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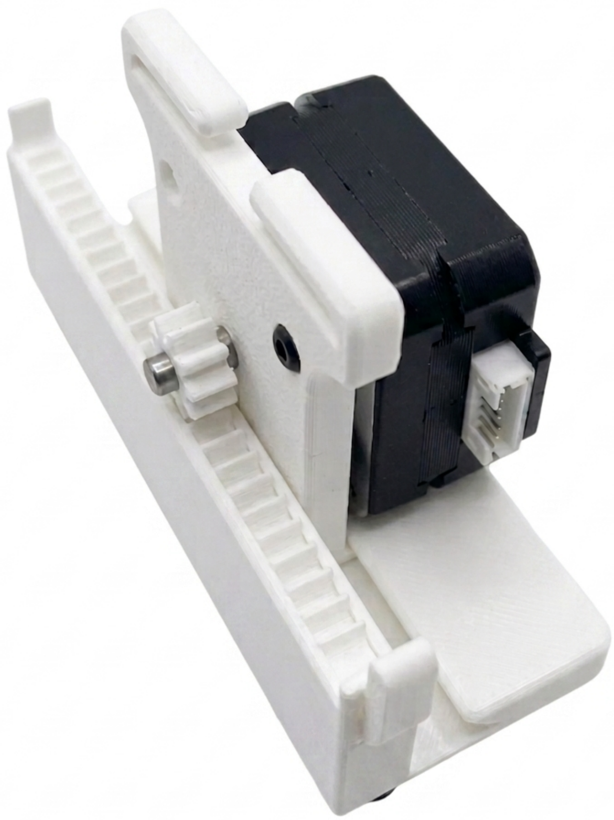

# Developing a motorized seatbelt positioning mechanism

## Designing to accommodate all passenger sizes through concept development for shoulder interaction in rear seats of cars

Master's thesis in Product Development


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CHALMERS UNIVERSITY OF TECHNOLOGY


Gothenburg, Sweden 2026
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Master's Thesis 2026
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Cover: Proof-of-concept prototype for the seatbelt positioning system, constructed with 3D-printed components to evaluate the rack and pinion mechanism.

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# Abstract

Seatbelt positioning is critical for occupant safety. However, a fixed position is not optimal for all occupants and is instead a compromise. When a seatbelt is positioned too close to the neck, it causes discomfort, which frequently leads to dangerous misuse, such as placing the seatbelt under the arm. While front seats are typically equipped with manual adjustment mechanisms, these are unsuitable for the rear seats, especially for children, as manual functions are often ignored or improperly used in these positions. The project was conducted at Volvo Cars and followed a structured product development process aimed at continuously increasing knowledge and concept maturity while strategically narrowing the design space to maintain design freedom in early stages. To define the problem space, a stakeholder analysis was conducted to map stakeholder needs for the mechanism. The system's functions were analyzed to generate possible sub-solutions to be synthesized into concepts using a morphological matrix. These concepts were subsequently systematically screened based on critical requirements utilizing an elimination matrix. Furthermore, the concepts were comparatively evaluated based on a set of criteria using the Pugh matrix. The Kesselring matrix further complemented the evaluation process with weighted criteria and more defined scoring to identify the most suitable solution for the application. Throughout the development process, several activities were utilized, including brainstorming sessions, modeling in CAD, rapid prototyping, and physical testing. While the final concept, "Rack and Roll", featuring a rack and pinion mechanism driven by a stepper motor, is proven to be functionally capable, it remains a proof-of-concept rather than an optimized production unit. The results indicate that an automated seatbelt positioning system is highly feasible and scalable for high-volume production. However, further development, design modifications, and rigorous testing are required before final integration into passenger vehicles.

Keywords: webbing, seatbelt, mechanism, mechatronic, adaptive, lateral, positioning, concept, rapid prototyping, deflect, motor, back row, C-pillar.

# Preface

This report constitutes our Master's thesis within the Master's Programme in Product Development at Chalmers University of Technology. The project encompasses 30 higher education credits and was conducted during the spring semester of 2026 in collaboration with Volvo Cars in Gothenburg.

The thesis details the complete product development process of an automated seatbelt positioning mechanism, documenting the progression from initial stakeholder analysis and concept generation to the physical testing of a proof-of-concept prototype.

The report is written for readers with a general technical or engineering background. While the text assumes a basic understanding of mechanical engineering principles and standard product development methodologies, the systematic approach is documented clearly to remain accessible to a broader technical audience.

# Acknowledgements

We would like to thank our examiner and supervisor at Chalmers, Kristina Wärmefjord, for her guidance throughout the project.

At Volvo Cars, we would like to thank our supervisor Peter Adolfsson for sharing his technical expertise regarding seatbelt systems, and our manager Martin Kinnander for providing the opportunity and resources to conduct this thesis. We also want to thank Tomas Nilsson for his direct input and for sharing his practical experience from similar previous work.

Furthermore, we would like to acknowledge Britta Mattsson, Christian Barnö, Anders Johansson, Fatma Zengin, William Norrblom, and Siddhant Gupta for their technical input and helpful discussions during our time at the department.

Love Smedberg, Gustaf Ström, Gothenburg, June 2026

# List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

| | |
|---|---|
| AI | Artificial Intelligence |
| BEMF | Back Electromotive Force |
| BOM | Bill Of Materials |
| CAD | Computer Aided Design |
| DC | Direct Current |
| DFA | Design For Assembly |
| DFMA | Design For Manufacturing and Assembly |
| DoF | Degrees Of Freedom |
| EMF | Electromotive Force |
| Euro NCAP | European New Car Assessment Program |
| FEM | Finite Element Method |
| FFF | Fused Filament Fabrication |
| FMVSS | Federal Motor Vehicle Safety Standards |
| FMEA | Failure Mode and Effects Analysis |
| IPC | International Patent Classification |
| NHTSA | National Highway Traffic Safety Administration |
| NVH | Noise, Vibration and Harshness |
| OEM | Original Equipment Manufacturer |
| OMS | Occupant Monitoring Systems |
| PA66 | Polyamide |
| PET | Polyethylene Terephthalate |
| PETG | Polyethylene Terephthalate Glycol |
| PLA | Polylactic Acid |
| POM | Polyoxymethylene |
| RPM | Revolutions Per Minute |
| RPN | Risk Priority Number |
| STL | STereoLithography |
| TR | Transmission Ratio |
| PTFE | Polytetrafluoroethylene |
| UNECE | United Nations Economic Commission for Europe |

# Nomenclature

Below is the nomenclature of parameters and variables that have been used throughout this thesis.

## Parameters

| | |
|---|---|
| $v$ | Target speed |
| $F$ | Target force |
| $T$ | Required torque |
| $\eta_{eff}$ | Mechanical efficiency |
| $K$ | Dimensionless wear coefficient |
| $W$ | Applied normal load |
| $L$ | Sliding distance |
| $H$ | Hardness |
| $C_{hour}$ | Hourly rate |
| $T_{hour}$ | Seconds per hour |
| $T_{cycle}$ | Assembly time |

## Variables

| | |
|---|---|
| $T$ | Required torque |
| $C_{assembly}$ | Assembly cost |
| $Q$ | Wear volume |

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# 1
# Introduction

Seatbelts are essential for crash protection, but achieving optimal seatbelt positioning has always been difficult. In the worst cases, the seatbelt is either uncomfortably close to the neck or unsafely close to the outer edge of the shoulder. A primary factor to its position is the exit from the car trim which greatly affects where the seatbelt interacts with the occupant's shoulder or neck. This project seeks to develop an automatic solution where internal sensors determine the occupant's size, translate the data to an optimal position, and then physically move the seatbelt to that position.

## 1.1 Background

In the event of a car crash, seatbelts are vital for protecting occupants. According to a thematic road safety report by the European Commission, the use of a seatbelt reduces the risk of fatal injury by 60% for front seat occupants and 44% for rear seat occupants, Schoeters et al. (2022). However, without a proper fit, the performance of the seatbelt drastically decreases, putting occupants in danger. A primary cause of inaccurate fit in the back row is the fixed exit outlet of the seatbelt by the C-pillar. For taller occupants, the seatbelt's fabric (webbing) tends to lie too close to the outer edge of the shoulder. Conversely, for shorter occupants, the webbing often lies uncomfortably close to the neck. This discomfort frequently leads to dangerous intentional misuse, such as passengers placing the webbing under their arm or behind their back, Schoeters et al. (2022). Such misrouting significantly reduces the safety effectiveness of the restraint system, bypassing the skeletal structures and increasing the risk of severe or fatal injuries, Schoeters et al. (2022). To counteract these issues, Osvalder et al. (2019) highlights that the optimal fit for daily use is achieved when the belt passes directly across the mid-portion of the shoulder, guaranteeing a balance between safety and passenger comfort. However, from a strict crash dynamics perspective, it is advantageous for the belt to be positioned closer to the neck rather than the outer edge. If the webbing is routed too far outboard, there is a significant risk of the torso rolling out of the shoulder belt during an evasive maneuver or an oblique collision, Bohman et al. (2011). Research shows that having the initial position closer to the neck heavily reduces the likelihood of the belt slipping off the shoulder during such events, Bohman et al. (2011).

In today's vehicles, including Volvo Cars', this problem is partially addressed in the front seats by a manual slide mechanism that adjusts the exit height of the seatbelt at the B-pillar. However, studies show that users often fail to use this function to correct a non-optimal belt fit. This disregard largely stems from limited safety awareness regarding what constitutes an optimal fit, as well as a general reluctance among passengers to explore the vehicle's manual adjustment functions, Osvalder et al. (2019). Implementing a similar manual solution in the rear seats would likely be even less effective, as children and temporary passengers have little inclination to adjust it. The problem is further amplified when different passengers share a seat; a misadjusted manual slider left by a previous taller occupant can lead to worse safety outcomes for a shorter passenger than a fixed point. To eliminate this reliance on manual intervention, near-future interior sensing and Occupant Monitoring Systems (OMS) introduce a new design space. By automatically scanning the occupant's size, the vehicle could dynamically adjust the seatbelt to an optimal position. For a manufacturer with a strong heritage in safety innovation, such an automated mechanism represents a natural evolution, effectively removing human error from the seatbelt adjustment equation.

Finally, this technological shift is strongly supported by upcoming regulatory and consumer safety testing frameworks. The Euro NCAP 2026 testing protocols introduce strict new requirements for occupant monitoring and adaptive restraints, Euro NCAP (2023). Vehicles will be evaluated and rewarded based on their ability to detect occupant size and out-of-position passengers, and to adapt the restraint strategies, such as airbag deployment and seatbelt geometry accordingly. An automated C-pillar positioning mechanism directly addresses these new rigorous safety standards, ensuring optimal protection for every individual passenger.

## 1.2 Purpose

The purpose of the project is to develop a concept for a mechanism that automatically moves the webbing along the shoulder to an optimal position based on the occupant's size.

## 1.3 Limitations

Considering the structure of the project, some limitations for the design space need to be introduced. Two vital limitations regard where and how the mechanism should be implemented. The space is limited to the back row's seats of a car. The mechanism should also be dependent on occupant sensing, meaning that the mechanism automatically should be calibrated and adapted between different occupants with various body sizes and shapes.

This project only covers the mechanism for the seatbelt itself. Therefore, the sensor part of the solution will not be treated in this project. Although in-cabin sensing of occupant dimensions is still an emerging technology, this project assumes it can provide the accurate anthropometric data (for example height, weight, and body shape) required for the mechanism to operate correctly. Moreover, the project will solely treat the mechanism for the belt. No modifications will be applied for the seatbelt assembly, which is considered as a fixed separate system.

Another restriction is the span of time available, and the project will span the spring semester of 2026. Therefore, the complexity and level of detail covered will be adapted to fit into the time span.

## 1.4 Ethical considerations

When designing new mechanical solutions, the first ethical consideration should always be justification: is the addition of this component truly necessary? The materials required for a motorized solution introduce significant sustainability concerns. This is particularly critical when an actuator is considered for implementation. According to Binnemans et al. (2013), standard end-of-life vehicle processing typically involves massive shredding, which mixes electronic and magnetic components into general ferrous scrap. Consequently, rare earth metals from electric motors end up lost in the dust or slag of metallurgical processes, making their recovery economically and technically highly challenging.

Furthermore, utilizing automation to enhance physical safety introduces a classical ethical dilemma between technological paternalism and user autonomy. A significant risk arises if the system's mathematically "optimal" seatbelt routing conflicts with the occupant's subjective comfort or physical restrictions. Because occupants deviate from standard norms in biological shape, volume, and posture, a forced position might cause severe discomfort. In the worst-case scenario, this could provoke a behavioral rebound effect where the occupant consciously bypasses the system entirely, for instance, by placing the shoulder belt under their arm or behind their back, thereby completely negating the intended safety benefits.

An additional ethical dimension related to automated safety features is the risk of over-reliance and behavioral adaptation, often associated with risk compensation. By automating the lateral positioning of the seatbelt, the system transfers the primary responsibility of ensuring a correct fit from the occupant to the vehicle. While intended to continuously optimize safety, this automation may unintentionally create a false sense of security. If the system miscalculates the optimal position, for instance, due to detection issues from thick winter clothing or an unconventional seating posture, the occupant might fail to notice or manually correct the error, trusting the system blindly. This shift in attention raises the ethical question of how to design automated safety interfaces that assist and protect users without completely degrading their own fundamental safety awareness.

Finally, as the system relies on recognizing and adapting to varying occupant lengths, weights, and shapes, it inherently processes sensitive anthropometric data. This raises significant questions regarding data privacy. Even if the system is designed to operate locally and only collect data strictly necessary for occupant safety, the handling of physical proportions requires strict adherence to ethical data principles such as data minimization. Ensuring that this information cannot be misused, stored unnecessarily, or linked to the occupant's identity is a fundamental requirement for the social acceptance of the mechanism.

## 1.5 Research Questions

Two research questions are formulated for this project. Their purpose is to guide the project toward the final objective, and will be answered throughout and at the end of this thesis work.

The selection of research questions is based on covering several key aspects regarding product development. The questions consider different perspectives such as the technical functionality, the design space provided, and the suitability of the design for mass production. The research questions (RQ) are as follows:

RQ1: Which mechatronic principles are most suitable for automating seatbelt positioning given the spatial constraints of this application?

RQ2: How can the selected conceptual architecture be engineered to balance diverse stakeholder needs while ensuring cost-efficiency and scalability for high-volume automotive production?

## 1.6 Declaration of AI Usage

During the preparation of this master's thesis, the authors utilized Gemini to assist in the product development process and report preparation.

The tool was employed within the following areas:

- Language Refinement: To review, structure, and improve the clarity of the English text throughout the report.
- Code Troubleshooting: To assist in debugging and optimizing software code utilized in the project.
- Visual Asset Generation: To assist in generating graphical assets and illustrations used within the report.

Following the use of this tool, the authors critically reviewed, verified, and edited all outputs. The final code, text, and figures were evaluated by the authors, who maintain full accountability for the content and conclusions of this work.

## 1.7 Thesis outline

This thesis is organized into seven chapters, providing a chronological overview of the project's progression from the initial problem definition to the final evaluation of the proposed solution. A brief description of each chapter follows:

- **Chapter 1: Introduction** – Introduces the background of seatbelt positioning issues, outlines the project's purpose and limitations, and presents the ethical considerations and research questions guiding the thesis.
- **Chapter 2: Frame of reference** – Establishes the theoretical foundation, common terminology, and system boundaries. It also explores the current technological landscape through a review of previous internal work and existing patents.
- **Chapter 3: Method** – Describes the systematic methodology applied for requirement definition, functional analysis, and the framework used for generating, screening and evaluating design concepts.
- **Chapter 4: Result** – Documents the outcomes of the development process, beginning with the definition of stakeholder needs and requirement specifications. It primarily focuses on generating, screening, and evaluating concepts. The chapter concludes with the results from prototype testing and the detailed design, including material selection for the final concept.
- **Chapter 5: Discussion** – Analyzes the project's findings and addresses the initial research questions, focusing on the chosen mechanical principles and their suitability for mass production. This chapter also incorporates various reflections on the project work and the development process as a whole.
- **Chapter 6: Conclusion** – Summarizes the main findings of the thesis and evaluates the overall success and feasibility of the developed proof of concept.
- **Chapter 7: Future recommendations** – Provides suggestions for further development, design modifications, and the rigorous testing required before the mechanism can be fully integrated into passenger vehicles.

# 2

# Frame of reference

This chapter establishes the foundation for the project by defining the system boundaries and the common terminology used throughout the report. Additionally, it explores the current technological landscape through a review of previous work and existing patents, providing the necessary context for the subsequent development phases.

## 2.1 Theoretical background

To start gauging the problem, a common coordinate system must be introduced. As illustrated in Figure 2.1, this spatial framework is defined relative to the vehicle's orientation. The $x$-axis denotes the longitudinal direction, pointing towards the back of the vehicle. The $y$-axis represents the lateral direction across the width of the cabin, while the $z$-axis indicates the vertical direction pointing upwards. Establishing this standardized reference frame is essential to accurately describe the physical architecture of the seatbelt system.

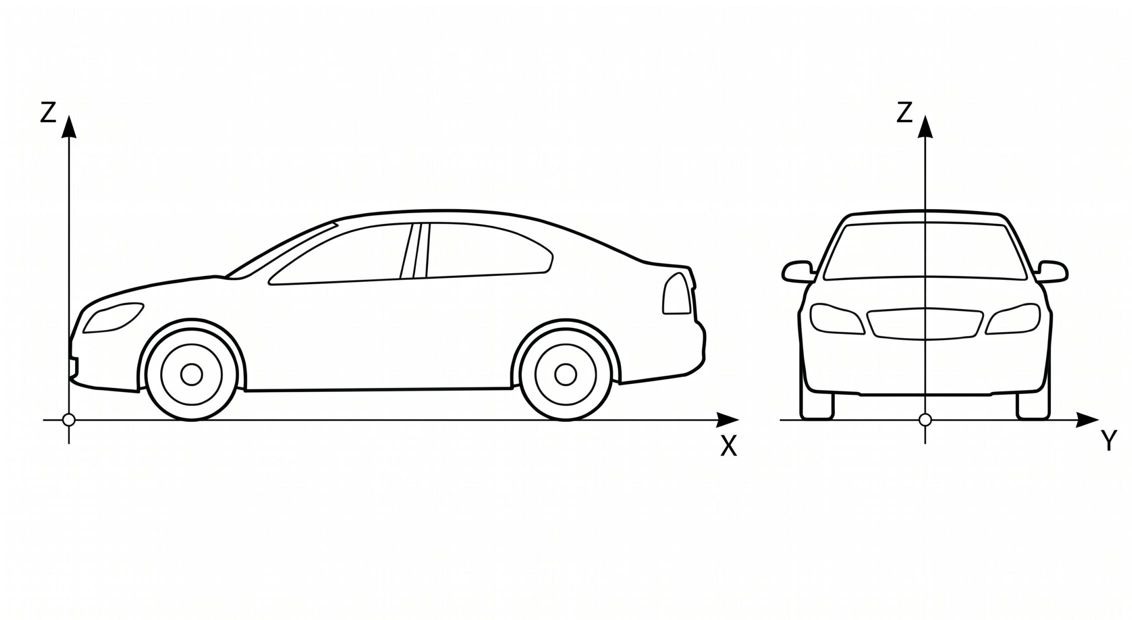
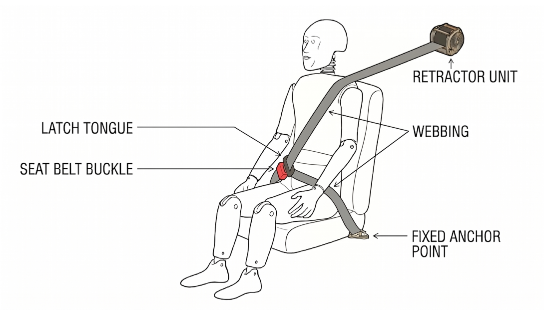


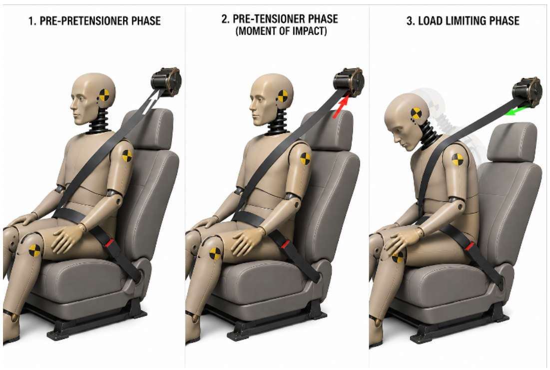

**Figure 2.1:** Vehicle coordinate system definitions, AI generated image from Gemini (2026).

The seatbelt system configuration is illustrated in Figure 2.2a, showing a representative second-row seat on the vehicle's left-hand side. The retractor is typically positioned posterior to the occupant in the $x$-direction, concealed behind interior trim panels. From the retractor, the webbing transitions into the cabin through a trim outlet. This outlet influences the initial point of contact between the webbing and the occupant's shoulder, and it is at this specific interface that the mechanism is designed to manipulate the belt's position, primarily by displacing the webbing in the $y$-direction. While the mechanism's influence is exerted at the shoulder contact point, the physical hardware is integrated behind the second-row seats and forward of the retractor, protected by the interior trim. A central variable in this architecture is the stroke length, defined as the displacement distance the mechanism imparts on the webbing at the mechanism's location. This should not be equated with the displacement along the occupant. The spatial integration is critical: the closer the mechanism can be positioned to the trim outlet, the more efficiently it can modify the webbing's path at the shoulder. This proximity optimizes the system by minimizing the required displacement, thereby reducing the total stroke length.

The modern seatbelt retractor is a highly advanced safety system that manages occupant kinematics through multiple sequential phases during a potential collision, illustrated in Figure 2.2b. Before a crash even occurs, such as during an evasive maneuver or automatic emergency braking, a reversible active pre-pretensioner can apply a moderate force, typically ranging from 200 N to 600 N (0.2 kN to 0.6 kN), to remove belt slack and actively reposition the occupant, Mishra et al. (2023). If a crash becomes inevitable, pyrotechnic pre-tensioners deploy within milliseconds to forcefully couple the occupant to the vehicle seat, maximizing the time available to absorb the crash energy, Hellenbrand et al. (2023). Following this initial coupling, the system transitions to a multi-stage load limiting phase, where the retractor in a controllable manner yields webbing to manage the peak forces exerted on the occupant's thorax, Wang et al. (2015). While the overall restraint system encompasses many complex details, what is most relevant for the proposed automated positioning mechanism is the dynamic force profile of the retractor. It is critical that the integration of the new mechanism does not add significant friction or otherwise disturb these main safety functions, particularly the delicate force levels of the active pre-pretensioning phase.




**(a)** Seatbelt system overview.




**(b)** Approximation of seatbelt behavior during a crash.

**Figure 2.2:** Comparison of the mechanism components and the system architecture, AI generated images, Gemini (2026).

The physical dimensions of the webbing are as measured 47 $mm$ in width and 1.15 $mm$ in thickness. The minimal thickness is a critical parameter for the system design, as the mechanism must be engineered to prevent the belt from jamming. This requires balanced dimensions that strictly prevent the webbing from doubling over itself within the guiding interface. Furthermore, the aspect ratio of the belt is wide and thin. Because the mechanism operates by displacing the webbing laterally in the $y$-direction, this specific geometry makes the material highly susceptible to buckling or folding. The physical interface must therefore be designed to accommodate these exact dimensions and mitigate any unintended deformation during lateral movement.

Although the development of occupant sensors falls outside the scope of this project, the system architecture must account for their data outputs. A significant opportunity enabled by an occupant monitoring system is the implementation of a closed-loop feedback control. By continuously tracking the webbing's real-time position on the occupant, the sensors could provide input signals to the mechanism. This would allow the system to continuously update the mechanism's coordinates, actively adjusting the webbing to maintain an optimal routing across the shoulder.

## 2.2 Review of previous work

This project builds on previous internal development at the company aimed at optimizing seatbelt positioning. This earlier work provided the initial inspiration and technical foundation for the current mechanism. Review of earlier concepts helped identify key requirements and potential failure modes, which serve as a reference for the ongoing design process. Due to corporate confidentiality, the specific technical details of these prior concepts cannot be fully disclosed in this report. However, extensive discussions regarding this previous work with the respective engineer at Volvo Cars ensured that learnings from this phase were integrated into our project. Patents have been filed for the concepts developed during that phase (see Chapter 2.3), highlighting the company's commitment to the technology and the strategic importance of the mechanism. Furthermore, the previous work established a cost target per vehicle, which this project aims to further reduce.

## 2.3 Patent landscaping

A patent search revealed several interesting solutions to similar problems. These patents served strictly as sources of inspiration, providing a diverse range of concepts varying in characteristics and complexity. The most relevant patents varied significantly across several aspects, including their publication date, which ranged from just a few years to over two decades old. Although the majority of the solutions involved repositioning the seatbelt, their execution differed. Some mechanisms adjusted the belt vertically, while others moved it laterally. Furthermore, the level of automation varied. Certain concepts utilized sensors to gather occupant data for automatic positioning, whereas others required manual adjustment. Additionally, several designs incorporated electronic components, typically electric motors to actuate the movement.

Subsequently, two patents filed by Volvo were identified. The first one was filed in August by Nilsson et al. (2025a), and the second one was filed in November by the same inventors Nilsson et al. (2025b). These patents are part of the earlier work conducted, mentioned in Chapter 2.2. Their IPC classification numbers could be utilized to discover additional solutions relevant to the given task.

Other notable patents focused on ergonomic enhancements, with a standout example filed by Sharif (2019). This concept features a robotic-style arm mounted on any vehicle pillar adjacent to the seat. By extending and retracting, the arm improves accessibility to the belt when entering or exiting the vehicle. Such a feature has the potential to improve overall user satisfaction.

Patents outside the automotive industry were also explored, with a greater focus on various mechanical principles for deflecting a webbing. One particularly interesting solution to investigate further is the use of rollers. Rollers can be designed with different shapes, such as conical, cylindrical, or crowned, allowing their shape to be tailored to achieve specific and desired behaviors from the belt. This train of thought was inspired by a patent filed by Le Viavant (2004), a French industrial company, using two roller-like components working as deflectors for a belt.

Two other patents were identified as highly relevant to this project, primarily because they feature fully automatic seatbelt adjustment systems that require no manual input from the occupant. The first patent, filed by Panejko et al. (2019), uses sensors to measure the angle of the seatbelt as it rests across the occupant's shoulder. This data is transmitted to an electric motor that raises or lowers the upper belt anchor until the belt achieves a pre-programmed optimal safety angle. The second patent, recently filed by Reed and Cech (2025), takes a more advanced approach. Using sophisticated cameras rather than angle sensors, the system visually scans exactly where the belt is positioned on the body and fine-tunes the anchor placement to perfectly fit the occupant's unique anatomy.

The patent search provided a foundational source of inspiration and valuable insights into existing concepts and technologies on the market. Additionally, it offered a clear perspective on the historical evolution of seatbelt technology. However, rather than obtaining a single critical insight, the aggregate results of the patent review facilitated our broader ideation process directly supporting the upcoming concept generation phase. The relevant patents found and valuable insight gained from each are presented in Table 2.1

**Table 2.1:** Summary of patent inspiration for the design process.

| Patent Owner | Date | Valuable inspiration |
|---|---|---|
| Volvo | Aug 2025 | This patent was identified as a direct result of the previous project conducted at Volvo. Discovering this document served as a validation of our search strategy, confirming that we had selected the correct keywords and classification codes to capture relevant innovations within this field. This patent also provided useful indications related to design and packaging space. |
| Volvo | Nov 2025 | This patent was identified as a direct result of the previous project conducted at Volvo. Discovering this document served as a validation of our search strategy, confirming that we had selected the correct keywords and classification codes to capture relevant innovations within this field. This patent also provided useful indications related to design and packaging space. |
| Nissan | Nov 2019 | This solution focuses on the motorized adjustment and positioning of the D-ring. While the core mechanism is highly comparable to our own, the primary design intent differs, as this system prioritizes ergonomic optimization rather than the specific functional requirements of our project. |
| VAI CLECIM | Jan 2004 | This design ensures that the webbing is guided in a controlled manner, preventing folding or twisting during operation. The system utilizes two deflectors to shape the belt's path across the user's shoulder, with the final geometry being directly dependent on the angular relationship between these two components. |
| BROSE | Feb 2019 | This patent encompasses both a method and a physical apparatus. Conceptually, it closely aligns with our project's target state: a sensing system identifies the required angle, which subsequently triggers the adjustment of the mechanism along the defined axis. |
| JOYSON | Jul 2025 | This system functions as a direct competitor to our proposed solution. Despite a lack of architectural detail, the integration directly into the seat structure presents potential safety challenges. The solution is developed by Joyson Safety Systems, a company with established partnerships with Brose and Brose Sitech. |

# 3

# Method

This section details the methods applied throughout the project. The work commenced with a review of existing internal research at Volvo Cars, followed by a patent landscape analysis to identify and examine comparable market solutions. A comprehensive requirement specification was then established, informed by a stakeholder analysis. Once the system's functional architecture was defined, an iterative concept generation process was initiated. These concepts underwent rigorous screening and evaluation, culminating in the selection of a final concept for further refinement within the detailed design phase.

## 3.1 Methodology

The project's overall methodology is illustrated in Figure 3.1. Following a comprehensive patent landscape analysis, it became evident that no directly comparable product currently exists on the market. This necessitated a structured new product development approach to ensure the entire design space was systematically explored. To avoid solution bias, the tendency to prematurely commit to the initial technically viable concept, an iterative development approach was employed throughout both the concept generation and evaluation phases. This process facilitated continuous refinement, ensuring the final concept achieved a higher level of optimization. During the detailed design phase, the project was supported by rigorous analyses, including Failure Mode and Effects Analysis (FMEA), cost estimation, and a systematic material selection process. Furthermore, Design for Manufacturing and Assembly (DFMA) principles were integrated to ensure the resulting product is robust, cost-effective, and streamlined. As the project progressed, the maturity level of each concept was systematically increased. In this context, maturity signifies that each concept becomes increasingly detailed and well-defined as more technical knowledge is systematically acquired.

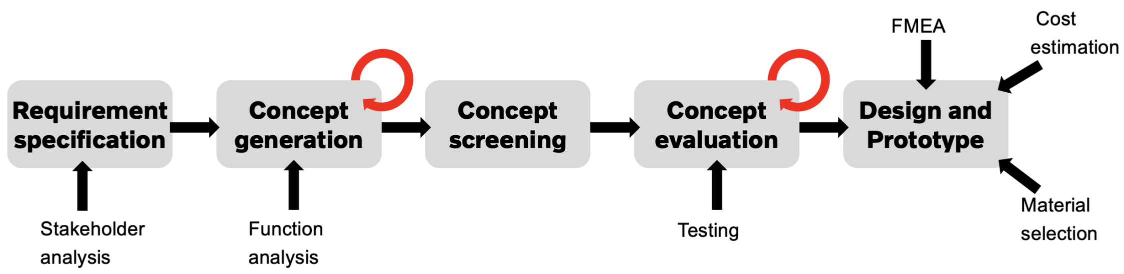



**Figure 3.1:** Overall methodology applied for the project.

## 3.2 Patent landscaping

The patent search was conducted using the European Patent Office (2026) database in order to explore similar existing applications, providing inspiration while eliminating the risk of copying prior solutions. The search was carried out in two different iterations, which served two separate purposes. In the first iteration, specific patents were sought within the automotive industry, with the objective to find patents aligned as close to the problem formulation as possible. In the second iteration, more general patents were sought outside of the automotive industry. This was carried out with the purpose of finding other possible technologies that could be creatively integrated into the automotive industry.

For the first iteration, project keywords such as "webbing", "automatic", "motor", "automotive" and "adjustable" were used in combination with boolean operators to generate a search for relevant patents within the automotive industry. Using keywords alone generated thousands of search results, which needed to be reduced. Therefore, when a relevant patent was identified, its classification number was analyzed and subsequently reused to refine the next search iteration. The second iteration was conducted in a similar way. However, more general keywords as "belt", "lateral movement" and "deflection" were used to ensure focus on various technical and functional principles for moving a belt.

## 3.3 Function analysis

To ensure that the development process remained solution-neutral, a systematic function analysis was performed. The purpose was to gain understanding of the system and create structure in the development process downstream.

The first step was to define the main function of the mechanism, which was derived from the problem formulation and the project's purpose. Given the variety of frameworks used in functional analysis, the initial step involved selecting the most suitable one. The flow-oriented function structure was selected due to the transforming nature of the main function.

To initiate this, a Black Box model was established, representing the inputs and outputs together with the execution, without explaining the internal mechanisms. This provided a representation of what the system is supposed to do, without detailing how the goal is achieved. A system boundary was defined around the main function with inputs and outputs specified in the form of energy, information and material. This gave the system context and fundamental information required for later stages of development. Next action was to decompose the main function into sub-functions, which was conducted through brainstorming sessions. This also included defining relations between the sub-functions in order to visualize their internal flow. All functions were intentionally worded as Verb + Noun.

## 3.4 Needs and requirements

This section outlines the method for acquiring foundational requirements that must be fulfilled by the mechanism, along with an analysis identifying the key stakeholders involved in the project.

### 3.4.1 Stakeholder analysis

A stakeholder analysis was conducted to clearly identify the various actors interested in and affected by the project. This analysis provided valuable insights into different perspectives, as each stakeholder has distinct needs and expectations regarding the mechanism. The value chain was analyzed to identify project stakeholders and their respective requirements. Understanding these diverse viewpoints directly influenced the development of the requirement specification, ensuring it comprehensively addressed as many needs as possible.

### 3.4.2 Requirement specification

The requirements specification served as the project's foundational document, establishing the mandatory benchmarks required for successful product verification and approval. Within this framework, a clear distinction was drawn between requirements (R) and desires (D). The former denote essential conditions for core system operation, whereas the latter represent non-critical enhancements aimed at improving user experience and overall product appeal.

During the idea generation phase, the specification acted as a repository to store and structure acquired knowledge. It subsequently informed the screening criteria and guided the testing and verification of prototypes to ensure performance goals are achieved. As new insights were gathered, the document underwent an iterative process of continuous refinement. Shifting priorities meant that criteria were regularly updated, with some demoted from requirements to desires, and vice versa.

To ensure clarity, each criterion was accompanied by a brief description and a specific, measurable method to evaluate whether it had been successfully fulfilled.

## 3.5 Concept generation

This section covers the concept generation process. In this phase of the project, different thoughts and ideas on how to solve the problem were discussed. In this phase, the sub-functions derived from the functional analysis served as the basis for generating sub-solutions. Each sub-function represents a critical component required to fulfill the main function, while the sub-solution constitute the specific technical implementation required to address these individual sub-functions. This phase prioritized creative exploration, which was essential to ensure that the entire design space was thoroughly investigated, thereby preventing the premature exclusion of viable technological solutions.

### 3.5.1 Morphological matrix

The concept generation phase was initiated by creating a Morphological matrix, which is a tool to structure the idea generation process. The matrix is used to decompose larger problems into smaller, more simplified forms, ultimately resulting in more innovative and creative solutions. In this matrix, the system's sub-functions were listed in rows, while sub-solutions to each sub-function were arranged in columns. The preceding decomposed sub-functions identified in the functional analysis were utilized in this matrix. Different alternative solutions to these sub-functions could then be discovered, primarily through internal brainstorming sessions and literature research. At this stage, preliminary sketches were also produced, especially for the solution attributes that seemed unclear and diffuse. This was done to support clarification of potential design ideas and create additional inspiration. The total number of potential concepts is determined by multiplying the number of sub-solutions available for each sub-function. This combinatorial approach ensures that every possible configuration of the system is considered. To ensure feasibility, incompatible combinations of different sub-solutions were identified, which reduced the number of total solutions.

## 3.6 Concept screening

Following the concept generation phase, a screening process was initiated to filter the generated ideas. This phase aimed to eliminate concepts that failed to meet fundamental requirements, ensuring that only feasible solutions proceeded to further development. The selection of screening criteria was a critical step. These were chosen based on their relevance to the project's objectives and the current maturity level of the concepts. To maintain an objective and balanced assessment, the criteria were defined to reflect key system requirements. A central component of this screening was the utilization of an Elimination matrix, which provided a structured framework for the screening process of the generated concepts.

### 3.6.1 Elimination matrix

The elimination matrix serves as a decision-making step in the product development process, where the concepts remaining after the concept generation process are reviewed to determine whether they satisfy the most fundamental and primary product requirements or not. In this matrix, each concept was arranged in a row, while the requirements were set in columns. Each concept was then assessed to see whether it met the selected requirements or not. If a concept was assessed to meet a specific requirement, a " + " was assigned. Conversely, if the concept was judged to not meet a requirement, a " − " was assigned instead and subsequent requirements for the specific concept were not evaluated. A "?" indicated uncertainty regarding requirement fulfillment, while a " ∗ " denoted that the concepts was not able to meet the requirement on its own, but as a combination with another concept. Concepts fulfilling all stated criteria move on for further analysis in the concept evaluation stage.

## 3.7 Concept evaluation

This section includes methods used in the concept evaluation process. In this section, the degree of maturity increased, and the remaining concepts were compared to each other to eventually select the best one.

### 3.7.1 Sketching of remaining concepts

In this phase, simpler sketches of the concepts that remained after the elimination matrix were created. The main purpose of the sketches was to create a visual representation of what the different concepts could potentially look like, without considering any specific scale or dimensions. This representation was important to begin the next part of the process, which is concept evaluation, where the concepts are to be assessed relative to each other.

### 3.7.2 Pugh matrix

The concepts that remained after the screening process were further evaluated in a Pugh matrix. In this matrix, the concepts were assessed against each other, based on a set of criteria. During the criteria selection process, it is important to recognize that not all desired metrics are suitable. Because the concepts in this phase lack maturity, certain criteria are difficult to measure accurately/fairly. Forcing an estimation for these metrics risks distorting the results and negatively impacting the final concept selection. Therefore, to ensure a fair evaluation, the chosen criteria should be both relevant to the project and align well with the degree of maturity. The criteria were arranged in columns, and each concept in a row. One concept was selected as the reference, and it will be this concept that all other concepts are compared to for each criterion. A " + " was assigned if a concept was judged to perform better than the reference for a specific criterion. Conversely, a " − " was assigned if it performed worse. If the concept was judged to perform equally well as the reference, "0" was assigned. The number of " + ", " − " and "0" further determined the total sum for the concept, which when compared to all other concepts sums resulted in a ranking position. The reference was awarded the sum "0", and also included in the ranking. After the matrix was completed, a decision was taken whether the concepts should be eliminated or not. The Pugh matrix is a powerful tool which can be utilized for several iterations to strengthen the validity. For each new iteration, the reference is also swapped to provide a fresh perspective and challenge previous assumptions.

### 3.7.3 Rapid prototyping and testing setup

After completing the Pugh matrix, it was decided to further increase the maturity of the remaining concepts. This was done by modeling these concept in Catia V5, in which scale and dimensions therefore were considered. The modeling of each individual part was done in the part design workbench, while the concepts as whole were composed using the assembly workbench. During this phase, an iterative approach was utilized, and this process included four distinct steps:

1. Brainstorming of design.
2. Modeling in CAD.
3. 3D printing.
4. Update in CAD.

The brainstorming sessions involved focused discussions on design ideas, with a primary emphasis on component integration and minimizing the overall size. Once a design reached satisfaction, it was modeled in CAD and exported as an STL (STereoLithography) file for 3D printing. Following the physical assembly of the prototypes, minor iterative adjustments to specific components were frequently required at the end. It should be noted that these models were not intended for direct integration into the vehicle. Instead, they were developed to demonstrate the underlying kinematics. To facilitate visual evaluation, the concepts were intentionally designed to leave as many internal components exposed as possible. An additional constraint during this phase was the chosen manufacturing method, additive manufacturing. Consequently, the designs had to accommodate the specific limitations of

3D printing. Although 3D printing is not suitable for large-scale manufacturing, the ultimate requirement for mass production was continuously considered throughout the design process.

To practically evaluate the physical prototypes, the initial strategy involved constructing a modular test rig to verify their functionality. To facilitate rapid changeovers between different design concepts, the rig required specific components, including a universal base plate and modular attachment mechanisms. Furthermore, the plan necessitated the procurement and programming of electronic hardware and control systems to successfully actuate the prototypes during testing. The objective was to demonstrate the functionality of the proposed concepts and verify that they performed as intended.

### 3.7.4 Kesselring matrix and cost evaluation

The next matrix for the concepts to be evaluated in is the Kesselring matrix. This matrix differs from the Pugh matrix in an important way, which is that the importance of each criterion is considered for this process, causing this to be a powerful decision making tool. Before implementation of the actual Kesselring matrix, a weight matrix needs to be completed. In this weight matrix, the criteria are arranged in a table, appearing once per row and once per column. Subsequently, the criteria are compared to each other, one by one. If a certain criterion is judged to be more important than another, "1" is assigned. Conversely, if the criterion is judged to be less important, "0" is assigned. If the criteria are judged to be equally important, "0.5" is assigned.

Furthermore, all criteria will be awarded a total sum, based on the number of 0, 1 and 0.5 that was assigned to that specific criterion. This sum will then be doubled for each criterion to obtain an integer, which will be the weight for the specific criterion, representing its relative importance.

Each criterion also possesses its own grading scale, ranging from 1 to 5, which is used to score the concepts based on their performance. The benchmarks for these grades vary: some are defined by quantitative, measurable values, whereas others rely on qualitative descriptions. Within the Kesselring matrix, each concept is evaluated independently against these criteria. A concept's score for a given criterion is calculated by multiplying its assigned grade by the established weight of that criterion.

Given its critical importance to the project, cost will be evaluated independently rather than included as a standard criterion within the Kesselring matrix. The estimated total cost of each concept will be plotted against its Kesselring performance score to generate a 2D performance-to-cost graph. This visual representation will ultimately serve as the foundation for the final concept selection.

## 3.8 Detailed design

Following the selection of the final concept, the project transitioned into the detailed design phase. This stage focused on refining the design to reduce total costs, primarily by simplifying the assembly process through minimized parts and straightforward interfaces.

Ideas generated during an internal brainstorming session were integrated into a new CAD model and a final prototype. Additional analyses in this phase included an Failure Mode and Effects Analysis (FMEA), material selection and a final cost estimation to ensure the design met all technical and economic requirements.

### 3.8.1 Failure Mode and Effects Analysis

A Failure Mode and Effects Analysis (FMEA) was conducted to evaluate potential risks, their associated consequences, and strategies to prevent them from becoming future issues. This method systematically identified potential failure modes, along with their root causes and resulting effects.

Subsequently, a value between 1 and 10 was assigned to three distinct categories: severity, occurrence, and detection. Severity evaluates the seriousness of the failure's effect. A higher value indicates a more critical impact if the failure occurs. Occurrence estimates the probability that the specific cause of the failure will occur given the current design, encompassing aspects as manufacturing phase and assembling. Higher score here reflects a greater likelihood of the cause arising. Finally, detection assesses the effectiveness of current control methods in identifying the failure or its root cause before the product reaches the market. In this category, a higher value indicates a poor ability to detect the issue proactively.

Implementing an FMEA allows for the early identification of potential issues during the product development phase. This proactive approach mitigates the need for costly late-stage design modifications while generating valuable insights early in the process.

### 3.8.2 Material selection

A systematic material selection process based on methodology from Ashby (2011) was conducted to identify the optimal material for the mechanism. Constraints that the material needs to be managed were defined, as well as objectives to optimize for. Constraints represent non-negotiable technical requirements used to screen out materials that could not fulfill the job. Objectives instead are the performance metrics to be optimized, typically through the maximization or minimization of specific properties.

The material selection was conducted using Granta EduPack, a comprehensive materials database and decision-support software. This tool facilitated a systematic screening process based on defined technical constraints, ranging from mechanical properties to processing requirements. Subsequently, Ashby plots were generated by assigning relevant material properties to the x- and y-axes. These plots visually mapped all materials that met the initial criteria, allowing for clear comparative analysis. Finally, further technical documentation regarding the top-performing candidates identified in the plots was reviewed to determine the final selection.

# 4

# Result

This chapter presents the findings derived from the project work, structured in chronological order. It begins with the functional and stakeholder analyses, followed by the concept generation, screening, and evaluation processes. Finally, the chapter ends with a detail design phase of the selected concept, including all subsequent technical analyses.

## 4.1 Function analysis

The resulting black box diagram is presented in Figure 4.1. The system's primary function was defined as 'Adjust webbing position on shoulder', with the operational inputs characterized by electrical energy and control signals. Electrical energy represents the power draw of the system, whereas the coordinate signal originates from the sensing system, providing the necessary positioning data for the mechanism to adjust the seatbelt.


**Figure 4.1:** Black box diagram.

A brainstorming session was then initiated, where the main function according to the black box diagram was broken down into sub-functions, which together can solve the main function. At first, three different sub-functions were identified as necessary to to fulfill the main function, and these sub-functions each serve a distinct purpose.

1. Generate motion: A motion needs to be initiated, and in this case most likely by a motor.
2. Transfer force: The force needs to be transferred, from the motor to the point of adjustment.
3. Deflect webbing: The generated force will then deflect and adjust the webbing to the correct position.

These three sub-functions are visualized sequentially in the flow chart diagram in figure 4.2 below.

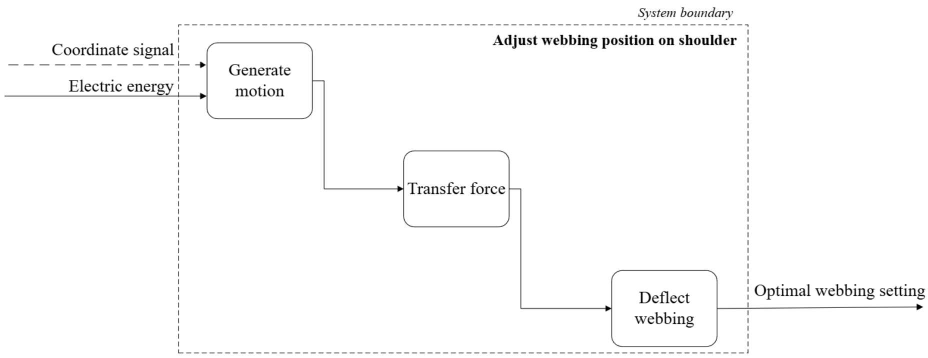



**Figure 4.2:** Functional flow diagram.

This functional flow diagram was the foundation for the later concept generation process, in which different sub-solution are generated to solve each individual sub-function. During the concept generation phase, it was determined that the initial set of three sub-functions was insufficient to achieve the main function. Specifically, a mechanism for controlling torque and velocity was identified as missing. Consequently, the functional diagram was iteratively refined to include an additional sub-function: 'Amplify torque'. The updated functional flow diagram is visualized in figure 4.3.

- Amplify torque: Adjustment of gear ratio to increase torque and overcome friction.

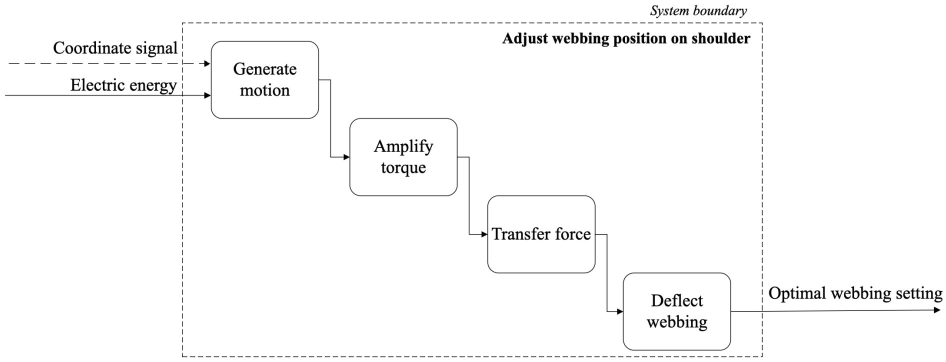



**Figure 4.3:** Updated functional flow diagram.

## 4.2 Needs and requirements

This section covers the result gathered from the stakeholder analysis, which provided input to the requirement specification.

### 4.2.1 Stakeholder analysis

Identifying and understanding the diverse needs of both internal and external stakeholders is a fundamental step in product development to ensure the final mechanism is competitive and functionally viable (Ulrich & Eppinger, 2015). In the context of an Original Equipment Manufacturer (OEM) like Volvo Cars, these needs span the entire product lifecycle, from supplier manufacturing to end-user interaction and aftermarket service. The key stakeholders and their respective needs are defined below:

- Suppliers and Sub-suppliers - The automotive supply chain relies heavily on two primary sourcing strategies: integrating "off-the-shelf" components developed entirely by the supplier, or utilizing a "build-to-print" approach where the OEM provides a complete design for external manufacturing. Because the intention is to outsource the assembly of this mechanism, the design must adhere to Design for Assembly (DFA) principles. This includes ensuring clear mechanical interfaces, minimizing part count, and utilizing standardized components to facilitate fast and cost-efficient production (Boothroyd et al., 2010).
- Volvo Assembly Plants - For operators installing the mechanism on the main assembly line, the primary focus is vehicle integration. The installation process must be ergonomically simple, require minimal tooling, and utilize short mounting trajectories. Furthermore, the design should incorporate error-proofing features and generous tolerances to prevent incorrect assembly inside the vehicle environment.
- User (Passenger) - The physical user of the mechanism prioritizes perceived quality, comfort, and safety. Based on internal discussions at Volvo Cars, key requirements include minimizing noise and vibration during adjustment, ensuring comfortable physical interaction with the webbing, and guaranteeing that the mechanism introduces no projectile hazards in the event of a collision.
- Customer (Car Owner) - While the vehicle owner may not frequently use the rear-seat mechanism, they prioritize reliability and a low total cost of ownership. A product lacking durability requires frequent workshop visits, increasing maintenance costs and causing frustration.
- Automotive Technicians - For aftermarket and warranty repairs, the mechanism must be designed for serviceability. The principles of Design for Assembly (DFA), such as ensuring unrestricted access, minimizing part count, and utilizing standardized fasteners, are directly applicable to disassembly and repair.

Applying these DFA principles ensures that the system is easily accessible and repairable using standard tools, which minimizes maintenance times and improves overall product maintainability (Boothroyd et al., 2010).

- Regulatory Bodies and Safety Organizations - The mechanism must strictly comply with international legal requirements, specifically UN ECE Regulation No. 16 and the U.S. equivalent FMVSS 209, ensuring it does not interfere with or reduce the primary safety function of the seatbelt (National Highway Traffic Safety Administration (NHTSA), 2024; United Nations Economic Commission for Europe, 2018). Additionally, achieving high ratings from safety assessment programs like Euro NCAP (Euro NCAP, 2025) is a critical metric for a well-developed automotive product.
- Volvo Cars - From a corporate perspective, the primary drivers are unit cost, functional performance, and packaging. As established through internal discussions at Volvo Cars, the mechanism must feature simple mechanical and electrical interfaces for seamless vehicle integration. Furthermore, the design needs to be highly modular and scalable, allowing the same fundamental architecture to be adapted across different vehicle models and platforms to facilitate the supply chain.

### 4.2.2 Requirement specification

The requirement specification consists of a total of 5 requirements and 24 desires. The large number of desires compared to requirements was deliberately chosen to encourage design flexibility, avoiding being locked in certain directions too early in the process while still ensuring that core functionality is met. These assessment criteria are distributed across several distinct categories. The categories, along with an overall description, are listed below:

- **Performance** - How well does the mechanism position the seat belt compared to the optimal location? What is the operation time, and is the energy consumption acceptable?
- **Comfort** - How is the comfort perceived by the user during operational movement?
- **Safety and compliance** - Does the addition of the mechanism alter the primary safety function of the seat belt? Does the design comply with regulations set by relevant authorities?
- **Environment** - Can the mechanism withstand the environmental conditions inside the intended trim area, such as temperature fluctuations, moisture, and dust?
- **Durability** - Is the mechanism robust over time, particularly regarding the lifespan of the motor and potential wear on the seat belt webbing?

- **Manufacturing and service** - Is the mechanism easy to install, assemble and service? Can it be serviced using standardized tools?
- **Size and design** - Does the mechanism fit within the designated space, and how does it interface with surrounding components?
- **Sound** - What is the noise level generated during operation, and is the sound consistent?
- **Cost** - What is the projected cost of the mechanism relative to the functional benefit it provides?

The criteria were primarily generated through internal brainstorming sessions and iterative discussions with Volvo Cars. However, establishing measurable target values and defining appropriate units for these criteria proved challenging. Consequently, consultations were held with subject matter experts at Volvo to define these metrics and finalize the target values for the majority of the requirements and desires. The resulting criteria are structured in various formats: some are evaluated through a binary "yes" or "no" compliance, while others dictate exact numerical values. Instances where target values are not specified are due either to corporate confidentiality constraints or a lack of available empirical data at this stage of the project.

To ensure clarity, certain complex criteria require further explanation. For instance, the "service life" of the mechanism is evaluated based on the motor's lifespan, which acts as the governing factor for the entire assembly. To accurately reflect real-world usage, this lifespan is measured in operational cycles rather than years.

Additionally, specific target values were derived directly from production forecasts. The production volume requirement of 1,000,000 units per year is based on an estimated sales volume of 100,000 cars per model annually, across five different vehicle models. Since each car requires two mechanisms (one for the left and one for the right rear seat), the total equates to one million units. Given this high production volume, it is highly advantageous for Volvo to utilize identical components for both sides of the rear seat; therefore, a symmetrical design is heavily favored. The full requirement specification is visualized in Appendix A.

## 4.3 Concept generation

This section presents the results of the concept generation process. Through internal brainstorming sessions, various sub-solutions were developed for specific sub-functions. These sub-solutions were then combined to form the final integrated concepts.

### 4.3.1 Morphological matrix

To systematically generate concepts, a morphological matrix was established based on the functional flow chart developed earlier in the project. Initially, the sub-functions identified in Figure 4.2 were arranged in rows. Sub-solutions for each function were subsequently identified through a combination of brainstorming sessions and literature research, and arranged in columns. First, the research for the "Generate motion" sub-function was based on mechatronics literature by Alciatore (2019) to identify and evaluate various electrical actuators. Subsequently, the research for the "Transfer force" sub-function was primarily grounded in established mechanical principles described by Norton (2020) and Budynas and Nisbett (2024), as well as linear motion handbooks (Bosch Rexroth AG, 2007). Conversely, the sub-solutions for the "Deflect webbing" sub-function were generated through internal brainstorming, with the exception of two specific roller designs identified and adapted from the researched patent by Le Viavant (2004), in Chapter 2.3. For these brainstormed sub-solutions, we have established a common understanding for the underlying solution concepts, and they are currently only represented by their names rather than detailed schematic illustrations. This initial compilation resulted in the first iteration of the morphological matrix, presented in Table 4.1.

**Table 4.1:** Morphological matrix first iteration.

| Morphological Matrix | Sub-solutions | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sub-functions** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** |
| **Generate motion** | Stepper motor | Brushless DC | Servo-motor | Brushed DC | Solenoid | | | | | | | | | | |
| **Transfer force** | Rail | Lead screw | Toothed belt | V-belt | Cable | Worm gearbox | Axle (Direct drive) | Spur gearbox | Helical gearbox | Planetary gearbox | Rack & pinion | Crank slider | Scotch yoke | Barrel cam | Mangle rack |
| **Deflect webbing** | Cone roller | Teeth | Slot | Compliant pressure grip | Diagonal pin | Flanged roller | Crowned roller | S-track | Buckle slot (small) | Multiple pins | Big screw | | | | |

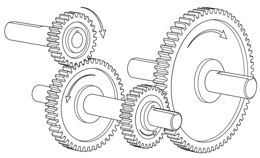
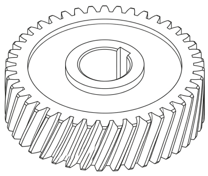
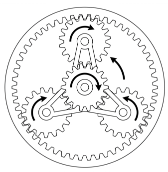
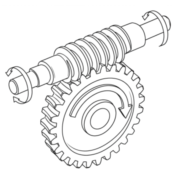
Upon reviewing the first iteration, it became apparent that the "Transfer force" category was functionally overloaded. Developing a feasible concept frequently required selecting multiple sub-solutions from this single row, such as combining a gearbox with a linear transmission mechanism, to form a complete and functional mechanical solution. To resolve this overlap and maintain the methodological integrity of selecting one solution per sub-function, a second iteration of the morphological matrix was developed. A new sub-function, "Amplify torque," was introduced to distinctly categorize the gear systems, thereby separating torque amplification from the actual mechanical force transfer. The matrix was subsequently updated in accordance with the revised functional diagram (Figure 4.3). The refined morphological matrix is shown in Table 4.2.

**Table 4.2:** Morphological matrix second iteration.

| Morphological Matrix | Sub-solutions | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sub-functions** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
| **Generate motion** | Stepper motor | Brushless DC | Servo-motor | Brushed DC | Solenoid | Linear actuator (stepper) | | | | | | |
| **Amplify torque** | Spur gearbox | Helical gearbox | Planetary gearbox | Worm gearbox | None | | | | | | | |
| **Transfer force** | Rail and carriage | Lead screw | Toothed belt | V-belt | Cable | Axle (Direct drive) | Rack & pinion | Crank slider | Scotch yoke | Barrel cam | Mangle rack | Cam and follower |
| **Deflect webbing** | Cone roller | Teeth | Slot | Compliant pressure grip | Diagonal pin | Flanged roller | Crowned roller | S-track | Buckle slot (small) | Multiple pins | Big screw | |

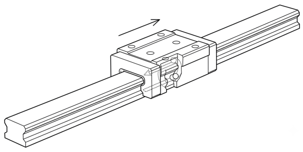
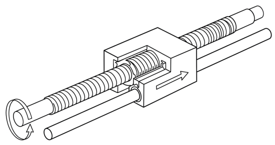
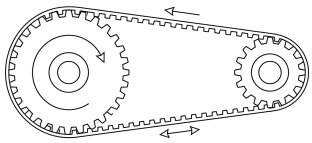
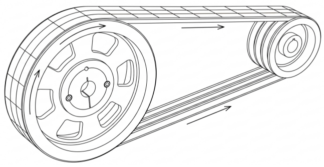
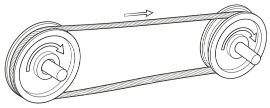
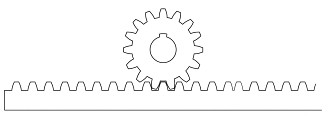
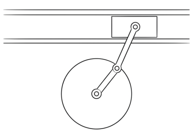
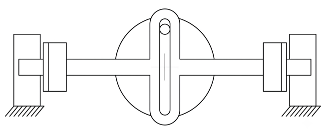
As seen in the updated morphological matrix, a wide variety of mechanical principles were identified to solve the sub-functions "Amplify torque" and "Transfer force". To provide a clear overview of these underlying mechanisms, their architectures, and their working principles, a systematic compilation of the 15 evaluated sub-solutions is presented in Table 4.3.

**Table 4.3:** Catalogue of the evaluated mechanical sub-solutions for the functions "Amplify torque" and "Transfer force". The table details their working principles and schematic illustrations. AI generated images.

| Mechanism | Sub-function | Illustration | Working principle |
|---|---|---|---|
| Spur Gearbox | Amplify torque |  | Transfers rotation and torque between parallel shafts using straight gears. It is a simple and effective way to change speed and torque. |
| Helical Gearbox | Amplify torque |  | Transfers rotation using angled gear teeth. This makes the movement smoother, stronger, and quieter than standard spur gears. |
| Planetary Gearbox | Amplify torque |  | Uses a central sun gear surrounded by multiple planet gears. It handles high torque and gives a large speed reduction in a very compact space. |
| Worm Gearbox | Amplify torque |  | Uses a screw (worm) to turn a gear at a 90-degree angle. It gives a high gear reduction and can only be driven with the worm screw. |

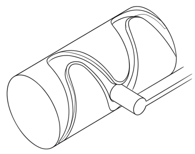
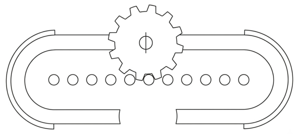
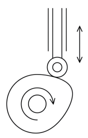
*Continues on next page*

**Table 4.3** – *Continued from previous page*

| **Mechanism** | **Sub-function** | **Illustration** | **Working principle** |
|---|---|---|---|
| Linear Rail and Carriage | Transfer force |  | Guides movement in a straight line. It helps support the weight and forces of moving parts along a track. |
| Lead Screw | Transfer force |  | Turns a rotational movement into a straight, linear movement using a threaded shaft and a nut. It is precise and holds its position well. |
| Toothed Belt | Transfer force |  | Transfers movement using a belt with teeth. This prevents slipping and ensures accurate timing and positioning between rotating parts. |
| V-Belt | Transfer force |  | Uses friction between a wedge-shaped belt and pulleys to transfer power. It runs quietly and is good at absorbing sudden shocks. |
| Cable | Transfer force |  | Uses a wire or rope to pull parts into position. It is light, flexible, and useful for transferring movement around obstacles. |
| Rack and Pinion | Transfer force |  | Uses a round gear to drive a flat, toothed bar. It directly changes rotation into a straight-line movement. |
| Crank and Slider | Transfer force |  | Uses a connecting rod to change continuous spinning motion into a back-and-forth straight movement. |
| Scotch Yoke | Transfer force |  | Changes spinning motion into a sliding back-and-forth movement. It creates a very even and smooth motion profile. |

*Continues on next page*

**Table 4.3** – *Continued from previous page*

| Mechanism | Sub-function | Illustration | Working principle |
|---|---|---|---|
| Barrel Cam | Transfer force |  | Uses a turning cylinder with a groove to guide a pin. As the cylinder turns, the pin moves along according to the groove's shape. |
| Mangle Rack | Transfer force |  | Uses a gear that follows a loop of teeth to create a back-and-forth movement from a constant spinning input. |
| Cam and Follower | Transfer force |  | Uses a specially shaped spinning wheel (cam) to push a lever or rod (follower) in a specific, customized pattern. |

The second iteration of the morphological matrix yields a theoretical total of 3,960 possible concept combinations ($6 \times 5 \times 12 \times 11$). Evaluating every single combination is practically impossible and inefficient, as many configurations are technically infeasible or mechanically contradictory. To narrow down the scope while maintaining a diverse range of architectural solutions, a handpicking strategy was applied. The objective was to select a broad variety of promising concepts that utilize different sub-solutions while remaining reasonable within the constraints of the project. This selection process resulted in 26 distinct concepts, which are further examined in the concept screening phase in Chapter 4.4.1.

## 4.4 Concept screening

The concepts were in the previous phase a combination of sub-solutions, and internal relations between major components are not yet known. To mature and develop the concepts one more step, they are described in words. This session describes the screening process of previous produced combinations of sub-solutions, which are now refereed to as concepts instead.

### 4.4.1 Elimination matrix

From the morphological matrix, a total number of 26 concepts were generated. To arrive at relevant screening criteria to use in the matrix, both brainstorming sessions and discussions with the supervisor at Volvo were conducted. What the screening criteria determined actually means are described below:

- Packaging - The concept has the potential to suit the assigned space inside the interior trim, behind the C-pillar and in front of the belt retractor.
- Manufacturability - Is it possible to manufacture the parts in the concepts?
- Not affect main function of webbing - The concept should not interfere with the webbing in a way that decreases crash safety.
- Technically feasible - Is the concept within reason technology-wise? Affects cost.

From just a combination of sub-solutions, the concepts here are developed with geometry in mind. To achieve a high variety of concepts and build knowledge faster, concepts that differ by only one sub-solution, or are too similar in other areas, can be removed from the list prior to the elimination matrix. They are also given a name that suits the embodiment as well as a number. The input concepts were evaluated, and given a comment of development ideas/question marks or a reason why it got eliminated. This is to build some knowledge that can be used in the next phases. The elimination matrix as a whole is visualized below in Appendix B. Out of 26 initial concepts, 12 successfully passed the elimination matrix and will proceed to further evaluation via Pugh matrices. These concepts are as following:

- Concept 1: Inline Screw
- Concept 2: Wall
- Concept 6: Diagonal Sled
- Concept 9: Step Slide Slot
- Concept 10: Helical Snake
- Concept 11: Mini Move
- Concept 13: Compact Deform
- Concept 14: Teleport Screw
- Concept 15: Pinned Barrel
- Concept 17: Gear S
- Concept 21: Compact Carriage
- Concept 23: Slotted Luggage

## 4.5 Concept Evaluation

This section describes the results of the methods used to evaluate and compare the remaining concepts to each other, before a final selection. In this phase, the maturity of the concepts increased, by creating simple 2D sketches of how the concept as a whole might look like, leaving out details regarding how parts are connected to each other. Additional maturity of the concepts took place as concepts become fewer, by modeling in CAD, and eventually build prototypes.

### 4.5.1 Concept catalog

This section discuses the remaining concept after completing the elimination matrix. Simple sketches and shorter descriptions of each concept is also presented. The colors in the sketches have different meanings. Firstly, red color indicates a motion, primarily rotation or translation. The black color is for the belt, while darker and lighter nuances of gray represents geometry of components. An anchor attached to a component indicates that this component is fixed, and will not move.

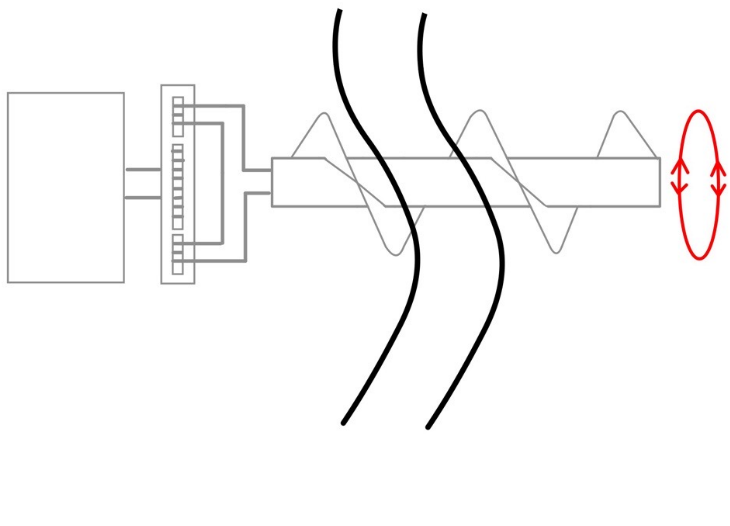


**Figure 4.4:** Concept 1: Inline screw.

The Inline screw concept, see Figure 4.4, consists of a large screw. The mechanism is designed so that the belt is placed between the threads and translates along the axis as the screw rotates. The screw is connected to a planetary gearbox, which is attached to a stepper motor. All components are in one line. The idea behind this concept is to skip the mechanical transformation from rotational to linear.

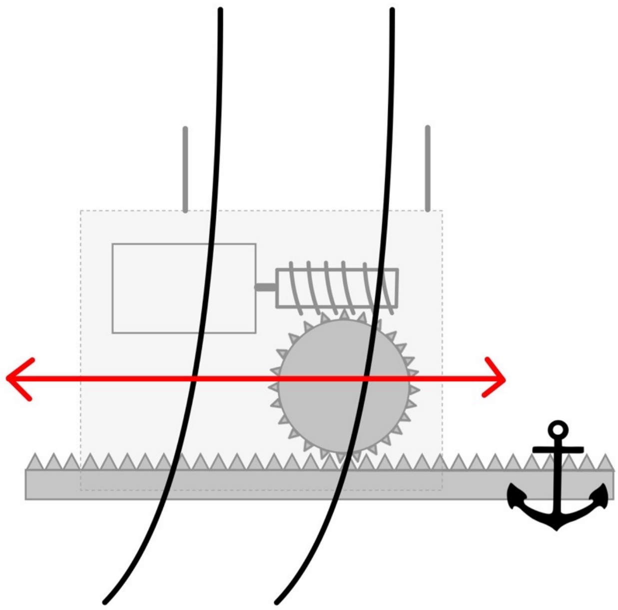


**Figure 4.5:** Concept 2: Wall

The Wall concept, see Figure 4.5, is built on a rack and pinion mechanism, in which a DC motor is connected to a worm screw, which drives a pinion along a rack. The belt is traveling on the top of the housing, between two walls shaped as a "Pringle", and everything except from the rack is moving horizontally. The rack and pinion mechanism is a well known mechanical phenomenon to convert rotational motion to linear.

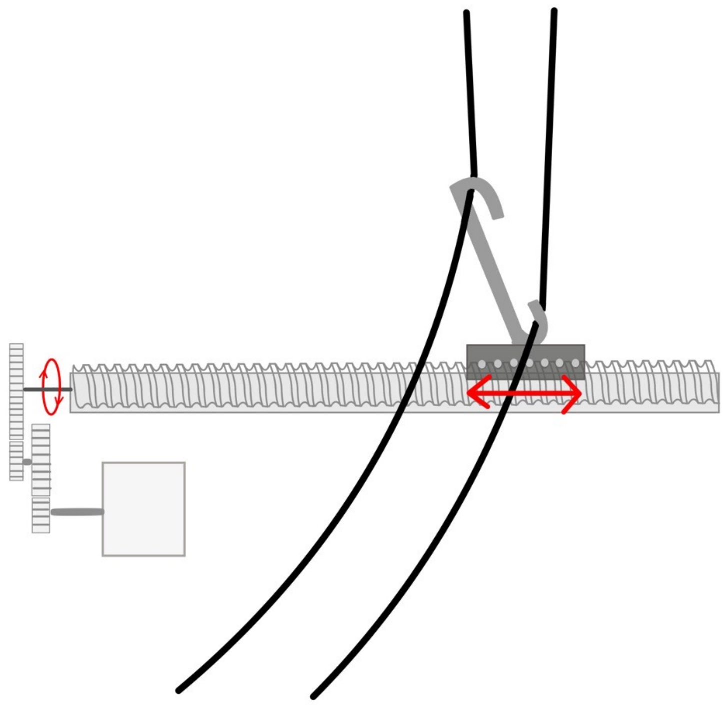


**Figure 4.6:** Concept 6: Diagonal sled.

The Diagonal sled concept (Figure 4.6) is based on a rotating lead screw driven by a DC motor. An appropriate gear ratio is obtained by connected spur gears. As the lead screw turns, it translates a carriage equipped with a diagonally mounted pin. The belt is designed to route across this pin, thereby altering its path.

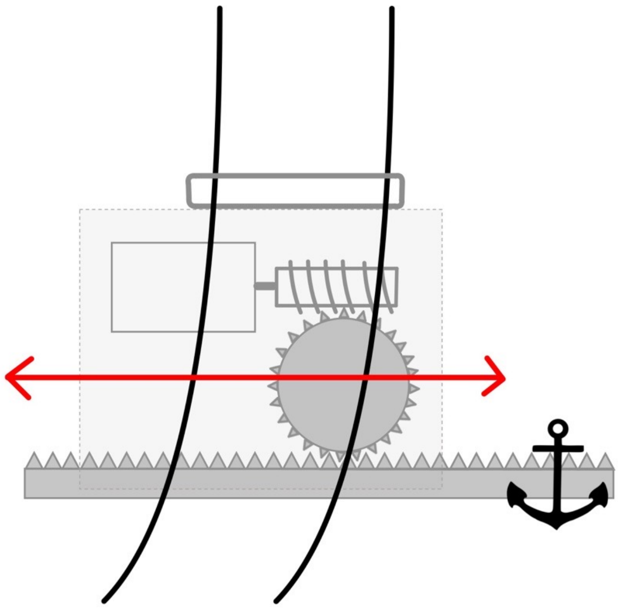


**Figure 4.7:** Concept 9: Step slide slot.

The Step slide slot concept (Figure 4.7) is also built on a rack and pinion mechanism as Wall, in which a DC motor is connected to a worm screw, which drives a pinion along a rack. Unlike concept 2, there is a slot mounted at the top of the housing which the belt is traveling through and everything except from the rack is moving horizontally.

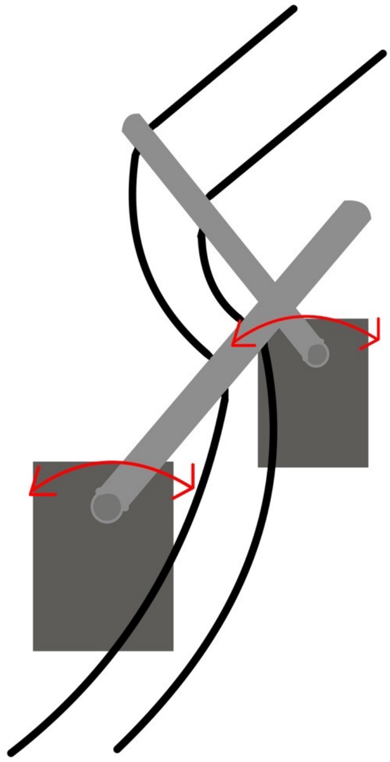


**Figure 4.8:** Concept 10: Helical snake.

The Helical snake concept (Figure 4.8) utilizes two inline servo motors, each driving an individual shaft. By rotating these shafts, the angular orientation of the attached components can be adjusted, thereby altering the path of the belt.

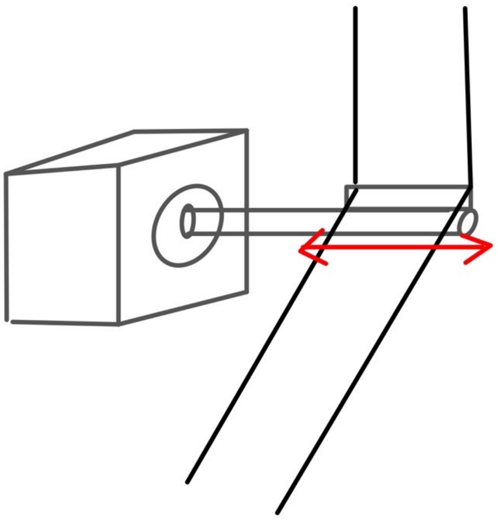


**Figure 4.9:** Concept 11: Mini move.

The Mini move concept (Figure 4.9) operates as a direct linear actuator, eliminating the need to convert rotational motion into linear displacement. In this design, the actuator extends a shaft equipped with a slotted guide, which the belt passes through to control its path.

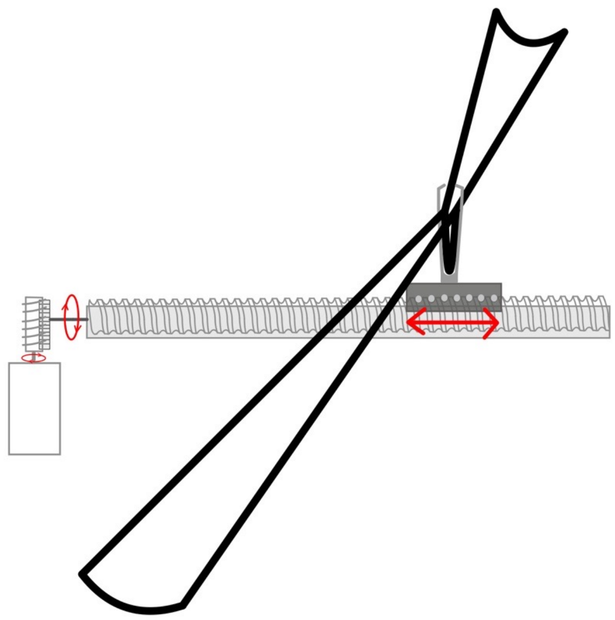


**Figure 4.10:** Concept 13: Compact deform.

The Compact deform concept (Figure 4.10) is similar to Concept 6, featuring a lead screw driven by a brushed DC motor. However, it utilizes a worm gear rather than spur gears. Additionally, the diagonal pin is replaced by a buckle slot, which intentionally tensions the belt to facilitate precise control over the outflow direction.

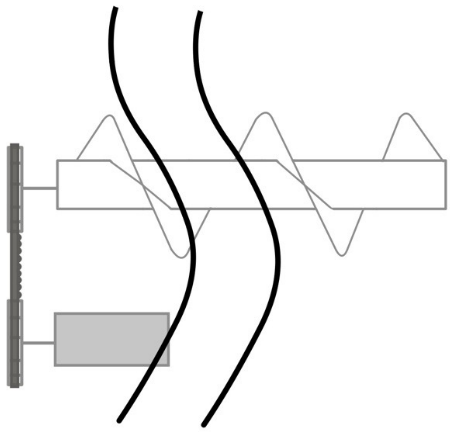


**Figure 4.11:** Concept 14: Teleport screw.

The Teleport screw concept (Figure 4.11) is similar to Concept 1. This design features a large screw where the belt is positioned between the threads, allowing it to translate along the screw's axis during rotation. The primary difference lies in the power transmission mechanism: this concept utilizes a toothed belt operating on a set of spur gears, driven by a brushed DC motor.

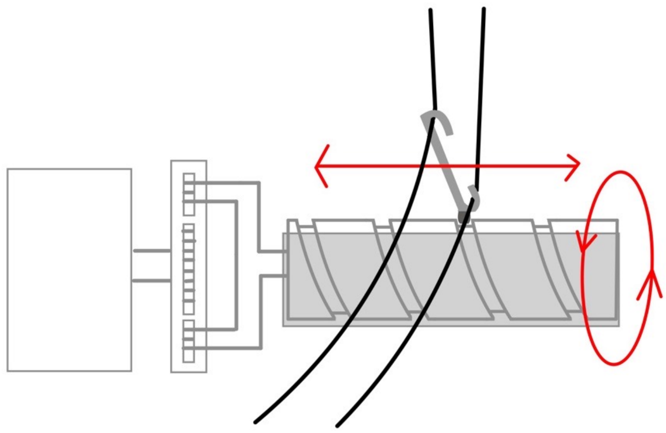


**Figure 4.12:** Concept 15: Pinned Barrel.

The Pinned barrel concept (Figure 4.12) is based on a barrel cam mechanism featuring a rotating cylindrical cam. A helical groove along the cam's surface translates the rotational motion into the horizontal movement of a sled. A diagonal pin is mounted on this sled to guide the belt. The entire mechanism is driven by a stepper motor coupled with a planetary gearbox.

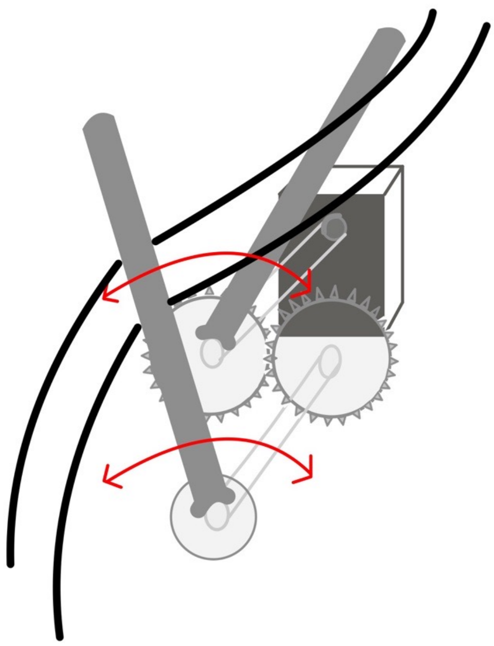


**Figure 4.13:** Concept 17: Gear-S.

The Gear-S concept (Figure 4.13) features one servo motor driving two larger pins in opposite directions to alter the angle of the webbing as it glides on the pins. The pins are directly mounted on the gears. It would be mounted in the car in the x-direction in the global coordinate system.

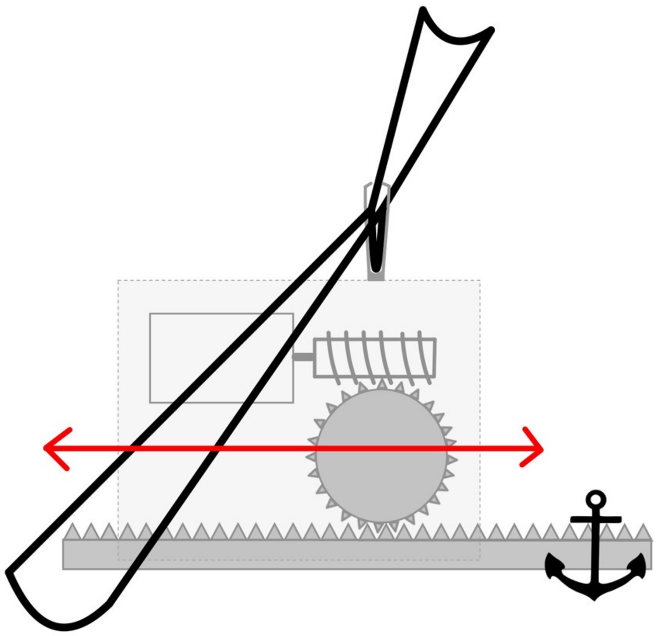


**Figure 4.14:** Concept 21: Compact carriage.

The Compact carriage concept (Figure 4.14) features a stepper motor geared down with a worm screw directly coupled to a rack and pinion mechanism. A small buckle slot is placed somewhere on the housing around the other components that interacts with the webbing. The rack is stationary while the rest of the assembly is moving relative to the rack. The idea behind this concept is to get a compact solution that can alter the angle of the webbing by almost 90 degrees unlike a slot which makes the webbing buckle unintentionally.

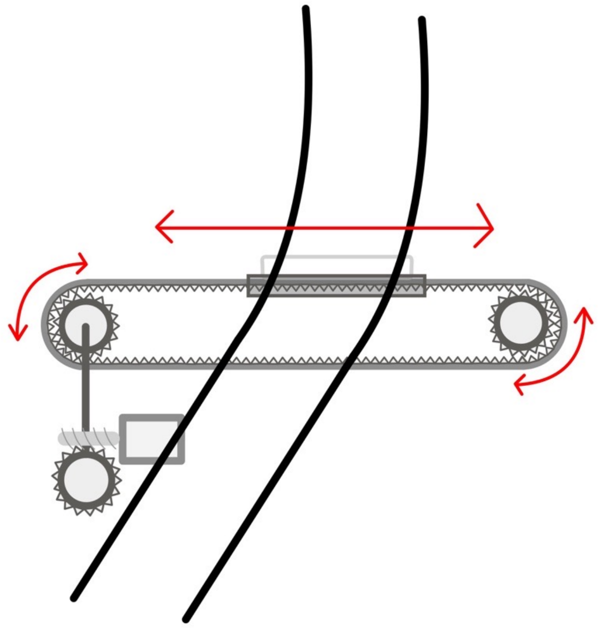


**Figure 4.15:** Concept 23: Slotted luggage.

The Slotted luggage concept (Figure 4.15) has a stepper motor driving a worm gearbox which is coupled to a toothed belt gear drive mechanism where the slot is mounted on the actual belt. The slot moves between the idler and the belt driver gear. The idea behind this concept is to utilize the precision of a toothed belt and stepper motor. The somewhat unconventional mounting directly on the belt itself could also generate valuable insights.

### 4.5.2 Pugh matrix

The concepts that remained after completion of the elimination matrix were passed on to the next screening process, the Pugh matrix. Unlike the elimination matrix, where concepts were evaluated one by one for a set of requirements, in this phase the concepts are instead evaluated against each other, based on a set of criteria. The following criteria were chosen:

- Complexity - How complex are interfaces with tolerances and how many parts that interface with each other?
- Cost - How much does the system cost?
- Reliability - How frequent is breakdown, and severity of consequences?
- Friction - How low and consistent is the webbing's friction?

- Packaging - How well it fits its designated space?

The complexity criterion was evaluated internally by quantifying the imagined total number of components and assessing the system interfaces. The assessment of the remaining criteria relied on established methodologies and expert input. Consultations with a Volvo cost engineer provided a framework for accurately estimating cost. To evaluate reliability, a basic Failure Mode and Effect Analysis (FMEA) was conducted, utilizing the resulting score to determine each concept's performance. In this FMEA, the most critical risk for each concept was considered, with its potential effect and cause. The severity, occurrence and detection for this risk was evaluated with a number between 1 and 10. The product of these three factors yields the Risk Priority Number (RPN), which serves as a metric for the reliability criterion. A higher RPN indicates diminished reliability, whereas a lower value signifies improved performance. Table 4.4 summarizes the outcome of this analysis.

**Table 4.4:** Basic FMEA analysis.

| Number | Concept name | Pot. Failure mode | Pot. Effect | Pot. Cause | Severity | Occurrence | Detection | RPN |
|---|---|---|---|---|---|---|---|---|
| 1 | Inline Screw | Webbing slip-out | Webbing jamming | Retractor tightens webbing | 8 | 3 | 7 | 168 |
| 2 | Wall | Sled wear-out | Annoying noise | High friction | 3 | 6 | 2 | 36 |
| 6 | Diagonal sled | Diagonal pin breaks | Loss of function | High loads on pin | 9 | 2 | 9 | 162 |
| 9 | StepSlideSlot | Sled wear-out | Annoying noise | High friction | 3 | 6 | 2 | 36 |
| 10 | HelicalSnake | Motor breaks | Loss of function | High loads | 8 | 4 | 10 | 320 |
| 11 | Mini Move | Axle is bending | Axle lock | High forces | 5 | 4 | 8 | 160 |
| 13 | Compact Deform | Structure with slot breaks | Loss of function | High load | 9 | 2 | 9 | 162 |
| 14 | Teleport Screw | Webbing slip-out | Webbing jamming | Retractor tightens webbing | 8 | 3 | 7 | 168 |
| 15 | Pinned Barrel | Diagonal pin break | Loss of function | High loads | 9 | 2 | 9 | 162 |
| 17 | Gear S | Motor breaks | Loss of function | High loads | 8 | 4 | 10 | 320 |
| 21 | Compact Carriage | Structure with slot breaks | Loss of function | High loads | 9 | 2 | 9 | 162 |
| 23 | Slotted Luggage | Belt breaks | Loss of function | High loads | 9 | 3 | 7 | 189 |

Furthermore, expert guidance from a Volvo supervisor established the performance benchmarks for friction. Lastly, for the packaging criterion, spatial constraints were analyzed by accessing digital vehicle models within the DMU Garage via Teamcenter and comparing the desired space to how the concepts would fit inside.

For the first iteration, it was decided to use concept 1 (Inline screw) as the reference. The result of this implementation is visualized below in Table 4.5.

**Table 4.5:** Pugh matrix evaluation first iteration.

| Criteria | Concepts | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1. In-line screw | 2. Wall | 6. Diagonal Sled | 9. Step Slide Slot | 10. Helical Snake | 11. Mini move | 13. Compact deform | 14. Teleport screw | 15. Pinned Barrel | 17. Gear S | 21. Compact carriage | 23. Slotted luggage |
| Complexity | REF | + | 0 | 0 | - | + | + | - | - | - | - | - |
| Cost | REF | + | + | 0 | - | - | + | - | - | - | - | 0 |
| Reliability | REF | + | 0 | 0 | - | 0 | 0 | 0 | 0 | - | 0 | - |
| Friction | REF | 0 | 0 | 0 | - | 0 | - | 0 | 0 | - | - | 0 |
| Packaging | REF | 0 | + | 0 | - | + | + | 0 | + | - | 0 | - |
| + | 0 | 3 | 2 | 0 | 0 | 2 | 3 | 0 | 1 | 0 | 0 | 0 |
| 0 | 0 | 2 | 3 | 5 | 0 | 2 | 1 | 3 | 2 | 0 | 2 | 2 |
| - | 0 | 0 | 0 | 0 | 5 | 1 | 1 | 2 | 2 | 5 | 3 | 3 |
| Sum | 0 | 3 | 2 | 0 | -5 | 1 | 2 | -2 | -1 | -5 | -3 | -3 |
| Rank | 4 | 1 | 2 | 4 | 8 | 3 | 2 | 6 | 5 | 8 | 7 | 7 |
| Decision | YES | YES | YES | YES | NO | YES | YES | YES | YES | NO | YES | YES |

Following the first iteration, Concepts 10 (Helical Snake) and 17 (Gear-S) were eliminated due to each receiving a score of -5, significantly underperforming compared to the alternatives, especially against the reference. Both concepts comprise multiple components, which increases cost and complexity. Furthermore, the additional contact points with the webbing result in higher friction, while their significant extension in one direction limits packaging feasibility. The remaining concepts were carried forward to a second evaluation round. For this subsequent iteration, Concept 9 (Step slide slot) was selected as the new reference. A mid-performing concept was deliberately chosen for this role to ensure a more balanced and nuanced comparison. The results of the second iteration are presented in Table 4.6.

**Table 4.6:** Pugh matrix evaluation second iteration.

| Criteria | Concepts | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 9. Step Slide Slot | 1. In-line screw | 2. Wall | 6. Diagonal Sled | 11. Mini move | 13. Compact deform | 14. Teleport screw | 15. Pinned Barrel | 21. Compact carriage | 23. Slotted luggage |
| Complexity | REF | 0 | + | + | + | 0 | - | - | - | 0 |
| Cost | REF | 0 | 0 | + | - | + | - | 0 | - | 0 |
| Reliability | REF | - | 0 | - | - | - | - | - | - | - |
| Friction | REF | 0 | 0 | 0 | 0 | - | 0 | 0 | - | 0 |
| Packaging | REF | 0 | 0 | + | + | + | 0 | + | 0 | - |
| + | 0 | 0 | 1 | 3 | 2 | 2 | 0 | 1 | 0 | 0 |
| 0 | 0 | 4 | 4 | 1 | 1 | 1 | 2 | 2 | 1 | 3 |
| - | 0 | 1 | 0 | 1 | 2 | 2 | 3 | 2 | 4 | 2 |
| Sum | 0 | -1 | 1 | 2 | 0 | 0 | -3 | -1 | -4 | -2 |
| Rank | 3 | 4 | 2 | 1 | 3 | 3 | 6 | 4 | 7 | 5 |
| Decision | YES | YES | YES | YES | YES | YES | NO | YES | NO | YES |

In this round, Concepts 14 (Teleport screw) and 21 (Compact carriage) were eliminated due to their low scores of -3 and -4, respectively. Their poor performance in the first iteration further validated this decision. Although the Compact Carriage design shares similarities with the Step Slide Slot reference, the inclusion of a buckle slot increases webbing friction and reduces reliability due to a higher risk of jamming. Similarly, the Teleport Screw exhibits lower reliability, while its toothed belt mechanism introduces additional complexity and cost. The remaining concepts advanced to a third and final iteration, where concept 13 (Compact deform) was selected as the reference. This choice was made because Compact deform demonstrated mid-range performance in the previous round and provided a distinct alternative to prior references. The results of this third iteration are illustrated in Table 4.7.

**Table 4.7:** Pugh matrix evaluation third iteration.

| Criteria | Concepts | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **13. Compact deform** | **1. In-line screw** | **2. Wall** | **6. Diagonal Sled** | **9. Step Slide Slot** | **11. Mini move** | **15. Pinned Barrel** | **23. Slotted luggage** |
| Complexity | **REF** | - | 0 | 0 | - | + | - | - |
| Cost | **REF** | - | 0 | 0 | - | - | - | - |
| Reliability | **REF** | 0 | + | 0 | + | 0 | 0 | - |
| Friction | **REF** | + | + | + | + | + | + | + |
| Packaging | **REF** | - | - | 0 | - | 0 | 0 | - |
| + | 0 | 1 | 2 | 1 | 2 | 2 | 1 | 1 |
| 0 | 0 | 1 | 2 | 4 | 0 | 2 | 2 | 0 |
| - | 0 | 3 | 1 | 0 | 3 | 1 | 2 | 4 |
| Sum | 0 | -2 | 1 | 1 | -1 | 1 | -1 | -3 |
| Rank | 2 | 4 | 1 | 1 | 3 | 1 | 3 | 5 |
| Decision | YES | YES | YES | YES | YES | YES | YES | NO |

In this final round, Concept 23 (Slotted luggage) was the sole concept eliminated, as it demonstrated the weakest performance with a score of -3. Consistent with previous evaluations, the toothed belt presents significant drawbacks regarding cost, complexity, and packaging constraints. These metrics, alongside earlier performance rankings, were utilized to drive the final decision. The remaining concepts that successfully progressed through all iterations of the Pugh matrix are as follows:

- Concept 1 - Inline Screw
- Concept 2 - Wall
- Concept 6 - Diagonal Sled
- Concept 9 - Step Slide Slot
- Concept 11 - Mini Move
- Concept 13 - Compact Deform
- Concept 15 - Pinned Barrel

The subsequent phase involves advancing the maturity of the remaining concepts through CAD modeling. However, the current number of concepts exceeds the capacity of the allocated time-frame. To address this, several concepts were consolidated. Concepts 2 and 9, which differ primarily in how the webbing is deflected, were combined into a single concept by adding a roof to the flanged rollers to effectively create a slot. Similarly, Concepts 6 and 13 were merged due to their shared characteristics; within this unified concept, both a diagonal pin and a buckle slot will be evaluated for webbing deflection. Finally, determining the most suitable gear mechanism, specifically comparing a spur gear to a worm gear, was established as a priority for further investigation.

A further critical decision involved Concept 11, which utilizes a linear actuator. Deeper investigation revealed that these specific actuators suffer from limited market availability in a suitable specification and a decision was made to exclude this concept, although the concept had significant potential. Thereby, the final selection of concepts to be further developed in CAD are:

- Concept 1 - Inline Screw
- Concept 2/9 - Rack and Roll
- Concept 6/13 - Lead Sled
- Concept 15 - Pinned Barrel

### 4.5.3 Testing setup

Parallel to the concept development phase, a dedicated test rig was designed and constructed. The primary purpose of the rig was to evaluate the functionality of each concept and to provide a clear demonstration of their respective working principles. To ensure a modular setup, a perforated plate was utilized as a universal mounting base for all concepts, as visualized in Figure 4.16.

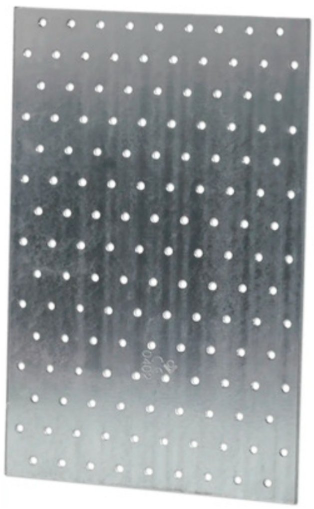


**Figure 4.16:** Perforated plate bought from Hornbach, with the dimensions 2x200x300 *mm*.

To facilitate physical demonstration and functional validation of the concepts by generating a motion, various motors were purchased. As established in the preceding chapters, the final concepts utilize two distinct motor types: stepper motors and brushed DC motors. Identical Nema 17 stepper motors were sourced from Electro:kit for two of the concepts. For the remaining concepts, one brushed DC motor featuring an integrated planetary gearbox was procured from Electro:kit, while a standard brushed DC motor without a gearbox was sourced from Kjell & Company. The specifications and visual appearance of these motors are presented in Figure 4.17 ((a)-(c))


**(a)** Stepper motor Nema17.

**(b)** DC motor with built-in planetary gearbox.

**(c)** Brushed DC motor.

**Figure 4.17:** The various motors used for the different concepts.

The subsequent phase focused on motor control and operational logic. During testing, control over parameters such as rotational speed, duration, and directional changes was essential. To facilitate this, an Arduino micro-controller was purchased from Electro:kit, see Figure 4.18a, integrated to serve as the system's central processing unit, capable of executing programmed instructions. However, since a standard micro-controller cannot handle the current levels required by electric motors, it was complemented with a motor driver shield, see Figure 4.18b. This shield acts as the system's power stage, handling the current supply to the motors while protecting the micro-controller's logic circuits.


**(a)** Arduino UNO R4 WiFi.

**(b)** Adafruit motor shield.

**Figure 4.18:** Arduino micro controller card and belonging shield.

Additional purchases were required in order for the system as a whole to work properly. Cables were utilized to transport the current from the Arduino to the motor of respective concept. The initial approach for the electrical connections was to first cut and strip the cables to appropriate length in both ends, and further solder one end of these cables directly to the DC motors and secure the opposing ends into the Arduino shield's screw terminals. However, this method was deemed impractical for the testing phase, as it lacked the modularity required to switch between concepts efficiently. The use of this method would have necessitated repeatedly loosening and tightening the screw terminals, leading to excessive setup times and potential wear. To resolve this, a quick-connect solution using Wago clamp connectors was implemented. Two permanent cable ends were secured to the Arduino shield, each connected in a Wago clamp. The Wago clamp is visualized in Figure 4.19, and this setup allowed for rapid transitions between the different DC motor concepts, as the motor leads could be interchanged instantly without the need for tools.

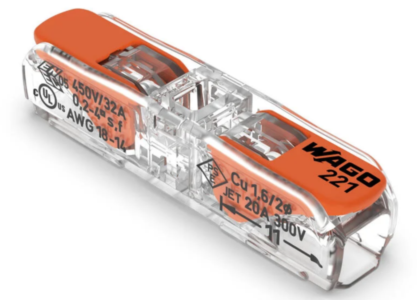



**Figure 4.19:** Wago clamp connector bought from Electrokit.

Integrating the stepper motor concepts proved more straightforward due to the pre-existing wiring. Each stepper motor was equipped with a four-lead cable, terminating in female DuPont connectors as illustrated in Figure 4.20 To interface these with the control system, male-to-male jumper wires were utilized as extensions, bridging the connection between the motor leads and the Arduino shield's terminals.

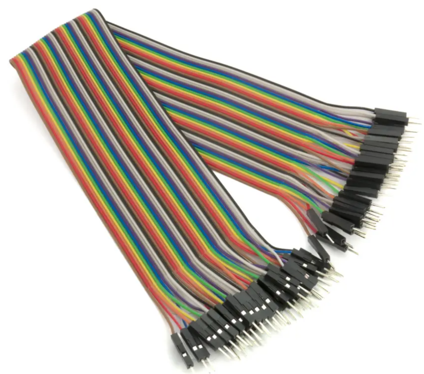


**Figure 4.20:** Male-to-male jumper wires bought from Electrokit.

As previously noted, the initial electrical connections to the DC motors were established via soldering. While this was sufficient for a few demonstrations, the solder joints eventually experienced mechanical failure under testing conditions. To ensure a more robust and reliable connection, the soldered joints were replaced with female spade connectors (Figure 4.21) sourced from Electro:kit. These terminals were secured to the cables using a crimping tool, providing a durable mechanical and electrical interface with the motor pins that could withstand the vibrations and handling of the testing phase.

**Figure 4.21:** Set of female spade connectors purchased from electrokit.

The switch controller (Figure 4.22a) was another important component that made demonstrating the concepts much easier. Originally, the motor ran on a hard-coded timer, spinning in one direction for a set period before automatically reversing. With the new controller, immediate manual control was gained, allowing start, stop, and reverse of the motor just by pulling a lever. The last purchased detail was the power supply (Figure 4.22b) desktop adapter, simply providing power to the system.


**(a)** Switch controller purchased from electrokit.

**(b)** Power supply adapter bought from electrokit.

**Figure 4.22:** Additional components bought.

To enable the manual control described above, custom Arduino firmware was developed for both motor types. Two separate scripts were programmed utilizing the

Adafruit Motor Shield library to interface with the power stage. The first script enables bidirectional control of the brushed DC motors, while the second script governs the stepper motors. Both scripts utilize the Arduino's built-in pull-up resistors to read the active state of the toggle switch, which is connected to pins 9 and 10. Based on the physical position of the switch, the software logic directs the respective motor to drive forward, drive backward, or release into a neutral, stationary state. The complete source code for both the DC and stepper motor configurations can be found in Appendix D.1 and D.2.

### 4.5.4 Concept development

To evaluate the feasibility and increase the maturity of the concepts, they were modeled in a CAD environment and subsequently subjected to physical testing. Rapid prototyping was utilized to facilitate quick iterations and resolve any mechanical interferences. Components not requiring high-precision tolerances were manufactured using Fused Filament Fabrication (FFF), commonly referred to as 3D printing. These parts were printed using either Polylactic Acid (PLA) or Polyethylene Terephthalate Glycol (PETG). Conversely, standard components requiring strict tolerances, such as electronics and hardware, were sourced from established commercial suppliers, primarily Electrokit and Kjell & Company (Electrokit Sweden AB, 2026; Kjell & Company, 2026). The primary objective of these prototypes was to visualize the design and verify functional performance. Consequently, to transition these conceptual designs into mass production, certain components will require adaptations to align with standard high-volume manufacturing processes.

**Concept 1 - Inline Screw**
The modeling of this first concept served as a primary learning phase, where fundamental knowledge regarding all concepts in general and 3D printing techniques was established. The concept's sketch was reviewed and constituent parts to be modeled were brainstormed. The brainstormed Bill of Materials (BOM) can be seen below in Table 4.8.

**Table 4.8:** Brainstormed Bill of Materials for Inline Screw.

| Part Name | Quantity |
|---|---|
| Planet gear | 3 |
| Sun gear | 1 |
| Gearbox housing | 1 |
| Stepper motor | 1 |
| Motor housing | 1 |
| Screw housing | 1 |
| Carrier + Axles | 1 |
| Big screw | 1 |

It was particularly difficult to constrain the correct degrees of freedom for all components, especially within the gearbox. It was essential to selectively restrict certain degrees of freedom while maintaining the necessary mobility for functional operation, as well as accounting for assembly requirements, as illustrated in the exploded view in Figure 4.23. For instance, the planet gears needed to rotate around their own axes and the sun gear's axis without translating along the longitudinal axis of the concept. A planetary gearbox usually consists of a sun gear, planet gears, a ring gear, and a carrier, where specific components can be held stationary to achieve a desired gear ratio. To gear down, the ring gear needs to be stationary while the planet gears and the carrier move. It was discovered that the ring gear and the planetary gearbox housing could share the same physical part to accommodate multiple functions, a principle known as function sharing.

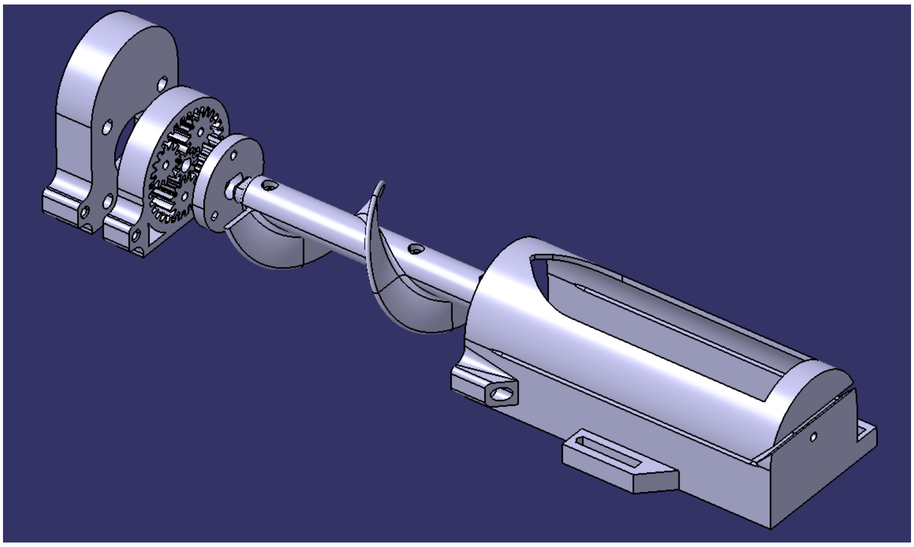


**Figure 4.23:** Exploded view of the Inline Screw concept.

However, the necessity of a gearbox was re-evaluated during the development process. Empirical testing and literature regarding stepper motor characteristics reveal that stepper motors provide peak holding and dynamic torque at very low speeds. As rotational speed increases, the available pull-out torque drops rapidly due to winding inductance and back-electromotive force (back-EMF) limiting the phase current, (Hughes & Drury, 2019). Incorporating a step-down gearbox requires the motor to operate at a proportionally higher speed to maintain the desired output velocity. For small motors, the torque degrades so significantly at higher RPMs (see Figure 4.24 for an illustration), that the mechanical advantage of the gear ratio is negated. In many cases, the amplified high-speed torque, subjected to the mechanical efficiency losses of the gearbox, results in a lower net output torque than a direct-drive configuration operating at a lower speed.

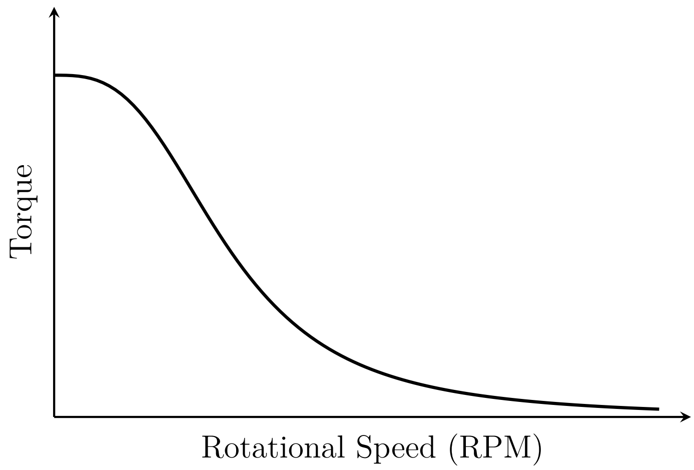



**Figure 4.24:** Typical pull-out torque curve for a stepper motor, AI generated image

Furthermore, adding a planetary gearbox introduces unnecessary mechanical complexity, friction losses, and backlash. For a low-cost concept, the added financial cost and manufacturing complexity of multiple precision gears cannot be justified when it yields diminishing, or even negative, returns in performance.

This turn towards a direct drive meant a potential for a simpler design with fewer parts, a smaller packaging volume, and higher precision with little to no backlash in the system, as seen in the revised BOM in Table 4.9. In addition, it was identified that the outer diameter of the housings could be greatly reduced from the existing 49 mm to around 30 mm. Unfortunately, this realization occurred late in the modeling phase. Due to strict time constraints, it was not feasible to alter the existing CAD models to reflect these dimensional reductions, although it would have been a beneficial improvement for the final design.

**Table 4.9:** Revised Bill of Materials for Inline Screw.

| **Part Name** | **Quantity** |
|---|---|
| Stepper motor | 1 |
| Motor housing | 1 |
| Screw housing | 1 |
| Big screw | 1 |

**Concept 2/9 - Rack and Roll**

The next concept to be modeled was Rack and Roll, a combination of the concept 2 "Wall" and concept 9 "Step Slide Slot". The modeling started with the same initial steps as Inline Screw, reviewing the concepts' sketches and figuring out what degrees of freedom should be locked in a certain part. The design comes from an idea to be as compact as possible with a worm gearbox sharing the gear with a rack and pinion mechanism. It featured a stationary rack beneath a housing that designed to accommodate the rest of the components. The pinion was decided to be 24 toothed, about the largest it could be without making the concept increase too much in height. The height both affects the packaging ability but also the stability and robustness of the concept as you get a larger lever arm around the rack. The CAD model of the concept is shown in Figure 4.25, and the brainstormed BOM is presented in Table 4.10 below.

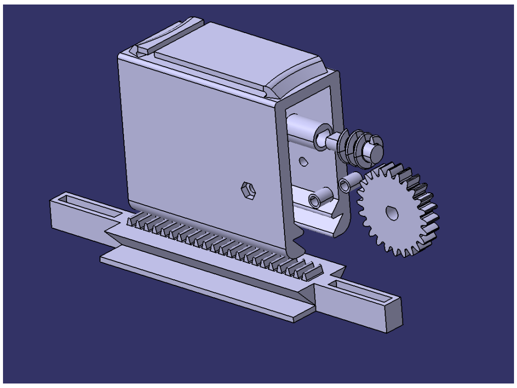


**Figure 4.25:** Exploded view of the Inline Screw concept.

**Table 4.10:** Brainstormed Bill of Materials for Rack and Roll.

| Part Name | Quantity |
|---|---|
| DC-motor | 1 |
| Worm screw | 1 |
| Worm gear / Pinion | 1 |
| Rack | 1 |
| Housing | 1 |

However, during the final assembly of all the latest parts and the electronics integrated, some problems were observed. Firstly, when having the pinion and worm screw hand-held together, the worm gearbox with a shared pinion did not achieve a gear reduction at all. The significant oversight was the relation between more pinion teeth making the gear larger in diameter (with the same "m-module") and the distance traveled linearly with one revolution. This is due to how the gear teeth count scales linearly with the gear diameter and thereby the gear's circumference. The circumference on a pinion is then translated to how long the pinion moves linearly with one rotation of the input.

If the concept was to work at all with the then-current system architecture, another smaller diameter pinion was to be placed on the same axle as the worm gear. But this approach would have been worse because the worm gearbox was only used to change direction of rotation 90 degrees and not actually used for gear reduction which would require a more costly DC-motor with built in gearbox.

This led to a new design iteration, involving a complete restructuring of the architecture while retaining most of the original components, except the worm gearbox. A brainstorming session, discussing whether the rack or motor should be stationary was held in the hope that a new architecture could be possible. The rack to be stationary was the more unconventional approach where the wires bending from the DC-motor moving would need to be managed. If the motor was stationary instead, it would pose potential packaging problems as the long rack would stick out to either side of the motor for the two extreme coordinates.

Instead, a decision for the rack to remain stationary and with a direct drive system where the pinion directly mounted on the motor axle and in turn directly rolling on the rack was seen to be the best compromise. The "deflect webbing" component could share function with the rail and slider part in the previous design to lock the rotation of the motor around its own axis, as well as only allowing for translation parallel to the rack. The final design for the prototype (see Figure 4.26) turned out to be compact but more importantly, simple. A further analysis of the stakeholder list from chapter 4.2.1, revealed that the direct supplier to Volvo Cars (sending the assembly unit) might not be experts in building small gearboxes with precision but the motor sub-supplier should be. A mass produced gearbox integrated with the brushed DC-motor should be more durable and have verifiable specifications of service temperature and corrosion resistance. The resulting updated parts list is presented in Table 4.11.

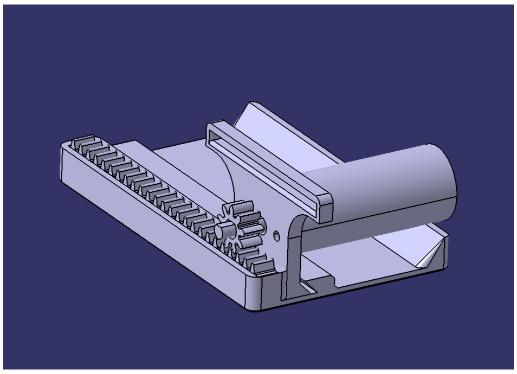


**Figure 4.26:** Revised CAD model of the Rack and Roll concept.

**Table 4.11:** Revised Bill of Materials for Rack and Roll.

| **Part Name** | **Quantity** |
|---|---|
| Geared DC-motor | 1 |
| Pinion | 1 |
| Rack | 1 |
| Housing | 1 |

**Concept 6/13 - Lead Sled**
The sketch for the next concept guided significantly in the design for it. The concept would have a lead screw, some rail and sled (with a screw nut geometry inside it) to lock rotation and allow translation only in one direction. The lead screw needed to be driven in one end, free in the other end while still being held in place to prevent dismount. The motor, gearbox housing and rail all needed to be stationary. The gearbox needs to have axles to spin but also prevent dismount longitudinally on the axle at the same time as being easy to assemble in the prototype. The gears were to be mounted in pairs, rotating together to transfer torque while spinning freely around the axle. All parts needs to be visible to showcase the motion for evaluation (see Figure 4.27).

Two main problems required resolution in this section: the gearbox with its housing and the nut for the lead screw. Starting with the gearbox, the primary objective was to achieve a compact design that could still be manufactured using 3D printing. An inline gear train would require excessive packaging space in the vehicle's y-direction. A brainstorm session regarding the layout concluded that a square, upside-down U-shape configuration would provide a relevant compromise between the y- and z-directions.

In a compound gear train, it is standard terminology to refer to the smaller wheel as the pinion and the larger wheel as the gear. To minimize the overall packaging space, the initial design concept utilized a sequence starting with the first axle at the motor, where a pinion meshed with a gear on the second axle positioned directly above it. This second axle was rigidly coupled to another pinion to drive the subsequent stage, a pattern intended to continue up to the fourth axle, which turns the lead screw. However, spatial evaluation in CAD revealed a diagonal clash between the components on the second axle and the fourth axle. To resolve this issue, the pinion on the second axle was replaced with a moderately larger gear. While this modification successfully eliminated the clash, it consequently resulted in a slightly lower overall gear ratio for the transmission.

For the mechanical assembly, the axles mounted to the housing are M2.5 screws secured by countersunk nuts on one wall. Because the paired gears needed to transfer torque while rotating freely around the stationary axles, custom adapters were created. These adapters feature a triangular outer profile to rotationally lock the gears together, combined with a smooth inner hole to act as a bearing surface against the screw. Finally, a press-fit motor adapter was designed utilizing the same triangular outer geometry to interface securely with the first driving pinion.

The second challenge involved the development of the internal thread geometry for the sled. The linear motion system utilizes a lead screw with a 2 mm pitch and four starts. Mechanically, a four-start thread consists of four independent helical ridges interleaved along the shaft. This dictates that while the distance between adjacent threads (the pitch) is 2 mm, the linear travel per full revolution (the lead) is 8 mm. Initially, the internal geometry of the 3D-printed nut was incorrectly modeled as a single-start thread, which prevented physical assembly. Once the geometry of the four starts was properly defined in the CAD environment, the model was updated to feature four parallel threads with an 8 mm lead, thereby achieving correct mechanical engagement.

Achieving functional tolerances for the 3D-printed sled required several iterations. Various parameters were systematically evaluated, including print orientation, adjusting thread clearances, and splitting the component for post-print assembly. A significant issue with printing a fully enclosed internal thread was the resulting poor surface resolution and internal overhangs, which caused binding and excessive friction against the metallic lead screw. To resolve this, the design was modified into a half-nut configuration by completely removing the top half of the internal thread geometry. This reduction allowed the component to be oriented optimally on the print bed. By printing the exposed thread profile facing upwards, internal overhangs were eliminated, yielding a significantly smoother surface finish on the active thread flanks. Consequently, this design change both enabled successful manufacturing with adequate resolution and minimized the frictional contact area between the lead screw and the printed polymer.

Furthermore, the diagonal pin on the sled requires a revision where it can handle the forces better than its current form. The lever arm around its bottom is to large for it to be viable in a production design. Suggestions for a performance increase includes choosing a strong material and building rib geometry behind it to support the moment.

Despite the extensive work on the custom gearbox, a late revision was made to the concept's powertrain. It was decided that utilizing a pre-geared DC-motor would be a more robust and reliable solution, eliminating the need for the complex, custom-built gearbox and significantly simplifying the housing design. However, due to time constraints during the project, the CAD model was not updated to reflect this final geared DC-motor configuration. Therefore, the visual representation in Figure 4.27 still showcases the initial custom gearbox layout, while the intended final components are reflected in the Bill of Materials in Table 4.12.

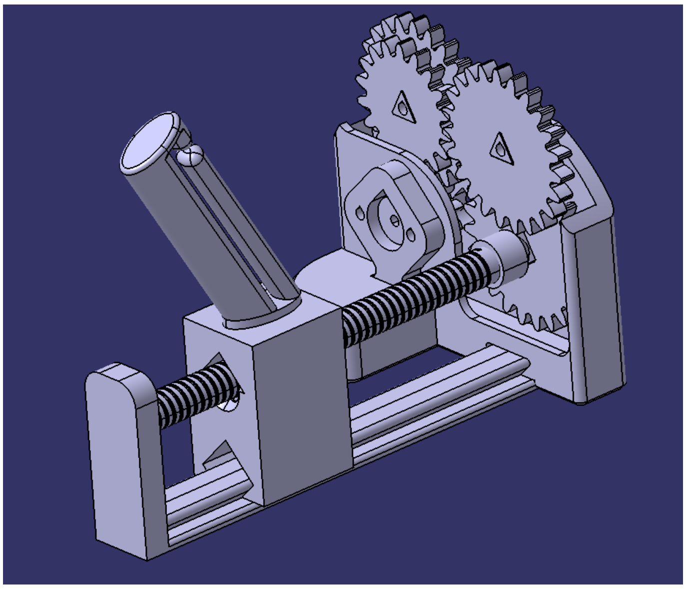


**Figure 4.27:** CAD model overview of the Lead Sled concept (showing the initial custom gearbox design).

**Table 4.12:** Intended Bill of Materials for Lead Sled (Revised Configuration).

| **Part Name** | **Quantity** |
|---|---|
| Geared DC-motor | 1 |
| Lead screw | 1 |
| Sled / Nut | 1 |
| Rail | 1 |
| Housing | 1 |

**Concept 13 - Pinned Barrel**

This concept features a stepper motor with its housing, a planetary gearbox and a barrel cam mechanism inside its housing, see Figure 4.28. On top of that housing and interacting with the barrel is a diagonal pin with an undercarriage geometry to both slide on the housing rails and to follow the barrel groove. Fortunately, this concept could share some components and geometry with Inline Screw. The barrel could be constructed inside a housing similar to the Big Screw housing with one end free and the other driven by the motor. The realization that a gearbox was unnecessary was shared by the Inline Screw concept, which is reflected in the final parts list presented in Table 4.13. On the same note, the outer diameter of the concept could also shrink with the Pinned Barrel concept.

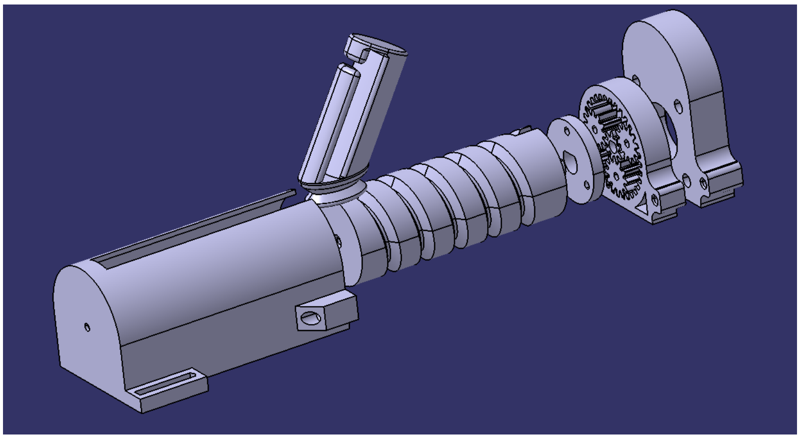


**Figure 4.28:** CAD model overview of the Pinned Barrel concept.

**Table 4.13:** Bill of Materials for the Pinned Barrel concept.

| **Part Name** | **Quantity** |
|---|---|
| Stepper motor | 1 |
| Barrel | 1 |
| Diagonal pin / Sled | 1 |
| Barrel Housing | 1 |

The diagonal pin's undercarriage is designed with an oval shape which allows it to swivel and thereby self-adjust its angle if the webbing demands it. The rails on the Barrel housing interacting with the oval undercarriage could be optimized to find a sweet spot between rattle noise and friction. Additionally, the diagonal pin's lever arm around the rail creates a large moment. Further development therefore suggests to modify the pin, alternatively supported by ribs at the bottom, or eventually use a stronger material.

### 4.5.5 Motor Selection Estimation

A primary objective during the detailed evaluation phase was to establish a standardized method for determining and comparing the required motor specifications across the different concepts. To achieve this, a kinematic and kinetic evaluation script was developed in MATLAB, see Appendix C. The core purpose of this script was to create a unified baseline for evaluating both stepper and brushed DC motors.

By calculating the required rotational speed and torque for each concept, the risk of over-dimensioning the motors was mitigated. This optimization was a crucial step in fulfilling the overarching project goal of reducing the total cost of the mechanism assembly.

The mathematical model was driven by the global system requirements, which were established using baseline approximations: a target linear force of 20 N and a target linear speed of 20 mm/s. The target speed was selected to ensure a subjectively natural motion, chosen to be within the same order of magnitude as standard motorized seat adjustments. The target force of 20 N was estimated based on the typical retraction force of a seatbelt retractor, representing the primary opposing force the mechanism must counteract when the seatbelt is buckled into the buckle assembly. It should be noted that both parameters serve as preliminary estimations and should be interpreted with caution until verified through empirical testing.

A critical component of the script involved estimating the varying mechanical efficiencies of the respective concepts. Frictional losses, particularly where the seatbelt webbing deflects around pins or screws, were modeled using the capstan equation (Eytelwein's formula) from Gupta, 2008. To accurately capture more complex webbing paths, these losses were evaluated in multiple sequential stages. For instance, in concept 1 *Inline Screw*, the total wrap angle was divided into successive deflections, specifically estimated as an initial 10° turn, followed by a 20° deflection, and a final 10° adjustment, to calculate the cumulative friction. Additional mechanical losses, such as sliding friction within lead screw nuts, were estimated utilizing standard machine element theory derived from Budynas and Nisbett, 2024. Furthermore, it must be acknowledged that several friction coefficients applied in these calculations are approximations. Due to the lack of specific literature covering the exact material pairings and varying surface roughness of the custom components, empirical testing would be required to establish definitive friction values. It should also be noted that while frictional forces were carefully accounted for, the system's moment of inertia was intentionally excluded from these preliminary sizing calculations to simplify the analytical model.

Based on each concept's specific Transmission Ratio (TR), defined as the linear distance traveled in millimeters per one full revolution of the input shaft, and its calculated mechanical efficiency ($\eta_{eff}$), the script computed the exact operational targets for the required RPM and Torque $T$ using the following Equations 4.1 and 4.2. In these equations, $v$ represents the target speed, while $F$ is defined as target force.

$$\text{Required RPM} = \frac{\text{v} \times 60}{\text{TR}} \tag{4.1}$$

$$\text{T (Nm)} = \frac{\text{F} \times \left(\frac{\text{TR}}{1000}\right)}{2\pi \times \eta_{eff}} \tag{4.2}$$

The output of the script provided a comparative graph mapping the required RPM and torque for the four final concepts, see Figure 4.29.

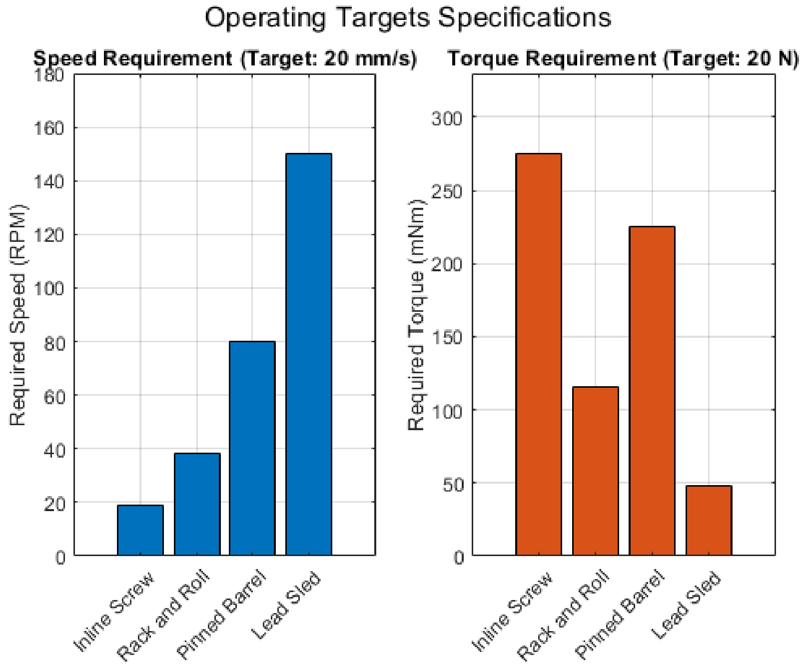



**Figure 4.29:** MATLAB generated bar charts displaying the required RPM and Torque (mNm) for the evaluated concepts to reach the 20 N and 20 mm/s targets.

The generated data effectively highlighted the inherent mechanical trade-offs between the mechanisms. For instance, the *Inline Screw* (TR = 63 mm/rev) required the lowest rotational speed (approximately 19 RPM) but demanded the highest torque output (275 mNm). Conversely, the *Lead Sled* (TR = 8 mm/rev) required a significantly higher speed (150 RPM) but operated under the lowest torque requirement (48 mNm). This comparative analysis was instrumental in the subsequent Kesselring evaluation, as it directly dictated the physical size, type, and economic feasibility of the motors required to successfully actuate each conceptual architecture.

### 4.5.6 Kesselring matrix and cost evaluation

Before the implementation of the actual Kesselring matrix, the included criteria first needed to be determined. These criteria were discussed with Volvo supervisor, to align well with the project scope and objectives. The significance of each criterion is discussed below;

- Complexity - This criterion addresses the challenges associated with component interfaces, including geometric tolerances and the total number of parts. These factors directly affect the value chain across development, transportation and assembly.
- Webbing Reliability - This criterion manages the pure functionality of the mechanism. How frequently does the belt end up at desired position, and what

is the general deviation? The criterion accounts for the risk of webbing jams or folding, and the impact of friction between the webbing and the mechanism on overall performance.

- Durability/Environment - This criterion evaluates the operational lifespan of the mechanism within the automotive environment. Because the entire mechanism is replaced as a single unit upon the failure of any individual component, the weakest part dictates the overall system lifetime. This has direct cost implications for either Volvo Cars (under warranty) or the customer (post-warranty). Furthermore, this criterion assesses the system's resistance to wear and environmental degradation, including corrosion, humidity, and temperature fluctuations.

- Vehicle Integration - This criterion evaluates how effectively the mechanism fits into the allocated packaging space. Because the various concepts may require different mounting orientations, their integration directly impacts the design of the interior trim and the surrounding structural body components.

- User Experience - This criterion assesses the mechanism's perceived quality, including its noise generation and resistance to misuse. These user-facing attributes directly influence overall customer satisfaction with the new feature.

For these criteria, a weigh matrix was initially established internally, and these results are illustrated in Table 4.14. The initial results of the weight matrix indicate that webbing reliability is the most critical criterion, receiving a weight of 7. This is followed by user experience (6) and durability/environment (5). Complexity and vehicle integration were ranked lowest, tying with a score of 1.

**Table 4.14:** Initial weight matrix.

| Criteria | Complexity | Webbing Reliability | Durability/Environment | Vehicle Integration | User Experience | Total sum | w |
|---|---|---|---|---|---|---|---|
| **Complexity** | X | 0 | 0 | 0,5 | 0 | 0,5 | 1 |
| **Webbing Reliability** | 1 | X | 1 | 1 | 0,5 | 3,5 | 7 |
| **Durability/Environment** | 1 | 0 | X | 1 | 0,5 | 2,5 | 5 |
| **Vehicle Integration** | 0,5 | 0 | 0 | X | 0 | 0,5 | 1 |
| **User Experience** | 1 | 0,5 | 0,5 | 1 | X | 3 | 6 |

To gather expert input and validate these initial assessments, an empty evaluation matrix (see Table 4.14) was distributed to four specialists within Volvo's Occupant Safety department. After reviewing their individual rankings, the initial weight matrix was slightly adjusted, resulting in the final weight matrix presented in Table 4.15.

**Table 4.15:** Final weight matrix.

| Criteria | Complexity | Webbing Reliability | Durability/Environment | Vehicle Integration | User Experience | Total sum | w |
|---|---|---|---|---|---|---|---|
| **Complexity** | X | 0 | 0 | 0,5 | 0 | 0,5 | 1 |
| **Webbing Reliability** | 1 | X | 0,5 | 0,5 | 0 | 2 | 4 |
| **Durability/Environment** | 1 | 0,5 | X | 1 | 0,5 | 3 | 6 |
| **Vehicle Integration** | 0,5 | 0,5 | 0 | X | 0 | 1 | 2 |
| **User Experience** | 1 | 1 | 0,5 | 1 | X | 3,5 | 7 |

In contrast to the initial evaluation, the final weight matrix indicates a shift in priorities, with user experience emerging as the highest-ranked criterion with a score of 7. Durability/Environment also increased in importance to a score of 6, while webbing reliability dropped to a 4. Vehicle integration and complexity retained their bottom rankings with scores of 2 and 1 respectively.

Tables 4.16-4.20 represents the grading scales for each criterion. Because it is difficult to assign strict numerical values to several criteria, qualitative descriptors such as "high" and "low" was utilized for the assessment. While explicit definitions for grades 2 and 4 are omitted from the rubric, concepts can still receive these scores if their performance is judged to fall between the defined benchmarks of 1 and 3, or 3 and 5. To perform the Kesselring matrix evaluation, four additional members from Volvo's Occupant Safety department were convened. The primary objective was to ensure a shared understanding of the grading scales across all participants, thereby minimizing subjectivity and securing an objective, consistent assessment of the concepts.

**Table 4.16:** Complexity grading scale.

| Complexity | Grade |
|---|---|
| **High complexity** | 1 |
| | 2 |
| **Moderate complexity** | 3 |
| | 4 |
| **Low complexity** | 5 |

**Table 4.17:** Webbing reliability grading scale.

| Webbing Reliability | Grade |
|---|---|
| **Low reliability** | 1 |
| | 2 |
| **Moderate reliability** | 3 |
| | 4 |
| **High reliability** | 5 |

Concepts demonstrating low complexity are awarded higher grades, whereas an increased level of complexity results in a lower grade. Similarly, a high grade is given to concepts judged to have robust webbing reliability, while a lower grade reflects a higher probability of reliability issues.

**Table 4.18:** Durability grading scale.

| Durability/Environment [Years] | Grade |
|---|---|
| **[0, 2)** | 1 |
| **[2, 5)** | 2 |
| **[5, 8)** | 3 |
| **[8, 12)** | 4 |
| **[12, $\infty$)** | 5 |

**Table 4.19:** Vehicle Integration grading scale.

| Vehicle Integration | Grade |
|---|---|
| **Poor integration** | 1 |
| | 2 |
| **Moderate integration** | 3 |
| | 4 |
| **Good integration** | 5 |

Concepts judged to be highly durable and capable of withstanding the automotive environment receive higher grades, whereas lower grades indicate poor long-term resilience. Uniquely, this is the only criterion evaluated using quantitative numerical data. Furthermore, concepts that offer spatial packaging advantages are awarded higher grades, while physically larger designs receive lower scores.

**Table 4.20:** User experience grading scale.

| User Experience | Grade |
|---|---|
| **Low satisfaction** | 1 |
| | 2 |
| **Moderate satisfaction** | 3 |
| | 4 |
| **High satisfaction** | 5 |

Concepts perceived as user-friendly and possessing a quiet, pleasant acoustic profile are awarded higher scores. Conversely, lower scores are assigned to concepts that generate harsh or disruptive, as well as not being user friendly.

The complete Kesselring matrix is presented in Table 4.21. Following the assessment of all concepts against the defined criteria and the calculation of their weighted scores, Rack and Roll achieved the highest total score of 73. Lead Sled ranked second with a score of 60, followed by Inline Screw with a score of 40. Pinned Barrel ranked lowest with a total score of 28. Consequently, Rack and Roll was selected for further development in the detailed design phase.

**Table 4.21:** Kesselring Evaluation Matrix.

| **Chalmers** | | **Kesselring Evaluation Matrix** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Concepts** | | | | | | | | | |
| | | **Ideal** | | **Inline screw** | | **Rack and Roll** | | **Lead Sled** | | **Pinned barrel** | |
| *Criteria* | *w* | *v* | *t* | *v* | *t* | *v* | *t* | *v* | *t* | *v* | *t* |
| Complexity | 1 | 5 | 5 | 3 | 3 | 4 | 4 | 3 | 3 | 1 | 1 |
| Webbing Reliability | 4 | 5 | 20 | 1 | 4 | 4 | 16 | 3 | 12 | 2 | 8 |
| Durability/Environment | 6 | 5 | 30 | 4 | 24 | 4 | 24 | 3 | 18 | 1 | 6 |
| Vehicle Integration | 2 | 5 | 10 | 1 | 2 | 4 | 8 | 3 | 6 | 3 | 6 |
| User Experience | 7 | 5 | 35 | 1 | 7 | 3 | 21 | 3 | 21 | 1 | 7 |
| Total | | 25 | 100 | 10 | 40 | 19 | 73 | 15 | 60 | 8 | 28 |
| Rank | | (1) | (1) | 3 | 3 | 1 | 1 | 2 | 2 | 4 | 4 |
| Decision | | | | No | | Yes | | No | | No | |

### 4.5.7 Detailed design

This section outlines the detailed design phase of the chosen concept. It covers key stages such as continuous development, material selection, assembly and cost analyses, and the construction of final prototype.

While Rack and Rolls design selected through the Kesselring matrix was deemed the most promising, several technical challenges remained. During the evaluation, the motor selection was scrutinized, particularly regarding the system's behavior during a high-G collision. As established in Chapter 1.1, the optimal positioning of the seatbelt is on the center of the shoulder, preferably closer to the neck. In a crash scenario, the pre-tensioner's activation requires the sliding bracket to move instantaneously to its innermost extreme position. Consequently, the mechanism must exhibit minimal resistance to external loads.

In the initial design, the DC-motor and gearbox assembly lacked the necessary *back-drivability*; the high gear ratio prevented the output shaft from being back-driven by the seatbelt's tension. To address this, a complex slip clutch mechanism was proposed. The conceptual design for this clutch involved a friction-based interface where the pinion would slip on the motor shaft when a specific force threshold was exceeded. This was envisioned using a circular bore pinion, two polytetrafluoroethylene (PTFE) washers, and a helical spring to provide a constant axial preload.

Although mechanically feasible, this solution would significantly increase the mechanical complexity, introduce additional wear surfaces, and create more potential points of failure. In contrast, a stepper motor inherently possesses the ability to "slip" electrically. When the external load exceeds the motor's holding torque, the magnetic bond is broken, allowing the motor to skip steps without any mechanical damage. Leveraging this characteristic simplifies the design by removing the need for a physical clutch. Following the Kesselring evaluation, the decision was made to transition to a stepper motor, necessitating a redesign of the bracket and housing to accommodate the stepper motor's larger diameter and shorter axial length. The final Rack and Roll concept occupies a total packaging envelope of 100 x 38 x 63 mm (y, z, and x directions, respectively).

The next natural step in the development process was to determine a robust method for the system to track and verify the motor's position at all times. While traditional mechatronic systems often rely on physical limit switches or Hall-effect sensors, it has become increasingly common within the 3D printing industry to utilize more streamlined solutions. By adopting similar principles, the need for external sensing hardware can be eliminated. Specifically, an integrated automotive stepper driver (Smart Power IC) can be utilized to implement sensorless homing by monitoring the Back Electromotive Force (BEMF) to detect mechanical stalls. This approach allows the system to define its zero-position upon start-up by driving the mechanism against a mechanical hard stop; the resulting drop in BEMF serves as a precise digital signal that the end-of-travel has been reached. In a high-volume automotive context, this method not only reduces the Bill of Materials (BOM) but also increases long-term reliability by removing potential points of failure such as wiring harnesses and mechanical switch fatigue.

The mechanical hard stops were conceptualized as physical barriers at each extremity of the $y$-axis, designed to terminate the translation of the sliding bracket and motor assembly, thereby constraining the webbing's travel. However, determining the optimal placement of these stops while ensuring the system remained manufacturable and easy to assemble presented a significant design challenge. Several configurations were evaluated, including integrating the stops into the guide track, the rack itself, or just outside the rack's guide slot. Through a series of brainstorming sessions, the advantages and drawbacks of each configuration were analyzed, particularly regarding structural integrity and spatial constraints.

Ultimately, all concept variants had almost equally valued advantages and drawbacks which meant no sole "winner" could be chosen, see below in Figure 4.30 for a hybrid version where the housing has one of the walls and the rack has the other wall. The choice remains when or if Volvo decides to follow through with this concept. What is most important is the learning gained when analyzing design for each component, what DoF need to be locked by which design feature and how that affects manufacturability and ease of assembly for both the supplier and Volvo factories. This can be exemplified by the sliding bracket, rack and housing. The sliding bracket need all DoF but $y$-translation locked. Additionally, in the end coordinates of the rack, some geometry needs to lock the translation unilaterally (in one direction). In the current designs, all DoF but one is locked by the mating geometry between the sliding bracket and guide slot. The sliding bracket is slid from the side into the triangular profile of the guide slot of which its overhang prevents $z$-translation.

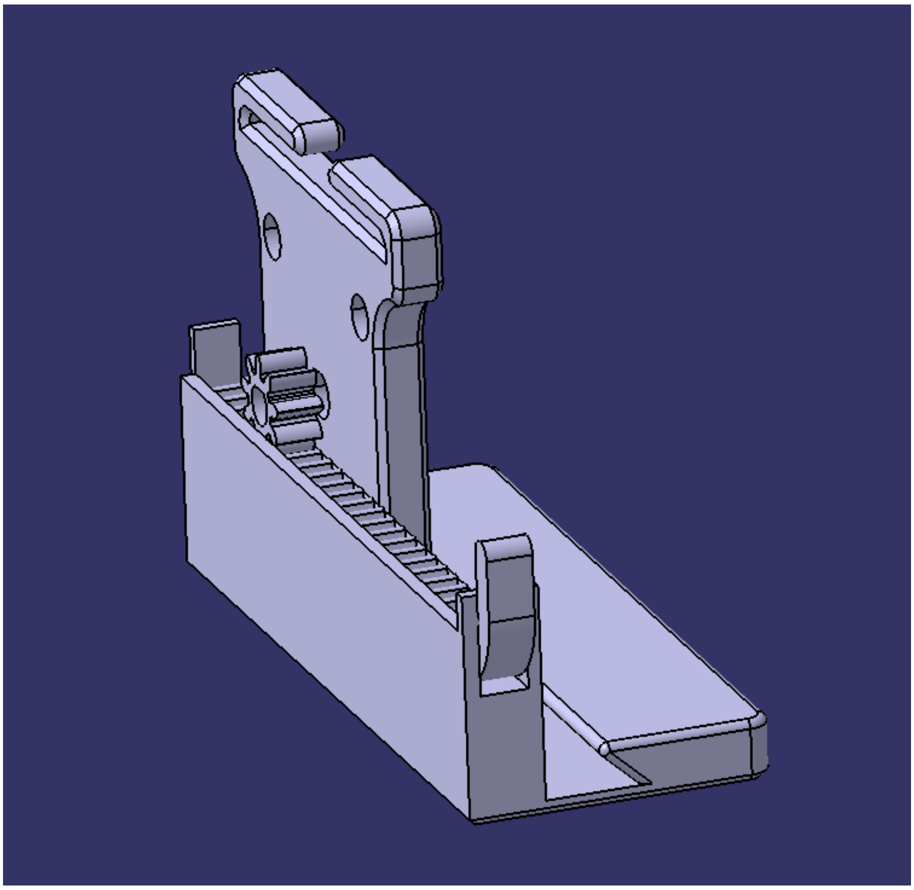
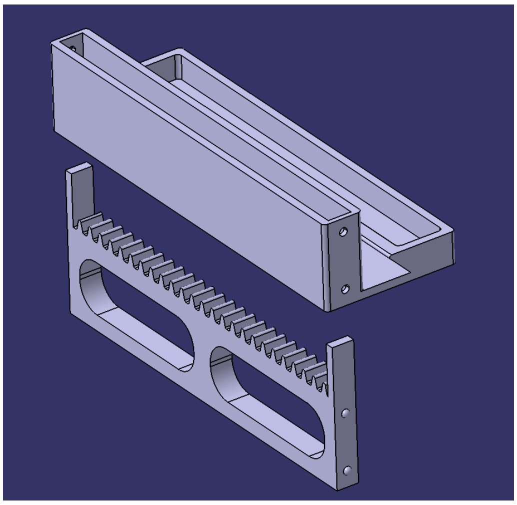


**Figure 4.30:** CAD model of the Rack and Roll concept.

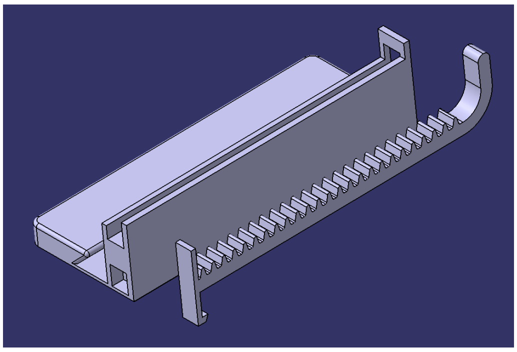
This overhang geometry however, increases the complexity for manufacturing with no traditional clear parting line for the injection molding process. If the side walls would be perpendicular against the bottom surface or even with a slight draft angle, it would improve manufacturability. It would also allow the rack to be entirely integrated into the housing, it could be the same physical part sharing multiple functions or features. The sliding bracket with motor and pinion could just be placed down instead of slid as it is now. This in turn would mean some other geometry has to lock the $z$-translation, probably other geometry on the housing.

To explore these assembly improvements, two distinct design variants for the rack mounting interface were developed, as shown in Figure 4.31. In the first variant (Figure 4.31a), a vertical insertion method was utilized, where the rack is pressed upwards into a corresponding hole profile in the housing. The rack is then positioned and secured by two indents built in the housing structure. This design minimizes the footprint but requires precise tolerances to ensure the indents engage correctly during assembly.

The second variant visualized in Figure 4.31b employs a 'hinge-and-latch' approach. In this configuration, one end of the rack is initially positioned using a hook feature that acts as a pivot. The rack is then rotated into place, where the opposite end is secured by a final cantilever snap-fit. This method potentially reduces the assembly force required compared to the first variant, offering a more ergonomic solution for high-volume factory assembly lines. However, this assembly method requires the motor and pinion to be positioned at the lowest extreme of the track, allowing the rack to rotate underneath the pinion before being secured by the hasp mechanism.



**(a)** Variant 1: Press-fit with dual snap-fits.



**(b)** Variant 2: Hinge-and-latch assembly.

**Figure 4.31:** Design variants for the rack mounting interface.

For a future production unit, it is crucial to ensure a secure mounting of the pinion to the motor shaft, as material swelling under high temperature or humidity conditions could lead to axial slip. This can be effectively mitigated by designing the pinion with an integrated set screw to mechanically lock on the shaft under all environmental conditions.

### 4.5.8 Failure Modes and Effects Analysis

To ensure an efficient and focused FMEA process, the scope was limited to the most critical and harsh risks. Furthermore, following the construction of the Rack and Roll prototype, practical test runs were conducted to better identify and evaluate these potential failure modes in a real-world setting. The full FMEA is visible below in Table 4.22.

**Table 4.22:** FMEA

| Potential Failure Mode | Potential Effect of the Failure | Potential Cause of Failure | Severity | Occurrence | Detection | Potential Action |
|---|---|---|---|---|---|---|
| Too high and inconsistent sound | Lower perceived quality | Motor jitters/vibrates / Too much clearance | 3 | 10 | 1 | Tune motor driver / Less clearance / Sound insulation material |
| Wear of rack and pinion | Pinion doesn't engage with rack / mechanism jamming | Too much contact pressure / Dirt and particles enter the system | 6 | 4 | 5 | Optimize teeth engagement consider helical gears. / Enclose the mechanism more by adding roof perhaps. |
| Motor skips steps | Motor doesn't know where it is | Lateral force exceeds stepper motors holding torque | 2 | 5 | 10 | Stronger motor/Feedback out of position |
| Cable shear due to fatigue | No power | Cable bends during use. | 6 | 2 | 6 | Design against small bends in cable |
| Wear on webbing | Less perceived aesthetics | Friction and sharp edges | 3 | 2 | 4 | Material choice |
| Jamming in mechanism | Webbing doesn't move towards the neck in a crash | Too large forces during crash | 10 | 1 | 6 | Material choice / Optimize teeth engagement and / or sliding bracket engagement. |
| Webbing slides out from slot | Loss of functionality. No adjustment of webbing | Poor design of slot. Forces pressing upwards. | 7 | 2 | 1 | New enclosed design of slot. |

The first failure mode addresses the excessive and inconsistent noise generated by the mechanism. The severity rating is low, as it's a perceived quality issue rather than a safety hazard. Conversely, the occurrence rating is high due to the persistent nature of the issue in the current design. However, the detection score is kept low, as the noise is highly noticeable and would easily be identified during quality control before the vehicle reaches the customer.

Another failure mode involves the mechanical wear of the rack and pinion components. The severity is rated higher for this mode, as excessive wear leads to a total loss of mechanism functionality. However, the occurrence is estimated to be low, and the detection score reflects that such wear can be identified through maintenance.

Motor skipping steps results in a loss of synchronization between the controller and the mechanism. While the severity is minimal, affecting only the precision of the adaptive function, the detection score is high due to the difficulty of identifying step loss before a functional deviation occurs. Though not frequent, the occurrence is rated to account for potential incidents during the mechanism lifespan.

Fatigue-induced cable shear results in a total loss of functionality, warranting a severity rating consistent with other functional failures. While the likelihood of this occurring is low, the detection score is higher because internal cable degradation is harder to monitor compared to mechanical wear.

Webbing wear is primarily considered an aesthetic issue rather than a critical safety failure, resulting in a low Severity rating. Given that both the Occurrence and Detection scores are also low, this failure mode is assigned a low overall priority in the risk assessment.

In contrast, a jam in the mechanism represents a critical safety risk, particularly during a collision. The severity is rated as maximum (10) because such a failure could be life-threatening. While the occurrence is judged to be rare, the detection rating is high, as this failure mode is difficult to identify until the system is subjected to extreme impact forces.

The final failure mode identifies the risk of the webbing sliding out of its designated slot. The severity is rated consistently with other functional losses, as it renders the adaptive mechanism inoperable. However, the occurrence is deemed highly unlikely under the current design constraints, and the detection score is low, as the displacement would be easily identified.

### 4.5.9 Material Selection

Table 4.23 outlines the initial parameters for the material selection process, which encompasses all plastic components of the mechanism. The Rack and Roll concept features both a gear mechanism and a sliding friction load case, necessitating a balance between thermal stability and mechanical performance. To ensure reliability across the diverse global markets served by Volvo Cars, a service temperature range of −40°C to +80°C was determined. This interval serves to screen out standard polymers that fail to maintain structural integrity or functionality at these extremes. Regarding mechanical requirements, the materials must possess sufficient rigidity to maintain their form under load while simultaneously exhibiting low-friction 'sliding' properties to ensure smooth operation.

Furthermore, the selected materials must be compatible with injection molding to facilitate high scalability and cost-efficiency. The material also must be resistant to water, to withstand potential condensation or moisture buildup within the trim panel. Furthermore, a minimum elongation constraint of $\geq 5\%$ was established. This degree of ductility is necessary to facilitate the snap-fit mechanism locking the rack, ensuring the material can undergo the required deflection without experiencing brittle failure.

Regarding the objectives, cost and material hardness were chosen as the primary properties to optimize. Cost-efficiency has been a central constraint driving design decisions throughout the project. Material hardness was prioritized as a metric to mitigate wear. While the mechanism operates within an automotive cabin experiencing ambient temperatures up to +90°C, this environmental thermal load is already accounted for by the standalone service temperature constraint. Furthermore, the mechanism features an intermittent operating profile with a low duty cycle, meaning that friction-induced heat accumulation, a primary driver of complex wear modes in polymers, is negligible. Consequently, the tribological evaluation can be simplified by utilizing Archard's wear Equation (4.3) as a relative estimation model:

$$Q = \frac{KWL}{H} \tag{4.3}$$

where $Q$ is the wear volume, $K$ is the dimensionless wear coefficient, $W$ is the applied normal load, $L$ is the sliding distance, and $H$ is the material hardness, Hutchings and Shipway (2017). Given that the normal load (approximately 20 N) and sliding distance remain constant across all material alternatives, the total wear volume becomes inversely proportional to the material hardness. Thus, maximizing surface hardness serves as a robust and reliable indicator for optimizing wear resistance under these specific operating conditions. The information is summarized below in Table 4.23.

**Table 4.23:** Summarizing table for the mechanism

| | |
|---|---|
| Component | All plastic parts in mechanism |
| Function | Adjust webbing position along shoulder |
| Constraints | Service temperature $-40\,°C$ to $+80\,°C$ |
| | Water resistance: Excellent |
| | Processability: Injection molding: Acceptable OR Excellent |
| | Elongation 5% |
| Objectives | Maximize Hardness |
| | Minimize Cost |

By implementing the constraints and objectives in Granta, the plot according to figure 4.32 was generated. Since price was assigned at the x-axis, and hardness at the y-axis, materials located as close to the top left corner as possible were relevant.

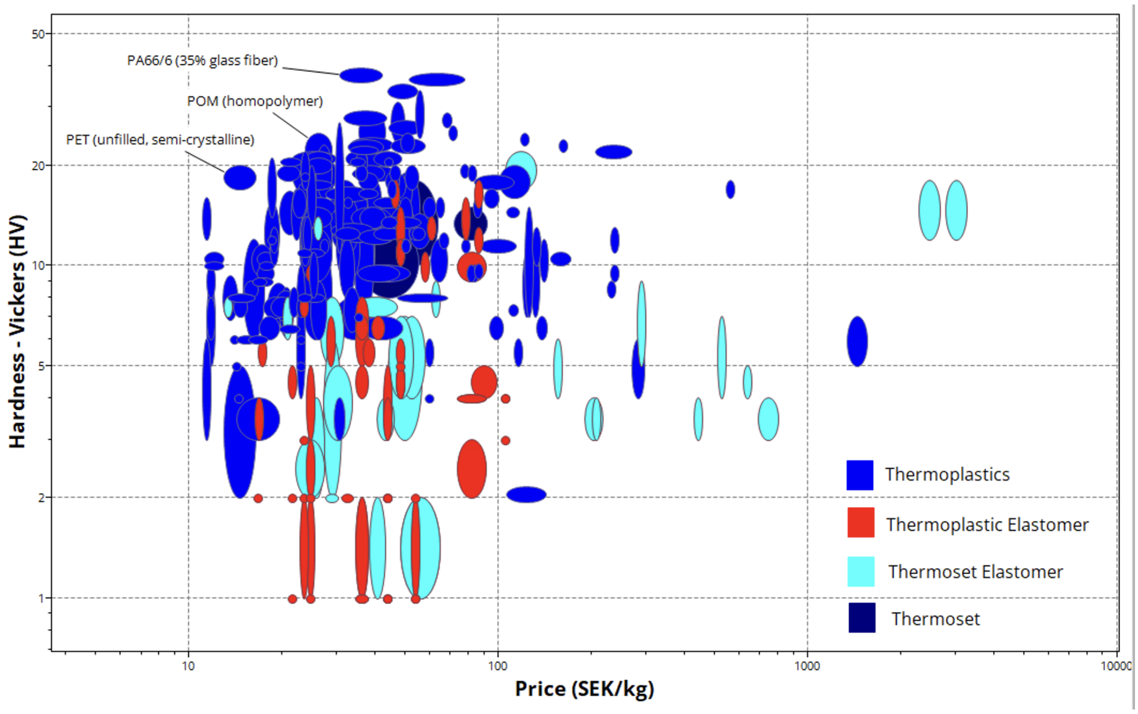



**Figure 4.32:** Bubble chart of remaining materials after applied constraints in Granta Edupack.

Three of the most promising materials were:

- PA66/6 (35% glass fiber)
- POM (homopolymer)
- PET (unfilled, semi-crystalline)

To comprehensively evaluate the remaining alternatives, further technical documentation was reviewed using the Granta database. While both PA66 with 35% glass fiber and PET are widely utilized in automotive and electrical applications, the documented properties of POM aligned exceptionally well with the specific project requirements, particularly its suitability for gears, snap-fit assemblies, and seatbelt components. Although all three polymers emerged as highly viable candidates, POM was ultimately selected as the best choice. This decision was primarily driven by its status as an industry standard for plastic gears. Furthermore, to simplify the design and streamline potential manufacturing, a strategic decision was made to use a single material for all plastic components. POM's versatility and strong mechanical profile made it the ideal choice to fulfill this requirement.

### 4.5.10 Final Cost Analysis

The initial project scope included a separate cost analysis designed to map each concept's Kesselring score against its estimated cost in a 2D diagram. However, due to the unavailability of a cost engineer at this stage, this methodology was adapted. Instead, the cost estimation was postponed to this stage when a cost engineer was available, but included all concepts evaluated in the Kesselring matrix. For the plastic components of all concepts, an online estimation tool was utilized. STL files generated from the CAD models were uploaded, and parameters regarding geometric dimensions, part complexity, surface finish, and production volume were specified. By selecting injection molding as the intended manufacturing method, estimated costs were obtained. Table 4.24 summarizes the total estimated unit cost of the plastic components for each concept. The complete breakdown of these estimations is presented in Appendix E.1 - E.13, were the production volume per component is set to 1 000 000 for a more realistic estimation. It should be noted that the online tool used defaults to US Dollars ($). Since the industry standard for this project is Euros (€), a currency conversion was performed based on current exchange rates.

**Table 4.24:** Total cost for each concept (plastic components).

| **Concept** | **Inline Screw** | **Rack and Roll** | **Lead Sled** | **Pinned Barrel** |
|---|---|---|---|---|
| **Price (€)** | 0,69 | 0,51 | 0,36 | 1,01 |

As shown in Table 4.24, the Lead Sled concept presents the lowest estimated cost at €0.36, followed by Rack and Roll at €0.51. The Inline Screw is more expensive at €0.69, while the Pinned Barrel has a significantly higher cost of €1.01. However, it is crucial to emphasize that these figures only account for the plastic components; including the remaining hardware for each concept would likely alter this cost ranking. For instance, although the Lead Sled is the most cost-effective regarding plastics, it requires a lead screw, which is excluded from this preliminary analysis. It is important to emphasize that this cost analysis did not serve as the primary decision-making basis. Instead, it was performed as a further validation step to confirm the viability of the selected concept.

Regarding motor costs, internal specialists within Volvo Cars' purchasing department provided guidance. The cost data used does not refer specifically to the stepper motor selected for the final 'Rack and Roll' concept, but rather reflects the general market pricing for motors of this scale. For large-scale production, it is estimated that the cost per unit would reduce to approximately 10% of the single-unit price. Based on a reference unit price of €31 Transmotec (2026), the estimated cost for mass production is €3.10 per unit. It should be noted that the motor utilized for the functional demonstrations is slightly oversized, as determined by MATLAB simulations, to ensure reliable performance during testing. Furthermore, an assembly cost estimation was performed based on supplier labor rates and a small assembly cycle time test. With an average hourly wage of €19.14 Statistics Sweden (Statistiska centralbyrån) (2025) and an estimated assembly time of 40 seconds per unit, the labor cost per mechanism was calculated using Equation (4.4):

$$C_{\text{assembly}} = \frac{C_{\text{hour}}}{\left(\frac{T_{\text{hour}}}{T_{\text{cycle}}}\right)} = \frac{19.14}{\left(\frac{3600}{40}\right)} \approx 0.21 \text{ EUR} \tag{4.4}$$

where:
$C_{\text{assembly}}$ = Assembly labor cost per mechanism [EUR]
$C_{\text{hour}}$ = Average hourly wage [EUR/h]
$T_{\text{cycle}}$ = Estimated assembly cycle time [s]
$T_{\text{hour}}$ = Time conversion factor (3600) [s/h]

To summarize the economic viability of the chosen concept, a preliminary cost compilation for the Rack and Roll mechanism is presented in Table 4.25. This estimation includes the injection-molded plastic components, the estimated mass-production cost of the stepper motor, and the calculated assembly labor.

It is important to emphasize that this constitutes a baseline direct manufacturing cost rather than a total final cost. Financial factors such as logistics, overhead, profit margins, and additional minor hardware (e.g., fasteners, wiring and a motor driver) are excluded from this estimation. Nevertheless, it provides a valuable baseline for evaluating the concept's feasibility.

**Table 4.25:** Preliminary direct manufacturing cost summary for the Rack and Roll concept.

| **Cost Item** | **Estimated Cost (€)** |
|---|---|
| Plastic components | 0.51 |
| Stepper motor (mass production est.) | 3.10 |
| Assembly labor | 0.21 |
| **Total Cost per mechanism** | **3.82** |

# 5 Discussion

This project has provided substantial insights into the product development process, encompassing the initial problem definition, iterative concept generation, continuous testing, and the selection of the final concept. This chapter discusses the knowledge acquired regarding both the technical problem and the proposed solution, and provides answers to the defined research questions.

A significant challenge encountered during the project was balancing concept maturity with time constraints. During the early stages of concept generation and screening, the concepts possessed a low level of maturity, characterized by extensive design freedom but limited empirical data. Consequently, several decisions during this phase relied on qualitative discussions with supervisors at Volvo, rather than quantitative metrics. Specifically, evaluating low-maturity, 2D-sketched concepts in the Pugh matrix proved difficult, as physical prototypes were not feasible within the given timeframe. This lack of maturity often resulted in ambiguous evaluations during expert consultations. While generating a large volume of diverse concepts is a fundamental aspect of this product development methodology and essential for acquiring foundational knowledge, it complicates the initial screening process. Furthermore, although cost evaluation was initially intended to be integrated into both the Pugh and Kesselring matrices, the conceptual immaturity restricted cost estimations to relative, rather than absolute values.

The process of detailed Computer-Aided Design (CAD) modeling prior to the Kesselring evaluation yielded critical technical insights. For instance, it was determined that pairing a stepper motor with a planetary gearbox introduced unnecessary complexity with diminishing returns in torque, given that stepper motors deliver peak torque at lower rotational speeds. Retrospectively, allocating more time to the concept generation phase to research mechatronic drive systems would have been highly beneficial, particularly since the project team had limited prior experience with motor integration.

Conversely, a disproportionate amount of time was expended on detailing specific CAD features, particularly for the "In-line screw" and "Wall" concepts. Several intricate details, such as snap-fits on the mounting plate and multiple iterations of a planetary gearbox, were ultimately discarded. This allocation of time was suboptimal and introduced a bias into the evaluation, as other concepts received less developmental focus. Had the torque-speed relationship of the stepper motor been understood earlier, these resources could have been reallocated more efficiently.

A crucial takeaway for future professional practice is the importance of verifying fundamental mechanical principles early in the development cycle. For example, utilizing 3D printing to manufacture generic, non-tailored mechanisms during the Pugh evaluation phase would have provided tangible models for expert review and facilitated a better system-level understanding. Creating one physical prototype per force-transfer mechanism in the concept generation phase would have been highly advantageous. Notably, the "Wall" concept, which utilized a worm gear driving a rack and pinion, failed in practical application; an early generic physical test of this specific drivetrain would have prevented the extensive CAD work invested in its housing integration.

Despite these challenges, several methodological approaches proved highly effective. Conducting structured whiteboard brainstorming sessions prior to executing major conceptual updates allowed for clear documentation of the advantages and disadvantages of specific design aspects, establishing a defined plan for subsequent CAD modeling. Furthermore, implementing the electronic setup early in the process was important. It enabled empirical testing of the concepts, facilitating the early identification of potential issues related to sound, assembly, and mechatronic integration.

The selection of the Rack and Roll concept presents a highly viable solution for mass production, primarily due to its minimized part count and inherent cost-effectiveness. A preliminary estimate places the unit cost of the mechanism at approximately €3.82. Whether this unit cost is justifiable for mass implementation ultimately remains a strategic business decision for Volvo Cars, requiring an evaluation of the financial investment against the added value in safety, ergonomics, and perceived customer comfort. From a technical standpoint, utilizing a direct-drive architecture significantly reduces the reliance on highly tolerance-driven components, which simplifies both the manufacturing and assembly processes for suppliers. A critical enabler of this architecture is the implementation of a stepper motor. While the stepper motor provides distinct advantages, such as precise positional control, sensorless homing, and the ability to slip electrically during high-load crash scenarios without mechanical failure, it also introduces specific challenges. Notably, stepper motors generally require continuous power consumption to maintain holding torque. This is an aspect that must be carefully managed within the vehicle's overarching electrical architecture to avoid unnecessary energy drain. However, when taking a broader system-level perspective into consideration, this power consumption challenge could potentially be mitigated. If the mechanism is primarily required to secure the position during the initial sequence of the occupant buckling the seatbelt, continuous power to the motor might not be strictly necessary. Once the optimal routing is established, the inherent friction between the webbing and the occupant's clothing may provide sufficient resistance to maintain the belt's placement. In such a scenario, the motor could be powered down during standard operation to conserve energy. Should the belt subsequently deviate from its intended position, the occupant sensing system could serve as a closed-loop feedback mechanism, detecting the shift and briefly re-engaging the motor to correct the position. While theoretically promising, relying on clothing friction and intermittent motor activation introduces new dynamic variables. Therefore, this hypothesis requires comprehensive empirical testing to ensure consistent reliability.

Furthermore, empirical testing of the prototype revealed that the mechanism generates a noticeable level of operational noise. To elevate the perceived quality, the mechanical interfaces between the sliding bracket, the guide slot, and the motor housing require further geometric optimization to effectively mitigate rattle and friction. Beyond mechanical refinements, the mechatronic control system presents an opportunity for sound improvement. Implementing software-based vibration-compensation within the motor driver can actively suppress motor vibrations, thereby lowering the overall noise level during adjustment. Additionally, while the current slot successfully deflects the webbing, further investigation into a diagonal pin configuration is recommended. Evaluating a diagonal pin alternative could optimize the interaction with the webbing to minimize friction-induced wear and buckling or folding. Moreover, this configuration provides substantial benefits regarding vehicle integration and spatial packaging. By altering the design to primarily delay the webbing's transition into the cabin trim, the mechanism could be oriented almost entirely along the longitudinal x-axis. Utilizing the less restricted spatial volume typically available in the x-direction presents a clear architectural advantage over the current lateral y-axis mounting, establishing this as a highly relevant area for future concept development.

# 6
# Conclusion

The development of this automated seatbelt positioning mechanism demonstrates a viable path toward improving occupant safety and comfort in the rear seat. The core findings of this project are synthesized by revisiting the research questions formulated in Chapter 1.5.

*RQ1: Which mechatronic principles are most suitable for automating seatbelt positioning given the spatial constraints of this application?*

The evaluation of various mechatronic principles concluded that a compact rack-and-pinion mechanism, driven by a stepper motor, is the most suitable architecture for this application. This configuration effectively meets the strict spatial packaging constraints behind the C-pillar while providing the necessary torque and precision. While alternative concepts, such as the Lead Sled or a brushed DC motor variant of Rack and Roll, were initially considered viable, they were ultimately eliminated. A critical safety requirement is that the mechanism must allow the webbing to move away from the occupant's neck during a crash. Because the mechanical transmissions in the alternative concepts cannot be backdriven, they would physically lock under such loads. Fulfilling the safety requirement would therefore necessitate the integration of a mechanical slip clutch. Introducing a slip clutch to manage these peak loads would significantly increase the complexity, physical volume, and potential failure modes of the system, making the stepper motor architecture the superior choice.

*RQ2: How can the selected conceptual architecture be engineered to balance diverse stakeholder needs while ensuring cost-efficiency and scalability for high-volume automotive production?*

To successfully balance complex stakeholder requirements, the engineering process prioritized simplicity and design for manufacturing (DFM). By significantly reducing the overall part count and selecting self-lubricating polyoxymethylene (POM), the system achieves low friction and high durability without the need for external lubrication. Furthermore, the implementation of sensorless homing for the stepper motor eliminates the need for physical limit switches, reducing both electronic complexity and wiring. Together, these design choices result in a robust and easily assembled architecture. With a preliminary estimated unit cost of approximately €3.82, the mechanism proves to be highly cost-efficient and suitable for mass production. Ultimately, this scalable solution aligns with upcoming automotive safety frameworks by providing a foundation for adaptive and personalized restraint systems.

# 7

# Future recommendations

Empirical testing to determine the force required for belt displacement is a necessary step for future work. The current project relies on a preliminary estimate of 20 N. Because this value directly dictates the motor specifications and the total system cost, obtaining empirical data will reduce design uncertainty and facilitate the optimization of the control algorithms. If the force requirement changes, the motor selector script provided in Appendix C is designed to accommodate new force and speed inputs, allowing for straightforward revision of the motor specifications. Additionally, it is recommended to expand this script to calculate the peak torque required during startup to overcome static friction and system inertia, as the current model only accounts for continuous operation.

A more comprehensive cost analysis is recommended for future development stages. Although initial estimates have been established, engaging cost engineering expertise would allow for a precise assessment of the 'safety benefit per Euro'. Such a refined analysis will provide the necessary data to support strategic decisions regarding the mechanism's value proposition and total cost of ownership.

For future work, it is recommended to perform structural analysis on the mechanism using specialized simulation software. Specifically, conducting Finite Element Method (FEM) analysis prior to manufacturing will verify the design's robustness by evaluating its overall strength and identifying potential stress concentrations in local areas.

Another promising addition for future exploration is the use of a diagonal pin to deflect the webbing. While initial iterations did not perform perfectly, the core kinematics of the pin work very well, particularly in designs where the pin is mounted on a sledge with some rotational compliance. The primary limitation currently is structural robustness; belt tension generates a significant bending moment that concentrates stress at the base of the pin. To address this, two design directions could be pursued: redesigning the pin's geometry to eliminate these high-stress concentration points, or integrating structural supports such as reinforcing ribs. However, adding ribs requires additional clearance behind the pin, which poses a packaging challenge for applications utilizing smaller sledges.

Future work should also address the Noise, Vibration, and Harshness (NVH) characteristics of the mechanism. Currently, the primary noise sources are motor-induced vibrations and frictional contact between the sliding bracket and its guide slot. To mitigate this, future iterations could incorporate vibration isolation materials around the motor housing, alongside low-friction dampening interfaces between the sliding bracket and the baseplate.

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# Appendices

# A Requirements Specification

| Criterion | R/D | | Description | Justification | Target | Unit | Verification method |
|---|---|---|---|---|---|---|---|
| **1. Performance** | | | | | | | |
| | **D1:** | Maximum time for adjustment | The maximum time to position the seatbelt in normal use | The system should not be too slow to operate | 5 | s | Prototype |
| | **D2:** | Maximum time for emergency adjustment | The maximum time to correct the seatbelt position during collision | Improved seatbelt performance to protect occupant | 100 | ms | Prototype |
| | **D3:** | Position accuracy | Deviation from the optimal seatbelt position | To avoid major deviations from optimal position | 5 | mm | Prototype |
| | **R1:** | Maximum peak power | Maximum power provided during adjusting | Avoid blowing a fuse | 10 | A | Motor specification |
| **2. Comfort** | | | | | | | |
| | **D1:** | Percieved discomfort | The seatbelt shall not cause perceived occupant discomfort during continuous use for the defined exposure time | Perceived discomfort might result in improper use of the seatbelt | <1 | h | User study |
| | **D2:** | Optimal position coverage | Able to optimally fit full anthropometric occupant range: 5%F (IIHS ODB, position4, not allowed webbing slide to neck),<br>95%M R18 dynamic zone, Q10 booster cushion MPDB EUNCAP | To ensure safety of occupants with different body types | Yes | - | CAD/user study |
| **3. Safety & Compliance** | | | | | | | |
| | **R1:** | Patent compliance | Must not intrude on published patents | Avoid legal disputes and protect Volvo Cars from intellectual property claims | Yes | - | Patent clearance check |
| | **R2:** | Regulatory compliance | Must comply with ECE R16 and FMVSS 209 | Legal requirements needs to be fulfulled in order to pass certification | Yes | - | Certification review |
| | **D1:** | Failsafe | Avoid malfunction in the case of misuse and electrical failure occurs | The mechanism must mechanically lock in its last position. | Yes | - | Prototype |
| | **R3:** | Impairment of seatbelt main function | Seatbelt function is not negatively affected by the mechanism | Avoid malfunction of the seatbelt | No | - | Prototype |
| **4. Environment** | | | | | | | |
| | **D1:** | Dust & moisture resistance | The mechanisms resistance to dust and moisture impairing its functions | Can negatively affect the performance of the system. | 40 | IP | IP Certification |
| | **R1:** | Service temperature interval | Range of operational temperature | No loss of function in extreme cold and warmth | [-40,80] | °C | Material properties |
| | **D2:** | Road vibration resistance | No function impairment when subject to road bumps and other road irregularities | Maintain correct mechanism performance independent of road conditions | Yes | - | Prototype |
| **5. Durability** | | | | | | | |
| | **D1:** | Service life | Total lifetime of the mechanism | Ensures long-term reliability and avoid repair | >20.000 | Cycles | Accelerated cycle test |
| | **D2:** | Webbing abrasion resistance | The mechanism guides must not induce wear, fraying, or roping of the seatbelt webbing | Friction points can damage the belt over time, compromising its strength. Also part of UNECE R16. | No | - | Abrasion test/Prototype |
| **6. Manufacturing & Service** | | | | | | | |
| | **D1:** | Installation | The installation process of the production unit shall be efficient, minimizing the number of steps, tools, and handling operations required. | Reduce complex steps in the installation process to minimize time and cost | >70 | % | Avix DFA2 Test |

| | | | | | |
|---|---|---|---|---|---|
| | **D2:** Easy to assemble | The assembly process shall be efficient, minimizing the number of steps, tools, and handling operations required. | Reduce complex steps in the assembly process to minimize time and cost | >70 % | Avix DFA2 Test |
| | **D3:** Servicability | Components subject to breaking should be easily accessible | Reduces downtime, which also reduces losses in production and costs related to maintenance | Yes - | Prototype/CAD |
| | **D4:** Part count | Minimize the total number of parts in BOM | Reduces complexity and costs | Yes - | BOM |
| | **D5:** Quantity | Total number of units to be manufactured per year across applicable cars | Ensurers that the design is suitable for mass production | 1 M units/year | Sales forecast |
| | **D6:** Tooling | Standardized tools should be sufficient for accessing the components | No need for unique and new tools that adds costs and complexity | Yes - | CAD |
| **7. Size & Design** | | | | | |
| | **D1:** Packaging constraints | The mechanism must fit within the provided space | Ensures that the mechanism does not clash with other neighbouring parts | Yes - | CAD |
| | **D2:** Mass | Total mass of all parts in BOM inside the system boundary | To minimize the weight of the total car | <300 g | CAD |
| **8. Sound** | | | | | |
| | **D1:** Noise level | Maximum volume of noise during operation | Noise should not be harmful or disturbing | Db | Prototype |
| | **D2:** Sound quality | Acoustic perception during operation | Noise should sound robust and premium | Yes - | Prototype/User study |
| **9. Cost** | | | | | |
| | **D1:** Value proposition | The relation between performance and cost | An important factor when evaluating whether the mechanism should be implemented in the car. | High P/SEK | Performance/Cost graph tool |
| | **D2:** BOM Cost | Total cost for all parts included in the mechanism unit | The mechasnism must be economically feasible and realistic | <150 SEK | Cost estimation |

# B Elimination matrix

| | Elimination Matrix | | | Criteria | | | | *Decision:*<br>*(+) proceed with concept*<br>*(-) Eliminate the concept*<br>*(*) Combined with other concept* | |
|---|---|---|---|---|---|---|---|---|---|
| **Sub-Solution Sequence** | **Number** | **Concept Name** | **Description** | **Packaging** | **Manufacturable** | **Not affect main function of webbing** | **Technically Feasible** | **Comments** | **Decision** |
| 1-3-6-11 | 1 | In-line Screw | In-line assembly consisting of a stepper motor, planetary gearbox, and a large pitch screw where the webbing fits in-between | + | + | + | + | Consider changing 90 degrees after motor (space) | Yes |
| 4-4-7-6 | 2 | Wall | A brushed motor geared down via a worm gear, driving a rack and pinion system with a flanged roller that moves laterally. Only about 20 degrees of the roller's cross-section is required | + | + | + | + | Motor with worm gear can be rotated to achieve better packaging. Difficult with housing. To make compact, the pinion has to be compatible with both worm screw and rack. | Yes |
| 3-1-6-1 | 3 | TwoTilt | A servo controlling the angle of a coned roller, likely requiring a reduction via spur gears | + | + | + | - | Probably too demanding in terms of torque and its load case | No |
| 5-5-6-10 | 4 | Fast fingers | Each pin is connected to an individual solenoid. The belt rests on these (recessed) pins due to gravity | + | + | - | | Pins need to be designed for the webbing not to get stuck | No |
| 4-1-2-5 | 6 | Diagonal sled | A diagonal pin moves the belt, which is driven by a lead screw. Powered by a stepper motor and a spur gear | + | + | + | + | Rail and carriage on the lead screw for the diagonal pin is needed | Yes |
| 5-5-6-2 | 7 | Clack Attack | Five to six solenoids press five to six teeth down onto the belt. An additional solenoid then pushes the entire assembly to the side | + | + | - | | Solenoid only has on/off, continous adjustment cannot be achieved. Need more solenoids in series in that case. Teeth will affect main function | No |
| 4-3-8-3 | 8 | Cranky Crack | A brushed DC motor is geared down via a planetary gearbox, followed by a crank slider that converts rotation into linear motion, featuring a slot at the end. The planet gear is the crank's axle | - | | | | This could face problems in packaging, the big wheel need to be as wide as the rail is long. | No |
| 1-4-7-3 | 9 | Step Slide Slot | A slot moving laterally along a rack. A worm gear ensures it is self-locking. The rack remains stationary while the Stepper motor and the slot travel along it | + | + | + | + | Motor with worm gear can be rotated to achieve better packaging. How should the housing be designed to allow it to move along the rack in a robust way? | Yes |
| 3-5-6-8 | 10 | Helical Snake | Two servos adjust the angle of two larger pins, altering the belt's path and consequently changing its angle | + | + | + | + | Is torque enough? Can the adjustment length be achieved? | Yes |
| 6-5-6-3 | 11 | Mini Move | A linear actuator that solely moves a slot back and forth laterally | + | + | + | + | How expensive is a linear actuator? Maybe buy ingoing components and build instead of buying a finished one | Yes |
| 6-5-6-7 | 12 | Crowned Courier | A linear actuator that solely moves a crowned roller back and forth laterally | + | + | - | | Crowned roller might result in the webbing sliding off | No |
| 4-4-2-9 | 13 | Compact Deform | A brushed DC motor drives a worm gearbox, and then another lead screw with a rail/carriage featuring a buckle slot that folds the belt | + | + | + | + | The small slot cannot be larger than 3 times the webbing thickness. Need to be folded once to maintain webbing functionality. Can change angle radically (90 degrees). Maybe has to be made out of PTFE to get low friction. Must have a gate to insert webbing during assembly | Yes |
| 2-1-3-11 | 14 | Teleport Screw | A stepper motor driving a large lead screw from a distance, depending on the length of the toothed belt | + | + | + | + | One needs to find a suitable location to mount the screw | Yes |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1-3-10-5 | **15** | Pinned Barrel | A stepper motor with a planetary gearbox drives a barrel cam with a diagonal pin mounted on it | + | + | + | + | Packaging can differ since the motor can be located differently. Can put a spring outside housing to adjust belt position. Has self-locking feature. Spring can look like a carabiner | Yes |
| 4-3-6-4 | **16** | Dual Motor Grip | Two brushed motors with planetary gearboxes drive a compliant pressure grip at differential speeds to steer the webbing | + | + | - | | Will be difficult to design this mechanism without affecting the webbing in some way. | No |
| 3-1-6-8 | **17** | Gear S | A servomotor drives a gear mechanism that controls the angle of two larger pins. They are connected via a gear that make the pins rotate opposite direction | + | + | + | + | When seatbelt retract, the pins would rotate as a consequence of the force. The pins could be design so that this setting when retracted is correct setting in a crash. | Yes |
| 1-3-1-7 | **19** | Rail King | A stepper motor with a planetary gearbox uses a rail and carriage to translate and control a crowned roller | + | + | - | | Crowned roller might result in the webbing sliding off | No |
| 3-5-12-2 | **20** | Servo Bite | A direct drive servomotor uses a cam and follower mechanism to engage teeth that grip and guide the webbing | + | + | - | | Teeth would damage the webbing | No |
| 2-3-7-9 | **21** | Compact Carriage | A stepper motor geared via a planetary gearbox converts rotation utilizing rack and pinion into translation to control a small slot | + | + | + | + | The small slot cannot be larger than 3 times the webbing thickness. Need to be folded once to maintain webbing functionality. Can change angle radically (90 degrees). Maybe has to be made out of PTFE to get low friction. Must have a gate to insert webbing during assembly | Yes |
| 2-4-12-10 | **22** | ICE | A mechanism where multiple pins are actuated vertically via a cam and follower system, driven by a brushless DC motor with a worm gearbox | + | + | + | - | Might work technically, but for this project it might not be suitable in terms of time and complexity. The reason is the required complex cam shapes to get adjustability. | No |
| 1-4-3-3 | **23** | Slotted Luggage | A stepper motor uses standard spur gears to drive a toothed belt. The belt in turn, moves a slot mechanism that adjusts the webbing position | + | + | + | + | This might not be too complex, and not that costly either. Although, we need to find a way to make sure that the slot does not follow the toothed belt all the way around the gears | Yes |
| 1-3-5-10 | **26** | SkiLift | A stepper motor with a planetary gearbox drives a cable with pins attached, just like a ski lift. A ramp mechanism then forces the pins to move up and down as the cable is driven | + | + | + | - | This might be a good idea in theory, but practically this is a worse variant of a toothed belt. Might impair the function of the belt to. | No |

# C Motor Selector Script

## Contents



```
% ========================================================================
% Linear Motion Motor Sizing: Target Generator & Selection Filter
% This script calculates the exact output shaft RPM and Torque required
% for 4 different mechanical concepts
% ========================================================================
clear; clc; close all;
```

## 1. GLOBAL SYSTEM REQUIREMENTS

---------------------------------------------------------------------------

```
target_force_N = 20;        % Required linear force (Newtons)
target_speed_mms = 20;      % Required linear speed (mm/s)
system_voltage_V = 12;      % Available voltage (Volts)
max_current_A = 10;         % Maximum allowed current (Amps)
max_power_elec_W = system_voltage_V * max_current_A; % Max electrical power limit

fprintf('System Constraints:\n');
fprintf('Target Force: %g N | Target Speed: %g mm/s\n', target_force_N, target_speed_mms);
fprintf('Available Electrical Power: %g W\n\n', max_power_elec_W);
```

```
System Constraints:
Target Force: 20 N | Target Speed: 20 mm/s
Available Electrical Power: 120 W
```

## 2. DEFINE EFFICIENCIES

```
% Concept 1: Inline Screw
slit_webbing_angle = deg2rad(10);
big_screw_webbing_angle = deg2rad(20);
webbing_friction = 0.3;

big_screw_efficiency = 0.9 * (1 / exp(slit_webbing_angle * webbing_friction)) ^2 * ...
    (1 / exp(big_screw_webbing_angle * webbing_friction));

% Concept 2: Rack and Roll
pinion_rack_efficiency = 0.95;
bracket_sliding_friction = 0.3;
bracket_friction_force = bracket_sliding_friction * (target_force_N * sind(20));
rack_roll_efficiency = pinion_rack_efficiency * (target_force_N /...
    (bracket_friction_force + target_force_N));

% Concept 3: Pinned Barrel
L_barrel = 15; % Lead or Pitch in mm
d_m = 36; % Mean diameter in mm

barrel_helix_angle = atan(L_barrel/(pi*d_m));

barrel_friction = 0.3;
barrel_friction_angle = atan(barrel_friction);

diag_pin_friction = 0.3;
diag_pin_angle = deg2rad(20);
barrel_losses = 0.8 * (1 / exp(diag_pin_friction * diag_pin_angle)); % Eytelwein
```

```
barrel_efficiency = barrel_losses * tan(barrel_helix_angle)/tan(barrel_helix_angle + barrel_friction_angle);

% Concept 4: Lead Sled
L_sled = 8; % Lead or Pitch in mm
d_m_sled = 8; % Mean diameter in mm

lead_helix_angle = atan(L_sled/(pi*d_m_sled));

lead_friction = 0.19; % Shigley
lead_friction_angle = atan(lead_friction);

lead_losses = (1 / exp(diag_pin_friction * diag_pin_angle)); % Eytelwein
lead_efficiency = lead_losses * tan(lead_helix_angle)/tan(lead_helix_angle + lead_friction_angle);
```

## 2. DEFINE MECHANICAL CONCEPTS

------------------------------------------------------------------------ TR = Transmission Ratio (mm traveled per 1 revolution of the input shaft) Eff = Mechanical Efficiency (Estimated percentage of power not lost to friction)

```
% Concept 1: Inline Screw (Stepper)
concepts(1).name = 'Inline Screw';
concepts(1).type = 'Stepper (Direct Drive)';
concepts(1).TR = 63; % The pitch in mm
concepts(1).eff = big_screw_efficiency; % High sliding friction on large threads

% Concept 2: Rack and Roll (DC + Gearbox)
concepts(2).name = 'Rack and Roll';
concepts(2).type = 'DC Motor + Gearbox';
concepts(2).TR = pi * 10; % Circumference of 10mm pinion
concepts(2).eff = rack_roll_efficiency; % Rolling friction, highly efficient

% Concept 3: Pinned Barrel (Stepper)
concepts(3).name = 'Pinned Barrel';
concepts(3).type = 'Stepper (Direct Drive)';
concepts(3).TR = 15;
concepts(3).eff = barrel_efficiency;

% Concept 4: Lead Sled (DC + Gearbox)
concepts(4).name = 'Lead Sled';
concepts(4).type = 'DC Motor + Gearbox';
concepts(4).TR = 8; % Lead = 4 starts * 2mm pitch
concepts(4).eff = lead_efficiency; % Standard lead screw nut sliding friction
```

## 3. KINEMATIC & KINETIC CALCULATIONS

------------------------------------------------------------------------ Pre-allocate arrays for table generation

```
Names = strings(4,1);
Types = strings(4,1);
TR_array = zeros(4,1);
Eff_array = zeros(4,1);
Req_RPM = zeros(4,1);
Req_Torque_mNm = zeros(4,1);
Req_Mech_Power_W = zeros(4,1);

for i = 1:length(concepts)
    % Extract current concept
    c = concepts(i);

    % 1. Calculate Required RPM
    % Formula: (Speed [mm/s] * 60) / TR [mm/rev]
    rpm = (target_speed_mms * 60) / c.TR;

    % 2. Calculate Required Torque (in Nm, then convert to mNm)
    % Formula: (Force * (TR / 1000)) / (2 * pi * Efficiency)
    torque_Nm = (target_force_N * (c.TR / 1000)) / (2 * pi * c.eff);
    torque_mNm = torque_Nm * 1000; % Convert to mNm

    % 3. Calculate Mechanical Power (Watts)
```

```
    % Formula: Torque [Nm] * Angular Velocity [rad/s]
    mech_power = torque_Nm * (rpm * 2 * pi / 60);

    % Store in arrays
    Names(i) = c.name;
    Types(i) = c.type;
    TR_array(i) = c.TR;
    Eff_array(i) = c.eff * 100; % Store as percentage for display
    Req_RPM(i) = rpm;
    Req_Torque_mNm(i) = torque_mNm;
    Req_Mech_Power_W(i) = mech_power;
end
```

## 4. GENERATE OUTPUT TABLE

------------------------------------------------------------------------ Create a MATLAB table for command window

```
ResultsTable = table(Names, Types, TR_array, Eff_array, Req_RPM, Req_Torque_mNm, Req_Mech_Power_W, ...
    'VariableNames', {'Concept', 'Motor_Type', 'TR_mm_rev', 'Efficiency_Pct', 'Required_RPM', 'Required_Torque_mNm', 'Mech_Power_W'});
disp('--- TARGET MOTOR SPECIFICATIONS ---');
disp(ResultsTable);
```

```
--- TARGET MOTOR SPECIFICATIONS ---
       Concept               Motor_Type            TR_mm_rev    Efficiency_Pct    Required_RPM    Required_Torque_mNm    Mech_Power_W
    ______________    ________________________    _________    ______________    ____________    ___________________    ____________

    "Inline Screw"    "Stepper (Direct Drive)"        63           72.993           19.048              274.73             0.54799
    "Rack and Roll"   "DC Motor + Gearbox"        31.416            86.16           38.197              116.06             0.46426
    "Pinned Barrel"   "Stepper (Direct Drive)"        15           21.208               80              225.13              1.8861
    "Lead Sled"       "DC Motor + Gearbox"             8           52.985              150              48.061             0.75494
```

## 5. PLOT THE TARGETS

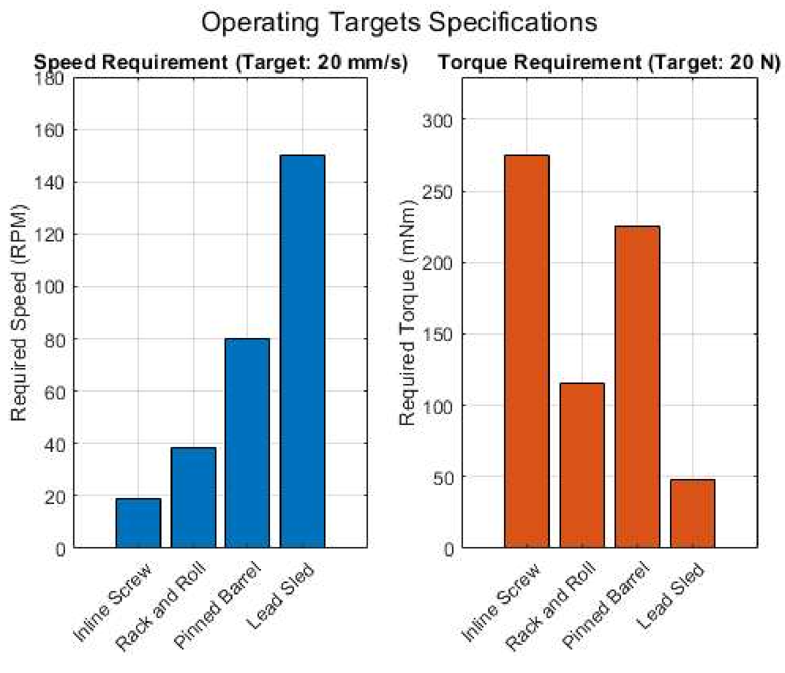
------------------------------------------------------------------------ Plotting the targets gives a visual representation of how TR affects the motor needs

```
figure('Name', 'Motor Requirements per Concept', 'Color', 'w');

% Subplot 1: RPM vs Concept
subplot(1,2,1);
bar(Req_RPM, 'FaceColor', [0 0.4470 0.7410]);
set(gca, 'XTickLabel', Names, 'XTickLabelRotation', 45);
ylabel('Required Speed (RPM)');
title('Speed Requirement (Target: 20 mm/s)');
ylim([0, max(Req_RPM) * 1.2]);
grid on;

% Subplot 2: Torque vs Concept
subplot(1,2,2);
bar(Req_Torque_mNm, 'FaceColor', [0.8500 0.3250 0.0980]);
set(gca, 'XTickLabel', Names, 'XTickLabelRotation', 45);
ylabel('Required Torque (mNm)');
title('Torque Requirement (Target: 20 N)');
ylim([0, max(Req_Torque_mNm) * 1.2]);
grid on;

sgtitle('Operating Targets Specifications');
```




*Published with MATLAB® R2024b*

# D Motor Code

## D.1 Arduino DC Motor Code

```
// Arduino firmware for bidirectional DC motor control using a toggle switch.

#include <Adafruit_MotorShield.h>

// Create an object for the Motor Shield
Adafruit_MotorShield AFMS = Adafruit_MotorShield();

// Attach a DC motor to port M1
Adafruit_DCMotor *myMotor = AFMS.getMotor(1);

// --- SWITCH SETTINGS ---
const int switchForwardPin = 10; // The inner pin on "Servo 1"
const int switchBackwardPin = 9;  // The inner pin on "Servo 2"

void setup() {
  Serial.begin(9600);
  // Initialize the Motor Shield. If not found, halt execution.
  if (!AFMS.begin()) {
    Serial.println("Could not find Motor Shield. Check that it is properly connected!");
    while (1);
  }
  Serial.println("Motor Shield found and initialized!");
  // Set motor speed (0 is stopped, 255 is maximum)
  myMotor->setSpeed(255);

  // Enable the Arduino's built-in pull-up resistors for the switch pins
  pinMode(switchForwardPin, INPUT_PULLUP);
  pinMode(switchBackwardPin, INPUT_PULLUP);
}

void loop() {
  // Read the state of the toggle switch (LOW means the pin is active)
  bool isForward = digitalRead(switchForwardPin) == LOW;
  bool isBackward = digitalRead(switchBackwardPin) == LOW;

  // --- MOTOR LOGIC ---
  if (isForward) {
    // Drive motor forward
    myMotor->run(FORWARD);
  }
  else if (isBackward) {
    // Drive motor backward
    myMotor->run(BACKWARD);
  }
  else {
    // Switch is in the neutral position; release the motor
    myMotor->run(RELEASE);
  }
  // Small delay for loop stability
  delay(10);
}
```

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## D.2 Arduino Stepper Motor Code

```
// Arduino firmware for bidirectional stepper motor control using a toggle switch.

#include <Adafruit_MotorShield.h>

// Create an object for the Motor Shield
Adafruit_MotorShield AFMS = Adafruit_MotorShield();

// --- STEPPER MOTOR SETTINGS ---
// "200" means 200 steps per revolution (standard for most stepper motors).
// "2" means port 2 (which corresponds to outputs M3 and M4).
Adafruit_StepperMotor *myStepper = AFMS.getStepper(200, 2);

// --- SWITCH SETTINGS ---
const int switchForwardPin = 10; // The inner pin on "Servo 1"
const int switchBackwardPin = 9; // The inner pin on "Servo 2"

void setup() {
  Serial.begin(9600);
  if (!AFMS.begin()) {
    Serial.println("Could not find Motor Shield. Check that it is properly connected!");
    while (1);
  }
  Serial.println("Motor Shield found! Ready to control the stepper motor.");

  // Set the speed in RPM (revolutions per minute).
  myStepper->setSpeed(50);

  // Enable the Arduino's built-in pull-up resistors for two switch pins
  pinMode(switchForwardPin, INPUT_PULLUP);
  pinMode(switchBackwardPin, INPUT_PULLUP);
}

void loop() {
  // Read the state of the toggle switch
  bool isForward = digitalRead(switchForwardPin) == LOW;
  bool isBackward = digitalRead(switchBackwardPin) == LOW;

  // --- STEPPER MOTOR LOGIC ---
  if (isForward) {
    // Take 2 steps forward.
    // "DOUBLE" means two coils are working together.
    myStepper->step(2, FORWARD, DOUBLE);
  }
  else if (isBackward) {
    // Take 2 steps backward.
    myStepper->step(2, BACKWARD, DOUBLE);
  }
  else {
    // The switch is in the middle position! Turn off the motor.
    myStepper->release();
  }
}
```

1

# E Cost Estimator Reports

## E.1 Inline Screw

5/19/26, 10:25 AM Workspace Dashboard | CustomPartNet

| | |
|---|---|
| Complexity | Very Simple |
| Feature Count | <10 features |
| Core Sides | 0 |
| Side Cores | 0 |
| Lifters | 0 |
| Unscrewing Devices | 0 |
| Parting Surface | Flat |
| Surface Roughness | 2 |
| Defect Rate | 5 % |
| Machine Setup Time | 8 hr |
| Machine Uptime | 95 % |
| Hourly Rate | 35 $/hr |
| Production Rate | 1144.3809154248836 parts/hr |
| Post Processing Time | 0 hrs |
| Production Markup | 10 % |
| Number of Cavities | 8 |
| Mold Making Rate | 65 $/hr |

**Cost Summary**

| Process | Cost |
|---|---|
| Material | $132 813,86 |
| Production | $33 950,64 |
| Tooling | $43 160,14 |
| **Subtotal** | **$209 924,64** |
| **Total** | **$209 924,64** |

https://www.custompartnet.com/workspace/estimates 1/1

**Figure E.1:** Motor Housing.

5/19/26, 10:25 AM Workspace Dashboard | CustomPartNet

| | |
|---|---|
| Complexity | Custom |
| Feature Count | <25 features |
| Core Sides | 2 |
| Side Cores | 1 |
| Lifters | 0 |
| Unscrewing Devices | 0 |
| Parting Surface | Angled or a single step |
| Surface Roughness | 2 |
| Defect Rate | 5 % |
| Machine Setup Time | 8 hr |
| Machine Uptime | 95 % |
| Hourly Rate | 45 $/hr |
| Production Rate | 1074.684101228834 parts/hr |
| Post Processing Time | 0 hrs |
| Production Markup | 10 % |
| Number of Cavities | 4 |
| Mold Making Rate | 65 $/hr |

## Cost Summary

| Process | Cost |
|---|---|
| Material | $217 167,98 |
| Production | $46 456,05 |
| Tooling | $71 001,47 |
| **Subtotal** | **$334 625,49** |
| **Total** | **$334 625,49** |

https://www.custompartnet.com/workspace/estimates 1/1

**Figure E.2:** Screw Housing.

5/19/26, 10:19 AM Workspace Dashboard | CustomPartNet

| | |
|---|---|
| Complexity | Custom |
| Feature Count | <10 features |
| Core Sides | 2 |
| Side Cores | 3 |
| Lifters | 0 |
| Unscrewing Devices | 0 |
| Parting Surface | More than 4 steps |
| Surface Roughness | 2 |
| Defect Rate | 5 % |
| Machine Setup Time | 8 hr |
| Machine Uptime | 95 % |
| Hourly Rate | 35 $/hr |
| Production Rate | 726.1979556894808 parts/hr |
| Post Processing Time | 0 hrs |
| Production Markup | 10 % |
| Number of Cavities | 4 |
| Mold Making Rate | 65 $/hr |

## Cost Summary

| Process | Cost |
|---|---|
| Material | $127 757,80 |
| Production | $53 323,85 |
| Tooling | $76 105,13 |
| **Subtotal** | **$257 186,77** |
| **Total** | **$257 186,77** |

https://www.custompartnet.com/workspace/estimates 1/1

**Figure E.3:** Big Screw.

## E.2 Rack and Roll

5/19/26, 12:13 PM Workspace Dashboard | CustomPartNet

| | |
|---|---|
| Complexity | Simple |
| Feature Count | <25 features |
| Core Sides | 1 |
| Side Cores | 1 |
| Lifters | 0 |
| Unscrewing Devices | 0 |
| Parting Surface | Angled or a single step |
| Surface Roughness | 2 |
| Defect Rate | 5 % |
| Machine Setup Time | 8 hr |
| Machine Uptime | 95 % |
| Hourly Rate | 30 $/hr |
| Production Rate | 1372.558947565947 parts/hr |
| Post Processing Time | 0 hrs |
| Production Markup | 10 % |
| Number of Cavities | 4 |
| Mold Making Rate | 65 $/hr |

### Cost Summary

| Process | Cost |
|---|---|
| Material | $22 606,03 |
| Production | $24 306,68 |
| Tooling | $31 560,60 |
| **Subtotal** | **$78 473,32** |
| **Total** | **$78 473,32** |

https://www.custompartnet.com/workspace/estimates 1/1

**Figure E.4:** Rack.

5/19/26, 12:13 PM Workspace Dashboard | CustomPartNet

| | |
|---|---|
| Complexity | Custom |
| Feature Count | <25 features |
| Core Sides | 0 |
| Side Cores | 0 |
| Lifters | 0 |
| Unscrewing Devices | 0 |
| Parting Surface | Flat |
| Surface Roughness | 2 |
| Defect Rate | 5 % |
| Machine Setup Time | 8 hr |
| Machine Uptime | 95 % |
| Hourly Rate | 25 $/hr |
| Production Rate | 2164.9691366960715 parts/hr |
| Post Processing Time | 0 hrs |
| Production Markup | 10 % |
| Number of Cavities | 4 |
| Mold Making Rate | 65 $/hr |

## Cost Summary

| Process | Cost |
|---|---|
| Material | $3 390,76 |
| Production | $12 922,26 |
| Tooling | $13 361,71 |
| **Subtotal** | **$29 674,73** |
| **Total** | **$29 674,73** |

https://www.custompartnet.com/workspace/estimates 1/1

**Figure E.5:** Pinion.

5/19/26, 12:13 PM Workspace Dashboard | CustomPartNet

| | |
|---|---|
| Complexity | Moderate |
| Feature Count | <50 features |
| Core Sides | 1 |
| Side Cores | 2 |
| Lifters | 0 |
| Unscrewing Devices | 0 |
| Parting Surface | 2-4 steps or a simple curved surface |
| Surface Roughness | 2 |
| Defect Rate | 5 % |
| Machine Setup Time | 8 hr |
| Machine Uptime | 95 % |
| Hourly Rate | 35 $/hr |
| Production Rate | 624.1853614850278 parts/hr |
| Post Processing Time | 0 hrs |
| Production Markup | 10 % |
| Number of Cavities | 4 |
| Mold Making Rate | 65 $/hr |

## Cost Summary

| Process | Cost |
|---|---|
| Material | $174 487,81 |
| Production | $61 988,40 |
| Tooling | $69 855,34 |
| **Subtotal** | **$306 331,55** |
| **Total** | **$306 331,55** |

https://www.custompartnet.com/workspace/estimates 1/1

**Figure E.6:** Housing.

| | |
|---|---|
| Complexity | Custom |
| Feature Count | <25 features |
| Core Sides | 1 |
| Side Cores | 1 |
| Lifters | 0 |
| Unscrewing Devices | 0 |
| Parting Surface | Angled or a single step |
| Surface Roughness | 2 |
| Defect Rate | 5 % |
| Machine Setup Time | 8 hr |
| Machine Uptime | 95 % |
| Hourly Rate | 35 $/hr |
| Production Rate | 1334.5201582090995 parts/hr |
| Post Processing Time | 0 hrs |
| Production Markup | 10 % |
| Number of Cavities | 8 |
| Mold Making Rate | 65 $/hr |

## Cost Summary

| Process | Cost |
|---|---|
| Material | $88 238,78 |
| Production | $29 157,32 |
| Tooling | $53 675,23 |
| **Subtotal** | **$171 071,33** |
| **Total** | **$171 071,33** |



**Figure E.7:** Sliding Bracket.

## E.3 Lead Sled

5/19/26, 10:34 AM Workspace Dashboard | CustomPartNet

| | |
|---|---|
| Complexity | Custom |
| Feature Count | <10 features |
| Core Sides | 1 |
| Side Cores | 1 |
| Lifters | 0 |
| Unscrewing Devices | 0 |
| Parting Surface | Angled or a single step |
| Surface Roughness | 2 |
| Defect Rate | 5 % |
| Machine Setup Time | 8 hr |
| Machine Uptime | 95 % |
| Hourly Rate | 30 $/hr |
| Production Rate | 893.7412033667596 parts/hr |
| Post Processing Time | 0 hrs |
| Production Markup | 10 % |
| Number of Cavities | 4 |
| Mold Making Rate | 65 $/hr |

### Cost Summary

| Process | Cost |
|---|---|
| Material | $76 781,34 |
| Production | $37 187,44 |
| Tooling | $39 778,93 |
| **Subtotal** | **$153 747,71** |
| **Total** | **$153 747,71** |

https://www.custompartnet.com/workspace/estimates 1/1

**Figure E.8:** Rail.

5/19/26, 10:35 AM Workspace Dashboard | CustomPartNet

| | |
|---|---|
| Complexity | Custom |
| Feature Count | <25 features |
| Core Sides | 2 |
| Side Cores | 4 |
| Lifters | 0 |
| Unscrewing Devices | 0 |
| Parting Surface | Complex curved surface |
| Surface Roughness | 2 |
| Defect Rate | 5 % |
| Machine Setup Time | 8 hr |
| Machine Uptime | 95 % |
| Hourly Rate | 30 $/hr |
| Production Rate | 581.6268803435141 parts/hr |
| Post Processing Time | 0 hrs |
| Production Markup | 10 % |
| Number of Cavities | 4 |
| Mold Making Rate | 65 $/hr |

## Cost Summary

| Process | Cost |
|---|---|
| Material | $141 753,54 |
| Production | $57 001,41 |
| Tooling | $63 568,10 |
| **Subtotal** | **$262 323,04** |
| **Total** | **$262 323,04** |

https://www.custompartnet.com/workspace/estimates 1/1

**Figure E.9:** Carriage and Diagonal Pin.

## E.4 Pinned Barrel

5/19/26, 10:25 AM Workspace Dashboard | CustomPartNet

| | |
|---|---|
| Complexity | Very Simple |
| Feature Count | <10 features |
| Core Sides | 0 |
| Side Cores | 0 |
| Lifters | 0 |
| Unscrewing Devices | 0 |
| Parting Surface | Flat |
| Surface Roughness | 2 |
| Defect Rate | 5 % |
| Machine Setup Time | 8 hr |
| Machine Uptime | 95 % |
| Hourly Rate | 35 $/hr |
| Production Rate | 1144.3809154248836 parts/hr |
| Post Processing Time | 0 hrs |
| Production Markup | 10 % |
| Number of Cavities | 8 |
| Mold Making Rate | 65 $/hr |

### Cost Summary

| Process | Cost |
|---|---|
| Material | $132 813,86 |
| Production | $33 950,64 |
| Tooling | $43 160,14 |
| **Subtotal** | **$209 924,64** |
| **Total** | **$209 924,64** |

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**Figure E.10:** Motor Housing.

5/19/26, 10:45 AM Workspace Dashboard | CustomPartNet

| | |
|---|---|
| Complexity | Custom |
| Feature Count | <25 features |
| Core Sides | 1 |
| Side Cores | 2 |
| Lifters | 0 |
| Unscrewing Devices | 0 |
| Parting Surface | Angled or a single step |
| Surface Roughness | 2 |
| Defect Rate | 5 % |
| Machine Setup Time | 8 hr |
| Machine Uptime | 95 % |
| Hourly Rate | 30 $/hr |
| Production Rate | 565.0706718792833 parts/hr |
| Post Processing Time | 0 hrs |
| Production Markup | 10 % |
| Number of Cavities | 2 |
| Mold Making Rate | 65 $/hr |

## Cost Summary

| Process | Cost |
|---|---|
| Material | $191 147,64 |
| Production | $58 663,77 |
| Tooling | $50 698,97 |
| **Subtotal** | **$300 510,38** |
| **Total** | **$300 510,38** |

https://www.custompartnet.com/workspace/estimates 1/1

**Figure E.11:** Barrel Housing.

5/19/26, 10:45 AM Workspace Dashboard | CustomPartNet

| | |
|---|---|
| Complexity | Custom |
| Feature Count | <10 features |
| Core Sides | 2 |
| Side Cores | 3 |
| Lifters | 0 |
| Unscrewing Devices | 0 |
| Parting Surface | More than 4 steps |
| Surface Roughness | 2 |
| Defect Rate | 5 % |
| Machine Setup Time | 8 hr |
| Machine Uptime | 95 % |
| Hourly Rate | 35 $/hr |
| Production Rate | 483.69176065778345 parts/hr |
| Post Processing Time | 0 hrs |
| Production Markup | 10 % |
| Number of Cavities | 4 |
| Mold Making Rate | 65 $/hr |

## Cost Summary

| Process | Cost |
|---|---|
| Material | $259 543,40 |
| Production | $79 904,15 |
| Tooling | $68 720,07 |
| **Subtotal** | **$408 167,61** |
| **Total** | **$408 167,61** |

https://www.custompartnet.com/workspace/estimates 1/1

**Figure E.12:** Barrel.

5/19/26, 10:44 AM Workspace Dashboard | CustomPartNet

| | |
|---|---|
| Complexity | Custom |
| Feature Count | <25 features |
| Core Sides | 2 |
| Side Cores | 3 |
| Lifters | 0 |
| Unscrewing Devices | 0 |
| Parting Surface | More than 4 steps |
| Surface Roughness | 2 |
| Defect Rate | 5 % |
| Machine Setup Time | 8 hr |
| Machine Uptime | 95 % |
| Hourly Rate | 30 $/hr |
| Production Rate | 468.5253373200677 parts/hr |
| Post Processing Time | 0 hrs |
| Production Markup | 10 % |
| Number of Cavities | 4 |
| Mold Making Rate | 65 $/hr |

## Cost Summary

| Process | Cost |
|---|---|
| Material | $127 601,07 |
| Production | $70 697,76 |
| Tooling | $55 517,37 |
| **Subtotal** | **$253 816,19** |
| **Total** | **$253 816,19** |

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**Figure E.13:** Sled and Diagonal Pin.

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