



CHALMERS
UNIVERSITY OF TECHNOLOGY



Driving Position Assurance in Passenger Cars

Master's Thesis in Product Development

Ismael Ayala
Sandra Holgesson

Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2015

Driving Position Assurance in Passenger Cars

ISMAEL AYALA

SANDRA HOLGESSON

Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2015

Driving Position Assurance in Passenger Cars
A Master's Thesis in Product Development
ISMAEL AYALA
SANDRA HOLGESSON

© ISMAEL AYALA & SANDRA HOLGESSON, 2015

Department Product and Production Development
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone + 46 (0)31-772 1000

Cover:

Picture showing a driver in a automotive seat. Accessed May 15th 2015 at:

http://www.motortrend.com/roadtests/suvs/1502_2016_volvo_xc90_first_drive/photo_102.html

Chalmers Reproservice
Göteborg, Sweden 2015

ABSTRACT

The demands from the customers of the automotive industry and the intense competitions from the international companies, make it necessary for all car manufacturers to reach a premium level of quality in order to be attractive and gain a share of the automotive market. Vehicle seats are one of the most important subsystems in the car, they provide the closest interaction with all the occupants in the vehicle, they are key in determining the user experience, and therefore they are connected to many of the functions and requirements for the whole product.

During the initial design of a car, the position of the seating occupant is used to determine most of the interior dimensions for the cabin. One of the most basic references to drive the packaging of the components inside the car, is the point where the occupant's hip will be located, this is known as the seating reference point (SgRP) during the design phase, and when it is measured on a finished physical seat it is named H-point. The fulfillment of many requirements depends on the location of the H-point and because of this it is very important to assure that the final position of this point corresponds to the one that was used during the design process.

The present report analyses in detail the consequences that having a deviation in the position of the H-point can have for the overall performance of the vehicle. It also researches the characteristics and activities inside an automotive company that can lead to such a misalignment and finally presents a suggested improvement to the design process of the vehicle seats in order to assure an exact correlation of the H-point measured in physical vehicles to the point that is used during design.

The improvement to the process that is suggested, is based on applying CAE software capability to determine the behavior of the seat, when it is supporting the load of the occupant, in order to simulate the final position of the H-point. In order to implement this, the behavior of the individual components and the properties that determine their response to a certain load have to be understood and controlled, this is detailed in the current work and finally put together into a series of proposed steps that allow to implement the new method which provides a more robust seat design process that can help the company to create the high quality products that are needed to satisfy the customer nowadays.

SAMMANFATTNING

Hårda kundkrav och intensiv konkurrens gör det nödvändigt för alla biltillverkare att eftersträva högsta möjliga kvalitet för att vara attraktiva för kunder och vara framgångsrika på fordonsmarknaden. Bilsäten är ett av de mest centrala delsystemen i bilar då de utgör den närmsta kontakten mellan fordon och förare och påverkar därför användarupplevelsen samt flertalet funktioner och krav som sätts på bilen i helhet.

Under utformningen av bilar används den tänkte passagerarens position i bilen för att bestämma de flesta av de inre dimensionerna. En av de mest grundläggande referenserna för att bestämma komponenters position inuti bilen är den punkt där passagerarens höft kommer att ligga. Denna punkt benämns som SgRP under konstruktionsfasen, när den sedan mäts på ett färdigt fysisk säte kallas den för H-punkten. Uppfylldandet av många krav beror på placeringen av H-punkten och på grund av detta är det mycket viktigt att säkerställa att den slutliga positionen för denna punkt motsvarar den som användes under designprocessen.

Den här rapporten analyseras i detalj de konsekvenser en avvikelse mellan SgRP och H-punkt kan ha för fordonets prestanda. Den analyserar också de egenskaper och aktiviteter inom ett bilföretag som kan leda till en sådan avvikelse. Slutligen presenteras ett förslag på en förbättrad designprocess för säten med avsikt att säkerställa en exakt korrelation mellan den uppmätta H-punkten i fysiska fordon och den punkt (SgRP) som används under designfasen.

Processändringen som föreslås är baserad på tillämpning av CAE-programvara för att bestämma beteendet hos sätet när det belastas av en passagerare (eller mätdocka), för att simulera den slutliga positionen av H-punkten. För att genomföra detta, behöver de enskilda komponenternas beteende och egenskaper analyseras och kontrolleras. Detta beskrivs i följande arbete och kulminerar i en reviderad designprocess med en rad förslag på åtgärder som skulle hjälpa företaget att skapa de robusta och högkvalitativa produkter som behövs för att vara konkurrenskraftiga på dagens marknad.

ACKNOWLEDGEMENTS

We would like to thank the support of Volvo Cars Corporation, for letting us conduct the current study and for providing us with the necessary information and tools during the project. Special thanks to our supervisors at Volvo Cars, Thomas Krusell and Peter Setterberg, and to our supervisor at Chalmers University of Technology, Lars Almfelt, for their continuous support and guidance throughout the study. We also want to thank all the other Volvo employees who allowed us to interview them and provided us with information that helped us in the project.

*Gothenburg, May 2015
Ismael Ayala and Sandra Holgesson*

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES	1
LIST OF ABBREVIATIONS	3
1 INTRODUCTION	4
1.1 BACKGROUND.....	4
1.2 PURPOSE.....	5
1.3 LIMITATIONS.....	5
1.4 OBJECTIVES.....	5
1.5 DELIVERABLES.....	6
1.6 KEY ACTIVITIES.....	6
1.7 OUTLINE OF THE REPORT.....	6
2 THEORY OF DRIVER POSITIONING IN AUTOMOTIVE SEATS	7
2.1 AUTOMOTIVE SEATS ARCHITECTURE.....	7
2.2 STANDARDS AND REGULATIONS FOR AUTOMOTIVE SEATS.....	9
2.3 METHODS AND TOOLS FOR SEATING POSITION SIMULATION.....	11
2.4 SUMMARY.....	11
3 METHODOLOGY USED TO DEVELOP A SOLUTION PROPOSAL	12
3.1 DEVELOPMENT PROCESS.....	12
3.2 PROBLEM EXPLORATION.....	13
3.2.1 <i>Research of Literature Related to Automotive Seats</i>	13
3.2.2 <i>Interviews with Volvo employees</i>	13
3.2.3 <i>Tear-down of Volvo seat</i>	13
3.2.4 <i>Observation of H-point measurement process</i>	14
3.2.5 <i>Analysis of Effects of deviations in H-point</i>	14
3.2.6 <i>Analysis of Causes of deviations in H-point</i>	14
3.3 SOLUTION FINDING PROCESS.....	14
3.3.1 <i>Generation of possible solutions to the H-point deviation problem</i>	14
3.3.2 <i>Exploration and Selection of Solutions</i>	15
3.4 SUMMARY.....	15
4 OUTCOME OF PROBLEM EXPLORATION	16
4.1 FINDINGS ON VOLVO SEAT COMPONENTS AND ASSEMBLY.....	16
4.2 SEAT DEVELOPMENT PROCESS AT VOLVO.....	17
4.3 IDENTIFIED EFFECTS OF DEVIATIONS IN H-POINT.....	18
4.4 IDENTIFIED CAUSES OF H-POINT DEVIATIONS.....	23
4.5 SUMMARY.....	31
5 RESULTS OF THE SOLUTION FINDING PROCESS	32
5.1 GENERATION OF POSSIBLE SOLUTIONS TO THE H-POINT DEVIATION PROBLEM.....	32
5.2 DESCRIPTION OF GENERATED SOLUTIONS.....	32
5.3 ASSESSMENT OF PROPOSED SOLUTIONS.....	34
5.4 SUMMARY.....	35
6 PROPOSED PROCESS FOR H-POINT ASSURANCE	36
6.1 IDENTIFICATION OF CONTRIBUTING COMPONENTS.....	39
6.2 ANALYSIS OF COMPONENT PROPERTIES IN UNLOADED STATE.....	44
6.3 ANALYSIS OF COMPONENT PROPERTIES UNDER LOAD.....	45
6.4 REQUIREMENT FORMULATION AND VERIFICATION.....	48
6.5 SUMMARY.....	49

7	DISCUSSION	50
7.1	ORGANIZATIONAL IMPLICATIONS OF THE GIVEN TASK	50
7.2	EFFECTIVITY OF THE METHODOLOGY USED IN THE PROJECT	51
7.3	IMPLEMENTATION AND FURTHER DEVELOPMENT OF THE RESULTS.....	51
8	CONCLUSIONS AND RECOMMENDATIONS	53
	REFERENCES	55

LIST OF FIGURES AND TABLES

FIGURE 1. SEATS ARE CRUCIAL IN DEFINING INTERIOR SPACE IN THE VEHICLE	4
FIGURE 2. REPORT OUTLINE	6
FIGURE 3. PICTURE SHOWING SEAT COMPLEXITY AND MAIN PARTS.	7
FIGURE 4. IFD TESTING MACHINE.	8
FIGURE 5. MAIN INTERIOR DIMENSIONS FOR PASSENGER PACKAGING (SAE J1100)	10
FIGURE 6. DEVICES FOR MEASURING H-POINT, FROM SAE J826 AND J4002	10
FIGURE 7. AREAS OF SEAT DEVELOPMENT IN WHICH COMPUTER SIMULATIONS HAVE BEEN USED.	11
FIGURE 8. CONCEPT DEVELOPMENT FUNNEL (ULRICH & EPPINGER, 2012) ADAPTED TO FIT THE PROBLEM AT HAND.	12
FIGURE 9. PROCESS OF FINDING AND RANKING CAUSES OF H-POINT DEVIATIONS	14
FIGURE 10. DIAGRAM OF STEPS FOR SOLUTION EXPLORATION.	15
FIGURE 11. PICTURE OF FOAM AND TRIM FROM TEAR DOWN.	17
FIGURE 12. SEAT COMPONENTS IN CUSHION AND BACK AFFECTING H-POINT.	17
FIGURE 13. H-POINT HEIGHT RANGES FOR DIFFERENT CAR SEGMENTS	18
FIGURE 14. SGRP COMPARED TO MEASUREMENTS ON PHYSICAL SEAT.	19
FIGURE 15. VIRTUAL TOLERANCE STUDY COMPARING H-POINT TO SGRP.	19
FIGURE 16. H-POINT INFLUENCE.	20
FIGURE 17. THE OCCUPANT PACKAGING PROCESS (ADAPTED FROM (BHISE, 2011))	21
FIGURE 18. CAUSE-EFFECT DIAGRAM FOR H-POINT DEVIATIONS	24
FIGURE 19. COMPARISON BETWEEN BASIC CUSHION PADDING (RED) AND SPORT VERSION (GREY).	25
FIGURE 20. Y-SECTION OF SEAT EQUIPPED WITH VENTILATION SYSTEM FOR COMFORT.	26
FIGURE 21. Y-SECTION OF SEAT EQUIPPED WITH HEAT MAT FOR COMFORT.	27
FIGURE 22. INTENDED DESIGN (GREEN LINES) COMPARED WITH A SCANNED SEAT (BLUE LINES).	27
FIGURE 23. BRAINSTORMING MIND-MAP	32
FIGURE 24. RELATIONSHIP BETWEEN DIFFERENT ASPECTS OF THE PROBLEM.	36
FIGURE 25. REQUIREMENT DEFINITION PROCESS.	37
FIGURE 26. NEEDED INFORMATION FOR NEW REQUIREMENTS.	37
FIGURE 27. PROCESS FOR FINDING MEASUREMENT AND TOLERANCE FOR UNLOADED CASE.	38
FIGURE 28. PROCESS FOR FINDING MEASUREMENT AND TOLERANCE FOR DEFLECTED STATE.	38
FIGURE 29. PROCESS OF ASSURING THE H-POINT POSITION.	39
FIGURE 30. THE VARIANTS OF THE SEAT CONSIST OF DIFFERENT COMPONENTS THAT WILL AFFECT THE H-POINT.	40
FIGURE 31. CROSS-SECTION OF SEAT CUSHION SHOWING THE LINE THROUGH SGRP IN Z-DIRECTION. THIS IS WHERE THE COMPONENTS MEASUREMENTS WERE ANALYZED.	42
FIGURE 32. ILLUSTRATION OF SEAT DEFLECTION CAUSED BY H-POINT MEASURING MANIKIN.	42
FIGURE 33. CROSS-SECTION OF THE SEAT SHOWING THE LINE IN Z-DIRECTION THROUGH THE SGRP THAT WILL BE THE REFERENCE DURING THE ANALYSIS.	44
FIGURE 34. MEASUREMENTS ON FRAME DO NOT INCLUDE ANY CHECKS ON THE SPRING MAT (RED AREA).	45
FIGURE 35. ZIG-ZAG FORMED SPRINGS ON THE VOLVO SEAT FRAME.	46
FIGURE 36. INDIVIDUAL ELEMENT LOAD DEFLECTION TEST.	46
FIGURE 37 SEMI-INDEPENDENT STEPS THAT COULD BE IMPLEMENTED BY VOLVO	53
TABLE 1. REGULATIONS RELATED TO DRIVERS' SEATING POSITION	20
TABLE 2. DIMENSIONS DEFINED FROM SGRP	22
TABLE 3. CAUSES MENTIONED IN INTERVIEWS.	29
TABLE 4. RELATIONSHIP BETWEEN THE CAUSES.	30
TABLE 5. CAUSES RANKING MATRIX.	30
TABLE 6. CONCEPT COMPARISON MATRIX	35
TABLE 7. SEAT VARIANTS AND PROPERTIES AND HOW THEY AFFECT THE H-POINT LOCATION.	40

TABLE 8. PROPERTIES THAT INFLUENCE THE DEFLECTION OF THE SPRING AND HOW REQUIREMENTS ON THEM COULD BE VERIFIED.	47
TABLE 9. PROPERTIES THAT INFLUENCE THE DEFLECTION OF THE FOAM AND HOW REQUIREMENTS ON THEM COULD BE VERIFIED.....	48
TABLE 10. REQUIREMENTS SPECIFICATION FOR H-POINT ASSURANCE	48

LIST OF ABBREVIATIONS

ACRONYM

CAD

CAE

FEM

H-point

IFD

OWS

PUR

SAE

SgRP

SPA

VCC

DEFINITION

Computer aided design

Computer aided engineering

Finite element model

Hip-point

Indentation force deflection

Occupant weight sensor

Polyurethane

Society of Automotive Engineers

Seating Reference Point

Scalable Product Architecture

Volvo Car Corporation

1 INTRODUCTION

This Master Thesis report presents the work that was carried out to identify the main causes of a misalignment between the designed seating position of a Volvo driver seat and the measured dimension of the position in the physical car, in order to propose actions which lead to a more robust seat design and method for determining driver seating position.

1.1 BACKGROUND

Volvo Cars Corporation is a Swedish manufacturer of premium cars for a global market including USA, China and Europe, its total global sales volume in 2014 was 465,866 cars (VCC, 2015). To gain a bigger share of the automotive market, Volvo has to stand out in an industry which is highly competitive and puts strict demands on companies to be fast, innovative and efficient. Customer expectations on quality, comfort and appeal are driving a level of requirements that is higher than before, which reflects on tighter control of all the development processes.

The all-new Volvo XC90 marks the beginning of a new chapter in Volvo's story. As a premium SUV, it features world-leading safety developments, progressive new human-centric technologies, an unrivalled combination of power and fuel efficiency, and superlative craftsmanship. It exemplifies both Volvo's future design direction and new Scalable Product Architecture (SPA) technology (VCC, 2015).



Figure 1. Seats are crucial in defining interior space in the vehicle

Front and rear vehicle seats are the main components to give the driver and occupants their position inside a vehicle. The close interaction that exists between these and the users makes them one of the most important systems in the car; they also provide comfort and are important to assure a sense of quality and good appearance. To produce high quality seats, many factors have to be considered including different materials, design geometry and production strategy. The fact that they contain a large number of subsystems and components makes it a complex system to design.

A large number of internal and external requirements are connected to the seating position of the vehicle occupants; they are obtained from legislation, quality rating tests and subjective judgments from customers. If the measured seating position deviates from the theoretically assigned seating reference point (SgRP) it can, among other things, lead to legal requirements being unmet and the need for major redesign; it also affects the available space for the passengers inside the car and their relative position to

other components around them. On top of this, the tight packaging that comes from including new systems in the car implies that all its components must be produced to high quality standards.

To meet all these requirements it is of vital importance to assure that the final manufactured seats are corresponding to the design intent, and that the measurements that relate to them are located as the company define them. In recent years the seating position of the driver has become a focus of attention to fulfill the expectations of the customer, and a reference point located at the pivot between the thigh and torso of the occupant (known as the H-point) has been identified as a key parameter whose position needs to be controlled to guarantee the quality of the seats.

Assuring that the actual H-point corresponds to the design H-point or SgRP is a difficult task given that it involves the work of many actors who participate in the definition and final location of this point. In the past the designed and actual points have been found to be deviating from each other more than desired, leading to substantial redesign late in the process or large margins having to be incorporated into the design of the car. These are both unwanted effects that are costly and time consuming. Therefore, an effort to identify the cause of this mismatch as well as propose a solution to the problem it creates has been deemed necessary. To develop new vehicles with big margins to compensate for deviations in seating position creates drawbacks in exterior design, aerodynamics and efficiency. The value of assuring the seating position lies in avoiding these drawbacks and by that, achieving a competitive leverage in the market.

1.2 PURPOSE

The purpose of the project is to identify the main causes for deviations in the driver's seating position and describe in detail the effects that it has in fulfilling the overall vehicle requirements. This project will be finalized with a proposal of a new or developed method for robust predictable seating position design based on a ranking of the main causes behind the deviation.

1.3 LIMITATIONS

While similar deviations in seating position can be found in both front and rear seats, the present work is only focused on the design and production of the driver seat. The investigation of requirements and legal regulations targets primarily the currently applicable documents in the North America and Europe regions, only including an overview of foreseeable changes to the regulations in future years. The time spent on the project is limited to 20 weeks, according to Master Thesis standards.

At the time of the realization of this project, the SPA platform seat was in the production ramp-up phase. This meant that the engineers responsible for the design as well as the supplier were concentrated on tuning up the production and had limited availability for other activities. It also represented that specific measurements about the deviation for the current design were not available further than production trials cases.

1.4 OBJECTIVES

The resulting solution from this thesis work is expected to have the following effects after its implementation:

- Compliance with all the requirements that are linked to the H-point position
- Minimized need for reworking of vehicle seats
- Assured fulfillment of current and upcoming international standards

1.5 DELIVERABLES

The work leading to the completion of the objectives will be reflected in the following documents which are considered the outputs of the project:

- List ranking causes of H-point deviations
- Revised process for efficient seat design
- Method for reliable prediction of the driver’s seating position in the vehicle.
- Updated requirement specification for the vehicle seats

1.6 KEY ACTIVITIES

During the progress of the project there were important activities which allowed the team to advance towards the deliverables and objectives, these activities include:

- Research of the internal process to define seating position in Volvo Cars by interviews of the main stakeholders.
- Inclusive analysis of the current seat design and tools used in the design process.
- Investigation and categorization of the causes and effects related to the deviation of H-point location in current vehicle seats
- Suggestion of solutions to deal with the main identified causes of the problem.
- Development of a comprehensive solution to guarantee the correct setting of the H-point in manufactured seats.

1.7 OUTLINE OF THE REPORT

The report outline can be seen in Figure 2. The report starts with a description of the background, purpose, limitations and objectives of the project can be found in chapter one. The second chapter presents a review on theory related to automotive seats and passenger position inside the car. In chapter three, the methods used in the project are presented along with a reflection on their effectiveness. The results that were obtained during the problem exploration stage of the project, are described in chapter four; while the outcomes of a solution finding process are discussed in chapter five. Chapter six contains a description of the main proposal for an improved seat design process. A discussion of the main aspects in the project is presented in chapter seven, and finally chapter eight contains the conclusions to the work and a reflection on how the project could be expanded in further efforts. At the end of each chapter, a summary will be presented in order to highlight the most important information to keep in mind through the rest of the report.

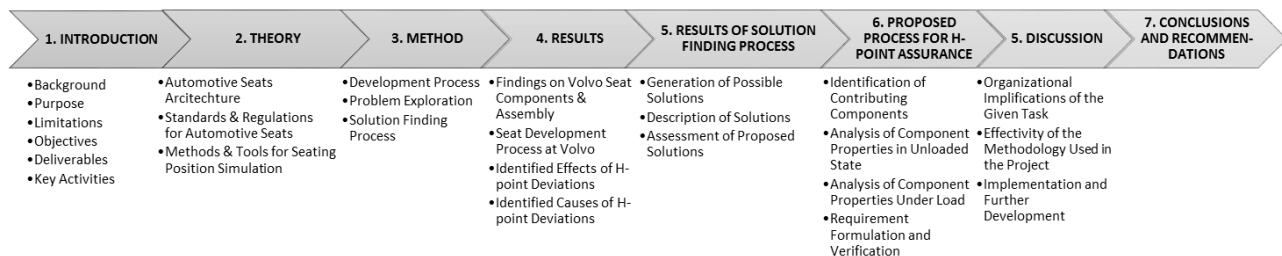


Figure 2. Report outline

2 THEORY OF DRIVER POSITIONING IN AUTOMOTIVE SEATS

This chapter presents theory that is related to the development of automotive seats as well as the definition and measurement of the driver seating position inside the vehicle, including the legal and standard documents involved and the tools used for this purpose.

2.1 AUTOMOTIVE SEATS ARCHITECTURE

Car seats have several purposes that, when combined, make it one of the most crucial and complex parts of the vehicle. The primary purpose of the driver seat is to position the driver in a manner that allows him/her to reach all the instruments and provide an adequate field of sight in order to operate the vehicle in a safe and comfortable way (SAE International, 2014). Additionally, in order to assure safety and comfort for all individuals within the target group the seat is adjustable (height, translation, tilt, lumbar support). Different functionality can also be included in the seat, examples are climate control (heating and cooling), airbags and massage.

The requirements on functionality, comfort and an appealing design result in a complex product with many interlinked components. Most car seats could be described as consisting of a track/adjuster assembly base, a seat frame, a cushion, a backrest and a headrest (in some cases integrated in the backrest). The cushion and backrest consist of several components, for example foam, electrical components, springs and upholstery. The track/adjuster assembly base make up the connection between the car and the seat and provides the adjustability of the seat. An example of a seat structure can be seen in Figure 3.



Figure 3. Picture showing seat complexity and main parts.

A wide variety of materials and production techniques are used in car seats. The track/adjuster assembly and the frame are for instance metal components and plastic is used to make covers and fasteners. A particularly interesting material to mention is urethane foam, it has been widely used in car seats since the 1960's (Blair, et al., 2008) with different manufacturing techniques and chemical composition. Cold cured/high resilience molded urethane foam is the most commonly used material in car seat cushions/pads

today (Blair, et al., 2008). The strength of this particular material and manufacturing technique is that it allows for complex forms to be molded, so that wires or other structures can be molded into the cushion. As the name of the material suggests it is also very resilient, which is important for good comfort, aesthetics and safety. The properties of the foam can be altered by changes in the chemistry of the material (Blair, et al., 2008). The following foam properties are closely connected to the occupant position in the seat.

- *Density* affects the foam's ability to provide support, comfort and durability. Generally, as foam density increases, durability also increases. Some of the factors related to durability are loss of firmness (flex fatigue), breakdown in the sitting area of the cushion (dishing), and fabric bagging caused by loss of foam dimensions (compression set) (Polyurethane Foam Association, 1991). Different densities can be assigned to certain areas of the cushion foam to achieve a desired feeling for the occupant, by changing the composition of the material. This in turn will create areas of different compression load around the seat that are hard to calculate.
- *Indentation force deflection* is a measure of foam firmness that is independent of density. IFD is determined by measuring the pounds of force required to indent a 4-inch thick FPF sample 25% of its thickness, or one-inch (Blair, et al., 2008). Firmness affects how much the occupant will sink into the seat (ride) of a cushion. The test to measure this property uses standard procedures and machines as shown in Figure 4.



Figure 4. IFD testing machine.

- *Support Factor* is the ratio of 65% IFD divided by 25% IFD (Polyurethane Foam Association, 1991). The higher the number, the greater the foam's ability to provide support. For greatest comfort, the support factor should be selected to maximize cradling, allowing a seated person to sit into the cushion rather than on top of it. When cushions are thick, lower support factor foam may be used to improve cradling and to achieve more even distribution of body weight. For thinner cushions, where the ride is limited, higher support factor can be used to provide softer initial contact and resist bottoming out.
- *Resilience* is an indicator of the surface elasticity of foam. It is measured by dropping a standard steel ball onto the cushion from a given height and measuring what percentage the ball rebounds. The surface resilience of a foam also affects comfort and design (Polyurethane Foam Association, 1991).

The seat trim, consisting of the upholstery and in some cases a thin layer of comfort foam, can be of various kinds and the buyer and/or designer can choose between colors and materials. The materials can be divided into two categories, fabrics and leather. Important aspects of the trim material is that it offers an aesthetically pleasing finish to the seat and should for example not wear, wrinkle or stain. Different coatings can be applied to the material in order to assure some of these factors. The manufacturing process (such as woven or knitted) and what raw material that is used (e.g. organic or synthetic) are factors influencing the fabrics elasticity, durability and look (Fung & Hardcastle, 2001).

All these different components, materials and manufacturing techniques make up a complex structure each with their own variations. This complex structure is the key component in assuring the seating position of the driver. In order to assure the seating position a method to define and measure it is needed, one way to achieve this is by using SAE standards.

2.2 STANDARDS AND REGULATIONS FOR AUTOMOTIVE SEATS

SAE International is a global association of more than 138,000 engineers and related technical experts in the aerospace, automotive and commercial-vehicle industries. SAE International's core competencies are life-long learning and voluntary consensus standards development (SAE International, 2015). Several of the SAE standards are used to develop regulations in different countries and are therefore very important to consider when developing the components of a car.

Car manufacturers use the SAE J1100 standard, named Motor Vehicle Dimensions (SAE International, 2009), to define the most relevant dimensions of the vehicle interior that are used for determining important benchmarking and regulatory parameters. One of the most important points that are defined in this standard is the one referred to as H-point, in the document the following four definitions of this reference point are presented:

- H-point: The H-point is the Pivot Center of the torso and thigh on the Two-or Three-Dimensional devices used in defining and measuring vehicle seating accommodation.
- Design H-point: The Design H-point is located on a drawing by the H-point on the two-dimensional drafting template placed in any designated seating position. If the designated seating position can be adjusted, the path of the Design H-point through the full seat adjustment establishes the Design H-point travel path, and can be dimensionally described by coordinates relative to the three-dimensional reference system
- SgRP: The manufacturer's design reference point is a unique Design H-point which:
 - Establishes the rearmost normal design driving or riding position of each designated seating position which includes consideration of all modes of adjustment, horizontal, vertical, and tilt, in a vehicle,
 - Has X, Y, Z coordinates established relative to the designed vehicle structure,
 - Simulates the position of the Pivot Center of the human torso and thigh, and
 - Is the reference point employed to position the two-dimensional drafting template with the 95th percentile leg described in SAE J826.

Actual H-point: The actual H-point is located in an actual vehicle by the H-point on the three-dimensional H-point Machine with the 95th percentile leg installed in any designated seating position per instruction in SAE J826 and can be dimensionally located by coordinates relative to the three-dimensional reference system.

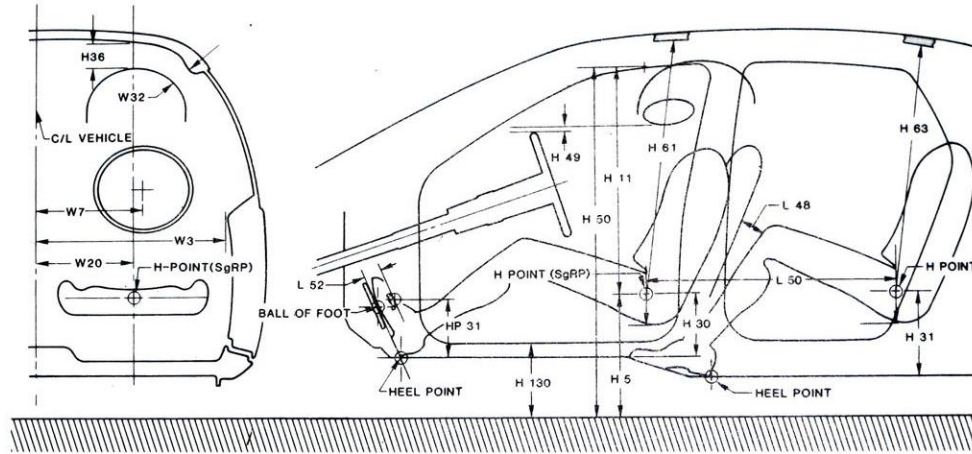


Figure 5. Main interior dimensions for passenger packaging (SAE J1100)

The importance of the H-point is evident in the J1100 standard since it is used as the reference for defining not only the position of the driver but also other key dimensions as: Entrance Height (H11), Belt Height (H25), Effective head room (H61), Leg room (L33), Shoulder room (W3). Elbow room (W31), Hip room (W5), Knee clearance (L62), Thigh room (H13) among others, all of which are used in determining the packaging strategy for a new vehicle.

As can be seen in the H-point definitions presented before, defining the H-point in the physical vehicle makes use of a separate SAE standard, The SAE J826 (SAE International, 1995) standard defines a special 2D template, a 3D machine and a process for defining and measuring the vehicle seating accommodation, both template and machine are designed to represent a male adult in sitting position and the deformed contour of the seat. This standard was developed in the 1960's and is still used in the industry and referenced by safety regulation documents and quality evaluating agencies mainly related to Occupant Protection in Interior Impact, Head Restraints, Seating Systems, Occupant Crash Protection, among other evaluations contained in both FMVSS and ECE practices.

Other SAE standards such as J941, J1052 and J287, which define measurements that are important for driver packaging and ergonomics also make direct reference to the H-point location.



Figure 6. Devices for measuring H-point, from SAE J826 and J4002

In the early 2000's a new machine and revised procedure for H-point measurement were developed to substitute the J826 standard (Schneider, et al., 1999), resulting in the SAE J4002 standard (SAE

International, 2010) which aims at resolving some issues with the previous model. While the old standard is still referred to mostly by the regulatory documents, a change into the new standard is planned for the next couple of years, therefore it should be considered when working with seating position definition and measurements.

2.3 METHODS AND TOOLS FOR SEATING POSITION SIMULATION

Computer simulation has become an important focus of product development efforts in the automotive industry, in order to reduce the cost and time of running multiple tests and move design decisions as close as possible to the initial phases of the process. The design of automotive seats is an area in which several simulation efforts have been made to predict the performance of the product in terms of ergonomics, comfort objectives and human modelling (Guerin, et al., 2003). These efforts have shown that it is possible to obtain and use models of the interaction between the driver and the seat, the interaction between seat elements and their contribution to overall seat stiffness (Paul, et al., 2009).

Figure 7 shows a schematic of the areas in seat development that have been explored with computer based simulation in order to predict occupant position. Implementing such models into the seat development process is a task that requires important resource and time investment but in the long run may help to reduce lead time and costs for the company (Guerin, et al., 2003).

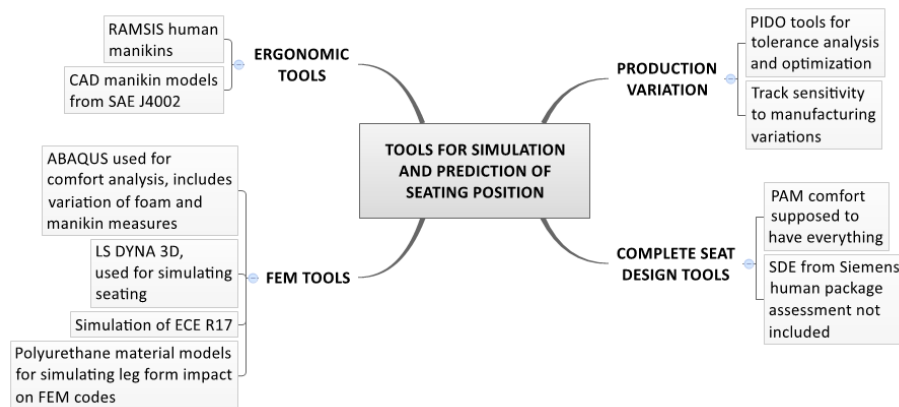


Figure 7. Areas of seat development in which computer simulations have been used.

Given the amount of available tools and previous efforts related to simulating the occupant seating on automotive seats, implementing some of these tools into the seat development process at Volvo could be helpful to reduce uncertainty during the design process.

2.4 SUMMARY

Automotive seats are one of the most important subsystems inside a passenger car. Because of their close interaction with the occupants, many requirements are related to them, involving comfort, ergonomics, safety, among others. One of the most important points that are used to define the internal dimensions of a car is the H-point, which defines the Pivot Center of the torso and thigh of the occupant on the seat. The importance of the H-point comes from the fact that it is used as the reference for defining not only the position of the driver but also other key ergonomic dimensions. The physical H-point is referenced by safety regulation documents and quality evaluating agencies. Implementing virtual simulation models of the seating position into the seat development process is a task that requires important resource and time investment but in the long run may help to reduce lead time and costs for the company.

3 METHODOLOGY USED TO DEVELOP A SOLUTION PROPOSAL

The methodology used in the project combined a selection of product development methods for exploring a problem, and finding a solution that fits the requirements of all the parties involved. The selected methods were also adjusted to fit the particular context in this project, some adaptations and changes to certain steps were put into place, as explained in this chapter.

The main consideration in choosing different methods for this project, was to take on account that it is not a new product development project; a large part of it is dedicated to investigate the root causes of a problem and the effects that are related to its occurrence, before proceeding to develop an improved process of design. In other words, these methods aim at finding the causes and effects connected to the H-point deviation from the SgRP and, based on their understanding, proposing a solution that could enable a more robust seating position design.

3.1 DEVELOPMENT PROCESS

The overall progress of the project was directed following a funnel type development process for finding the solution to the problem, the main steps of which can be viewed in Figure 8. The five stages that can be seen in it, were devised to alternatively obtain information and then narrow down the options of development. This was intended to have a thorough exploration and understanding of the available possibilities, before proceeding to select a single path for further development.

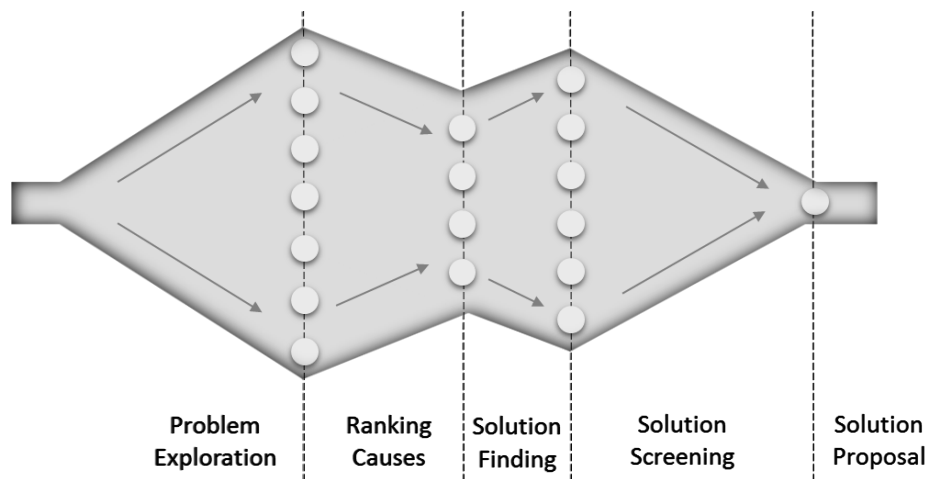


Figure 8. Concept development funnel (Ulrich & Eppinger, 2012) adapted to fit the problem at hand.

This kind of funnel is normally used to select a product concept from a series of design options (Ulrich & Eppinger, 2012). The funnel approach was selected to guide the process, based on the capability that it has to filter the potential choices during a development process.

In the beginning of the project, a problem exploration was conducted in order to gain knowledge regarding the problem and available technology related to it. The engineering departments within the company, which work with the occupant position, were analyzed to determine the existing links between each other and classify them, as affecting the H-point location, or being affected by a deviation from the design location. A ranking of the causes was the basis for a first screening step, in which the most

important activities, which could result in a different occupant position, were separated from the ones that were considered secondary.

This was followed by a solution finding stage, in which the objective was to generate a wide range of possible ways to address the H-point deviation. The number of solutions was narrowed down in the solution screening step leading to a selection of a single solution proposal, which was afterwards analyzed and detailed further. The different steps of the process, methods used and their purposes are described more in detail in the following sections, while the outcome and the resulting concept proposal can be found in chapters four and five.

3.2 PROBLEM EXPLORATION

The first phase of the project, problem exploration, consisted of several activities aimed towards gaining an understanding of the product, the design process inside Volvo and the problem that was presented before. It consists of an investigation of the process from concept to production of a commercial vehicle seat, an analysis on the effects of deviations in the H-point location as well as a determination and ranking of the causes of this deviation.

3.2.1 Research of Literature Related to Automotive Seats

Literature about automotive seats was an important source of information throughout the project. This source of information is particularly important in the beginning to gain an understanding of the different subjects dealt with in the project. Literature regarding ergonomics, seating comfort, automotive seat design and materials are some of the areas within which knowledge was gathered. Literature research was used in other parts of the project, for example concept generation to find and evaluate ideas and benchmark competitors.

3.2.2 Interviews with Volvo employees

The purpose of the interviews was to acquire company specific knowledge that cannot be found in a literature research. It allows for a flexible approach when talking to a person who is related to the topic of interest, in order to obtain the most adequate information from the respondents (Hannabuss, 1996). Therefore, the people being interviewed were Volvo employees working in departments connected to the H-point definition.

The interviews were conducted using a semi-structured approach, meaning that questions were prepared in advance, but clarifying and additional exploratory/probing questions were also used as needed to clarify the information given by the interviewees. This kind of interview allows the researcher to delve deeply into a topic and understand thoroughly the answers provided (Harrell & Bradley, 2009). The same interview structure was used for all interviews, the questions were altered, added or removed to fit each case. The aim was to keep the duration of each interview to approximately one hour. Each interview was ended with informing the interviewee that he/she might be contacted again if additional questions would occur.

3.2.3 Tear-down of Volvo seat

A tear-down of a physical seat was conducted with the aim of gaining an understanding about the architecture of the seat. Different methods on how to conduct a teardown study are available, the one that was used in this project is highly influenced by (Robert W. Messler, 2014). He describes the general product tear-down process by consisting of the following steps:

1. List the design issues of interest (i.e., the purpose for the teardown).
2. Prepare for physical teardown or mechanical dissection of the product.

3. Examine the product distribution and installation through accompanying or available product documentation.
4. Disassemble, measure, analyze data for, and model the product's overall assembly and major subassemblies.
5. Create system models for the product.

This process was deemed to suit the intent of the current tear-down event, to gain knowledge about the seat architecture. The outcome can be seen in chapter 4.

3.2.4 Observation of H-point measurement process

In the literature research and interviews, information regarding the standard H-point measurement process was gathered, as a complement and confirmation of this, an observation of a measurement event was performed inside Volvo facilities. The objective of having a direct observation of the activity was to find possible misalignments with the standard method or steps in the process that could be improved (McQuarrie, 2012).

3.2.5 Analysis of Effects of deviations in H-point

With the help of information from the literature research, interviews and observations, the effects of deviations in the H-point were analyzed and described. This was done in order to clarify the extent of the problem, and to determine which effects are most severe and should be the main focus for improvement, while proposing a solution.

3.2.6 Analysis of Causes of deviations in H-point

The information gained through interviews and observations was also used to analyze the causes of deviation in H-point location. The process of identifying customer needs described by (Ulrich & Eppinger, 2012) was used as an inspiration in this process. The process has been altered to fit the specific task, as can be seen below:

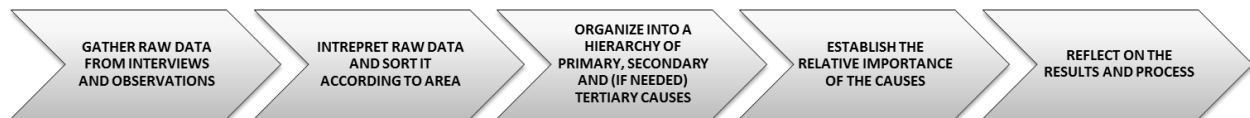


Figure 9. Process of finding and ranking causes of H-point deviations

The first step, consisting of a raw data collection, used the information gained from the activities of the problem exploration. The process was used to define a strategy with which the causes could be established and evaluated in terms of severity.

3.3 SOLUTION FINDING PROCESS

In order to elaborate a single solution proposal to address the H-point deviation problem, it was determined that an organized method should be used, the steps to be followed were based on the suggestions from (Ulrich & Eppinger, 2012), in order to guide a complete exploration of alternatives and select the most promising of them. The process from the literature was adapted to fit the project, this is explained in the following sections.

3.3.1 Generation of possible solutions to the H-point deviation problem

The first guidance provided by the literature, in the process to find a concept, is to clarify and decompose the problem that needs to be addressed. This was performed with the series of activities presented in

section 3.2, culminating with the ranking of the causes for the problem at hand. When the causes and effects for the deviation of the H-point were understood, the process to find an appropriate solution was initiated.

It is important to make sure that as many solutions as possible, which could mean an improvement for the company regarding the problem, are identified during the concept phase. A solution mind-map was used in a brainstorm activity with the aim of covering activities within all areas of the problem and, at the same time, exploring options that are internal and external to the company.

Utilizing mind mapping appropriately is expected to help in keeping the balance of sciences and arts, as well as of logical and imaginary thinking (Chen, 2008). It can give the team a clear panorama picture, so that one can appreciate the details as well as observe the whole. This tool was used for visualizing the different actors and departments that relate to the H-point position and which could improve part of their process, in this way it becomes easier to find information gaps regarding the possible paths and methods of improvement.

3.3.2 Exploration and Selection of Solutions

Although concept solutions were proposed for all the causes of deviation that were found, an initial screening of the proposals was done after the ranking of causes was completed, thus the solutions that were related to the three causes in the bottom of this ranking were left out of the subsequent screening to decide the final solution proposal. This was done in a three step process as shown in Figure 10.

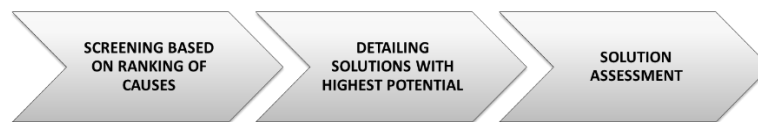


Figure 10. Diagram of steps for solution exploration.

The solution alternatives related to the top four causes in the ranking were elaborated further to translate them into an understanding level that was the same between all of them. Once this was achieved, the solutions were analyzed in terms of requirements to be fulfilled and their possibility to be implemented. The criteria that was used for the final selection of solutions to be elaborated was based on the project team's judgment and discussion with supervisors from Chalmers and Volvo Cars, it was arranged in a table to submit all the options to a comparison between all of them which was inspired on the process for a Pugh Matrix for concept selection (Ulrich & Eppinger, 2012). In this way, a single solution was selected to be developed further in the last stage of the project, this will be presented in more detail on chapter 5.

3.4 SUMMARY

This chapter has presented the methods and tools that were used to perform the study in this project. The overall progress of the project was directed following a funnel type development process for finding the solution to the problem. It was divided in two mayor phases, named Problem Exploration and Solution Finding Process.

The first phase of the project, problem exploration, consists of an investigation of the process from concept to production of a commercial vehicle seat, using literature resources, interviews and direct observation to deliver an analysis on the effects of deviations in the H-point location as well as a determination and ranking of the causes of this deviation. The Solution Finding Process consisted of a brain storming session for obtaining a vast number of ideas to address the problem, which were later analyzed using evaluation matrices to determine the best fitted solution for recommending further work.

4 OUTCOME OF PROBLEM EXPLORATION

The problem exploration phase included several activities which involved the interaction with the persons responsible for each step in the process under study, the findings that are described in this report include the interpretation of comments from the personal interviews, as much as from observing the performed activities on site.

4.1 FINDINGS ON VOLVO SEAT COMPONENTS AND ASSEMBLY

The purpose of the teardown was to gain an understanding of the seat assembly and its components. This was mainly achieved by the teardown activity itself. The tear-down of a Volvo seat resulted in the following observations, which are presented according to the steps that were followed to perform the activity.

1. List the design issues of interest (i.e., the purpose for the teardown).

Information interesting to the project was noted in a data sheet along the process. The information in this case was: component name, number of components, names of assembly/subassembly, material and notes. Pictures were taken on parts and assemblies to document the event and provide a way to revisit the information later in the project if needed.

2. Prepare for physical teardown or mechanical dissection of the product.

In addition to preparing the data sheet and a location for the workshop, a list of tools needed to disassemble the seat was made in order to avoid forgetting anything on the day of the workshop. This list consisted of: camera, ruler, computer and tools.

3. Examine the product distribution and installation through accompanying or available product documentation.

Before the tear down a presentation of the seat was given to the project group and the different components were presented. The presentation material and other information about seats found in the literature research were studied to gain an understanding of the seat architecture which were aimed at ease the tear down process.

4. Disassemble, measure, analyze data for, and model the product's overall assembly and major subassemblies.

The data sheet from the tear down can be found in Appendix B, it shows some of the parts of the seat that were disassembled and divided into different subassemblies. The seat was only disassembled to a point where the project group deemed that all interesting parts for the project could be analyzed. Besides the main purpose of understanding the seat architecture some other interesting aspects were found. The foam was found to have a few imperfections and had a cavity in one of the bolsters. The trim was noticeably tighter on the right side compared to the left, the foam didn't fit and creases had formed in the upholstery (see Figure 11).



Figure 11. Picture of foam and trim from tear down.

Other considerations from the tear down were that the number of different screws/fasteners were more than expected, particularly for the trim attachment, the need for a close fit to the foam shape makes it important to hold the fabric in very short space intervals that pull it close in all directions, but this makes it hard to predict exactly where all the fixing points will be and can cause creases in the final seat.

5. Create system models for the product.

Pictures of the different components in the cushion and their placement were taken. For the particular task at hand it was deemed to be a valuable model of the seat in order to analyze the deviations in H-point. The pictures below were taken during the tear down and show the main components affecting the H-point in the backrest and cushion of the seat.



Figure 12. Seat components in cushion and back affecting H-point.

4.2 SEAT DEVELOPMENT PROCESS AT VOLVO

Understanding the causes and effects of a variation in the position of the H-point is closely related to the activities that take place during the design, manufacture and testing of the seats. During the first stage of the project, information was gathered about the process that is followed at Volvo to develop the driver seats in the car. This information was obtained through a literature research, interviews with the stakeholders in the process and observations of key activities to define the H-point.

Analyzing the organization of the stakeholders involved in the process as a system that delivers the output of a particular seating position, offers a structured way to define the connections from one actor to the rest

as well as the inputs and outputs from each stage in the process (Harmon & Tom, 2007), the use of this is to get insight of possible causes of deviation that could arise from miscommunication or disconnections in this process which can be addressed to guarantee that the final driving position reflects the intention of all the people participating in its definition.

A cross-functional flowchart of the actual seat development process in the company was elaborated to picture the exchange of information that is necessary to go from CAD versions of the vehicle to a finished product and aid in analyzing the possible misalignments in the process that could lead to a deviation in the seating position. Figure A1 in Appendix C shows the final Flowchart for the development process, the layout is adapted from the guidelines offered in (Harmon & Tom, 2007). The activities flow from left to right and the departments inside Volvo, which come together during the process, are represented in the horizontal sections (swim lanes) of the diagram.

It can be seen that deviations in the manufactured seat will affect testing that is directly related to at least three departments in the company and that failure to meet the requirements from any of these departments will represent a regression of several steps in the process.

The initial definition of the SgRP is a decision made by the company that depends on strategy among other things. Therefore, the position of this point will vary between different companies and car models even for cars targeting the same market. This is exemplified by the difference that can be found between measured H-points for different cars seen in Figure 13, which shows the range of H-point heights divided by car segment (A2MAC1, 2015).

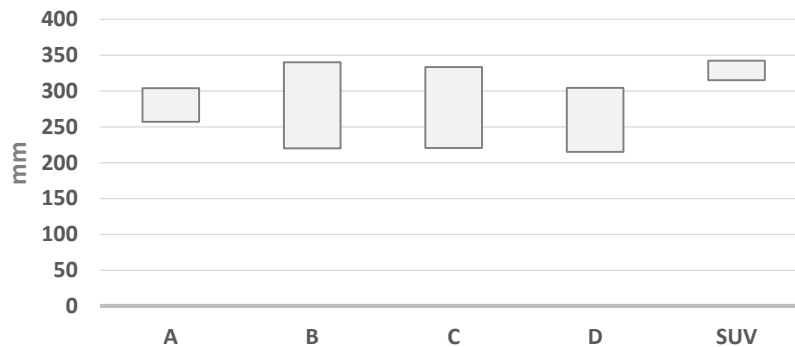


Figure 13. H-point height ranges for different car segments

The analysis of the seat development process at Volvo was a step in determining the main causes of the H-point deviation and its effects. These causes and effects are described in the following sections of this chapter.

4.3 IDENTIFIED EFFECTS OF DEVIATIONS IN H-POINT

It has been stated in previous sections that the fulfillment of several requirements for passenger vehicles is dependent on the position of the driver inside the car, and that guaranteeing the compliance of the manufactured seat to the design is necessary to assure quality standards. The company has experienced difficulties accomplishing an H-point that coincides with the intended SgRP, this is displayed in Figure 14. The green line represents the manikin torso and thigh achieved from the SgRP, the blue lines shows the same manikin originating from measurements of the H-point in a physical seat.

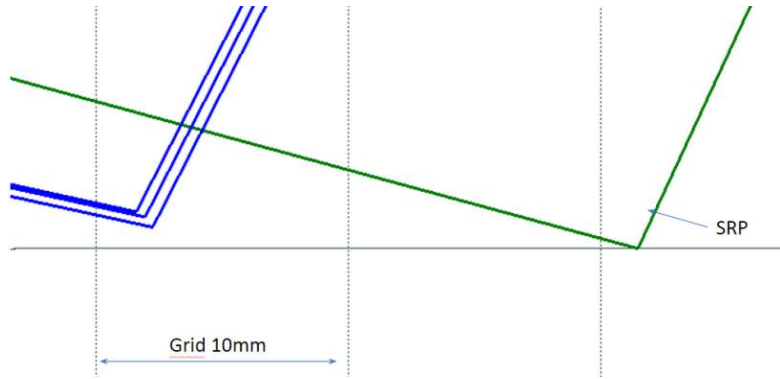


Figure 14. SgRP compared to measurements on physical seat.

As can be seen in the picture above the deviations in H-point at Volvo has been found to be higher and further forward than the intended position. In Figure 15 a tolerance study (made in the software RDnT) is shown, exemplifying one of the effects deviations in H-point has.

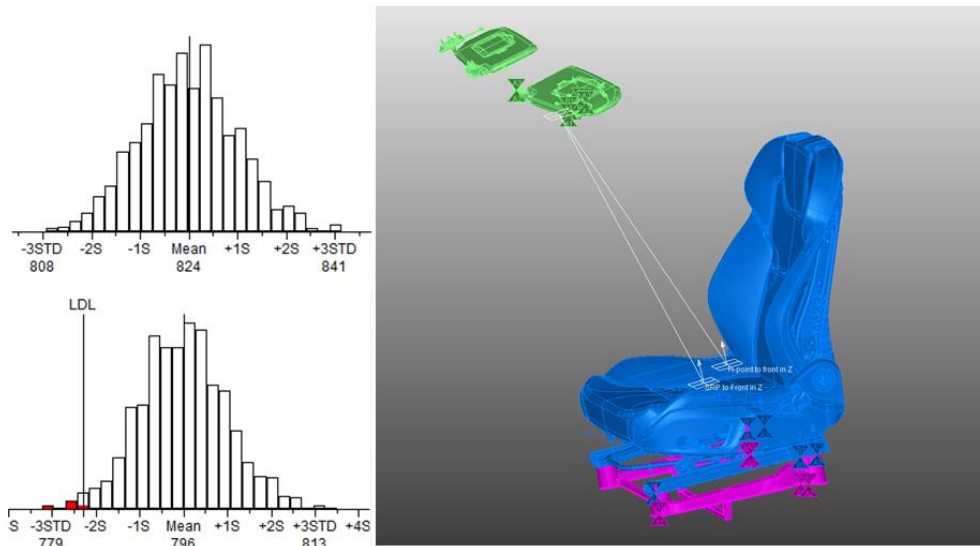


Figure 15. Virtual tolerance study comparing H-point to SgRP.

The picture shows a seat and sun visor with corresponding tolerances and requirements assigned to them. To the left the resulting mean distribution is presented, the top one representing the SgRP and the bottom one corresponding to the H-point. In the SgRP all simulated seats meets the required distance to the sun visor but if looking at the H-point instead some of the seats (displayed in red) does not meet the required distance. This is a clear example of the problems an H-point deviating from the designed SgRP will imply, the car is designed to fulfill requirements based on the SgRP but if that point does not coincide with the H-point requirements might not be met in the final car. Several similar effects can be found as a result of H-point deviations, Figure 16 shows how the H-point is linked to a number of attributes in the car.

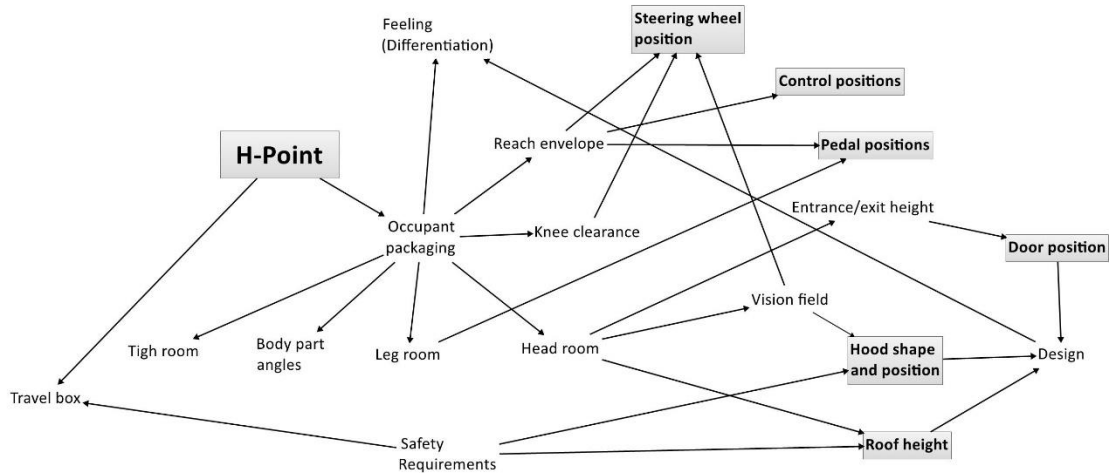


Figure 16. H-point influence.

In the following sections the effects of the H-point deviating from the design SgRP will be described more in detail.

Regulation conformance effects

One of the main sources for vehicle requirements are the legislation documents that are applicable for every country in which a company wants to sell their vehicles. Not fulfilling all of these requirements could result in not being able to offer a particular vehicle for sale in a specific market and therefore losing potential clients.

Seating position is used to measure many aspects of the vehicle interior and sometimes to a very strict margin. In the United States the Federal Motor Vehicle Safety Standards utilize the H-point and associated measurements to implement many of the safety standard requirements. And in addition, the Environmental Protection Agency uses H-point related measurements to calculate the Interior Volume Index for vehicle fuel economy classifications.

The equivalent in Europe to these regulations is the ECE regulations. A list of FMVSS and ECE documents that are related to the measurement of the H-point is presented below, some of the regulations are affected by the H-point position indirectly by defining measurements based on this reference point. An example of this is ECE 125 which regulates the forward field of vision for the driver. It is also worth mentioning that the ECE R17 document includes a tolerance requirement for the H-point that states it should lie within a square of 50 mm side length with horizontal and vertical sides whose diagonals intersect at the SgRP.

Table 1. Regulations related to drivers' seating position

AMERICAN REGULATION	Occupant Protection in Interior Impact	FMVSS 201
	Head Restraints	FMVSS 202
	Seating Systems	FMVSS 207
	Occupant Crash Protection	FMVSS 208
ECE REGULATION	Seat Belts	ECE R16
	Seats, anchorage and head restraints	ECE R17
	Interior fittings	ECE R21
	Child restraint system	ECE R44
	Head rests	ECE R25
	Forward field of vision	ECE 125

Because of the increasing importance that safety has for the customers of current vehicles, there are specialized organizations which conduct tests of the vehicle under crash conditions to measure their performance during these events. One of these rating organizations is EuroNCAP which has the purpose of pushing car manufacturers to pursue higher safety requirements than the legally imposed.

The position of the occupant is evidently important for the crash tests that the EuroNCAP carries and in some cases the hip point is even used for determining the impact of the simulating rigs which will have an impact on load distribution and in case of a different position from design, could cause a lower performance in the test.

Design/Ergonomics effects

During the process of vehicle development, one of the first parameters that is defined is the SgRP which will drive many measurements to define the overall dimensions of the vehicle and its components. This in turn will affect the way in which the driver moves inside the vehicle and operates the instruments around him/her, a change in dimensions can also alter the looks of the vehicle and therefore have an aesthetical impact on the car.

Figure 17 shows the process that is followed to define occupant packaging during the vehicle design, it can be seen that the definition of the Seating Reference Point (SgRP) is one of the initial drivers for the whole process, its definition is only preceded by the determination of the car segment, target population and overall exterior dimensions, basically all the dimensions in the interior are determined after the SgRP, therefore a misalignment in its location can have an impact in all the interior packaging.

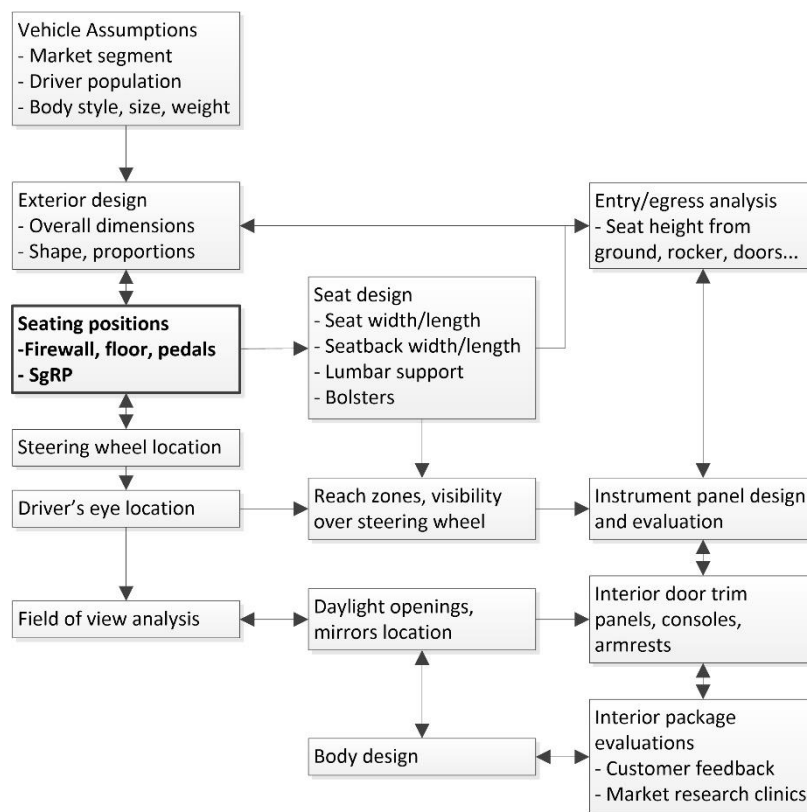


Figure 17. The occupant packaging process (adapted from (Bhise, 2011))

The relation that exists between the H-point and the main dimensions for occupant packaging can be seen in the SAE J1100 standard, amongst the dimensions that are defined in this standard, several use the H-point for reference as can be seen in Figure 5. While the number of dimensions related to the SgRP is big, the most directly linked to its position and which are also in themselves important for occupant packaging are listed in Table 2. For more detail on how these dimensions are put together to define the overall position of the occupant inside the vehicle (Bhise, 2011) can be consulted.

Table 2. Dimensions defined from SgRP

Entrance Height (H11)	Elbow room (W31)	Leg room (L33)
Belt Height (H25)	Hip room (W5)	Shoulder room (W3)
Effective head room (H61)	Knee clearance (L62)	Thigh room (H13)

The SgRP is also used as a reference for defining the relationship between accelerator pedal, steering wheel and seat track positions, the definition of the visual field of the driver can also be affected along with the head contour envelope, the reach zones and even the measures for ingress and egress of the vehicle.

Comfort Effects

The high demands from the customers in recent years have led to a considerable increase in vehicle features and ever more complex systems to satisfy all the requirements. One of the main concerns or desires that a customer has for his/her vehicle is that it has to be comfortable to drive. The seat plays a vital role in achieving vehicle comfort and in order to increase its performance, newer subsystems for creating an enjoyable experience have been added to the seat.

The extra features that have to be packaged in the seat, like heating or cooling systems, inflatable lumbar support systems or massage systems, pose a packaging challenge that relates to the seating position in a sort of struggle in which they can both push each other in order to achieve its final specifications. The repercussions that the comfort requirements have in making it harder to guarantee the seating position are covered in a separate report, but because the design of these systems is dependent of the seating position, just as much as the opposite is true, a variation on the position measurements will also affect the comfort results on the final vehicle.

One way in which comfort results are affected by the seating position is the method in which comfort parameters are measured. The SAE provide a standard J2896 for testing characteristics of a finished seat which are related to passenger comfort. While it is acknowledged that the H-point, measured with the standard machines from the same organization, does not fully represent any category of occupant, the measurements for sections and references used in the test are referred to it and therefore will be affected by variations from manufacturing or seat set-up differences.

Ultimately the measure of how comfortable is the interior of the vehicle and the seat, is measured through a series of clinic in which representative customers are asked to evaluate their impression of the general seat, the perceived quality and sensations produced by it. This clinics are performed on several occasions during the development of the vehicle to allow for some changes to be made to the seat in case that the desired level of comfort has not been achieved.

The relation between the materials used in vehicle seat manufacturing and the comfort performance of the product is also a considerable relation that will sometimes lead to a trade-off between technical requirements like the fatigue resistance of the foam in the cushion and the subjective comfort evaluation of the customer.

Safety Effects

In order to elaborate a single solution proposal to address the H-point deviation problem, it was determined that an organized method should be used in order to maintain a focus during the ideation of possible solutions and then while narrowing them into a single one that was developed further.

Safety engineers at Volvo design the systems to protect the customer based on the input from the seats department about where the passengers will be positioned, this parameter determines many factors that are decisive in making a car safe during driving conditions and in case of an accident occurrence.

Because the performance of the car in safety tests is very sensitive to the actual position of the occupants, safety engineers need to consider the possible variation on the location of the H-point when the physical seats are installed in the car. A range of acceptable H-point location variance is negotiated by the safety and seats department to take on account during testing simulation, and it is very important to assure that the tolerance on this range is not exceeded because a large misalignment could result in a behavior that is different from what was designed for and eventually lead to inferior performance, or even failure to meet legal requirements.

If the location of the H-point is not controlled, it could affect the available headroom for the passenger, the space between the passenger and the instrument panel, or the relative location of the seat belt fixing points which are important parameters for a vehicle to be safe, especially during a crash.

It is important to note that during the testing for safety requirements, the H-point that is measured with the H-point machine from the SAE J826 standard (actual H-point) is used to position the crash test dummies. Since the dimensions of both are somewhat different, the H-point that is used for the test could be different from the originally measured one. A misalignment between them, however small, would add to the difference between the actual H-point and the designed SgRP which could lead to higher difference in performance results.

Volvo cars is a leading company in terms of vehicle safety standards. In order to achieve their goal of making their vehicles safe to withstand actual usage conditions, requirements are set that exceed the legal requirements and even rating tests. In designing to meet these extra requirements, the safety team at VCC run several simulations that account for a variation of occupants, seating in several positions that are considered critical. CAE software is used to run these tests and a model of the seating position that closely resembles the reality is of paramount importance in this case.

Money and Time Effects

All the effects that have been mentioned so far will be reflected in a series of necessary corrective measures that will require to invest additional time and money in implementing changes to the seats to assure that the requirements which were set from the beginning are met. To avoid the need for such extra investments, the company should identify the main causes which can lead to the deviation in seating position, the next section in this report will elaborate on these causes.

4.4 IDENTIFIED CAUSES OF H-POINT DEVIATIONS

The analysis of why deviations between H-point and SgRP occur will be presented in the following sections. First a presentation of information gathered about the causes will be presented. This will be followed by the process of ranking them based on severity.

Analysis and Interpretation of raw data

Due to the complexity of the seat with its many components, materials, manufacturing methods and stakeholders, finding the cause(s) of deviation is a cumbersome task. A main contributor to solving this problem has been to conduct interviews with employees at Volvo. The nature of the problem makes it a necessity to gain knowledge from employees in different departments in the company in order to gain an understanding of the specific process used at Volvo and, in turn, the problem. The tear-down of a physical seat contributed to an understanding of which parts of the seat contributed to the location of the H-point and how they are assembled to give the final shape of the seat.

The information from the problem exploration phase was analyzed and divided into four categories to identify the attributes and functions that affect the seating position. The list contains the following categories:

1. Design process
2. Physical parts in the seat
3. Manufacturing
4. Measurement process

A cause-effect diagram for the deviations can be seen below, with the H-point deviations being the effect and the different causes leading to it divided in our five categories. In each category, sub-causes were listed, see Figure 18, to further specify the attributes contributing to deviations in seating position. The aim of the list and categories is to cover all possible causes, these will be explained in more detail in the following sections.

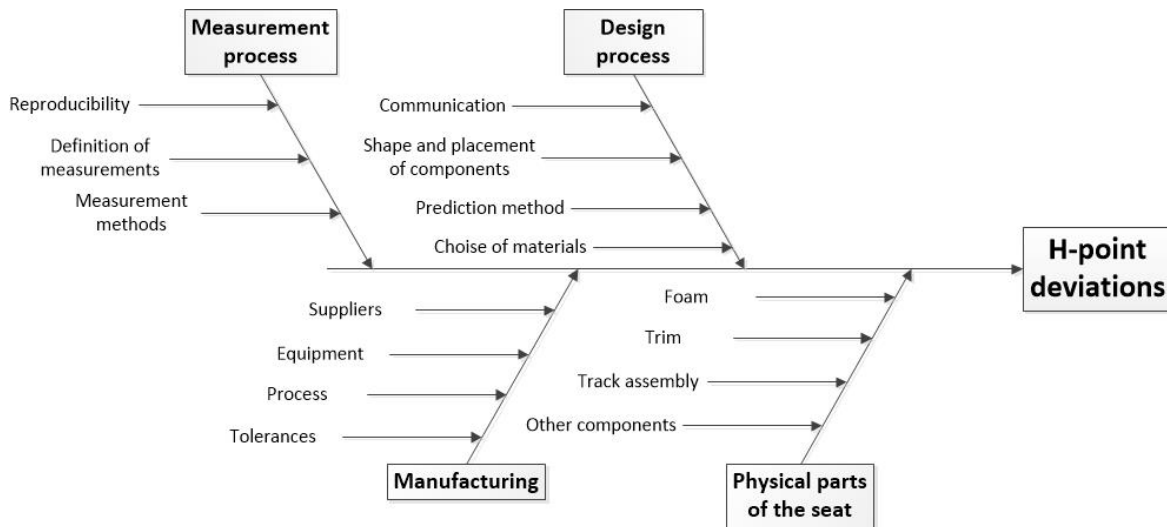


Figure 18. Cause-effect diagram for H-point deviations

1. Characteristics of the Seat Design Process

When proposing a new seat design, it is important to consider how the changes might affect the seating position. If components are added or material is changed it should be evaluated regarding how it affects the H-point. Problems related to this have been found during the problem exploration. An example is that the company experienced an unforeseen change of the H-point in x-direction caused by altering the structure of the backrest from soft to hard. All variations in the seat were, due to this, pushed forward instead of being distributed in two directions.

Another cause of problem has been that no alterations in, for example, foam thickness are made to account for different seat variations. This has resulted in that the seat variant with heating is approximately 2,6mm higher than the variant without heating (the heating component is 2,5mm high), see Appendix D for measurement data (Wickman, 2015).

Because of the subjective nature of the definition of comfort, the task of designing a comfortable seat can be challenging. One way to account for these requirements during the design process, which has been used in the past, is to use data from previous cars that give an insight on what customers consider more comfortable. Many guidelines and numbers obtained from previous projects are used in the design process. These are estimations and contribute to the difficulty in prediction of the H-point, especially in new designs where previous knowledge is not applicable. However, using only historical data and experience for comfort design and conducting only subjective evaluations of the performance makes it harder to predict how the seating position is affected by the comfort characteristics of the seat.

Sourcing of the vehicle seats is handled in such a way that there is no explicit connection between the individual component specifications and the system requirement on the H-point position considering the entire assembled seat. This means that the design has to account for deviations that can accumulate from the assembly of the individual components before they are delivered to Volvo Cars, these compensation cannot exceed the legal requirement of +/- 25 mm tolerance on the H-Point position.

2. Inherent Variation from Physical Parts of the Seat

Different components of the seat have been identified to affect the location of the H-point in previous developments. Firstly, the foam used in the seat is a big contributor to where the H-point will be located. The foam will be deflected when the passenger or manikin is placed in the car. This is one of the foams' purposes, however it needs to be taken into account when predicting the final H-point. Aspects like the foam composition, the components placed underneath the foam, the shape of the foam, trim properties and environment will all influence how much the foam will deflect.

The shape of the foam surface which comes in contact with the driver is designed with the use of carry over curves which dictate the traditional shape of a Volvo seat, these curves are adjusted for each program and are based on information from many years of experience. To provide a different sensation and comfort to the occupants, the cushion padding can be configured in a series of different versions, which include: a basic padding designed to be comfortable, adjustable leg extension padding, ventilated padding and a sport padding for a more dynamic feeling. A comparison between the basic padding and the sport version can be seen in Figure 19.

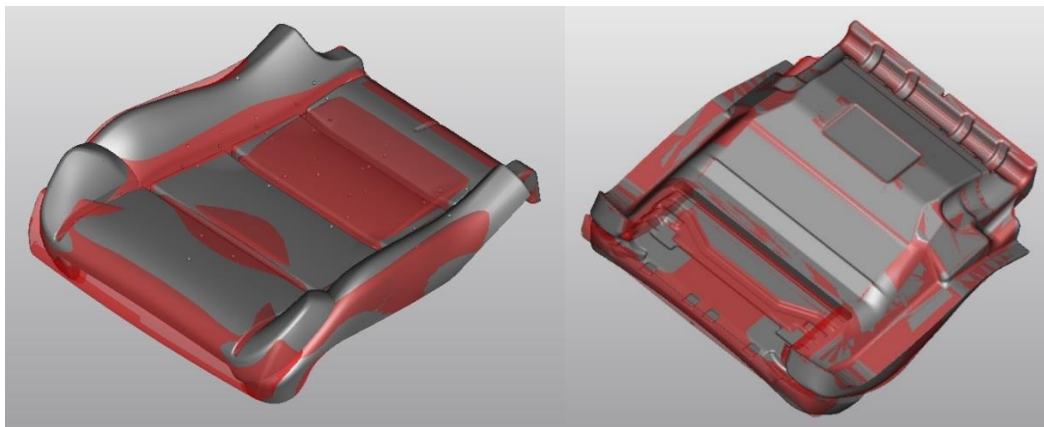


Figure 19. Comparison between basic cushion padding (red) and sport version (grey).

The differences between the geometry of each foam padding version can result in a different position for the H-point, this should be taken into consideration given that in the end all of them should allow for the occupant to be situated in the same level. Another option to increase comfort in the seat is adding a system to ventilate the occupant's body. This is achieved by incorporating a different version of the cushion foam padding which has ventilation holes distributed along its surface and channels to direct the air through the foam towards a fan, which sucks the air out and is attached to the seat frame, as can be seen in Figure 20.

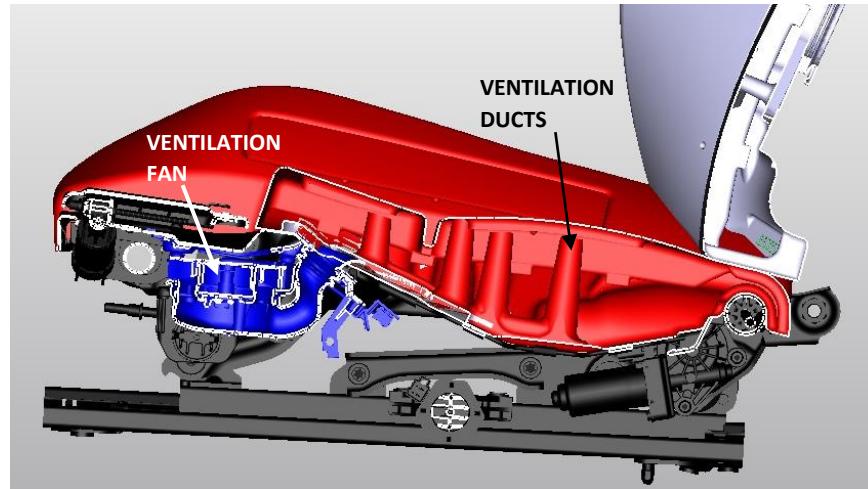


Figure 20. Y-section of seat equipped with ventilation system for comfort.

In order to compensate for the difference in cushion performance that the channels for ventilation could cause, the perimeter around these is reinforced with stiffer foam, calculating the right compensation has been challenging in the past, leading to an overcompensation which doesn't allow for the needed deflection of the foam to take place and moves the H-point higher as a result.

Predicting the behavior of the foam is a difficult but crucial task in order to make a valid H-point prediction, today this is only done by using previous experience. A difficulty in predicting the behavior of the foam is that different compositions are used in different parts of the seat and the behavior of the foam itself is non-linear (Krusper, 2015). Since the foam is made by a supplier Volvo have to rely on material data given to them to model it. Factors such as manufacturing equipment is also out of Volvo's hands. This in combination with the non-linear behavior and sensitivity to environmental parameters (temperature, humidity etc.) makes it a very difficult task to model the foam.

Heating mats can be included for both the cushion and the backrest of the seat to improve the comfort of the occupants in cold weather. These mats are added on top of the foam padding before the trim is adjusted to it, as pictured in Figure 21.

The current Volvo seat can be found in versions that feature textile trim cover as well as leather and vinyl covers. The attachment and adjusting of the cover to the final seat can alter the overall dimensions of the foam padding as well as its behavior to compression due to the effort needed to get as close contour to the desired as possible, to create an attractive look of the seat. The adjustment of the trim cover can create an extra pre-tension effect on the foam.

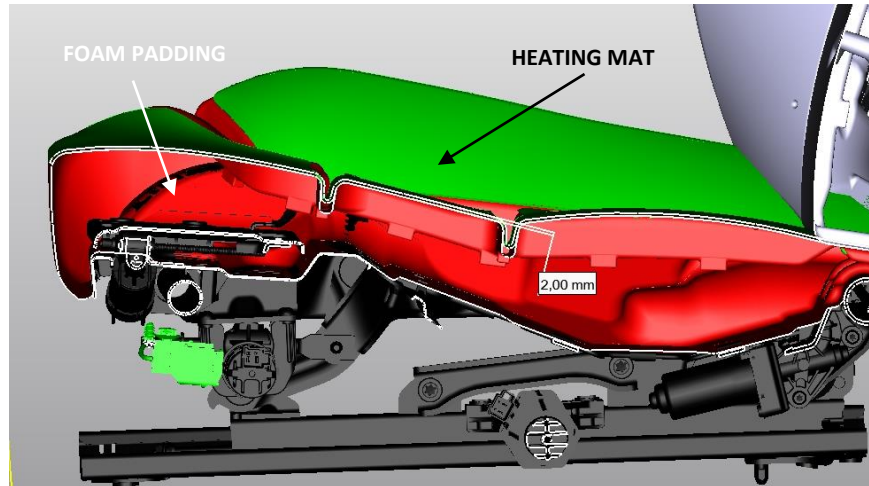


Figure 21. Y-section of seat equipped with heat mat for comfort.

The metal frame of the seat is measured at the manufacturer, however it was found that the measurements only are made on the rigid parts of the seat frame. No measurement points were placed on the springs of the seat. This is a problem in terms of H-point assurance since the variations of the springs cannot be assessed, something that is thought to be affecting the H-point to a big extent. Another possible problem with the measurement data is that no requirement on the seat's position during the measurement exist. This means that the manufacturer could readjust the seat until the sought values on the different measurement points are achieved.

3. Manufacturing

The seat consists of many components and sub-assemblies that are provided by a number of different suppliers. The requirements on how much the H-point is allowed to deviate are only stated for the final seat, no individual tolerance requirements exist for the different components. This poses problems when predicting and finding the source of the H-point and when communicating with suppliers due to that it is not possible to know which components that are different from the specifications. When the H-point deviates it is hard to make any of the suppliers take responsibility for it and correct it and no single supplier can be held responsible for not fulfilling their required tolerance.

Previous analysis on the deviations in H-point have shown that the C_{pk} value is below the required level for all seat variants (Wickman, 2015) meaning that the production process does not produce parts within the expected limits. It also showed that there is a mean shift in x- and z-direction in all analyzed seats, approximately 5mm in z-direction and -10mm in x-direction (Wickman, 2015). The result is that the H-point will be higher and further forward than expected. The mean should ideally be as close to zero as possible. Hence, the main problem is more a matter of tuning the process to achieve the right mean value rather than a too big spread. An example of the H-point



Figure 22. Intended design (green lines) compared with a scanned seat (blue lines).

deviation can be seen below, the green line represents the manikin positioned in SgRP and the blue lines are data from three measurements done on a physical seat.

The foam was found to be varying a lot from the intended design. During a discussion with people in the comfort department it was discovered that the foam could vary up to a centimeter in any given direction from the designed form, even for the prototypes used for assessing the comfort. An example of this can be seen in Figure 22 where the green lines are the original design and the blue lines are scans of a physical seat. A result of this is that the comfort of the seat is very hard to predict since the design might not even correspond to the seat that will be tested. This in turn leads to no matter how well designed a seat is, comfort readjustments will have to be done late in the process and these affect the position of the H-point.

4. Uncertainty Derived from the H-point Measurement Process

The H-point location is used in many activities such as benchmarking and design of the seats in many companies. Standard procedures have been developed to assure the conformance of the measurements. These standards are mostly based on the SAE J826 document which describes a machine to be used as a simulation of a passenger and the procedure to take the H-point measurement on a finished seat. Another standard document which can be used is the ECE R17 which resembles SAE standard and uses the same machine.

One of the main problems with the procedure is to make sure that it is as repeatable as possible and delivers the same results regardless of outside parameters, otherwise the comparison between measurements may be unreliable. This was detected as a matter of attention in the past by VCC during their measurements and therefore an effort to create an internal procedure that guarantees the compliance between measurements inside the company and those performed by suppliers, an important requirement was to make the measurement equal between a seat that is fixed on a measuring rig and one that is measured on an already finished car.

The revised procedure from VCC is based on the ECE R17 standard and includes additional instructions on setting the right conditions before the measurement, it also specifies that 2 individuals should conduct the test and gives general guidelines on how to perform each step in the process. An additional project which was connected to the development of the internal procedure was a Measurements Systems Analysis (MSA) to determine the influence that each element in the process had over the difference that was detected in measurements, however the MSA was not completed.

The internal document for H-point measurement was implemented during the tests for the V40 car program with satisfactory results, it contains instructions on how to adjust the measurements for other vehicles but requires new changes to be applicable in the current cars. The team that developed the standard is not connected to current measurements. Although the internal standard of measuring was analyzed and improved it is still a manual process with many tasks. Several factors such as equipment, temperature and who is performing the test may influence the result. This uncertainty may be a reason why the H-point deviates from the theoretical SgRP.

Volvo is currently working on a method based on finite element analysis (mainly of the foam) to predict the H-point virtually. However, during the interviews it was found that there seems to be a long way to go. The company was described as not being “CAE ready”, the resources assigned to the project seemed to be relatively scarce and the attitude towards the project was not very optimistic by most. Problems regarding finding information about the foam and other components as well as modelling the properties of the foam were described as the main contributors.

Ranking causes of deviation

Given the variety of causes for deviation that were found during the project, it is important to make a distinction between them that allows to narrow the scope of the work. Since not all of them can be addressed at the same time, ranking the causes was considered as the best way to find the most critical causes to concentrate on. The information that has been presented before was condensed into seven elements of the seating design process, which are considered to be possible to improve as described below:

- **Inaccurate H-point Prediction method:** The lack of an established computerized procedure to estimate the parameters of the seat that will influence the H-point without relying on experience alone.
- **Uncertain Foam Properties:** The difficulty of accurately knowing the behavior of the padding material due to its properties during deformation and its varying manufacturing process.
- **Lack of control over manufacturing process:** The supplier strategy for the seat, which depends a lot on supplier expertise and cedes many decisions to them.
- **Inaccurate measurement method:** The complex process that is needed to measure the H-point according to the international standard, in which many steps can be performed differently and produce false results.
- **Insufficient data transfer:** A complicated internal communication between the different functions inside the company that can lead to misinterpretation of information.
- **Redundant/Lacking Requirement Specification:** A requirement specification for the seating position that is not optimized can lead to misunderstanding and unclear definition of internal components in the seat
- **Omitting variant differences:** The high number of components inside the seat and different configuration possibilities which are not fully taken into account during the H-point position definition and create differences between each other when they are measured.

These seven elements were analyzed, using an organized method to obtain the final ranking by applying a series of tools that were adapted from known engineering methods. In order to rank the causes in a structured way, a number of matrices were used. The first matrix consisted of an analysis of the different interviews, conducted during the problem exploration, with the 7 causes on one axis and the people being interviewed on the other. For each cause mentioned in an interview, a mark was made in the column corresponding to the interviewee. The interview matrix can be seen below.

Table 3. Causes mentioned in interviews.

	PER	BABAK	CASPER	ALEK-SANDRA	PETER	BO	
INACCURATE H-POINT PREDICTION METHOD	X		X	X			3
UNCERTAIN FOAM PROPERTIES			X	X	X		3
LACK OF CONTROL OVER MANUFACTURING PROCESS			X	X	X		3
INACCURATE MEASUREMENT METHOD		X				X	2
INSUFFICIENT DATA TRANSFER	X			X		X	3
REDUNDANT/LACKING REQUIREMENT SPECIFICATION	X		X				2
OMITTING VARIANT DIFFERENCES	X		X	X			3

The aim of the matrix was to determine whether any of the causes was mentioned significantly more times than the others, if that was the case it would be deemed as more severe than the others. However,

the resulting score for all causes was 2 or 3, indicating that no conclusions of their severity could be made solely based on this analysis.

In the next step of the ranking, the relationship between the causes was analyzed, in an attempt to find the most influential cause. The assumption was, that if a cause is directly promoting the occurrence of other causes, it is important to address such cause since it might lead to improvements in several aspects. This was done by implementing a variant of a DSM matrix, with the 7 causes on both axes. In the horizontal direction, a mark was made if the cause was deemed to influence another.

This judgment was based on the information gathered in the problem exploration. The matrix can be seen below. The horizontal direction shows affecting and the vertical affected causes. This shows that the insufficient data transfer and requirement specification are the most influential to other causes, which means that an improvement within these areas might help with all other causes as well.

Table 4. Relationship between the causes.

	1.	2.	3.	3.	4.	5.	6.	
1. INACCURATE H-POINT PREDICTION METHOD			X		X	X	X	4
2. UNCERTAIN FOAM PROPERTIES	X		X	X		X	X	5
3. LACK OF CONTROL OVER MANUFACTURING PROCESS	X	X			X			3
4. INACCURATE MEASUREMENT METHOD			X		X	X		3
5. INSUFFICIENT DATA TRANSFER	X	X	X	X		X	X	6
6. REDUNDANT/LACKING REQUIREMENT SPECIFICATION	X	X	X	X	X		X	6
7. OMITTING VARIANT DIFFERENCES	X					X		2

The final ranking was made by taking the results of the previous matrices into account, as well as other aspects that were considered to be affecting the importance of the cause (see Table 5). A 1 to 5 rating scale was used with one being least severe and 5 being most severe.

The first column comes from the interview matrix stating the quantity of mentions each cause had. The second column states the cause impact on other causes (from the second matrix). In the third column, process influence, the causes are ranked based on what parts of the process they affect. The measurement method gets a low score since it only matters in later stages of the process (physical prototypes) while the prediction method gets a high score since it will have influence on the entire process. Finally, the potential for changing the different causes was evaluated, basically stating the possibility of addressing the problem. The scores were added and ranked based on the sum. The results can be seen below.

Table 5. Causes ranking matrix.

	NUMBER OF MENTIONS	IMPACT ON OTHER CAUSES	PROCESS INFLUENCE	POTENTIAL FOR CHANGE	SUM
INACCURATE H-POINT PREDICTION METHOD	3	3	5	4	15
UNCERTAIN FOAM PROPERTIES	3	4	5	2	14
LACK OF CONTROL OVER MANUFACTURING PROCESS	3	2	3	2	10
INACCURATE MEASUREMENT METHOD	2	2	1	3	8
INSUFFICIENT DATA TRANSFER	3	5	5	4	17
REDUNDANT/LACKING REQUIREMENT SPECIFICATION	2	5	5	5	17
OMITTING VARIANT DIFFERENCES	3	1	2	5	11

The ranking shows that the most important issues to address are the requirements specification and data transfer. The measurement method and manufacturing process get low scores which can be explained by them not addressing the cause of the problem but rather dealing with the effects of it. The process of ranking the causes of the deviations in the driver's H-point has made it even clearer that this problem is affected by many factors.

All of these factors are closely interlinked and affect each other, which indicates that all of them should be considered throughout the rest of the project. This ranking was the base of the generation of solutions to address the problem of deviations in the H-point. The knowledge gained through ranking the causes was also used to evaluate the generated solutions in order to find the conceptual idea to be developed further, and which the final proposal should be based on.

4.5 SUMMARY

The problem exploration phase included several activities intended to understand the links between all the different functions and each step in the process. The first analysis was performed on the physical components of the seat with a tear down activity, which allowed to identify the main components that are connected to the occupant position on the final seat assembly.

It was explained how seating position is used to measure many aspects of the vehicle interior and sometimes to a very strict margin. Motor Vehicle Safety Standards utilize the H-point and associated measurements to implement many of the safety standard requirements. And in addition, the Environmental Protection Agency uses H-point related measurements to calculate the Interior Volume Index for vehicle fuel economy classifications.

Having identified the consequences of an H-point deviation, it was necessary to recognize the potential causes of this deviation in order to determine the possible actions to improve this condition. The information from the problem exploration phase was analyzed and divided into four categories to identify the attributes and functions that affect the seating position. The list contains the following categories:

1. Design process
2. Physical parts in the seat
3. Manufacturing
4. Measurement process

Given the variety of causes for deviation, ranking them was considered as the best way to find the most critical causes to concentrate on. The information that has been presented before was condensed into seven elements of the seating design process, which are considered to be possible to improve, including: Inaccurate H-point Prediction method, Uncertain Foam Properties, Lack of control over manufacturing process, Inaccurate measurement method. Insufficient data transfer, Redundant/Lacking requirements, and Omitting variant differences

These seven elements were analyzed, using an organized method to obtain the final ranking by applying a series of tools that were adapted from known engineering methods. In order to rank the causes in a structured way, a number of matrices were used. The ranking shows that the most important issues to address are the requirements specification and data transfer. The measurement method and manufacturing process get low scores which can be explained by them not addressing the cause of the problem but rather dealing with the effects of it.

5 RESULTS OF THE SOLUTION FINDING PROCESS

Proposing a solution, that could help to solve the misalignment between designed SgRP and measured H-point, was done in a systematic way. Seeking to take on account the different aspects of the problem, to achieve an inclusive application. The steps that were followed during the solution finding process, along with the results of each step are presented in this chapter.

5.1 GENERATION OF POSSIBLE SOLUTIONS TO THE H-POINT DEVIATION PROBLEM

As a first step in finding a solution to the H-point deviations a brainstorming session was conducted. As many ideas as possible were sought and represented in the form of a mind map, this can be seen in Figure 23 below. The ideas were placed in different functional areas in order to consider all stakeholders who were found to be affected by the deviated H-point. Within each functional area, solutions solving their problem were generated.

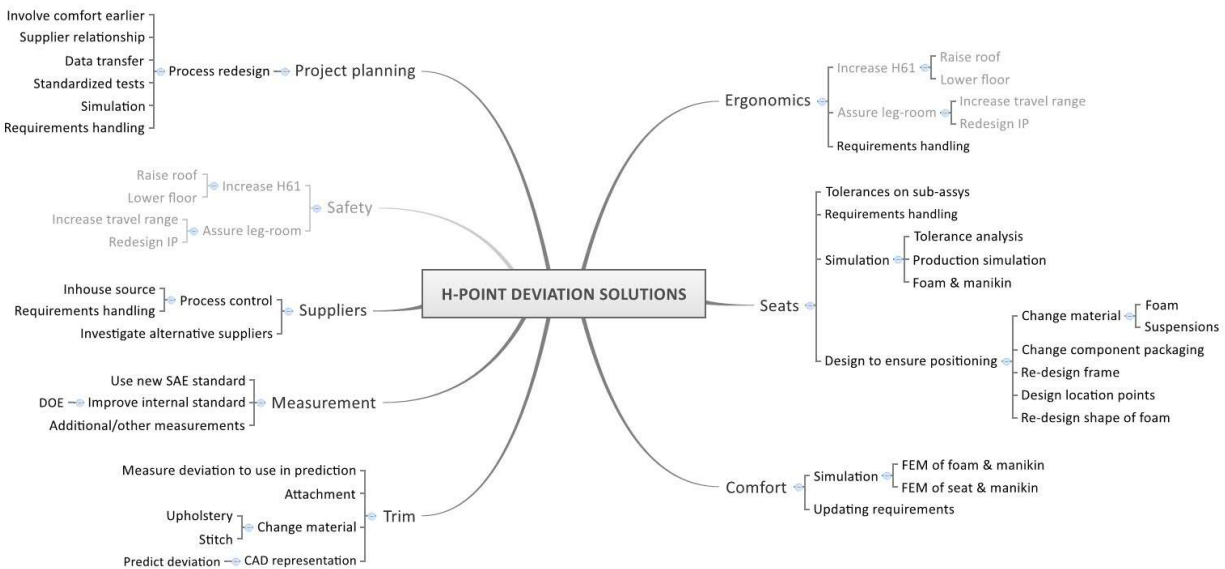


Figure 23. Brainstorming mind-map

When the brainstorming reached a point where no more ideas were generated the result was analyzed. Ideas that only addressed the effects of the problem rather than solving it (e.g. raising the roof, increase travel range) were omitted. The omitted ideas are shown as grey in the figure of the mind map. This resulted in that all ideas related to ergonomics and safety were eliminated, which was found to be reasonable since their requirements mainly are of legal or other, similar origin that is hard to manipulate but rather has to be met. Also they come into play quite late in the process and by then the deviations are already a fact. The remaining ideas were overviewed, rephrased and condensed into a list of conceptual ideas, these are described more in detail in the following section.

5.2 DESCRIPTION OF GENERATED SOLUTIONS

The ideas obtained from the previous process were condensed into a list of possible solutions, below each solution is described in detail.

Tolerance analysis

It was found during the interviews that no individual tolerances, relating to the general H-point system requirement, were specified for the components of the seat. This led to difficulties in communication within the company as well as with suppliers. During one of the interviews it was stated that assigning individual tolerances to components could mean an improvement regarding H-point deviations. This idea would imply a detailed component study and result in recommendations regarding how the tolerances should be distributed amongst the components.

Requirements reformulation

The whole seat development is based on the requirements it has to fulfill, this concept consists of reviewing these requirements and making sure that they are not redundant or that any requirements are lacking. Extra attention could be given to formulating requirements towards suppliers in order to assure quality on components that are manufactured outside the company. It was expressed during interviews that redundant and lacking requirements regarding the seat do occur.

Foam behavior determination

The uncertainty that comes from not being able to determine the exact properties of the cushion padding material, or relying exclusively on advice from the supplier make it necessary to keep big tolerance margins for the seat design. If more experience and knowledge was gathered about the foam properties and behavior, the design could benefit from it and become more robust.

Simulation of foam deformation

As presented in the theory section, there have been several works in the past which aim at simulating the way in which the cushion padding behaves during a sitting condition, this allows engineers to predict in a more accurate way the position in which the occupant will be after the actual seat is installed in the car. If a simulation of this kind was implemented in the development process at Volvo, it would help to design better seats by eliminating the uncertainty that comes from designing based on experience, thus allowing to decrease the tolerance margins for production. This solution however would require that effort was made in determining the actual properties of the foam material to be used in the simulation.

Process redesign

Implementing some standard channels for data transfer and communication during the seat development process could be a solution to avoid that work gets repeated between different departments and making sure that everyone involved is using the same kind of information during their particular functions. Guaranteeing the requirements requires that this channels and processes are known by all. At the same time, the flow of information and activities could be optimized to obtain a smoother transition between the phases of development.

Measurement process improvement.

The process of measuring the H-point is highly manual and is affected by several factors, this leads to uncertainty of the measured result and might in itself be a contributor to the H-point deviations. By analyzing the process and identify factors that influence the result followed by a suggested revised process could give a more robust measurement. This concept could also include reviewing how and when the new SAE manikin would be implemented and what effects it would have.

5.3 ASSESSMENT OF PROPOSED SOLUTIONS

The next step in the project was to assess all the solution proposals to identify the most promising one and develop it further. Given that the actions which could be followed to improve the process of seat design, were diverse in terms of people involvement, phases of the development process, resources needed, among other factors; an organized method to analyze them together and compare their characteristics had to be put in place in order to narrow down the possibilities and move further in the project.

The assessment process used information from the problem exploration phase of the project, the analysis of causes and their importance, discussion of feasibility with the project supervisors, as well as the knowledge of the project team. The first step was to develop a decision matrix, inspired by the Pugh matrix method for concept selection, a set of evaluating criteria were used to compare all the solutions against one which is used as a reference. The criteria which were used for this selection were the following:

1. *Solution Potential*

The extent to which the results from implementing the solution in the company are expected to reflect in a reduction of the problem occurrence or severity.

2. *Required Time*

The amount of time which would be needed to develop and implement the solution for Volvo Cars.

3. *Required Knowledge*

The amount of specific knowledge and expertise that is required for the team to develop the solution.

4. *Required Information*

The necessary research that would be needed in addition to the previous efforts by the team to make a good solution proposal.

5. *Scope Definition*

The clarity with which the content of the solution is defined already and how much it would need to be further specified to avoid scope creeping during the development.

6. *Stakeholder Availability*

An evaluation on how much of the solution development would depend on the participation of stakeholders outside the Volvo Cars departments which are directly involved in the project.

7. *Solution Precedence*

The promises or difficulties a concept has shown previous to the current project. This was based both on findings from the literature study as well as information gained from interviews.

Using these criteria, the matrix for solution selection can be seen in Table 6 below. A concept gets marked with a plus if it fulfills the criteria better than the reference, a minus if it is deemed as inferior to the reference and a zero if it is equal to it. Extra attention was decided to be put on the first criteria, solution potential (highlighted in the table), since it was deemed to be more important, in order to achieve the best possible solution.

Table 6. Concept comparison matrix

	TOLERANCE ANALYSIS	REQUIREMENTS REFORMULATION	FOAM BEHAVIOR DETERMINATION	SIMULATION OF FOAM DEFORMATION	PROCESS REDESIGN	MEASUREMENT PROCESS IMPROVEMENT
SOLUTION POTENTIAL	R E F E R E N C E	0	-	+	-	-
REQUIRED TIME		0	-	-	0	0
REQUIRED KNOWLEDGE		+	+	-	+	+
REQUIRED INFORMATION		-	+	-	-	+
SCOPE DEFINITION		0	+	+	-	+
STAKEHOLDER AVAILABILITY		0	-	0	+	+
SOLUTION PRECEDENCE		0	-	0	0	+

After the internal assessment done by the team with the presented table, the result was further discussed with the supervisors of the project. This assessment pointed to develop a tolerance analysis for the components of the seat as a means to prevent the occurrence of H-point deviation during the seat development at Volvo.

While planning to develop this further, the team realized that it was necessary to initiate the tolerance analysis with breaking down the H-point requirement for the whole seat into individual geometrical requirements for each component and afterwards defining the tolerance range for each of these. The process that was followed and the final proposal for improving the assurance of the H-point location are presented in the next chapter.

5.4 SUMMARY

Chapter 5 presented the potential proposals that the team considered for improving the prediction of the H-point during the development of automotive seats. After suggesting several paths of action, based on the information from the problem exploration phase, the ideas that were evaluated further were: performing a tolerance analysis, proposing a requirements reformulation, analyzing the foam behavior, performing a simulation of foam deformation, suggesting a process redesign, or analyzing the current measurement process.

These possible solutions were examined using selection matrices and a series of criteria to determine the most feasible one, which would be elaborated further. The assessment gave more clearance to the interdependence of the ideas that were found to be more important, namely the redefinition of requirements, tolerance analysis and simulation of component behavior. It was decided to elaborate on a solution that encompassed these three areas in a process to develop automotive seats with an accurate H-point prediction.

6 PROPOSED PROCESS FOR H-POINT ASSURANCE

According to the current system requirement on the seat, the H-point and SgRP should be made to coincide on the finished vehicle. However, engineers at Volvo have experienced difficulties in minimizing the deviation between them to a value below an imposed tolerance. As mentioned previously in this report, the deviation between the two is caused by several factors involving the design process, variations on the components of the seat and the manufacturing process, among others. Meanwhile, the requirement for the H-point position is only stated for the complete seat.

Because of the complexity of the seat and the many interactions inside it, a main contributor to the problem is the lack of an efficient requirement strategy that considers the parts of the seat individually, to make sure that their particular requirements are in line with the system requirement, according to the design intent for the H-point location. This can be also explained from a systems engineering perspective, by considering that the requirements on single components should always be derived from the subsystem requirements, in a way that they can be traced back and assure that both levels are aligned (Weber, 2009). In this case, there is not a clear connection between the H-point subsystem requirement, for the whole seat, and the individual seat component requirements. Therefore, it cannot be guaranteed that there will be an alignment of the design intent to the finished product, during system verification, if all the component requirements are fulfilled,

To provide efficient requirements that guarantee the occupant position, it is necessary to consider how each component affects the overall result, as well as an understanding of how the applied materials behave under use, and how much variation can be expected during their manufacturing process. This creates a deep correlation between defining individual requirements, setting a tolerance strategy for these requirements and simulating the behavior of the parts, which has to be taken into consideration in order to make a reliable H-point assurance strategy.

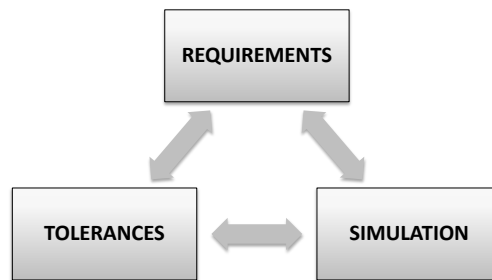


Figure 24. Relationship between different aspects of the problem.

Therefore, the process that will be presented in the following sections, will focus on the necessary steps to be taken in order to make these aspects come together to guarantee a better H-point position assurance. Breaking down the H-point requirement on the whole seat into several requirements on individual components and/or subassemblies was concluded to be a necessary first step in controlling and assuring the H-point location.

The individual requirements would provide a base to simulate and predict the contribution of each part to the overall measurement of the seat. Such requirements should be based on individual part data, such as manufacturing variation and material properties of the affecting components. The steps to be followed in defining the new individual requirements and tolerances was defined as in Figure 25.



Figure 25. Requirement definition process.

Different inputs need to come together for this process to be achieved and to obtain the new requirements and tolerances for the seat. Information from the design engineers, material suppliers and quality measurements have to be applied to fully understand the level of accuracy that can be expected from the components. In the case of the seat, an additional information requirement emerges from the fact that several components are flexible and need to have requirements specified for the state in which they will be when an occupant is using the seat or when a manikin is placed on it for H-point measurements. In this report such a condition will be named as *deflected state*. The original condition for the components as they are manufactured and assembled in the car will be called *unloaded state*.

Figure 26 shows an overview of how different types of information would come together to create the individual requirements and tolerances for the seat components which would result in a better predicted and controlled H-point. In the figure, information of the components in their nominal state and when subjected to load comes together to formulate individual requirements.

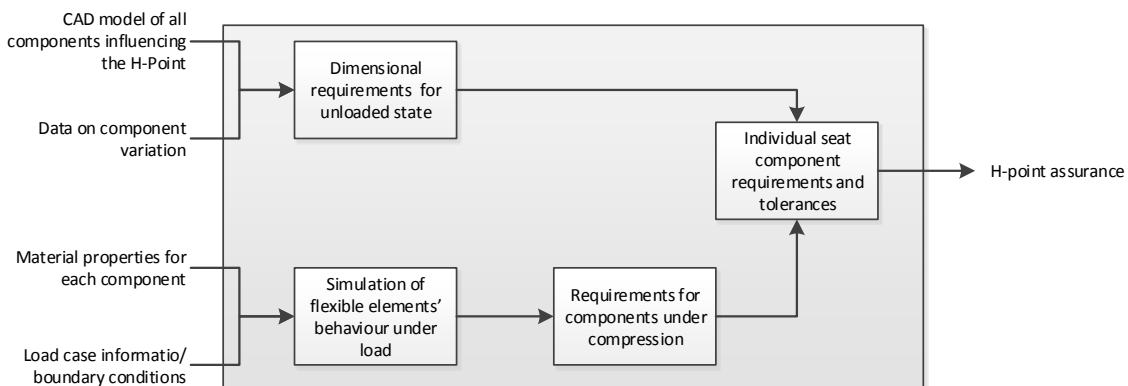


Figure 26. Needed information for new requirements.

Some of these inputs and actions are relatively easy to achieve, while others are more difficult due to their complexity and/or the extent to which they are currently performed in-house at Volvo. The inputs needed for the deflected state constitute the biggest challenge in assuring the H-point and a lot of information is missing, since generic guidelines are currently the main tool in predicting the deflection. The process of acquiring these inputs will be described below, first for the unloaded state and then for the deflected state.

The general process described by the flowchart in Figure 27 is recommended to be followed to assign requirements for the unloaded case. It is initiated by conducting a geometry study to identify the contributing components (and points on these) that affects the position of the H-point. These can then be analyzed in the CAD-model (given that this is updated to include all components of the seat) to give the nominal measurements of the affecting components. The data will then be used to define which points that should be assigned tolerance requirements to achieve a robust design. The requirements can be based on generic tolerance recommendations, another possibility is to base the tolerance requirements on manufacturing potential by looking at measurements made on manufactured parts. The result of these

steps will be a measurement and variation for the H-point in the unloaded case that can either be seen as the output of the process or the tolerance step could be iterated if the values are deemed to be unsatisfying.

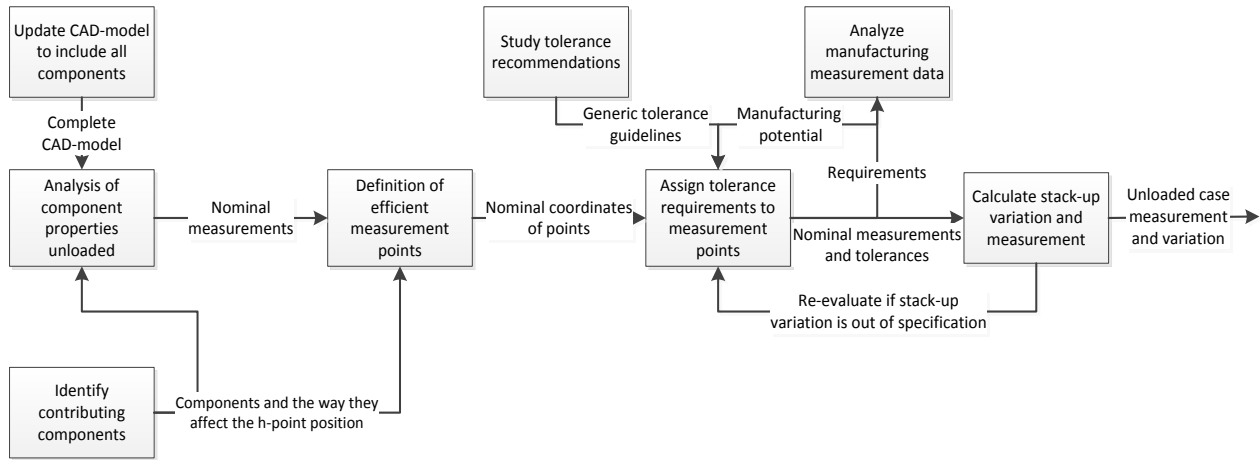


Figure 27. Process for finding measurement and tolerance for unloaded case.

By performing the above mentioned process it can be determined how the parts vary in their nominal state. However, in order to assure the H-point position the deflection and its variations also need to be taken into account. This can be achieved by using a similar process, as described in the flowchart in Figure 28. Just as in the previous process identifying contributing components is the initial step, aiming towards finding which parts to analyze. This is followed by a component analysis where the factors influencing the deflection of each component is sought (material properties for example). Simulation of the deflection and formulation of requirements are then made in terms of/with help of these factors. Measurements on manufactured parts can be used to see if the requirements are in line with the capability of the manufacturer as well as for quality control and evaluation of manufacturing variation. These actions will allow for the measurement and variation of the seat assembly during deflection to be calculated. As in the case of the unloaded state, parts of the process could be iterated if the achieved values are not as wanted.

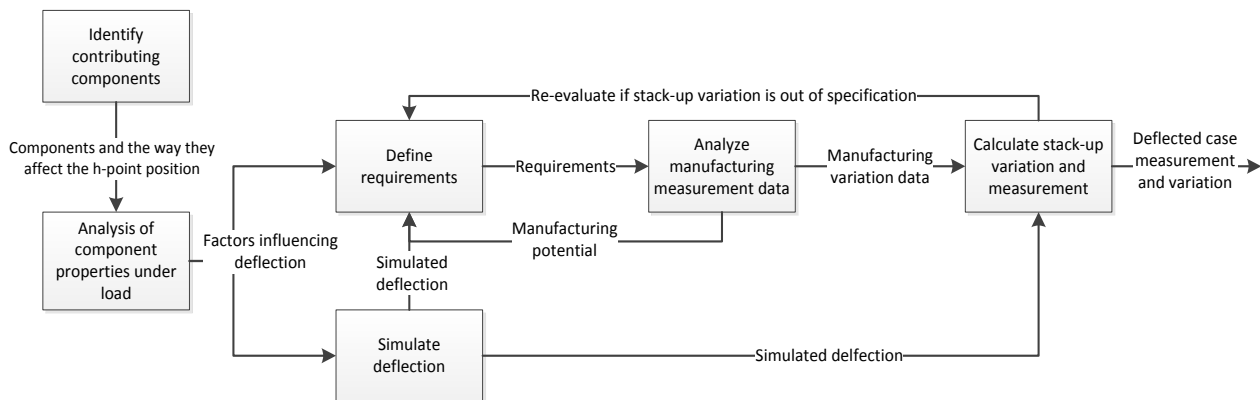


Figure 28. Process for finding measurement and tolerance for deflected state.

The process for the unloaded and deflected state can be merged to constitute one, common process describing the complete method suggested to achieve a more robust H-point position, this is shown in Figure 29. The outputs of the previous described processes is here the input to an analysis of the results which aim is to evaluate the measurements and tolerances of the two states to find the final H-point position and its variation. If the analysis shows that the variation and measurements are not as intended,

the process (or parts of it) can be iterated to improve the values. All actions described in the flowcharts are deemed to be necessary in order to achieve a robust H-point position. However, some of them are only needed to be performed once, to get the process started. When the components, measurement points and appropriate tolerance requirements have been found that information can be used to calculate the H-point position and variation for several variants of the same seat.

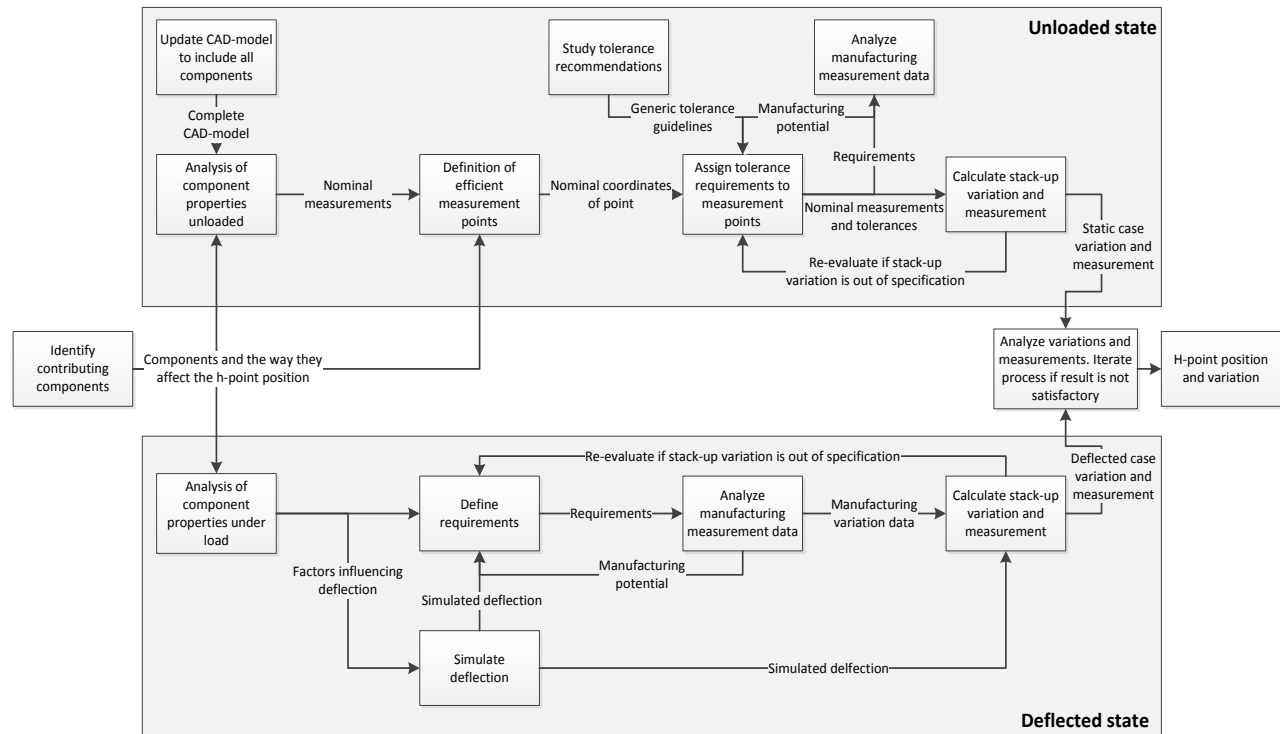


Figure 29. Process of assuring the H-point position.

Some steps of the H-point assurance process will be explained more detailed in the following sections in order to clarify it even further. Recommendations regarding important aspects and how to conduct the steps will be given.

6.1 IDENTIFICATION OF CONTRIBUTING COMPONENTS

The starting step in defining the new requirements for the seat was to study the geometrical characteristics of each component, to analyze their influence on the H-point location. In order to begin this process, the different configurations of the seat were inspected to obtain a list of all the components that can be included in a Volvo seat. This list of components was then arranged in a modified product structure that is shown in Figure 30. The components that are directly related to the H-point position are arranged in the figure accompanied by the versions that each of them can have. The OWS (occupant weight sensor) and heat pad do not have options due to that these configurations only can be included or not included.

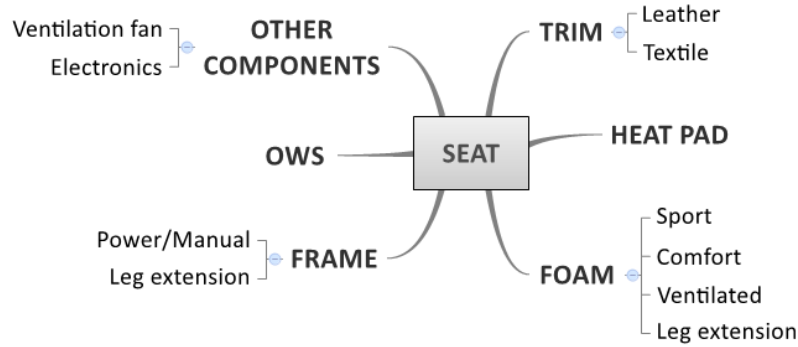


Figure 30. The variants of the seat consist of different components that will affect the H-point.

Afterwards, these components were analyzed to determine which of their properties should be taken into consideration (and how), as related to affecting the location of the H-point. The different variants were also studied to determine how they should be handled to prevent unwanted effects on the overall seat. The outcome of this analysis is presented in Table 7 which details the different factors that have to be accounted for during the design of the seat to assure a determined H-point location.

Table 7. Seat variants and properties and how they affect the H-point location.

TRIM	Properties	SHAPE	The shape of the trim should follow the geometry of the foam as close as possible to prevent overstretching the material or deflecting the foam more than expected.
		ELASTICITY	The elasticity of the trim material will affect the foam shape and deflection, therefore it has to be predicted and controlled.
		THICKNESS	The thickness of the trim will be part of the accumulated height that builds up to the H-point, in addition it will be compressed during the deflected case.
		ATTACHMENT	The attachment strategy regarding type, number and position of fasteners will affect the shape and deflection of the foam, as well as the assembly process.
		COMFORT FOAM	The laminate that is attached to the trim could create variation in the overall thickness and hardness as well as affect the behavior due to how it is attached to the trim (glued, sewed or laminated).
	Variants	TEXTILE	The properties of the trim material for a synthetic fabric or textile will vary according to how it is made (woven, knitted...) And thread elasticity.
		LEATHER	The properties of the trim material for an organic material are expected to have more variation than a synthetic material.
HEATING PAD	Properties	THICKNESS	The thickness of the heating pad will be part of the accumulated height that builds up to the H-point, in addition it will be compressed during the deflected case.
FOAM	Properties	SHAPE	The shape of the foam is one of the main contributors to the H-point. Location. The contour metrics such as insert width, bolster height and bolster insert radius, will determine the contact surface between the manikin and the seat.
		IFD	The relation between applied load and foam deflection is a main contributor to the H-point location. It will determine how much the manikin sinks into the cushion.
		INSERTED WIRE	The addition of a wire inside the foam (to attach the trim) might influence the behavior of the part under load.

		PROTECTIVE FELT	The addition of felt on the foam (to protect it from wear) might influence the behavior of the part under load. It will also add to the accumulated height that builds up to the H-point.
		HARDNESS VARIATION	The different foam mixtures, intended to create different hardness in areas of the seat, can float into each other and create another behavior than predicted.
	Variants	SPORT	The sport version of the foam is generally thinner and has a higher IFD value, both characteristics have to be balanced in order to obtain the same H-point location as other versions
		COMFORT	The shape and IFD value of the foam need to be balanced to obtain the same H-point location as other versions while differentiating comfort and aesthetical properties between them.
		VENTILATED	The channels for directing air through the foam might affect the IFD, this needs to be compensated for by adjusting the foam properties.
		LEG EXTENSION	The leg extension variant of the foam should not affect the H-point location directly, however the modification involves different characteristics in several components (trim, heat pad...) and therefore it should be controlled.
OWS	Prop-erties	THICKNESS	The thickness of the occupant weight sensor will be part of the accumulated height that builds up to the H-point, in addition it will be compressed during the deflected case.
SBR	Prop-erties	THICKNESS	The thickness of the seat belt reminder will be part of the accumulated height that builds up to the H-point, in addition it will be compressed during the deflected case.
FRAME	Prop-erties	SPRING BEHAVIOR	The area of the frame that supports most of the manikin's weight is composed of springs. The deflection of this area needs to be calculated to predict the H-point location.
	Variants	MANUAL	The mechanisms to adjust the seat position should not affect the H-point location. However the components required for the manual configuration have to be controlled to assure that they do not affect other parts.
		POWER	The mechanisms to adjust the seat position should not affect the H-point location. However the components required for the power configuration have to be controlled to assure that they do not affect other parts.
		LEG EXTENSION	The leg extension variant of the frame should not affect the H-point location directly, however the modification involves different characteristics in several components (trim, heat pad...) and therefore it should be controlled.

Due to the complexity of the seat, that the table above illustrates, several simplifications have been made in the following analyses in order to be completed within the given time period but still provide as an illustration of the process. However, it is the project team's belief that the same method could be used to extend the analysis to include more components and be more detailed.

The first decision was to limit the study to include only the configuration with comfort foam and heat included. Initially only the cushion part of the seat is studied in order to decrease the amount of components that are interacting and which need to be specified. Further simplifications were to only consider the deviation in z-direction directly underneath the SgRP as seen in the x-z-plane, see Figure 31. This is only a first step in assuring the position of the H-point and more requirements would need to be added to both the cushion and the backrest. The manikin will be in contact with a large surface of the seat, if for example the front part of the cushion deviates a lot this will also affect the H-point position. Hence, it is not enough to only consider the seat according to the simplifications just mentioned. However, the intention is to describe a methodology that can be extended to include the entire seat.

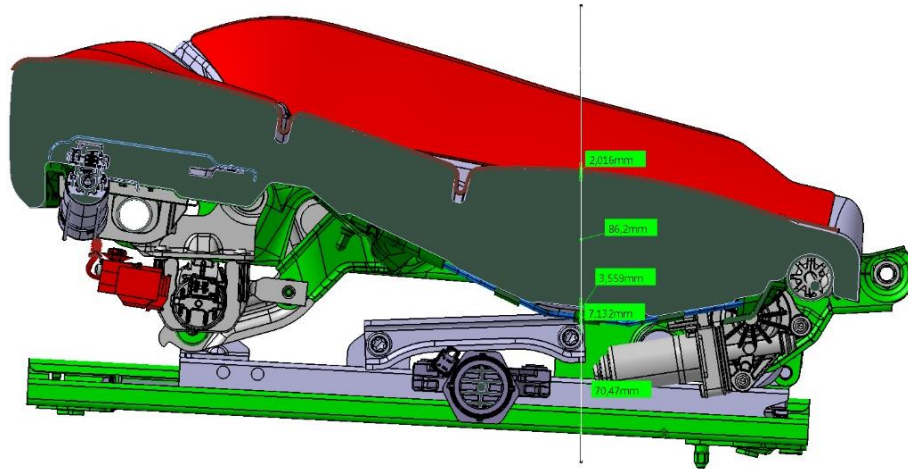


Figure 31. Cross-section of seat cushion showing the line through SgRP in z-direction. This is where the components measurements were analyzed.

Figure 31 shows the components located directly underneath the H-point, which for the selected configuration of the seat are: trim, heating mat, cushion foam and frame. These were the components selected to be included in the study as the main determinants of the z-coordinate of the H-point, given the limitations mentioned above. The position of the H-point is determined by the geometry of these components when compressed by the H-point measuring manikin, as represented in Figure 32.

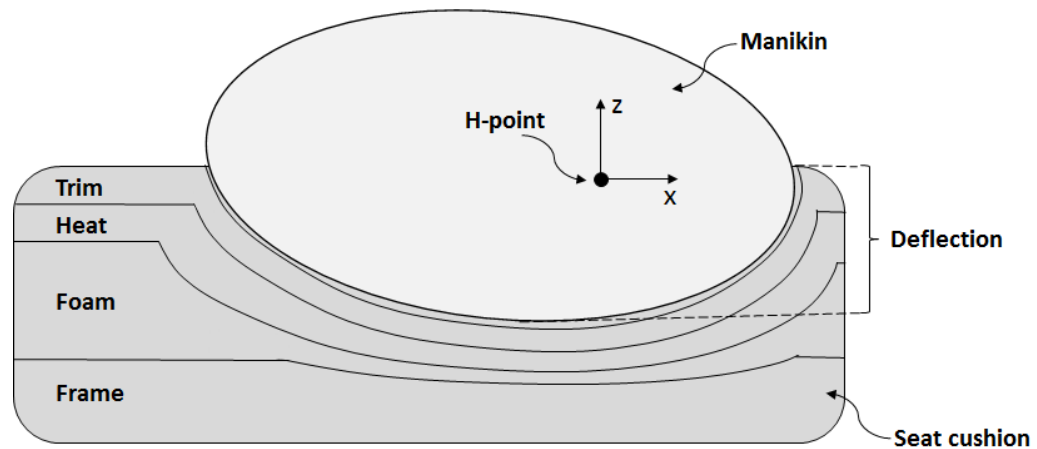


Figure 32. Illustration of seat deflection caused by H-point measuring manikin.

In order to know which characteristics from the components had to be included in the requirements, an analysis of the elements that determine the design seating position was made. To start with, the SgRP is defined by its 3 space coordinates.

$$SgRP = SgRP_x + SgRP_y + SgRP_z$$

As explained before only $SgRP_z$ will be analyzed in this first step. If concentrating only on defining the z-coordinate for the SgRP, it will constitute of the accumulated height of the deflected elements in the seat. Using the parts from Figure 32 we can develop an equation like the following:

$$Frame_z + Foam_z + HeatPad_z + Trim_z - Deflection = SgRP_z - Manikin$$

Because the manikin that is used to measure the H-point is a standard machine, regulated by the SAE, it can be considered to be irrelevant for the study and taken away from the equation. The components' properties that contribute to the deflection could include: deflection of the spring mat on the frame, the compression of the foam, compression of the trim and heat pad and the internal movement of the frame mechanisms due to the weight of the occupant.

The compression of the trim and the foam mat were excluded from the rest of the analysis given that their magnitude is relatively small and therefore considered negligible. The movement of the frame mechanisms is also expected to be relatively small and its study requires complex calculations which could be included for further development (Mazur, 2013). Because of this, the deflection term was considered as mainly comprised of the deformation of the spring mat of the frame (which is just below the occupant at the defined point) and the compression of the foam, the expression will then look like below.

$$Frame_z + Foam_z + HeatPad_z + Trim_z - Deflection_{Spring} - Deflection_{Foam} = SgRP_z$$

In order to have all the terms as positive, the deflection components are moved to the right side of the equation, this gives:

$$Frame_z + Foam_z + HeatPad_z + Trim_z = SgRP_z + Deflection_{Spring} + Deflection_{Foam}$$

This expression represents the main elements that are considered to be accountable for the SgRP position definition. However, in order to reflect the real seating position for the manufactured seat, the deviations from nominal measurements due to manufacturing process variation, material properties differences, etc. also needs to be included. In that case, the SgRP would become the H-point and the equation would look like:

$$Frame_z \pm VAR_{Frame} + Foam_z \pm VAR_{Foam} + HeatPad_z \pm VAR_{HeatPad} + Trim_z \pm VAR_{Trim} = SgRP_z \pm VAR_{SRP} + Deflection_{Spring} \pm VAR_{SpringDeflection} + Deflection_{Foam} \pm VAR_{FoamDeflection}$$

The above equation can also be simplified by grouping its contributing factors. In that case what will make up the H-point position is the deflection of the flexible components subtracted from their nominal height in combination with the variation for both. These relationships are presented in the expression below.

$$H-Point_z = SgRP_z \pm VAR_{SgRP} = \sum Unloaded_z \pm VAR_{unloaded} - \sum Deflection_z \pm VAR_{Deflection}$$

This equation represents, in a mathematical form, the information which was elaborated in the process diagram presented before. Written in this way the expression describes the general inputs needed to find the H-point position and its variation regardless of the earlier assumption and simplifications. This means that it can be used to analyze other variants of the seat and could also include components that were omitted in this analysis (trim and heat mat for example).

In the following sections, the two separate cases (unloaded and deflected) will be analyzed further to detail the necessary considerations and actions to be made in order to define the parts in each case and achieve a more robust prediction and control of the H-point position. This will be done by explaining in detail the most critical steps in the process to complete each case, detailing the requirements on inputs for the process to be possible, the expected outcomes and the limitations related to the process.

6.2 ANALYSIS OF COMPONENT PROPERTIES IN UNLOADED STATE

In order to control the dimensions and variation of the components when unloaded, dimensions that are defined during the design phase of the product can be used. In the same way as the components for the body of the car are checked, coordinate measurements and 3D scans can be performed on a special rig or when the seat is assembled in the car to control that each component is as specified. It is important during these checks that all the configurations of the seat are considered in terms of different content and changes in the components design. Currently, Volvo is using this technique for the seat to some extent, they use the measurements of the components to estimate the height of the seat and in turn make a prediction of the H-point location. However, not accounting for the change of measurement caused by the component setup in some of the variants has caused problems in assuring the H-point.

While the particular differences between seat versions, in terms of content and configuration, will have to be analyzed individually during the design, in the current analysis we consider a particular configuration of the seat which includes a power adjustable frame, a comfort version of the cushion foam, heating equipment and leather trim cover. The nominal measurements of the parts affecting the H-point, given the previously mentioned definition, were analyzed in the current CAD-model and the results can be seen in Figure 33.

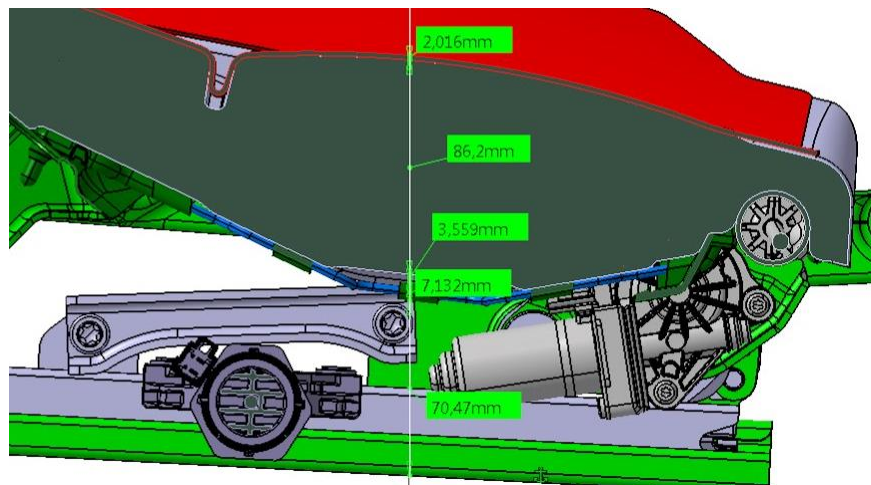


Figure 33. Cross-section of the seat showing the line in z-direction through the SgRP that will be the reference during the analysis.

No component can be manufactured perfectly according to the predefined dimensions, there will always be some variation. This variation is generally controlled by assigning tolerances to parts of the components stating how much they are allowed to vary, this can then be controlled by measuring the point. The trick with assigning tolerances is usually to balance accuracy and cost, the tighter tolerances (which means more accurate parts) the higher the cost.

Component measurements are currently done at the supplier's facilities, data are available to Volvo and could be used to evaluate reasonable tolerance requirements for the components. However, the problem with these measurements is that in some cases they have been found to not be measuring the appropriate dimensions. In the case of the frame, no measurements are done on the spring mat geometry, even though this part is where the main contribution to the H-point position will be found, see Figure 33. Geometrical tolerances for the spring assembly would be possible to specify given that the process for obtaining a formed spring of this kind uses machines with an accuracy that is similar to stamping machines, reaching tolerances of a few millimeters (Bolz, 1977). The reference system to be used for frame measurements is

also ill-defined. Measurements are to be made with the seat in “design position”, this position is not pre-defined and the supplier could theoretically adjust the seat until it coincides with the expected values.

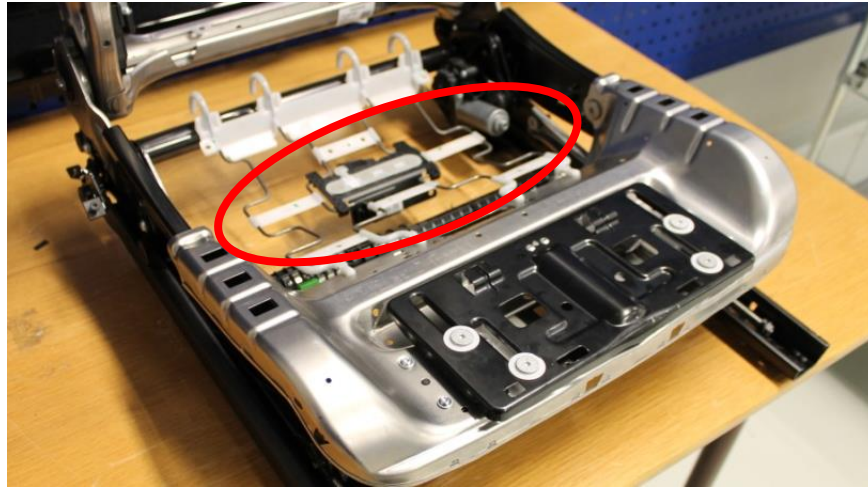


Figure 34. Measurements on frame do not include any checks on the spring mat (red area).

Moreover, one constant source of uncertainty for all the variants is that the trim is currently not included in the CAD-model of the seat, which is a contributor to why the seat can't be measured accurately. The trim is not a main contributor of the dimension of the seat, given that its thickness is relatively small, and it can be accounted for generally if the deflection and dimension of the seat are estimated based on previous experience, without it being included in the CAD model. However, as the design requires more accuracy and the need to make a more accurate prediction of the seat behavior in the future it becomes important for the trim to be included in the CAD model to enable the design and analysis of its contribution to the cushion shape and properties, which will reflect on the final seat form.

6.3 ANALYSIS OF COMPONENT PROPERTIES UNDER LOAD

One of the main reasons why assigning specifications and tolerances on the individual components of the seat is a challenging task, is the flexible nature of several of these components. The spring assembly and cushion foam are deformable parts that will have different shapes when the occupant is sitting on them as to the ones that they are originally supplied in and assembled on the seat.

Defining requirements and tolerances that relate to the H-point location, necessarily must include a way to account for the deformed components, as they will be in such a state when the H-point is measured. However, the design of the components currently only compensates for this partially, the pre-study showed that an estimation of 40% compression for the foam padding is used during the initial design of the seat. This approximation is standard for all the foam versions and does not make an explicit distinction about the influence of the trim cover, heating mat or the deflection of the spring assembly on the frame.

Each of the factors that account for the overall deflection of the seat cushion could be analyzed individually to find the influencing properties and calculate their contribution to the final placement of the occupant on the seat. In this way a comparative tool to assess the behavior of each part and improve the quality control of the manufactured seats would be provided. As explained earlier, in this initial study we concentrate on the deflection of the spring assembly and the compression of the foam. In order to

calculate and predict the behavior of these elements, relevant material properties of both components have to be defined and measured. These properties were analyzed for each as presented below.

Deflection of spring assembly

The spring assembly in the rear part of the seat frame is meant to distribute the load of the occupant to the frame, its purpose is to absorb shock and vibration; and support the occupant with maximum comfort and safety. In the case of the Volvo seat under study, this assembly is made of formed springs, where each element provides a load-supporting span by being formed (two-dimensionally) into a ribbon-like flat pattern which is anchored at or near each end. The material is typically steel, manufactured by the open hearth or electric furnace process and cold drawn to develop the desired mechanical properties (SAE International, 2014).

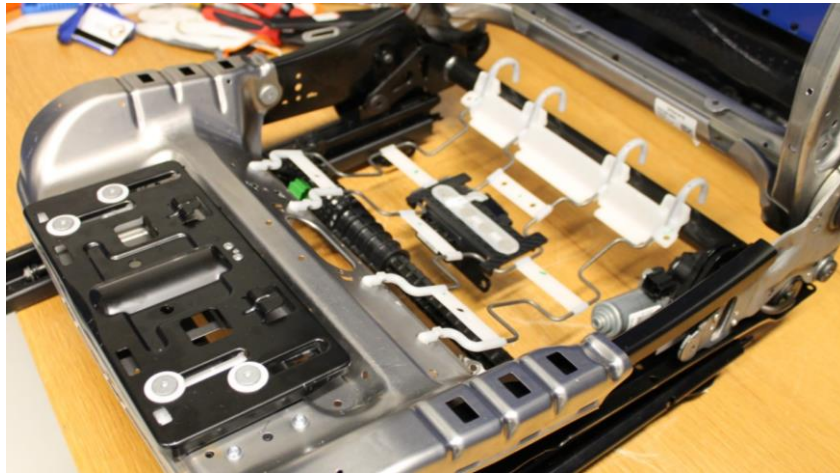


Figure 35. Zig-zag formed springs on the Volvo seat frame.

Spring action results from the twist of the torsion bars and the flexing of the radii joining them. Additional springing results from crowning the ribbon element, high near the middle. However, the most pronounced spring action is created when bends are placed in the surface near the front (and sometimes rear) (SAE International, 2014).

Spring deformation has not been measured in the current seat as an isolated element, to investigate the extent to which this contributes to the final H-point location. Being able to determine the final position/shape in which the spring will be found with the driver's weight on the seat, would allow for a better approximation of how much the foam and trim need to compress in order to reach the desired location of the occupant.

It is possible to calculate the deformation of the spring mat by using FEM software (Shimoseki, et al., 2003) given that the properties of the spring is known. If the results of such a simulation were later corroborated with physical tests, this model could be used for future developments in determining the final H-point location before the production starts.

In order to test the accuracy of the simulation, a load deflection test can be performed on single elements of the spring assembly, an individual element may be evaluated by placing it in a rigid fixture that duplicates its attachment to

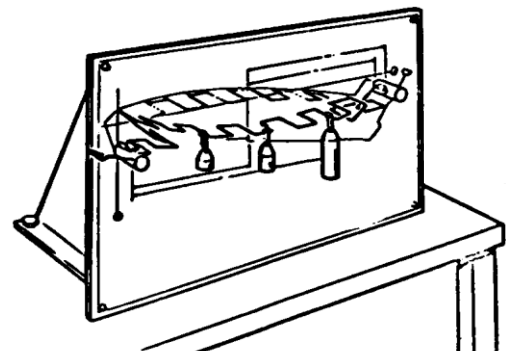


Figure 36. Individual element load deflection test.

the seat frame. Each element bar is loaded with a dead weight whereby the loaded position of the element is measured against a grid background. (SAE International, 2014)

This simulation and test procedure could allow to specify additional requirements for the spring assembly such as the total deflection under load that it is required to have in order to locate the occupant in the desired position. It could also give means to evaluate the effects of a change in the properties of this component which would aid in the design process. The requirements proposed for the spring assembly are summarized in Table 8.

Table 8. Properties that influence the deflection of the spring and how requirements on them could be verified.

PROPERTIES	VERIFICATION METHOD
Spring deformation (single spring)	Load deflection test
Spring assembly deflection	FEM simulation

Foam compression

The polyurethane foam is in itself a fairly complex material with nonlinear material properties and sensitive to manufacturing variations (as explained in section 2.1). In addition, the variety of configurations for the company's seats requires that a set of different cushion foams are designed and integrated in the final product. These different versions of the foam will have very different behaviors between them, given that the foam has a complex set of parameters such as density, resilience and hardness determined by the chemical mixture. Moreover, each seat cushion can consist of areas with different hardness, these mixtures can float into each other in unpredictable ways.

All these properties are currently selected using rules of thumb from manufacturers and they are evaluated with respect to their influence on passenger comfort by performing clinics with representative users, to rate their perception of the seat. Being able to translate this kind of subjective evaluation into an objective definition of comfort requirements, based on cushion foam properties, would allow to evaluate the seat earlier in the design process and contribute to a better prediction and assurance of the H-point location.

It is worth mentioning that one of the most difficult aspects to consider about the behavior of the foam during compression is that, while the occupant is settling to the final position, the area that will be in contact with his/her body will be continually changing, tending to surround the body more. This effect will vary depending on the material properties as well as depending on the shape of the particular foam. Accurately predicting the effect that this will have on the H-point location is not achievable without an advanced FEM model given the number of variables that come into play.

Analyzing the effects of changes to the foam, including shape and other properties, would benefit the design process by increasing the accuracy of the foam modeling, which allows to have the different versions of the seat, including the standard version, sport version and ventilated version, without obtaining different H-point locations. In conclusion, the main recommendation regarding the foam deflection is to implement FEM simulations. This would allow for more objective comfort evaluations as well as a way to assure the H-point between different foam variants. In order to do this the material properties and interfaces with the manikin and other components need to be known. In Table 9 the required properties and verification methods are presented.

Table 9. Properties that influence the deflection of the foam and how requirements on them could be verified

PROPERTIES	VERIFICATION METHOD
IFD	IFD test
Compression when loaded with manikin	FEM simulation

6.4 REQUIREMENT FORMULATION AND VERIFICATION

In previous sections the components of the seat cushion affecting the occupant position have been identified, and it has been analyzed which of their properties determine the way in which they contribute to a change in said position. This allows for a requirement specification that handles the components inside the seat individually and enables a design that estimates the final position of the occupant based on calculation, replacing the estimation based on experience.

The characteristics of each component that needs to be considered, since they affect the occupant position, were explained in Table 7. A deeper examination of these properties and the overall behavior of the seat, led to some simplifications of the parameters for each part that need to be controlled with specific requirements, as was explained in the previous sections. Taking together the different aspects that were explained in two separate states, for measuring the components, it is possible to create a summarized set of requirements for the seat, which can lead to a more accurate control of the H-point location, if it is paired with the correct verification tests for each property.

Table 10 shows the compiled properties and requirements for the seat components that were discussed in previous chapters. These would need to be specified and controlled in order to have an accurate prediction of the H-point location from the early stages of the design process. The nominal measurements and thickness requirements are the result of the unloaded case analysis and the rest of the requirements are derived from the deflected case and need to be taken into consideration during the design as well.

Table 10. Requirements specification for H-point assurance

	REQUIREMENTS	VERIFICATION METHOD
TRIM	<i>Shape variation</i>	<i>Measure part</i>
	Thickness	<i>Measure part</i>
HEAT PAD	<i>Shape variation</i>	<i>Measure part</i>
	Thickness	<i>Measure part</i>
SEAT FRAME	<i>Shape variation</i>	<i>Measure part</i>
	Height	<i>Measure part</i>
SPRING ASSEMBLY	<i>Shape variation</i>	<i>Measure Part</i>
	Spring mat deflection	FEM simulation
	Spring deformation (single spring)	Load deflection test
FOAM	<i>Shape variation</i>	3D Scan and compare with CAD
	Thickness	<i>Measure part</i>
	Foam compression	FEM
	IFD	IFD Test
COMPLETE SEAT	H-point location	HPM II and simulation

As explained in the section dealing with the unloaded state, suitable measurement points and how much these can vary before it affects the H-point position need to be found for stating requirements on the shape variation. The values for the rest of the requirements also need to be decided on as well as the way some of them are measured. However, it does exemplify the intended end result of the proposed process and gives recommendations on some of the central requirements.

As previously mentioned, Table 10 states the requirements for the simplified case explained in this report, this can be elaborated further to include more aspects (see Table 7). When all of these properties are taken into consideration during the design of the seat components, they can also be controlled with assigned requirements and tolerances during the production phase, and verified for compliance through individual tests in the quality verification stage of the building process. In this way, the H-point position can be assured with individual actions which guarantee the correct function of each component that makes part of the subsystem, achieving a higher level of quality in the final seat.

6.5 SUMMARY

This chapter presents the final process improvement proposal to breakdown the general H-point requirement in the seat subsystem level, into an explicit definition of individual requirements for the components that interact to define the occupant position. The process acknowledges the fact that the flexible nature of the components inside the seat has to be taken into account and it was explained how it is necessary to understand the properties of each component. It is advised to determine, through computer simulation, their individual contribution to the final H-point position in order to predict and control the final result in an accurate way. The collaboration of the different departments into making sure that all these requirements are met is essential to a robust assurance of the H-point that reflects the designed Seating Reference Point (SgRP).

7 DISCUSSION

After the completion of the project, some aspects that deserve special consideration were analyzed by the team in order to determine their possible repercussions on the presented information. These considerations were not addressed during the project due to the limitations, which were mentioned in the beginning of the report. The present chapter elaborates on such aspects surrounding the thesis work.

7.1 ORGANIZATIONAL IMPLICATIONS OF THE GIVEN TASK

Because of all the different factors that come into play within the seat development, finding the main cause for a problem needs to start with a broad exploration phase; the information that was needed for understanding all the aspects of the seat development process was not readily available for analysis when the project started, and therefore, methods for finding out how the activities are done were implemented. As the project advanced and more information was available, the target of the study became more evident and the flow of the work became more focused.

It became apparent during the initial exploration phase, that the present problem had generated a good amount of awareness inside the company even from before this study. Interviews with the responsible engineers showed that previous efforts to address this problem had been made in different departments. However, it was also noticeable that these previous efforts had not been planned to collaborate between each other, in order to give a cross-functional solution to a cross-functional problem. Therefore, the project aimed at bringing together the work of all the people involved in order to address the problem in all its implications and achieve an integral solution.

Some of the causes for the problem occurrence, which were found in the exploration phase, are typical of large, established companies, such problems as communication issues, difficult relation with suppliers, fuzzy boundaries on task assignment, among others, are difficult to address with single actions but rather need a joined effort within the company to work in an integrated manner.

A distinguishing characteristic of the particular problem, is that it deals with a product that has been improved in many ways during the time that it has been available. The incremental changes, which are needed in order to make a better design of the seat, are typical in these kinds of products that have reached a design maturity. Such changes are frequently hard to implement due to the fact that the production of them is already undergoing, agreements with suppliers make strong bindings, as well as implemented procedures inside the companies which are difficult to change from the current way in which they are carried out. All these factors may hinder the actual implementation of the proposed improvements on the seat development process, it is however important to outline such required changes and present them to the organization in order to apply at least part of them in the actual daily work.

It should also be noted that the relationship with the supplier of the seats was not included in detail in this report in order to keep focus on the internal activities of Volvo. In spite of this, it was observed that this relationship should also be deeply analyzed for further improvement opportunity search, given that variation from the highly manual assembly process of the seat, or missed agreements on process responsibilities, like failing to follow the same measurement procedures to monitor product quality, may lead to increased cases of misalignment in the H-point location.

7.2 EFFECTIVITY OF THE METHODOLOGY USED IN THE PROJECT

The project's intention was to look at the H-point deviation starting from the wider overall company perspective, including as many aspects of the overall development as possible, to avoid omitting any key activity that could affect the problem, and then narrowing the scope to fit what was considered the main source for the occurrence of the deviation.

Since this approach involved considering different paths of action for a big part of the project, there was a risk of incurring in scope creep during the project (Russell, 2007). In order to keep the efforts under control and channel the work, it was decided to use a design methodology, which provided tools and frames of reference, allowing the team to analyze all the information that was gathered and the ideas that were proposed during the project. However, given the nature of the methods employed, which are designed for the development of a physical product (mostly new product development), several adaptations of the methods and tools were necessary in order to handle a problem exploration and solution project.

Developing the adapted features for using the selected methodology, gave an additional degree of understanding about the project, given that special evaluation criteria had to be determined for the particular solutions, which were different from the criteria that is normally used in the original context of the methods that were used. The adaptations to the selection matrices were made in a subjective manner, with no assignment of numerical values and the selection of words to describe the solution proposals, and the evaluation criteria, was very important in this case in order to make a clear evaluation.

Some specialized problem solving methodology is available in the literature, for example six sigma DMAIC and others (Okes, 2009) which could also be utilized to find the root cause of the H-point deviation and propose a solution, such methods may be applied for this project and in turn may generate results that are different from the ones presented here. However the tools that were used in the project, after being adapted to fit the problem, actually gave results that are found in line with the initial objectives and are therefore considered successful. Therefore, the use of specifically designed methods from problem exploration, is considered to be a possible different approach that could add to the exploration that was performed in this project.

7.3 IMPLEMENTATION AND FURTHER DEVELOPMENT OF THE RESULTS

The requirement strategy that has been described in this report, which includes specification and tolerances on single components of the seat cushion and accounts for the deformation of the flexible elements, can be used as a base to define similar requirements on the components that are included in the backrest as well, in order to control the dimensions on the x-axis and assure the occupants position in this direction.

Additional requirements would need to be added in order to address some of the components and factors that were excluded in this report, in order to assure the H-point location as good as possible. The factors that would need to be considered, are all described in Table 7, the deflection of the trim and heat pad as well as the addition of variant specific components, are examples of this. The exact position where the measurement should be defined, and the values that should be assigned, would be the result of the unloaded case analysis if the required manufacturing data was available (as was not the case during the project).

It was presented before, how a simulation of the seat components deflection under load is necessary for defining new requirements that account for how they will deform. At the moment of the realization of this

project, an ongoing effort to develop such a simulation was in place. The expected results of this effort will help to develop more robust requirements for seating, ergonomics and comfort. In order to perform these simulations, a series of tests are planned to take place in order to measure the properties of the material, which include a series of tests to gather data about how the foam compresses when it is by itself, including the heating pad and including the heating pad and the trim cover

The type of results presented here, reflects that the problem is very broad and involves many different activities and types of data, it also considers the possibility of application on multiple designs of the automotive seat, both present and future. This is the main reason why the level of detail of some of the summarizing tables do not contain a numerical specification but instead remain as general guidelines for the design process. In order to generate specific requirements, the solution process has to be implemented with specific data from each seat design.

The main contribution of this report, to other efforts in the field, is considered to be that it analyzed the relationship that exists between the different activities of a seat development process, which can lead to a misalignment between design specifications and the actual product, if they are not managed correctly. It presented an exploration of a number of possible paths to improve such process and showed the connection between the main ideas for improvement of the current situation. This resulted in an integration of activities using an ordered process to increase product quality through requirement management and the use of computer simulation to predict product performance.

8 CONCLUSIONS AND RECOMMENDATIONS

In this thesis, the effects and causes of the H-point deviating from its intended position (the SgRP) have been analyzed at VCC. A problem exploration consisting of a product teardown, literature research and interviews with company employees, was performed to gather data that later was used to rank the causes of deviations. Solutions were sought based on this ranking and finally resulted in a process suggested to be undertaken by Volvo in order to assure that the H-point coincides with the SgRP.

It was found that the H-point deviations affect a number of aspects of the car, the main ones being safety and ergonomics, which results in that the car has to be designed with higher safety margins in order to fulfill all legal requirements, given the uncertainty of the H-point position. The main causes of the problem's occurrence were found to be the lack of efficient prediction methods for the deflection of the seat under load, and difficulties related to the fact that requirements for the occupant position only exist for the complete seat and are not reflected directly in the requirements defined for individual components.

The process that is proposed, states the initial changes required in the development of seats at Volvo. It is based on substituting the use of rules of thumb, based on experience, with a more reliable procedure for taking the flexibility of the seat components into closer consideration during the prediction of the H-point location. The procedure includes simulation of seat deformation, and definition of requirements on individual seat components that take on account their influence over the H-point. The individual requirements allow for the H-point to be calculated more accurately and provide a way to account for variant differences or new seat models.

Given that the simulation of the seat deformation is a key part of the proposal. It is considered that certain steps could be implemented in isolation from the rest of the process to help in getting more information needed to perform the calculation. These steps are summarized in Figure 37, they are considered to be related to each other but somewhat independent, and therefore, each of them could be basis for a single project, the elaboration of them all would give the necessary tools to obtain a robust H-point position.

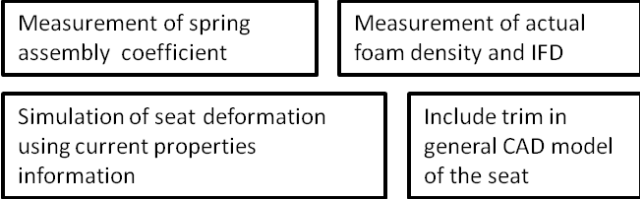


Figure 37 Semi-independent steps that could be implemented by Volvo

Two of those projects are related to the physical measurement of the component actual properties, both for the spring assembly that is mounted on the frame as well as for the foam cushion. The results from these measurements would give more certainty about the data that should be used for a FEM simulation of the seat. Regardless of the results from actual measurement of the components, it was found that some assumptions about the foam properties are made during the current design, if a similar assumption could be made for the spring coefficient, then an initial simulation could be carried out to test the software configuration and later tune the data with the results of actual testing. Lastly it could be useful to elaborate a digital model of the trim for use in the CAD of the complete seat and compensate the foam geometry according to it. The data from previous 3D scans of the production seats could be refined to obtain a model from it.

If the entire process cannot be implemented, addressing some of the process steps can still make an improvement. Hence, even if it is recommended in this report to include all components in the H-point prediction, starting with a few will also mean a positive change. In this case gathering the component data by conducting the experiments needed to obtain the required component data such as elastic properties of the spring assembly and the foam as well as dimensions to measure and material properties is most likely the most rewarding first step. It will result in more knowledge about the product which is needed if it is to be simulated but will also likely improve the result of the rules of thumb currently used. If this approach would be chosen Table 7 would provide considerable guidance to what aspects to consider.

Moreover, it is recommended to look into the possibility of applying six sigma or other quality tools to this problem since it is believed to be a suitable method for the type of problem, and could provide validation of the results presented in this report as well as detailing it further. It would also be useful to complete a study of the H-point measurement process, which could provide more improvement possibilities, given that this activity is also an important aspect of the H-point assurance.

REFERENCES

- A2MAC1, 2015. *A2MAC1 - Automotive Benchmarking*. [Online] Available at: <https://www.a2mac1.com/> [Accessed 3 February 2015].
- Bhise, V. D., 2011. *Ergonomics in the Automotive Design Process*. Boca Raton: CRC Press.
- Blair, G. R., Reynolds, J. I. & Weierstall, M. D., 2008. *Automotive Cushioning Through The Ages*, s.l.: The Molded Polyurethane Foam Industry Panel.
- Bokvist, P., 2015. *Ergonomics Related to H-point* [Interview] (28 January 2015).
- Bolz, R. W., 1977. *Production Processes: a Productivity Handbook*. s.l.:Industrial Press Inc.
- Chen, J., 2008. *The Using of Mind Map in Concept Design*. Wuhan, P.R. China, Computer-Aided Industrial Design and Conceptual Design, 2008. 9th International Conference on.
- Eriksson, B., 2015. *H-point Measurement Procedure* [Interview] (5 February 2015).
- Fung, W. & Hardcastle, M., 2001. *Textiles in Automotive Engineering*. 1 ed. Cambridge: Woodhead Publishing Limited.
- Guerin, L., Brianso, C., Rochat, E. & Pajon, M., 2003. *Seat/Occupant Interaction Modelling for Comfort Analysis and Integration of a Smart Safety System (Occupant Sensing)*. s.l., ABAQUS Users' Conference.
- Hannabuss, S., 1996. Research Interviews. *New Library World*, 97(5), pp. 22-30.
- Harmon, P. & Tom, D., 2007. *Business Process Change: A Guide for Business Managers and BPM and Six Sigma Professionals*. s.l.:Morgan Kaufman.
- Harrell, M. C. & Bradley, M. A., 2009. *Data collection methods Semi-structured interviews and focus groups*. First ed. Pittsburgh PA: Rand Corporation.
- Krusper, A., 2015. *Simulation of PUR at VCC* [Interview] (17 February 2015).
- Mazur, M., 2013. *Tolerance Analysis and Synthesis of Assemblies Subject to Loading with Process Integration and Design Optimization Tools*, Melbourne: RMIT University.
- McQuarrie, E. F., 2012. *The market research toolbox: a concise guide for beginners*. Third ed. Thousand Oaks California: Sage.
- Nejabat, B., 2015. *Safety Related to H-point* [Interview] (5 February 2015).
- Okes, D., 2009. *Root Cause Analysis: The Core of Problem Solving and Corrective Action*. Milwaukee: American Society for Quality, Quality Press.
- Paul, G., Pendlebury, J. & Miller, J., 2009. *The Contribution of Seat Components to Seat Hardness and the Interface Between Human Occupant and a Driver Seat*. s.l.:Inderscience Enterprises.
- Polyurethane Foam Association, 1991. The Importance of Density. *In Touch: Information on flexible Polyurethane Foam*.
- Robert W. Messler, J. P. F. F., 2014. *Reverse Engineering: Mechanisms, Structures, Systems & Materials*. New York: McGraw-Hill Education.

- Russell, L., 2007. *10 Steps to Successful Project Management*. s.l.:Association for Talent Development.
- SAE International, 1995. *SAE J826 JUL. 1995 Devices for Use in Defining and Measuring Vehicle Seating Accomodation*. s.l.:SAE International.
- SAE International, 2009. *SAE J1100 JUN. 1984 Recommended Practice for Motor Vehicle Dimensions*. s.l.:SAE International.
- SAE International, 2010. *SAE J4002 JAN. 2010 H-Point Machine (HPM-II) Specifications and Procedure for H-Point determination - Auditing Vehicle Seats*. s.l.:SAE International.
- SAE International, 2012. *SAE J2896 JAN. 2012 Surface Vehicle Recommended Practice*. s.l.:SAE International.
- SAE International, 2014. *Motor Vehicle Seating Manual*, s.l.: SAE International.
- SAE International, 2015. *About SAE International*. [Online]
Available at: <http://www.sae.org/about/> [Accessed 22 April 2015].
- Schneider, L. W. et al., 1999. *ASPECT: The Next-Generation H-point Machine and Related Vehicle and Seat Design and Measurement Tools*. Detroit, Michigan, International Congress and Exposition.
- Shimoseki, M., Kuwabara, T., Hamano, T. & Imaizumi, T., 2003. *FEM for Springs*, s.l.: Springer Science and Business Media.
- Ulrich, K. T. & Eppinger, S. D., 2012. *Product Design and Development*. Fifth ed. New York: McGraw-Hill.
- VCC, 2015. *This is Volvo Cars*. [Online]
Available at: <http://www.volvocars.com/intl/about/our-company/this-is-volvo-cars>
[Accessed 22 April 2015].
- Weber, J., 2009. *Automotive Development Processes*. Berlin: Springer-Verlag.
- Wickman, C., 2015. *Ergonomics and Tolerances* [Interview] (10 February 2015).

APPENDIX

A. GENERIC INTERVIEW MANUSCRIPT	A-1
B. DATA SHEET FROM SEAT TEAR DOWN	A-2
C. PROCESS FOR SEATING POSITION H-POINT DEFINITION	A-3
D. MEASUREMENT DATA XC90	A-4

A. GENERIC INTERVIEW MANUSCRIPT

1. From where do your function's requirements come regarding the H-point?
2. How are your requirements communicated to other departments?
3. How are the requirements verified? How do you measure?
4. What software(s) do you use?
5. Which are the main problems in fulfilling your requirements?
6. How would you predict future requirements for the H-point?

B. DATA SHEET FROM SEAT TEAR DOWN

SUB-ASSY	COMPONENT TYPE	COMPONENT NAME	#	MATERIAL	NOTES
LEFT	Screw	Round	2	Metal, black	
	Screw	Round, short	1	Metal, silver	
		Belt buckle with harness	1	Metal & plastic	
		Cable holder	1	Plastic	Holds cable
	Screw	Long	2	Metal, black	Holds plastic side
	Bolt	Long	1	Metal, black	Holds plastic side
	Frame	Plastic side	1	Plastic	Supports foam
	Cover	Plastic side back	1+1	Plastic	
RIGHT	Nut	Washer/nut small	2	Metal, silver	Holds airbag
	Nut	Washer/nut big	2	Metal, silver	
	Screw	Long	1	Metal, silver	
	Cover	Control cover	1	Plastic	
	Screw	Short	3	Metal, black	2 Holds Control cover, 1 Back side cover
	Cover	Back side cover	1	Plastic	
	Frame	Metal bar frame	1	Metal, black	Allows for control cover to be snapped in place
	Screw	Round, v2	1	Metal black	Holds metal frame bar
	Screw	Extra inclined, round	1	Metal, black	Holds metal frame bar
	Screw	Round, short	1	Metal, silver	Holds metal frame bar
	Airbag	1			
BACK-REST	Screw	Long	6	Metal, black	
	Screw	Screw/washer/nut	4	Metal, black	2 holds headrest, 2 top plastic
	Cover	Back cover	1	Plastic	
	Frame	Top plastic frame	1	plastic	
		Spring pan	1		Lumbar support....
	Foam	Back foam pad	1	PUR, metal	"holes" on right side
	Trim	Upholstery, hooks	1+22	Leather	
BOTTOM	Screw	With plug	4	Plastic, black	Holds side back cover
		Plugs	4	Plastic	Holds side back cover
	Screw	Short	2	Metal, black	Holds side back cover
		Electric harness			
		Plastic holder	1	Plastic	Holds electric harness & connections
	Foam	Cushion	1	PUR	Two parts
	Trim	Seat trim	1	Leather	

C. PROCESS FOR SEATING POSITION H-POINT DEFINITION

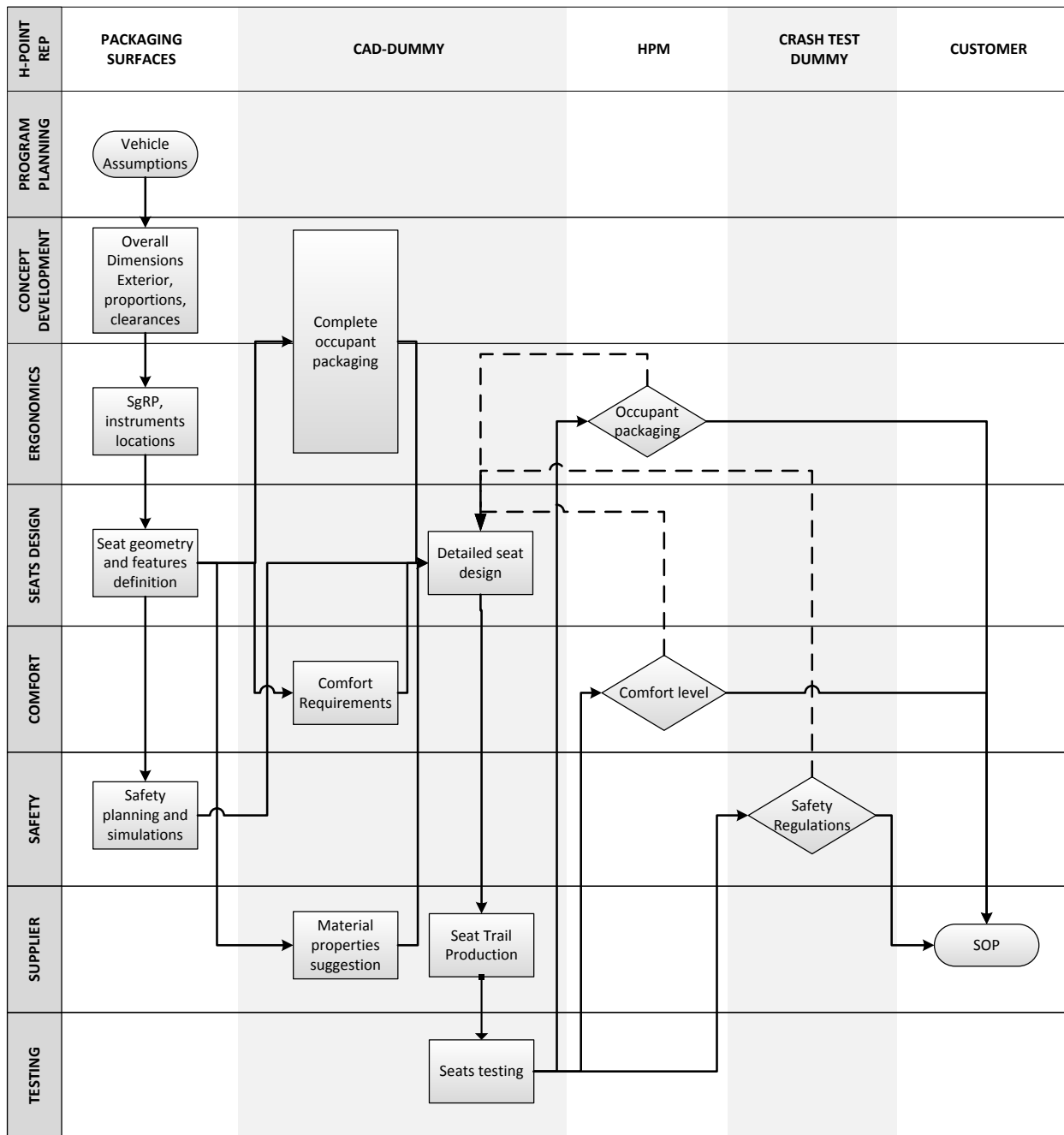


Figure A1. Flow chart of seat development process at Volvo Cars.

D. MEASUREMENT DATA XC90

Heat				Textile				OWS				Ext					
H-Point LH & RH		TA		H-Point LH & RH		TA		H-Point RH		Z		H-Point LH & RH		Z		TA	
SRP	3151,5	800	25	SRP	3151,5	800	25	SRP	3151,5	800	25	SRP	3151,5	800	25		
Average	-10,0	6,3	0,1	Average	-9,1	5,9	0,4	Average	-10,6	6,1	0,3	Average	-9,8	6,4	0,0		
std dev	2,7	4,6	0,5	std dev	1,7	3,8	0,3	std dev	3,4	6,7	0,7	std dev	2,6	5,8	0,7		
Cpk	1,5	1,1	2,0	Cpk	2,5	1,4	2,5	Cpk	1,1	0,8	1,4	Cpk	1,6	0,9	1,4		
3 Sigma	8,0	13,8	1,4	3 Sigma	5,1	11,3	1,0	3 Sigma	10,1	20,2	2,0	3 Sigma	7,8	17,4	2,1		
6 Sigma	15,9	27,6	2,8	6 Sigma	10,1	22,7	2,1	6 Sigma	20,2	40,3	4,0	6 Sigma	15,7	34,8	4,3		
No heat				Leather and Vinylye				No OWS				No Ext					
H-Point LH & RH		TA		H-Point LH & RH		TA		H-Point RH		Z		H-Point LH & RH		Z		TA	
SRP	3151,5	800	25	SRP	3151,5	800	25	SRP	3151,5	800	25	SRP	3151,5	800	25		
Average	-10,2	3,7	0,0	Average	-10,3	5,5	0,1	Average	-9,6	7,4	0,2	Average	-10,5	4,4	0,2		
std dev	2,6	6,8	0,9	std dev	2,8	5,6	0,7	std dev	1,8	5,0	0,4	std dev	2,6	4,8	0,5		
Cpk	1,5	0,9	1,1	Cpk	1,4	1,0	1,5	Cpk	2,4	1,0	2,2	Cpk	1,5	1,2	1,8		
3 Sigma	7,8	20,4	2,7	3 Sigma	8,3	16,8	2,0	3 Sigma	5,3	15,1	1,3	3 Sigma	7,8	14,5	1,6		
6 Sigma	15,6	40,9	5,5	6 Sigma	16,6	33,6	3,9	6 Sigma	10,5	30,2	2,6	6 Sigma	15,6	29,1	3,1		
Difference between variants				Difference between variants				Difference between variants				Difference between variants					
ΔAverage	0,2	2,6	0,2	ΔAverage	1,2	0,4	0,4	ΔAverage	-1,0	-1,3	0,2	ΔAverage	0,8	2,0	-0,2		
ΔStd dev	0,0	-2,2	-0,4	ΔStd dev	-1,1	-1,8	-0,3	ΔStd dev	1,6	1,7	0,2	ΔStd dev	0,0	0,9	0,2		
Requirements "development"				Requirements "development"				Requirements "development"				Requirements "development"					
Average	±4,5	-	-	Average	±4,5	±4,5	-	Average	±4,5	±4,5	-	Average	±4,5	±4,5	-		
Variation	22	22	3	Variation	22	22	3	Variation	22	22	3	Variation	22	22	3		
Cpk	1,67	1,67	-	Cpk	1,67	1,67	-	Cpk	1,67	1,67	-	Cpk	1,67	1,67	-		
Within spec "development"				Within spec "development"				Within spec "development"				Within spec "development"					
Average	-10,1	5,0	-	Average	-9,7	5,7	-	Average	-10,1	6,7	-	Average	-10,1	5,4	-		
Ave+3sig	18,0	22,1	2,1	Ave+3sig	16,4	19,8	1,7	Ave+3sig	17,8	24,4	1,9	Ave+3sig	18,0	21,3	2,0		
Cpk	1,5	1,0	-	Cpk	2,0	1,2	-	Cpk	1,7	0,9	-	Cpk	1,5	1,1	-		
Requirements "serial production"				Requirements "serial production"				Requirements "serial production"				Requirements "serial production"					
Average	±10	±10	-	Average	±10	±10	-	Average	±10	±10	-	Average	±10	±10	-		
Variation	±22	±22	3	Variation	±22	±22	3	Variation	±22	±22	3	Variation	±22	±22	3		
Cpk	1,33	1,33	-	Cpk	1,33	1,33	-	Cpk	1,33	1,33	-	Cpk	1,33	1,33	-		
Within spec "serial production"				Within spec "serial production"				Within spec "serial production"				Within spec "serial production"					
Average	-10,1	5,0	-	Average	-9,7	5,7	-	Average	-10,1	6,7	-	Average	-10,1	5,4	-		
Ave+3sig	18,0	22,1	2,1	Ave+3sig	16,4	19,8	1,7	Ave+3sig	17,8	24,4	1,9	Ave+3sig	18,0	21,3	2,0		
Cpk	1,5	1,0	-	Cpk	2,0	1,2	-	Cpk	1,7	0,9	-	Cpk	1,5	1,1	-		

Mechanical				Tilt				Vent			
H-Point LH & RH		TA		H-Point LH & RH		TA		H-Point LH & RH		TA	
X	Z			X	Z	X	Z	X	Z	X	Z
SRP	3151,5	800	25	SRP	3151,5	800	25	SRP	3151,5	800	25
Average	-10,9	5,5	0,4	Average	-10,6	5,6	0,0	Average	-8,3	8,3	0,3
std dev	3,1	3,9	0,4	std dev	2,6	5,8	0,7	std dev	1,7	6,3	0,5
Cpk	1,2	1,4	2,2	Cpk	1,5	0,9	1,5	Cpk	2,7	0,7	1,8
3 Sigma	9,2	11,8	1,2	3 Sigma	7,9	17,3	2,0	3 Sigma	5,0	19,0	1,5
6 Sigma	18,3	23,7	2,3	6 Sigma	15,7	34,7	4,0	6 Sigma	10,1	38,0	3,1
Power				Manual tilt				No vent			
H-Point LH & RH		TA		H-Point LH & RH		TA		H-Point LH & RH		TA	
X	Z			X	Z	X	Z	X	Z	X	Z
SRP	3151,5	800	25	SRP	3151,5	800	25	SRP	3151,5	800	25
Average	-10,6	5,6	0,0	Average	-11,2	5,7	0,4	Average	-10,8	4,5	0,1
std dev	2,7	6,0	0,7	std dev	3,4	4,3	0,4	std dev	2,6	4,6	0,7
Cpk	1,4	0,9	1,4	Cpk	1,1	1,3	2,2	Cpk	1,4	1,3	1,5
3 Sigma	8,2	18,0	2,1	3 Sigma	10,1	12,8	1,2	3 Sigma	7,9	13,9	2,0
6 Sigma	16,3	36,1	4,1	6 Sigma	20,2	25,6	2,4	6 Sigma	15,8	27,7	4,0
Difference between variants				Difference between variants				Difference between variants			
ΔAverage	-0,3	-0,1	0,4	ΔAverage	0,6	-0,1	-0,4	ΔAverage	2,5	3,8	0,2
ΔStd dev	0,3	-2,1	-0,3	ΔStd dev	-0,7	1,5	0,3	ΔStd dev	-1,0	1,7	-0,2
Requirements "development"				Requirements "development"				Requirements "development"			
Average	±4,5	±4,5	-	Average	±4,5	±4,5	-	Average	±4,5	±4,5	-
Variation	22	22	3	Variation	22	22	3	Variation	22	22	3
Cpk	1,67	1,67	-	Cpk	1,67	1,67	-	Cpk	1,67	1,67	-
Within spec "development"				Within spec "development"				Within spec "development"			
Average	-10,7	5,5	-	Average	-10,9	5,7	-	Average	-9,6	6,4	-
Ave+3sig	19,4	20,5	1,8	Ave+3sig	19,8	20,8	1,8	Ave+3sig	16,0	22,9	1,9
Cpk	1,3	1,2	-	Cpk	1,3	1,1	-	Cpk	2,1	1,0	-
Requirements "serial production"				Requirements "serial production"				Requirements "serial production"			
Average	±10	±10	-	Average	±10	±10	-	Average	±10	±10	-
Variation	±22	±22	3	Variation	±22	±22	3	Variation	±22	±22	3
Cpk	1,33	1,33	-	Cpk	1,33	1,33	-	Cpk	1,33	1,33	-
Within spec "serial production"				Within spec "serial production"				Within spec "serial production"			
Average	-10,7	5,5	-	Average	-10,9	5,7	-	Average	-9,6	6,4	-
Ave+3sig	19,4	20,5	1,8	Ave+3sig	19,8	20,8	1,8	Ave+3sig	16,0	22,9	1,9
Cpk	1,3	1,2	-	Cpk	1,3	1,1	-	Cpk	2,1	1,0	-