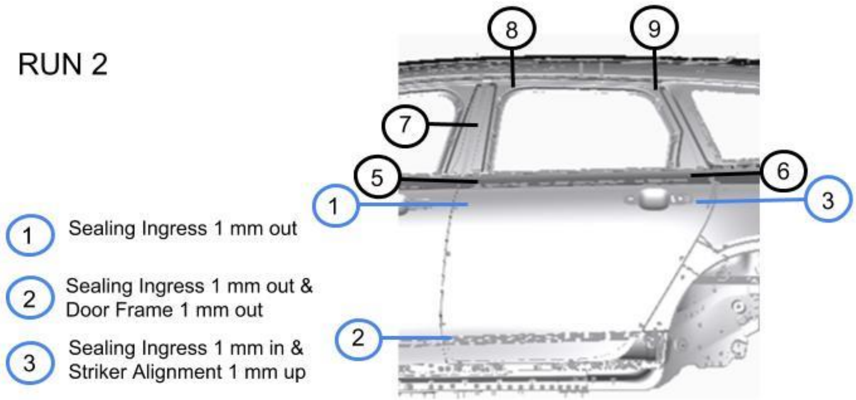
Below are the reference points for all factor adjustments outlined.

RUN 1



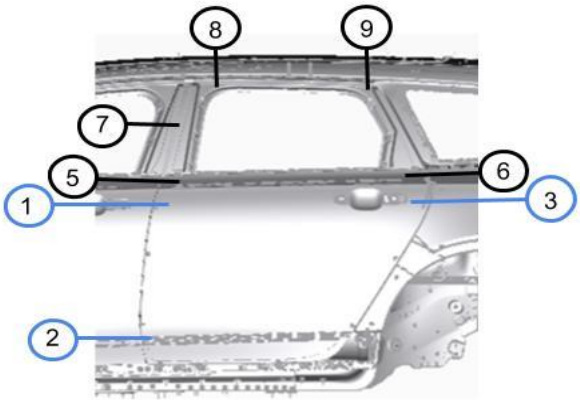
	1	2	3	4	5	6	7	8	9
Run 0	-0,6	0,3	-0,3	X	-0,8	1,6	-0,6	2,8	3,1
Run 1	-1,6	0,2	0,6	X	-2,0	3,0	-2,2	4,4	4,1

RUN 2



	1	2	3	4	5	6	7	8	9
Run 0	-0,6	0,3	-0,3	X	-0,8	1,6	-0,6	2,8	3,1
Run 2	0,5	2,5	-1,4	X	-0,8	0,8	0,8	3,1	3,0

RUN 3



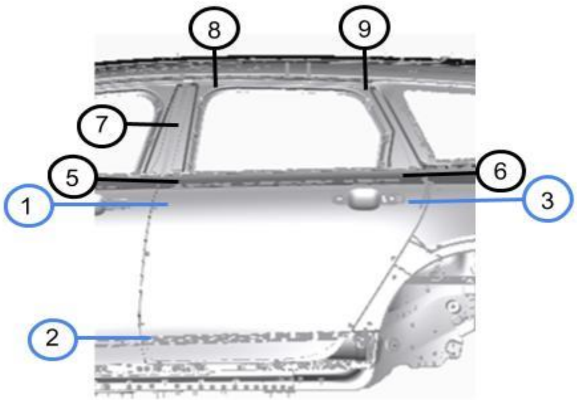
1 Sealing Ingress 0 mm

2 Sealing Ingress 0 mm & Door Frame 0 mm

3 Sealing Ingress 0 mm & Striker Alignment 0 mm

	1	2	3	4	5	6	7	8	9
Run 0	-0,6	0,3	-0,3	X	-0,8	1,6	-0,6	2,8	3,1
Run 3	-0,6	0,3	-0,3	X	-0,8	1,6	-0,6	2,8	3,1

RUN 4



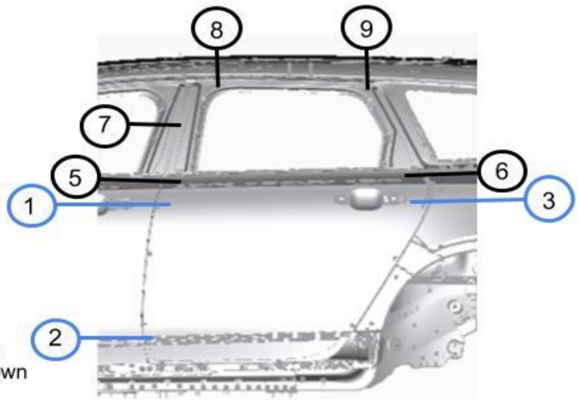
1 Sealing Ingress 0 mm

2 Sealing Ingress 0 mm & Door Frame 0 mm

3 Sealing Ingress 0 mm & Striker Alignment 0 mm

	1	2	3	4	5	6	7	8	9
Run 0	-0,6	0,3	-0,3	X	-0,8	1,6	-0,6	2,8	3,1
Run 4	-0,6	0,3	-0,3	X	-0,8	1,6	-0,6	2,8	3,1

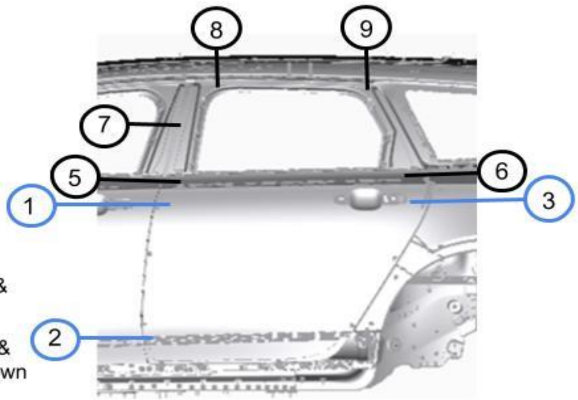
RUN 5



1. Sealing Ingress 1 mm in
2. Sealing Ingress 1 mm in & Door Frame 1 mm
3. Sealing Ingress 1 mm in & Striker Alignment 1 mm down

	1	2	3	4	5	6	7	8	9
Run 0	-0,6	0,3	-0,3	X	-0,8	1,6	-0,6	2,8	3,1
Run 5	0,4	1,8	-1,3	X	-0,5	1,2	-0,1	2,8	3,3

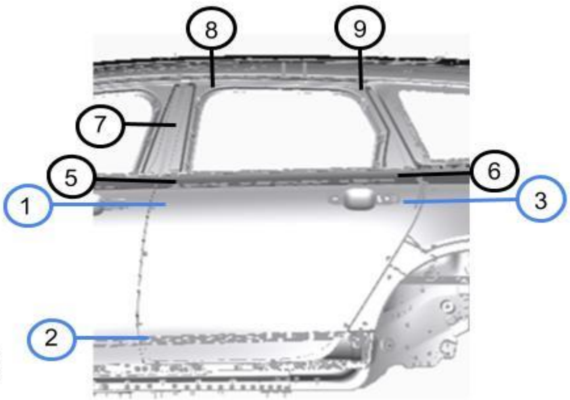
RUN 6



1. Sealing Ingress 1 mm out
2. Sealing Ingress 1 mm out & Door Frame 1 mm
3. Sealing Ingress 1 mm out & Striker Alignment 1 mm down

	1	2	3	4	5	6	7	8	9
Run 0	-0,6	0,3	-0,3	X	-0,8	1,6	-0,6	2,8	3,1
Run 6	0,5	2,3	-1,2	X	-0,7	1,4	-0,2	3,1	3,3

RUN 7



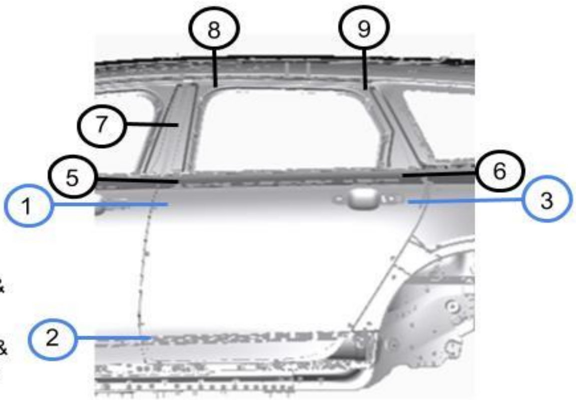
1 Sealing Ingress 1 mm in

2 Sealing Ingress 1 mm in & Door Frame 0,5 mm

3 Sealing Ingress 1 mm in & Striker Alignment 1 mm up

	1	2	3	4	5	6	7	8	9
Run 0	-0,6	0,3	-0,3	X	-0,8	1,6	-0,6	2,8	3,1
Run 7	-1,5	-0,5	0,8	X	-1,5	2,1	-1,4	3,5	3,4

RUN 8



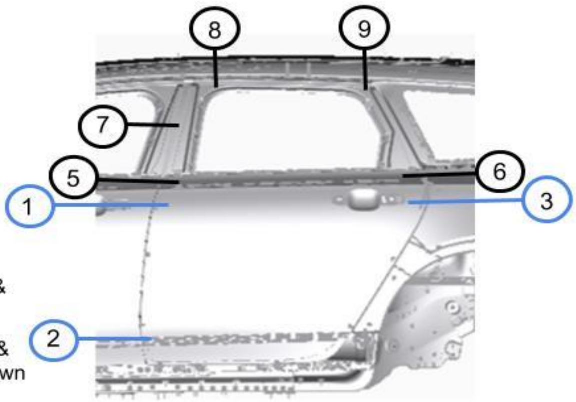
1 Sealing Ingress 1 mm out

2 Sealing Ingress 1 mm out & Door Frame 1 mm

3 Sealing Ingress 1 mm out & Striker Alignment 1 mm up

	1	2	3	4	5	6	7	8	9
Run 0	-0,6	0,3	-0,3	X	-0,8	1,6	-0,6	2,8	3,1
Run 8	-1,5	-0,2	0,8	X	-1,6	2,1	-1,8	3,6	3,4

RUN 9



(1) Sealing Ingress 1 mm out

(2) Sealing Ingress 1 mm out & Door Frame 0,5 mm

(3) Sealing Ingress 1 mm out & Striker Alignment 1 mm down

	1	2	3	4	5	6	7	8	9
Run 0	-0,6	0,3	-0,3	X	-0,8	1,6	-0,6	2,8	3,1
Run 9	0,4	1,9	-1,3	X	-0,7	1,3	-0,1	2,7	3,0

Appendix 12: Numerical Simulation of Door Seal Structure Provided by FCC

Collaboration with Fraunhofer-Chalmers Centre (FCC) for simulation opportunities was initiated during the master thesis. *The Numerical Simulation of Door Seal Structure* is a recommendation for future projects provided by Johan S. Carlson, director and head of department of FCC. Note, the following text is written by Johan S. Carlson from FCC only.

Numerical Simulation of Door Seal Structure

In collaboration with FCC, Johan S. Carlson writes:

Numerical simulation is an indispensable tool for rapid prototyping. Design geometry and materials can easily, and quickly, be varied in order to find an optimal design. Simulations can also contribute to an increased understanding of the physical process and key influencing parameters.

The seal resistance has been reported to be a major contributor to the door closing effort (Wagner, Morman, Gur, & Koka, 1997). A numerical model of the deflection and compression of the seal is highly complex due to the nonlinear conditions with contact, large compression and material incompressibility. If the entrapped air in the seal and the cabin are also considered in the model, the complexity is further increased.

Several finite element analyses of the door sealing have been reported; analyzing two-dimensional seal sections (Wagner, Morman, Gur, & Koka, 1997) (Zhao, Zhou, & Zhu, 2004), three-dimensional models of critical areas (Zhu, Wang, & Lin, 2014) and complete seals (Ordieres-Meré, Bello-García, Muñoz-Munilla, & Del-Coz-Díaz, 2008; Ordieres-Meré, Muñoz-Munilla, Bello-García, & González-Marcos, 2012; Moon, Kim, Kim, Kim, & Kim, 2011). Gur and Morman (1997) used an analytical model for the expulsion of air in the seal and Moon used one to model the pressure change in the inner cabin.

Although a full three-dimensional model of the complete seal is the final objective, it would be advantageous to start with a smaller section, with a detailed solid model of the cross-section including the entrapped air. This could then be used to quantify the effect of air expulsion and to derive a simpler shell model for the full seal.

Fraunhofer-Chalmers Centre develops novel simulation software, including a state-of-the art flow solver IBOFlow (Mark & Wachem, 2008; Mark, Rundqvist, & Edelvik, 2011) and a finite element software for large deformation analysis (Svenning, Mark, & Edelvik, 2014; Lorin, Cromvik, Lindkvist, & Söderberg, 2014), that combined, are perfectly suitable for fluid-structure interaction problems with moving and interacting boundaries.

The construction of a full simulation model requires a targeted industrial project. Existing methods and models in the software for contact- and constitutive modelling would have to be further developed as well as new implementations of pressure models for the air. The software would also have to be optimized for speed due to the large resulting computational model.

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