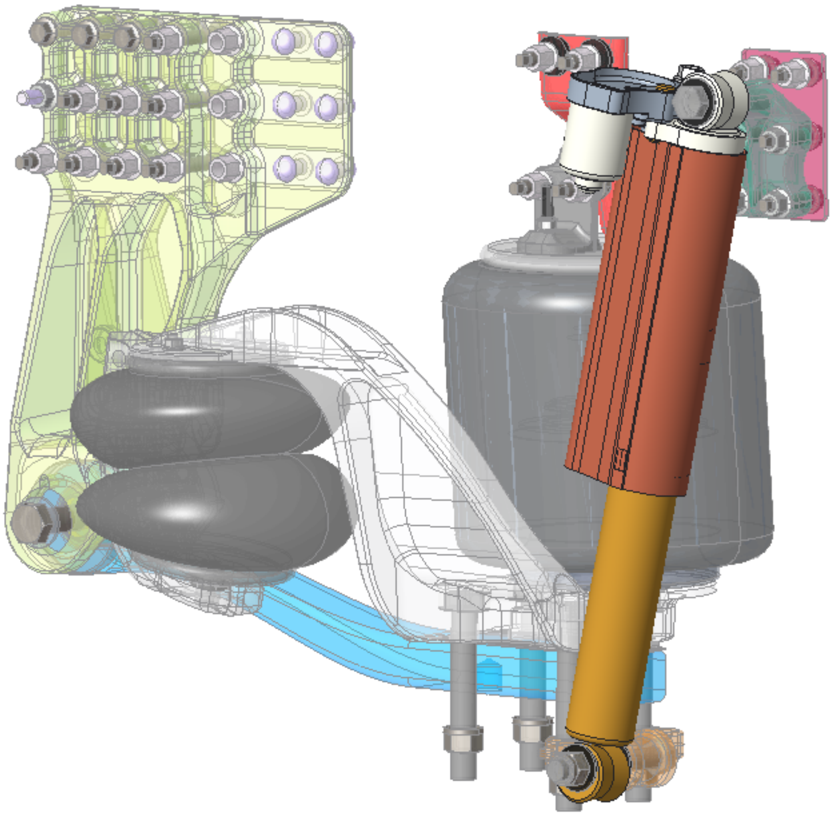

Reducing truck emission by reducing truck weight:

The development of a new lightweight axle lift system driven by electric motor

Master’s thesis in Product Development

Calixthe MATTEI

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DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
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MASTER'S THESIS 2022

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Abstract

Volvo GTT has long been one of the most prominent players in the global commercial vehicle market and a key player in developing new technology for a safer and greener future. With the ever-increasing focus on emissions and fuel efficiency in the retail vehicle market, the segment is shifting towards greener solutions to meet regulations. This holds true even for heavy-duty and long-haul trucks, which come with many challenging tasks. One way to make trucks greener is to reduce the truck's weight. There are regulations on the maximum weight of a loaded truck. By lowering the truck's weight, the user can increase the amount of cargo per transportation, thus improving the ratio of the truck to cargo weight - leading to more emission-efficient transportation of cargo.

A truck contains several axles to split heavy loads it has to carry. When the truck is unloaded, extra axles are inconvenient. They lead to increased energy consumption by higher road friction and increased tire wear. Currently, the axles are lifted in these cases through air bellows axle lift systems. Due to the requirement of large and heavy levers to transfer the lifting force from the air bellows to the axles, the current solution is heavy and requires a lot of packaging space.

This product development project aimed to conceptualize and create a new solution for the current system to find a lightweight concept. The product aims to keep the same robustness and efficiency as the air bellow axle lift system while weighing less.

During the project, a new lifting system was developed. The solution works based on connecting a sliding screwing device to the dampers of the axles. An electric motor then actuates the sliding screw. The product uses a sliding mechanism to handle unpredicted external forces during the lifting process, such as road bumps.

A detailed design CAD model was created and a prototype of the concept. Tests were done using both physical measurements of the prototype, analyses of the CAD model, and calculations based on data from available databases.

During tests performed for validation purposes, it was seen that the concept manages to properly handle the lift of the axle. It does so while weighting 75% less, costing 34% less and reducing main assembly line steps in the factory by 66%. Also, conducted environmental *EPS* studies showed an 80% reduction in material emission cost.

Acknowledgements

The thesis authors would like to express the deepest gratitude for all the precious help received throughout this master thesis in product development.

First, we would like to earnestly acknowledge the sincere efforts and valuable time given by our supervisor at Volvo GTT, Anders Olsson. The unparalleled reactivity, utmost inclusion and outstanding dedication throughout this project helped us immensely, from start to finish.

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Furthermore, we would like to recognize the assistance that we received from Moreira Campani Marcio in reviewing and coordinating the manufacturing of the physical prototype during this project.

Lastly, we gratefully acknowledge the assistance of Axel Bolmvall and Ghazan Khattak for taking their time to do the opposition of the thesis.

Abbreviation List

CAD	Computer-aided design
EPS	Environmental Priority Strategies
FEM	Finite element method
HWP	High-weight Pusher
HWT	High-weight Tag
LWP	Light-weight Pusher
MAL	Main assembly line
PAL	Preassembly line
SLS	Seletive Laster Sintering
WTP	Willingness to pay

Contents

1 Introduction

1.1 Company Background

Volvo Trucks has long been one of the most prominent players in the global commercial vehicle market and is essential in developing new technology for a safer and greener future. However, the commercial vehicle segment is now under immense pressure to reduce emissions and environmental impact. The whole industry is changing quickly, and to stay one of the leaders, Volvo Trucks has to keep pushing the limitations of technology and development.

With the ever-increasing focus on emissions and fuel efficiency in the commercial vehicle market, the segment is shifting towards greener solutions to meet regulations. Even for heavy-duty and long-haul trucks, this holds true, which comes with many new challenges.

1.2 Problem Definition

A truck contains several axles to split heavy loads it has to carry. Some trucks have more than the two necessary axles, to even further spread the load. When unloaded, these extra axles are not required, hence increasing the rolling resistance. This leads to increased energy consumption and tire wear. Lifting the extra axles during unloaded cases is essential for a truck's longevity and environmental impact.

The force required to lift the axle is dependent on where the lift system is placed. This is so due to the axle being attached to the truck through a pivoting point. Depending on the placement of the axle lift, the force required will change as per the level arm principle. This is further showcased in section 2.2, and Figure 1. The current axle lift system, uses air bellows and lever arms to lift the axle, making it a rather heavy solution. There are regulations on the maximum weight of a loaded truck, and by reducing the weight of the truck itself, the user may increase the amount of cargo and thus reduce emission per weight of cargo.

The trucks are built in a factory with the main assembly line (**MAL**) supported by preassembly lines (**PAL**) in a fishbone structure. The main assembly line is tightly timed, and adding assembly steps into the main assembly line is not an easy or desired feature. Thus, an ideal replacement for the old axle lift system should not add any steps to the main assembly line - even better, it should reduce the number of steps in it. Adding steps to the preassembly lines is not as disadvantageous. Moving steps from the main assembly line to preassembly lines can yield future flexibility in the main assembly line for other solutions with different problems.

1.3 Purpose and Goals

The goal of this project in product development is to develop a new axle lift system for trucks.

The new system should provide the same function as a currently available axle lift system, which uses pressurized air bellows. The new system is to be lighter.

The score of the new system will be based on a cost-weight budget. This is to make sure that the lighter system is also within a reasonable production cost.

The cost-weight budget is calculated as the production cost of the system with the addition of the system's weight multiplied by a factor, see Equation 1. The value of the factor is confidential to Volvo Trucks, and is based on what the company has calculated to be the total economic benefit of the weight reduction of the axle lift.

$$CW_{Budget}[SEK] = Cost_{production}[SEK] + Weight_{total}[kg] \cdot Factor[\tfrac{SEK}{kg}] \tag{1}$$

1.4 Scope

Since this thesis is within the R&D department of Volvo Trucks, there is no aim of doing market research for this product. The legitimacy of the product to be funded and produced by Volvo Trucks will rely on the product's ability to fulfill its requirements and fulfill Volvo Truck's strategies.

1.5 Limitations

The thesis will focus on solutions based on lifting power generated by electrical motors. This is a wish set by the company in order to connect the concept created in the thesis to their current strategic mission.

This would remove solutions based on e.g., pneumatic or hydraulic technologies

1.6 Deliverables

The project will include the following deliverables:

- **CAD files**

  A final detailed CAD model (parts and assembly), with specifications and requirements verified through appropriate methods (e.g., simulations and physical tests). This deliverable is considered the most important one of the project.

- **Bill of Materials (BOM)**

  A detailed BOM containing the assembly structure, the number of parts, part definition and material assignment.

- **Requirements list**

  A detailed requirements list for the product with specifications based on the air bellow axle lift system and proper verification results and documentation.

- **Physical demonstration prototype**

  A 1:1 scale plastic prototype that can be used for product demonstration and packaging tests.

1.7 Outline of the Report

The report will first briefly describe some Fundamental Concepts required to understand later calculations and studies on the product. This section is then followed by the Method description of this product development project, followed by the corresponding Results section mainly going through product concepts and the verification and refinement of the remaining one. Then, what has been conducted will be discussed and emphasis will then be on a development plan about the remaining steps to lead this product to production. This report ends with Conclusions to sum up the main outcomes of this project. Appendices provide the different sketches and drawings used for idea generation.

2 Fundamental Concepts

This section aims to explain the main theoretical parts of the different technical problems encountered in this report and to explain definitions of some concepts.

2.1 Truck Glossary

A non-driven axle is called a "pusher" in front of the drive axle and a "tag" if behind. Both setups have pros and cons regarding weight, load capacity, traction force, load distributions and turning radius. Depending on the carrying weight (low or high weight) and whether a truck has a pusher or tag, it is called a combination of those, e.g., Light-weight Tag (**LWT**), Light-Weight Pusher (**LWP**), or even the heavier 7.5 and 9 tonnes pushers - in this report called High-Weight Pusher (**HWP**).

2.2 Axle Lift technology

The current axle lift system is an air bellow lift system. An air bellow is an inflatable pressurized rubber chamber able to apply pressure on its outer surfaces. The generated pressure can be used to lift the system; the air bellow axle lift system works on a lever arm principle. An example of it can be seen in Figure 1. On this picture the entire system consists of the left rubber bellow and the two white lever arms. This system is used on both sides of the axle.

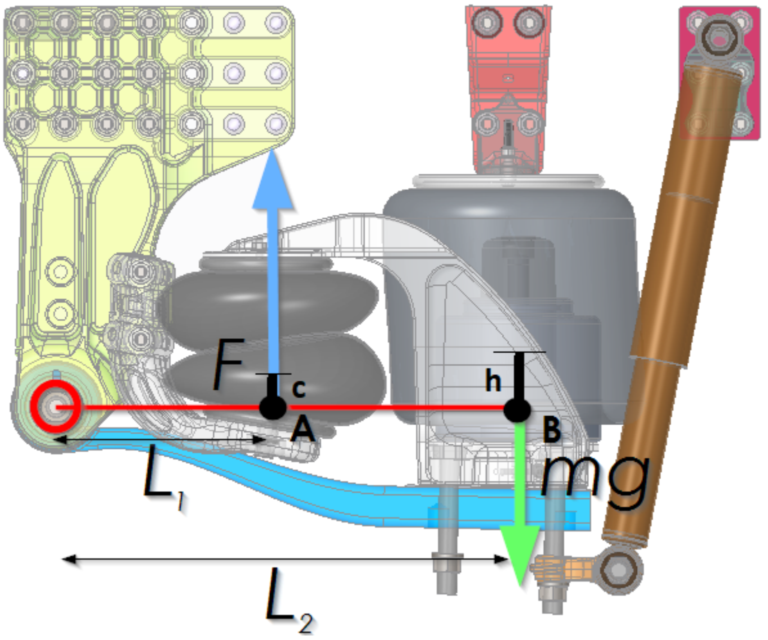


Figure 1: Lever arm principle used with the air bellows, side view

The axle in point B needs to be lifted to a certain height, h, so an air bellow provides a lifting force F in point A. To start lifting, moment equilibrium gives:

$$F = \frac{L_2}{L_1} \cdot mg \tag{2}$$

The desired height h gives the required stroke c in A:

$$c = h \cdot \frac{L_1}{L_2} \tag{3}$$

2.3 Design Formulas

Different formulas were used throughout the project and are described below with the corresponding concept development phase.

Formula to get the torque T for lifting a load F with a screwing device, based on the bolt connection efficiency μ and the screw lead l, see Equation 4

$$T = \frac{F \cdot l}{2\pi \cdot \mu} \tag{4}$$

Formula to get the lifting time t (in s) of a screwing device based on a certain rpm n of an electrical motor, the screw lead l and the stroke c to travel, see Equation 5.

$$t = \frac{c \cdot 60}{l \cdot n} \tag{5}$$

Formula to get the power to output a certain force at speed. This is broken down to calculate a motors ideal power requirement to lift a certain load, through a stroke length within a specific time.

$$P = F \cdot v = mg \cdot \frac{c}{t} \tag{6}$$

3 Method

This chapter provides the main guideline of the process used to solve this product development project. The product development was done through a systematic process using the following steps, Figure 2:

- **Problem formulation**

  The project's goal and context were set during this phase.

- **Requirements**

  The product requirements were set during this step. This was done so that the result of the project could be methodically compared to itself and reference products; the air bellow axle lift system in the case of this project.

- **Prestudy**

  Existing technologies and solutions were reviewed to create a base for the concept development phase.

- **Concept development**

  The iterative idea generation and screening phase. Ideas were generated and then reviewed using the requirements as references; the least impressive concepts were screened out, while the most promising were refined further. The idea was to end this phase with a final concept.

- **Detailed design**

  The final concept was further developed in detail.

- **Verification and refinement**

  The verification phase is when the product was tested to ensure that the requirements were met. Refinements were done on areas of potential improvement and places where the requirements were not yet fulfilled.

After the final phase, Verification & Refinement, the goal was to have a concept tested and verified as a potential replacement for the air bellow axle lift system.

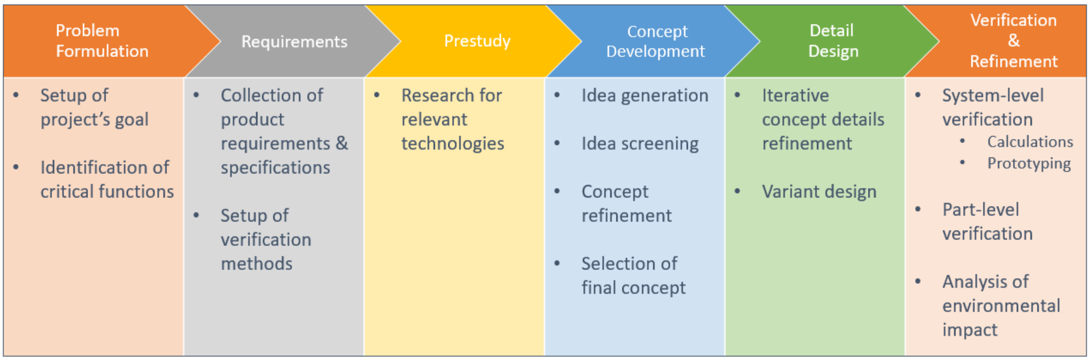


Figure 2: Flowchart view of the product development process used throughout this project

3.1 Problem Formulation

The task of the project was to develop a new lightweight axle lifting system for the trucks at Volvo. The master's thesis project was initialized with the problem formulation already at a mature state but was complemented through internal discussions at Volvo Trucks to define the problem clearly.

3.2 Requirements

Once the problem was formulated, a requirements list was created. Several methods were necessary to identify the product constraints fully. This was due to a lot of knowledge and information about the requirements of the air bellow axle lift system being tacit knowledge, or simply due to lack of current and updated documentation. The Pugh design Core was used as a reference to conduct a comprehensive requirements list study. This standardized method provides a framework of critical fields to consider during product development.(Pugh, 1991)

During the setup of the requirements list, different truck models were looked at. Looking at different truck models was done to make sure that the requirements were extensive enough so that a product fulfilling them would work on every intended truck. The requirements were set to work with the most extreme versions, i.e., if trucks A, B, and C, required a lifting force of 1, 2, and 3 kN, respectively, then the requirement of the lifting force would be set to the highest value, 3 kN.

The following methods were used to justify the values set for the requirements:

- **Measurements of air bellow axle lift system**

  Since the expected functions of the developed system were the same as those of the air bellow axle lift system, some performance requirements were gathered through direct measurements of the air bellow axle lift. These performance requirements were the following:

  - **Lifting time**
    The lifting time was gathered by using a time watch to measure the air bellow axle lift's lifting time several times. The average value of the measurements was rounded to the closest integer and set as the requirement value.
  - **Lifting force**
    The lifting force was gathered through calculations using the pressure required by the air bellow axle lift system to perform a lifting session and its effective pressure area, in combination with the position of the lever arm to calculate lifting force depending on the position. Equation 2 is used.
  - **Lifting stroke**
    The lifting stroke was gathered through length measurements on the axle. The stroke in other positions on the side of the truck was obtained thanks to Equation 3.

- **Analysis of CAD models**

  Geometrical dimension specifications were gathered through analysis of available CAD models, using available internal measurement tools. The number of steps to assemble the air bellow axle lift system in the factory main assembly line was also assessed by analyses of available CAD models.

- **Volvo database**

  The cost requirement was gathered through an analysis of the Volvo database. The weight requirement was gathered through calculations based on an analysis of the database in combination with CAD model geometries.

- **Volvo expertise and tacit knowledge**

  Tacit knowledge and requirements were gathered through creating, showcasing and scrutinizing early phase concepts. This was done through regular design review meetings with the Volvo Trucks department made of experts in charge of this subsystem and the area where it is implemented on the truck.

The requirements list was set up with a validation column to explain the method used to validate requirement fulfillment.

The requirements list was not structured with categorizations for wishes versus demands. It was structured this way since all the items in the requirements list were identified as crucial to the product, i.e., demands. No items that fall under the section of wishes were identified. This is mainly due to the internal expectations at Volvo. It was deemed that what is crucial for the product to properly function, needs to be done, and the rest should not - *"if it's not broken, don't fix it"*.

3.3 Prestudy

Before going into idea generation, a search for relevant technologies was done. Different technologies were searched to find ways that independently solve the identified critical functions. This phase aimed to build up a table of technologies to act as inspiration during the creative process of the concept development.

This phase was a short phase that acted as a filler before gaining full access to the working facilities.

3.4 Concept Development

Several iterations of idea generation and screening were done to get the best possible product. The idea was to start with a wide design space to acquire project knowledge and screen out unfeasible solutions. In between each screening session, the remaining ideas were refined and tweaked to maximize the chance of understanding the utmost potential of each concept.

This method, a "Funnel product development" method, made so that the number of concepts was gradually diminished until only one final concept was left, see Figure 3 (Wheelwright & Clark, 1992).

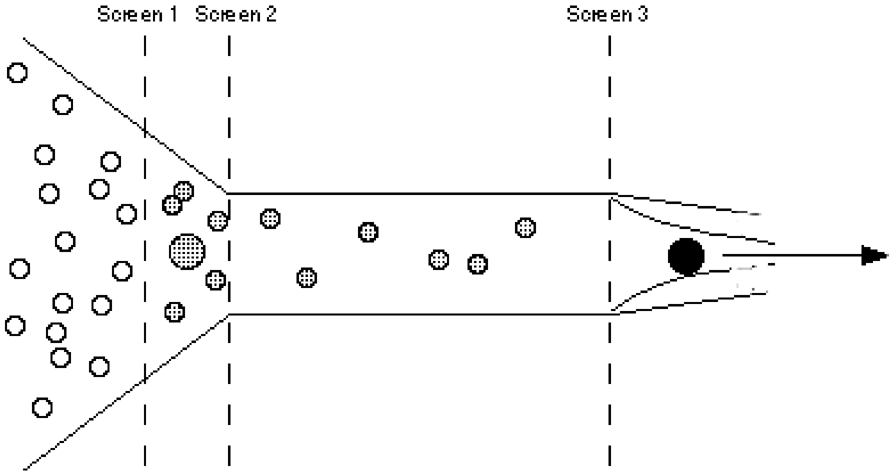


Figure 3: Scheme of Product Development Funnel (Wheelwright & Clark, 1992)

The screening of the products was done through continuous supervision and team design review meetings. It was a somewhat unstructured and resource-heavy (in terms of availability of experts' knowledge) way of conducting an early phase product development project. However, given the large amount of tacit knowledge, project unknowns, and preferred Volvo Trucks standard procedures, it was considered the most suitable screening method. More structured methods, such as Pugh and Kesselring matrices, would not have been feasible given the difficulties of performing proper early concept evaluations.

Also, to properly engage (and make use of the vast amount of experience and expertise of) the team at Volvo Trucks, it was critical to include them in the decision-making process.

3.4.1 Phase 1: Idea Generation & Screening

A wide design space was used during the first iteration to look for ground-breaking innovations. The idea was mainly to gain insights and understand the scope of the problem, the project and its requirements, understand interfaces and interactions, and learn about Volvo Trucks' needs, insights and tacit knowledge.

The practical method used was to sketch on a whiteboard to brainstorm, and after each session, the most promising concepts were summarized in final drawings on paper. These ideas were then discussed and refined with regular team review meetings with the Volvo Trucks department.

After refining the results from the idea generation, the most unfeasible concepts were screened out. The concepts were screened based on their ability (or lack of ability) to fulfill the requirements.

3.4.2 Phase 2: Concept Refinement & Screening

In this idea generation phase, the goal was to create simple CAD models for every remaining concept to increase the understanding of their feasibility, scale, and flexibility regarding packaging and truck model adaptability.

The goal of Phase 2 was to end up with one promising concept. A team review meeting with the Volvo Trucks department was held to gauge the feasibility of the current concepts and find possible design flaws that could lead to interface issues with other parts and systems of the truck.

3.4.3 Phase 3: Concept Refinement & Final Concept Selection

The task of Phase 3 was to take the final concept and expand it into different sub-versions by switching component positions and placements. This idea was to get the best possible version of a final concept before going into a later detail design phase. The optimal position for the motor was looked at, as well as whether or not a lead screw would yield any issues due to friction. The concept's assemblability was looked at as well.

This phase was done with the help of a team review meeting with the Volvo Trucks department. Calculations were done for lifting time of different configurations, weight analyses and cost estimations. Material selections were done to be able to start the later processes.

3.5 Detailed Design

Once a final concept was set, the detailed design phase began and was conducted in iterations. Each iterative step consisted of fixing several functions followed by a design review with the Volvo Trucks department. CAD models, animations, renderings, and context visualizations allowed efficient and extensive design reviews. Knowledge of similar parts, produced internally, was used to design parts with a satisfactory quality and good manufacturability.

3.6 Verification & Refinement

In parallel to, and succeeding, the detailed design phase, the different requirements were evaluated and verified to help refine and finalize the whole product and its separate parts.

Prototyping, Finite Element Method (**FEM**) simulations and calculations were done to verify and refine the parts, parts' interfaces, and the entire system. Calculations were also done for standard parts and machine elements to predict performance values.

This section is divided into system-level verification, part-level verification, and environmental impact to give a comprehensive understanding of the verification and refinement steps done to achieve a product that fulfills the requirements.

3.6.1 System-level Verification - Calculations

Further calculations were made to assess whether the concept would fulfill the lifting time requirement. A first study was made during *Concept Development - Phase 3* to determine whether the chosen concept was fulfilling the requirement R.1 - *Lifting time* and a second study was later done to refine some parameters of the concept. The Matlab code used is displayed in Appendix B.

Working on a similar principle of lever arm shown in Figure 1 shown in Section 2, all the potential positions on the side of the truck were looked upon and lifting time was computed based on the formulas in Section 2, Equation 4 and 5. The lifting force and stroke vary depending on the distance compared to the pivot point. This means the required strength of the material and screwing speed vary.

Moreover, the missing inputs were the motor characteristics (motor map of the torque and rotational speed) and the screw lead.

The wiper motor of Volvo Trucks was used as a reference motor throughout the project. It was chosen due to its robustness, acceptable power range (more than 400W) and cost. The motor is over-dimensioned, but the large production volume of that motor variant makes it cheap and reliable. If the project's concept was to go into serial production, a tailor made motor would most likely be used.

Regarding the screw lead, a library of available lead in the industry was implemented in the calculations, while the program was finding the optimal settings (torque, rpm and lead) for each position to minimize the lifting time.

An estimation of the system's weight was also computed depending on the position.

3.6.2 System-level Verification - Prototype Analysis

A physical prototype session has been done to test the concept on a holistic view to test the functions of the product on a system level. This prototype tested requirements R.4, R.8, R.13 and R.14. The purpose was to detect unanticipated phenomena. An assembly analysis was done by looking at the connection points to assess the assembly complexity of the product at the factory.

The prototype is an adapted version of the second generation of the detailed design (see Section 4.5.2). It has been 3D-printed in full scale in SLS. The prototype was sized to lift a 3D-printed version of an axle that was printed previous to this prototype for other purposes. Minor changes were made to fit the strength of the SLS plastic and the interfaces of the available motor. It was assumed that these changes would not impact the verification of the requirements it is intended to verify.

3.6.3 Part-level Verification

FEM analyses and calculations were made to assess the mechanical integrity of the product's parts to ensure the system-level mechanical integrity.

The FEM was done using the software Creo Paramteric's native FEM system. The meshing was autogenerated using the softwares application AutoGEM (PTC, 2022)

FEM analyses were done on the first and, after refinement, the second detailed design CAD version. The load condition throughout the verification was set to a vertical (lifting) force of 15 kN.

The magnitude of the force was to account for the forces during the vehicle dynamics and axle weight during the most extreme conditions, being set to 7.5 kN. The force was multiplied by 2 to add a safety factor.

The FEM analysis was set to scale the displayed color about peaks of allowed maximum stress. The stress peaks were set to 200 MPa for aluminum parts and 500 MPa for steel parts. This means that in the displayed FEM analysis figures, the zones marked in red represent the areas in which the maximum allowed stress is breached. Thus the specific material of the analyzed part would not withhold a safety factor of 2. The areas that breached the maximum stress would warrant a look-over and refinements.

3.6.4 Environmental Impact

The environmental impact of changing the air bellow axle lift system to the new system was calculated using weight and material analysis.

Two main approaches were looked at, Material impact and Weight impact.

- **Material impact, MI**

  In the material impact approach, the predicted emissions produced during the lifecycle of the products' parts were looked at and compared between the air bellow axle lift system and the system developed in this project.

  The system's emission was calculated by looking at the parts of the system. The weights and the material impacts of the parts were multiplied to get the parts' emissions and were gotten from the EPS method, which assesses the emission as being the financial cost people have the willingness to pay (WTP) to avoid marginal changes in the availability of the environmental goods and services required for human basic needs (IVL Swedish Environmental Research Institute, 1990). The sum of the parts' emissions is the product's total emission (due to produced material), as can be seen in Equation 7.

$$Emission_{product} = \sum_{i=1}^{n} Weight_{part_i}[kg] * ME_{part_i}[\tfrac{SEK}{kg}] \tag{7}$$

  To analyse the impact of the developed product the emission difference, Equation 8, as well as the emission ratio, Equation 9, were calculated.

$$Emission_{difference} = Emission_{new}[SEK] - Emission_{old}[SEK] \tag{8}$$

$$Emission_{ratio} = \frac{Emission_{new}[SEK]}{Emission_{old}[SEK]} \tag{9}$$

- **Weight impact, WI**

  Reducing the truck's weight, aside from the reduced production emissions, also increases the amount of cargo that can be transported. Reducing weight also reduces the wasted fuel consumption transporting the vehicle itself.

  Two calculations were used to estimate the impact of the reduced weight.

  The first calculation, Equation 10, was used to look at the ratio of the truck's total weight using the air bellow system versus the developed system.

$$WI_{ratio} = \frac{Weight_{new}[kg]}{Weight_{old}[kg]} \tag{10}$$

The second calculation was done using the knowledge that reducing the weight of a truck can also be loaded with more cargo. How much more cargo can be added to a truck depends on the amount of weight removed and the location of the removed weight, as seen in Equation 11.

$$Cargo_{increase} = A \cdot (Weight_{airbellow} - Weight_{new})[kg] \tag{11}$$

A is a factor that varies between trucks and truck models. It is a confidential value.

3.6.5 Final Verification

The project ended with all the gathered metrics from the tests compared to the requirements list. The aim was to assess the completion of every detail. In the end, the weight-cost trade-off of the concept was evaluated.

3.7 Prestudy for further development

After the final verifications, a prestudy was conducted to identify the necessary steps of continuation to take the product closer to production.

The first items added to the list were the missing verification steps in the requirements list. After that, each part was looked at to find necessary improvements that would be required to get the product into production.

4 Results

This chapter consists of providing the main results of this thesis. It will extensively describe the results gotten after each step explained in Section 3. Problem formulation, requirements lists, critical functions, concept explanations, and requirements verification are discussed.

4.1 Problem Formulation

The problem formulation was finalized as: *"Our goal is to develop a new axle lifting system that has the same features as the currently available air bellow axle lift system, while also having a lower weight - within a cost-weight based budget"*.

In Figure 4 the area in which the weight-cost is lower than the air bellow axle lift system can be seen - the green area. You can also see where the currently used air bellow axle lift system is located on the graph. The cost-weight budget is confidential, and this report will not exhibit direct values.

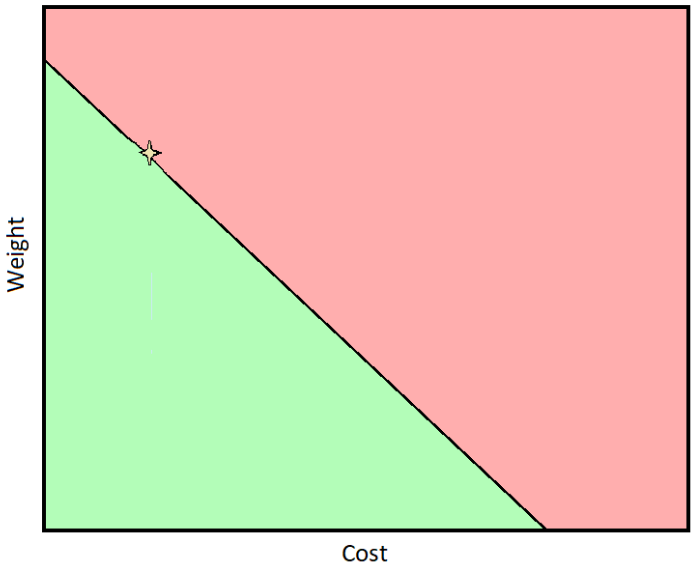


Figure 4: Graph of weight-cost line. The star symbol marks the currently used air bellow axle lift system. The green area represents the area in which the weight-cost is lower than that of the air bellow system. No values are given to the axes as these values are confidential

Ideally, to maximize the likelihood of the product getting into production, a concept that costs less while being lighter, rather than just having a lower cost-weight budget, should be created. In Figure 5 the blue area represents the area in which such a product would exist. This is due to several stakeholders in the project that have their priority set on the cost. The project is to create a lightweight axle lift, but to get it into production an increased cost could be met with opposition from those certain stakeholders.

From a cost and weight perspective, the project would be deemed successful as long as the weight is lower than the currently used air bellow system while being within the cost-weight budget. However, the cost should not be increased at all to get the product into production - preferably decreased.

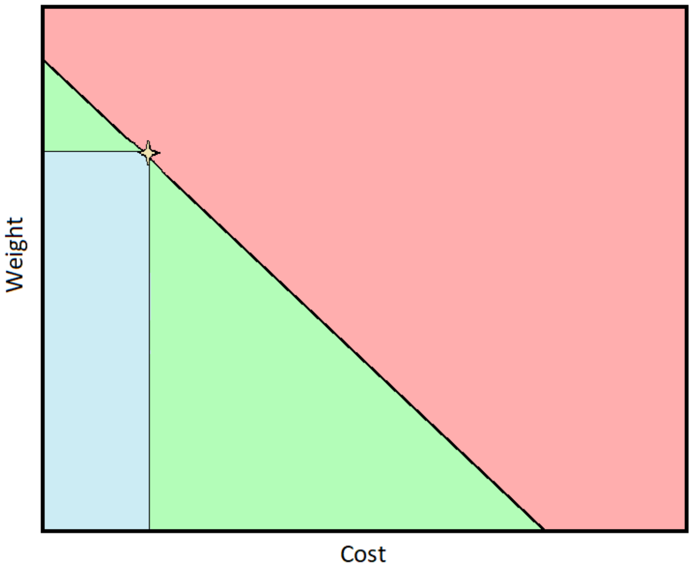


Figure 5: Graph of weight-cost line. The star symbol marks the currently used air bellow axle lift system. The blue area represents the area in which both the cost and the weight are simultaneously lower

To make sure that a new product keeps the same features as the air-bellow axle lift system, three key critical functions were identified:

- **Lifting function**

  The system's primary function is to handle the lifting of the axle.

- **System locking function**

  The system needs to be lockable in a lifted position to keep the axle raised even when the truck is not powered.

  This means that an active lift system relying on power to keep the axle lifted would not suffice.

- **External environment adaptability**

  The system needs to handle external inputs and forces without failing. Most critical, this can be bumps on the road during the lifting.

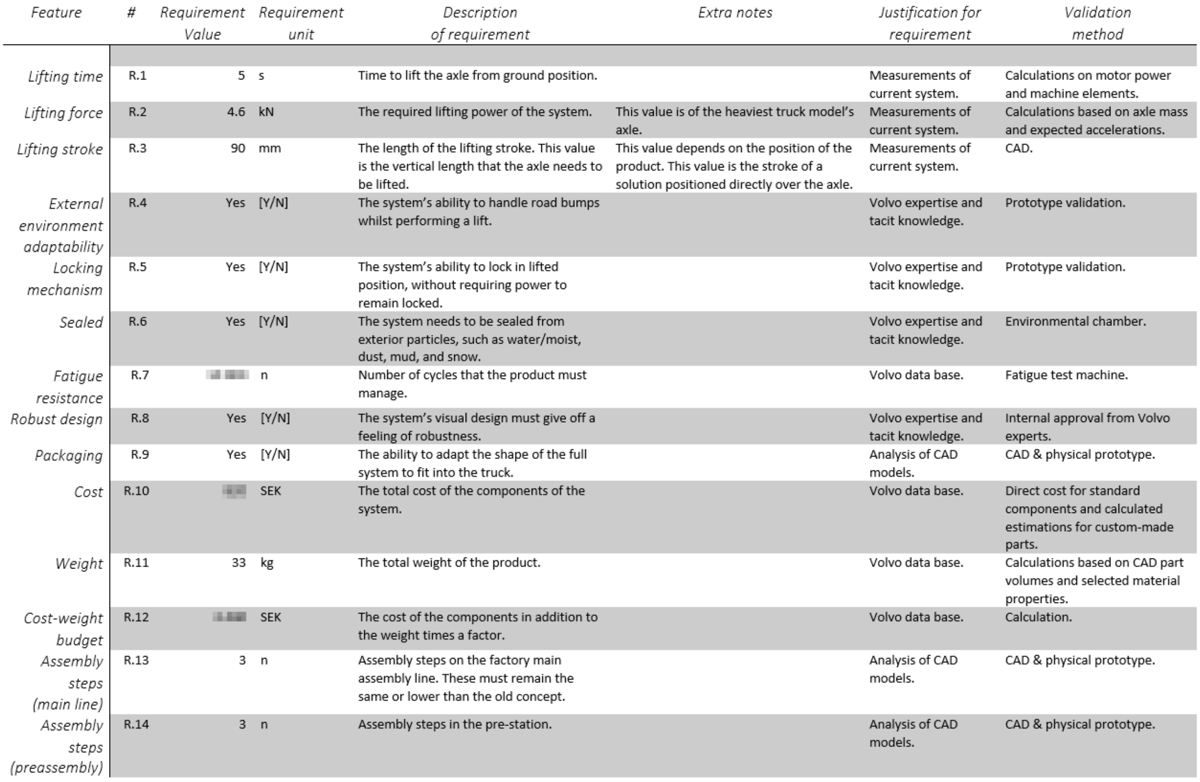
  This means that a rigidly locked system should be avoided, as the load case set from hitting bumps on the road while lifting would result in an over-dimensioned, heavy and expensive system so as to handle the extreme forces.

4.2 Requirements

4.2.1 Requirements List

Based on the different methods used a requirements list was created, Figure 6. Some values (R.7, R.10, R.12) are blurred due to confidentiality issues.

The justification column explains the method used when setting the requirement values. The validation column describes the process for validating that the final product fulfills the requirements.



Feature	#	Requirement Value	Requirement unit	Description of requirement	Extra notes	Justification for requirement	Validation method
Lifting time	R.1	5	s	Time to lift the axle from ground position.		Measurements of current system.	Calculations on motor power and machine elements.
Lifting force	R.2	4.6	kN	The required lifting power of the system.	This value is of the heaviest truck model's axle.	Measurements of current system.	Calculations based on axle mass and expected accelerations.
Lifting stroke	R.3	90	mm	The length of the lifting stroke. This value is the vertical length that the axle needs to be lifted.	This value depends on the position of the product. This value is the stroke of a solution positioned directly over the axle.	Measurements of current system.	CAD.
External environment adaptability	R.4	Yes	[Y/N]	The system's ability to handle road bumps whilst performing a lift.		Volvo expertise and tacit knowledge.	Prototype validation.
Locking mechanism	R.5	Yes	[Y/N]	The system's ability to lock in lifted position, without requiring power to remain locked.		Volvo expertise and tacit knowledge.	Prototype validation.
Sealed	R.6	Yes	[Y/N]	The system needs to be sealed from exterior particles, such as water/moist, dust, mud, and snow.		Volvo expertise and tacit knowledge.	Environmental chamber.
Fatigue resistance	R.7	[redacted]	n	Number of cycles that the product must manage.		Volvo data base.	Fatigue test machine.
Robust design	R.8	Yes	[Y/N]	The system's visual design must give off a feeling of robustness.		Volvo expertise and tacit knowledge.	Internal approval from Volvo experts.
Packaging	R.9	Yes	[Y/N]	The ability to adapt the shape of the full system to fit into the truck.		Analysis of CAD models.	CAD & physical prototype.
Cost	R.10	[redacted]	SEK	The total cost of the components of the system.		Volvo data base.	Direct cost for standard components and calculated estimations for custom-made parts.
Weight	R.11	33	kg	The total weight of the product.		Volvo data base.	Calculations based on CAD part volumes and selected material properties.
Cost-weight budget	R.12	[redacted]	SEK	The cost of the components in addition to the weight times a factor.		Volvo data base.	Calculation.
Assembly steps (main line)	R.13	3	n	Assembly steps on the factory main assembly line. These must remain the same or lower than the old concept.		Analysis of CAD models.	CAD & physical prototype.
Assembly steps (preassembly)	R.14	3	n	Assembly steps in the pre-station.		Analysis of CAD models.	CAD & physical prototype.

Figure 6: Requirements list for the developed concept. Fatigue resistance (R.7), cost (R.10) and cost-weight budget (R.12) are confidential values, and therefor masked

Following are the detailed results leading to the justification of the values for the requirements gathered through *Measurements of air bellow axle lift system* & *Analysis of CAD models*.

The requirements gathered through *Volvo expertise and tacit knowledge* & *Volvo database* are fully explained by the content in the requirement list itself.

4.2.2 Measurements of Air Bellow Axle Lift System

R.1: Lifting stroke

Direct measurements, with a ruler, gave a stroke of 90 mm for the required stroke of the axle.

R.2: Lifting force

Pressures in the air bellow lift system were measured during a lifting session, giving the lifting force. The obtained values averaged around 4.6 kN.

R.3: Lifting time

Lifting time were measured during a lifting session. The obtained values averaged around 5 seconds.

4.2.3 Analysis of CAD Models

R.8: Packaging CAD

Internal measuring tools in the CAD software in combination with a truck model gave a design space of 300x500x680 mm. The true design space is more complex than a box. However, the above-mentioned volume is the available space. Depending on the shape of the concept, the design space could be expanded at different points.

R.13 and R.14: Assembly steps

An assembly analysis was conducted on CAD models to estimate the number of assembly steps to gauge the time required to assemble the air bellow lift system. Every step on the main assembly line is considered being a simple step, mainly consisting of installing a screw. The connections between the parts involved in this subsystem and the frame were examined to get the preassembly steps number and the main assembly line steps number. The air bellow axle lift system is first preassembled onto the axle subsystem on the PAL, and then the axle is mounted on the frame on the MAL. Results can be seen in Figure 7 and Table 1 for the PAL and in Figure 8 and Table 2 for the MAL.

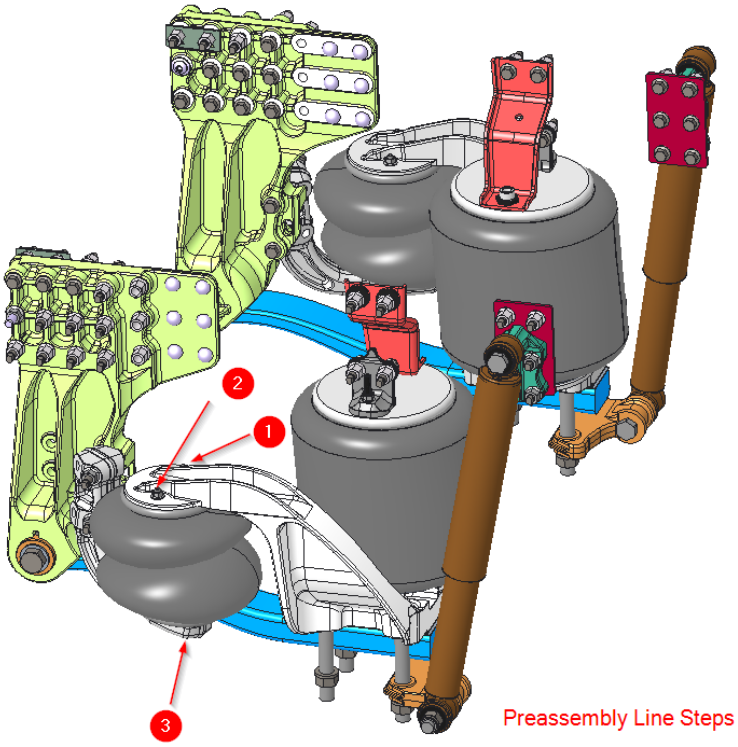


Figure 7: Preassembly Line analysis

Subsystem	Number
Lever arm to air bellow top connection 1	*1*
Lever arm to air bellow top connection 2	*2*
Lever arm to air bellow bottom connection	*3*

Table 1: Part description of the PAL

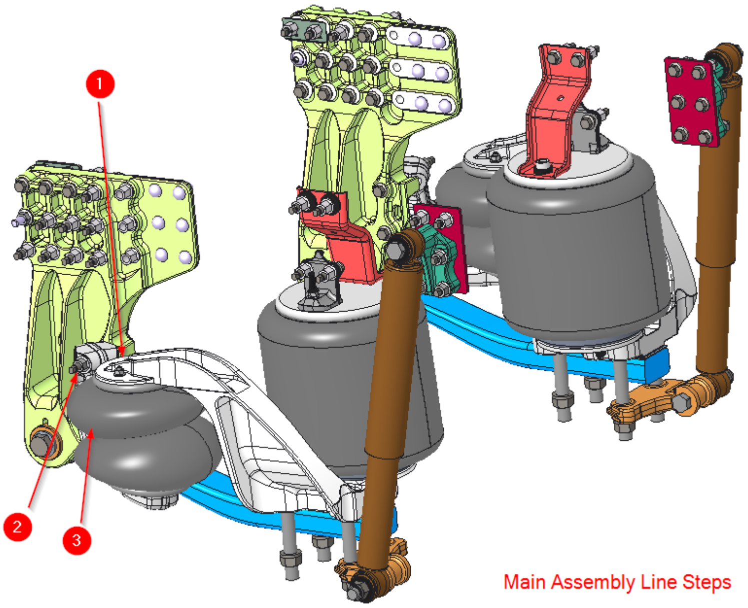


Figure 8: Main Assembly Line analysis

Subsystem	Number
Air valve connection	*1*
Lever arm screw 1	*2*
Lever arm screw 2	*3*

Table 2: Part description of the MAL

4.3 Prestudy

The three critical functions, Lifting, Locking and External environment handling, were studied independently. Some solutions managed to fit multiple functions and are included under every solved function. They will only be explained in their first appearance.

4.3.1 Lifting Function

For the lifting function, three separate concepts and technologies of interest were found:

A **torsion spring** is a system used to store rotational energy that can later be distributed back to the system, see Figure 9. The most common application of this system is on garage doors to help reduce the necessary load to open and close the garage door. (Veteran Garage Door Service, 2022)

Figure 9: A garage torsion spring. This would reduce the force required to lift the truck axle by preloading the lift (Veteran Garage Door Service, 2022)

A rope **pulley system** works by using a single rope to move tension force through tackles to lift a load, see Figure 10. By doing so, the force required to perform a lift decreases. The load required to lift a load using a pulley system decreases with a factor of $F = mg/p$. F is the required force, mg is the load, and p is the number of tackle loops. (John et al., 2010)

Using a pulley system would reduce the load to lift the truck's axle. Also, by working in tension and not being stiff in compression, a pulley system would work for external environment handling.

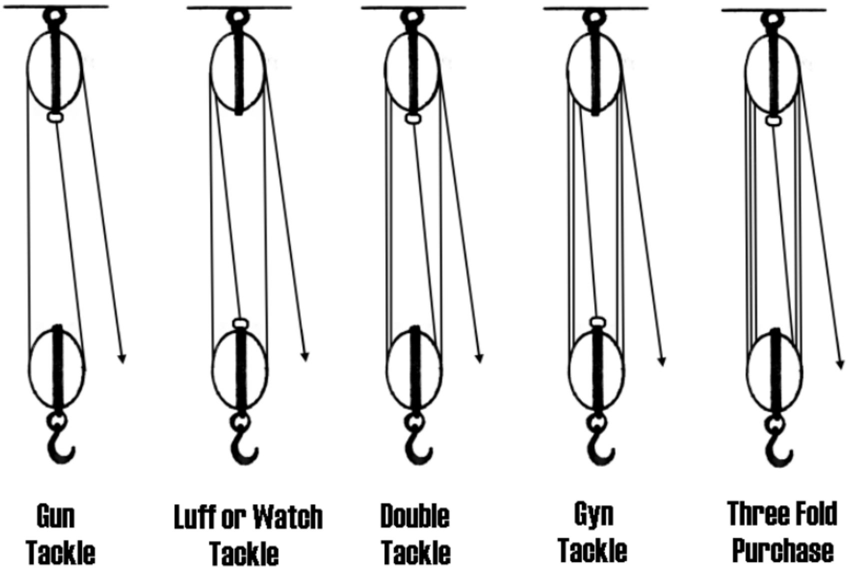


Figure 10: A display of different setups of pulley systems. This would use mechanical advantage to reduce the force required to lift the truck axle (Joseph, 2009)

A **linear actuator** is a device used to convert rotary motion into linear motion, see Figure 11. The linear actuator works by transferring a rotary motion (e.g., a motor) to a screw. When the screw rotates, a nut connected to the screw is pushed into linear displacement. (Automation, 2021)

Using a linear actuator to lift the truck's axle could reduce the required motor torque by changing the screwing element's lead.

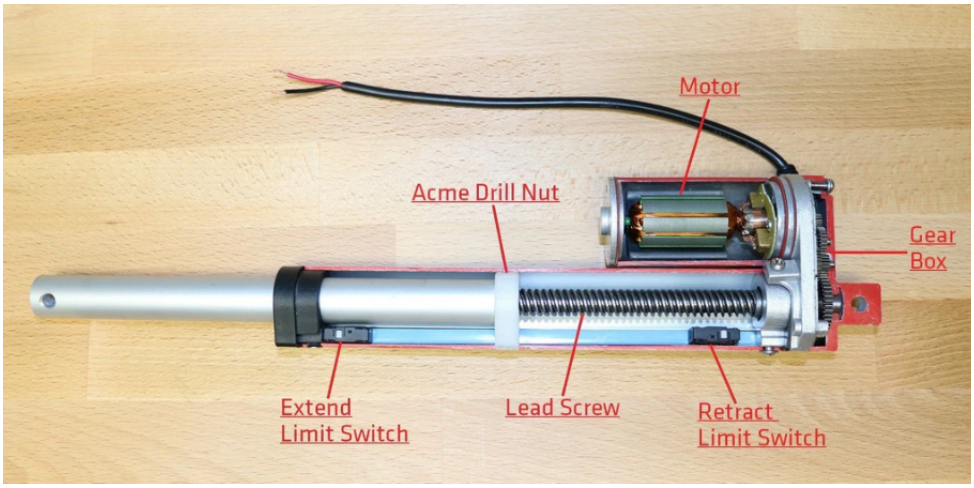


Figure 11: A linear actuator. This technology would enable the conversion of rotational movement (e.g. from an electric motor) into a linear movement that could lift the truck axle (Bong, 2021)

4.3.2 System Locking Function

For the system locking function two concepts and technologies of interest were found:

A **Geneva mechanism** device, also called Geneva stops, is a mechanism used to produce intermittent motion. It also allows for no reversal motion (The Editors of Encyclopaedia Britannica, 1998). In Figure 12 a display of such a mechanism is showcased. Driving a rotation through Part A would transfer the rotating motion to Part B, which would start to rotate intermittently. However, driving a rotation from Part B would not be possible, and the system would act as locked when rotating in that direction.

If integrated into a lifting system it could allow for motion induced by one side only while stopping the movement driven from the second side. This could block rotation of part B due to the axle's load while still allowing motion driven from, e.g., a motor on the driving side i.e., part A.

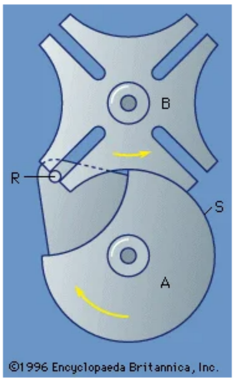


Figure 12: A Geneva mechanism device. This mechanism would enable driving the lift with a motor and having the mechanism block all reverse direction drive, thus locking the system (The Editors of Encyclopaedia Britannica, 1998)

The **lift hill mechanism** is a system used in roller coasters to allow for the forward motion of a roller coaster truck while completely blocking the reverse direction by the use of an anti-rollback device, as can be seen in Figure 13 (Weisenberger, 2013). The one-directional drive would allow a system based on this technology to move in one direction while blocking the reversal - this could be used for external environmental handling.

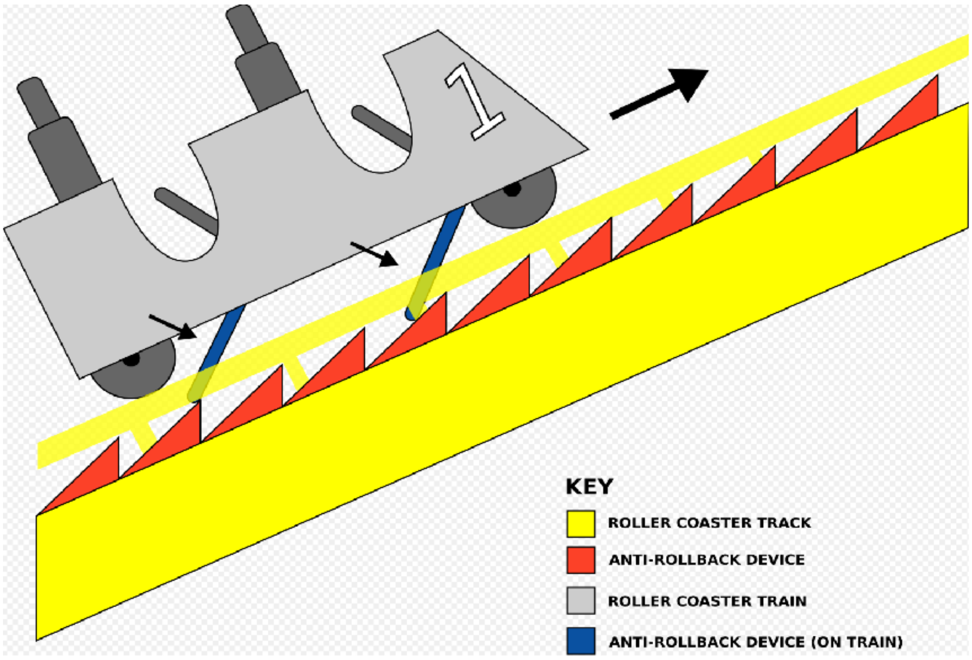


Figure 13: A lift hill mechanism. This mechanism would enable a system that lifts the axle in a linear motion while having the mechanism block all reverse direction drive, thus locking the system (Alton, 2007)

4.3.3 External Environment Adaptability

Two concepts and technologies of interest were found for the external environment adaptability. Both concepts found had applications in the previous functions.

The pulley system, as previously seen in Figure 10, would, aside from enabling lifting of the truck axle, also withstand bumps during axle lift due to the ropes not acting rigidly under compression that would occur during a bump (Joseph, 2009).

A lift hill mechanism, as seen in Figure 13, would enable a system that allows for bumps to quickly move the lifting system in one direction while being rigid in the other direction. Thus lift while still being able to manage bumps during the lifting (Alton, 2007)

4.3.4 Summary of the Prestudy

The main takeaway from this phase was the linear actuator. This technology, as can be seen at later phases, was kept and readapted to fulfill more functions. The phase was short, but set an inspirational foundation for the subsequent phases.

4.4 Concept Development

To develop the final product, several concept iteration phases were gone through. The results displayed in this section will show and explain the different ideas generated and what the screening sessions resulted in. More figures and drafts from early sketch sessions during these phases will be found in Appendix A.

The flow of the concept development phase can be seen in Figure 14. The sections 4.4.1-4.6.1 explains each concept development phase separately.

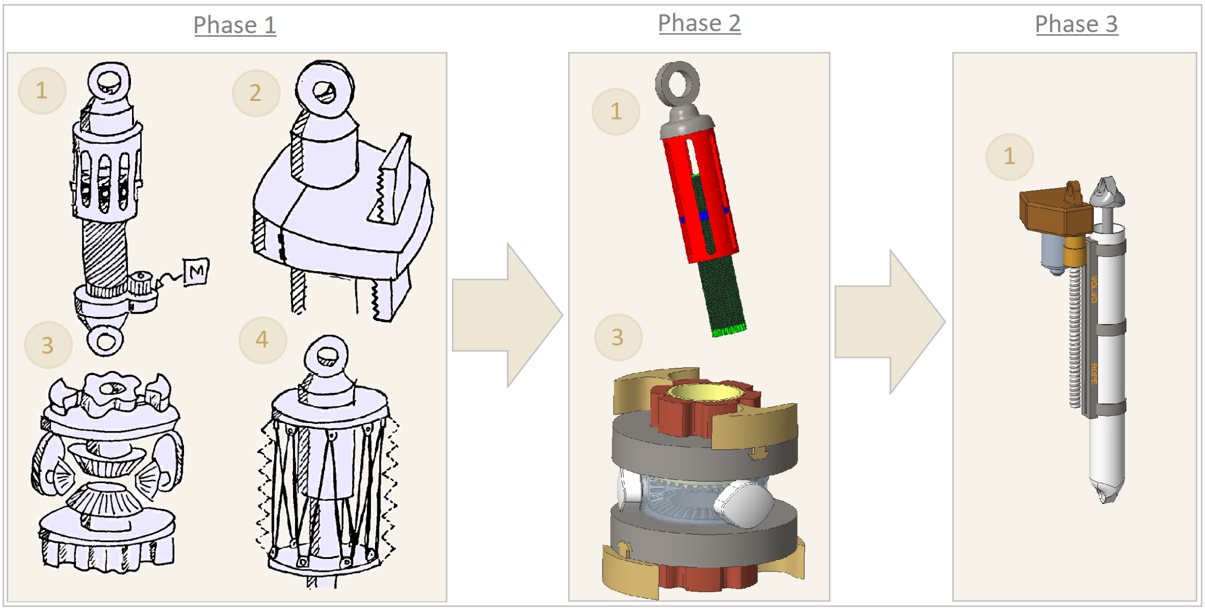
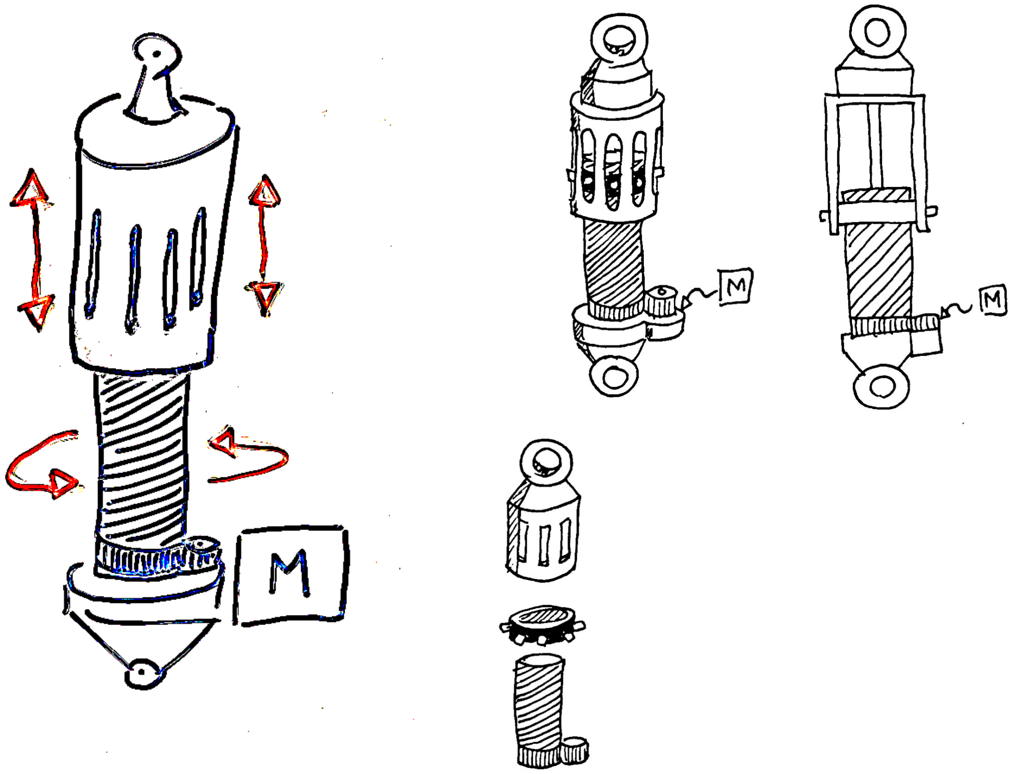


Figure 14: A flow chart of the concept development phase. In the figure, the concept generated at each phase can be seen. As the concepts can be seen going from Phase 1 to 2 to 3, the maturity can be seen to increase for some concepts while some concepts are eliminated during the screening part of the phases

Four main concepts have been generated and are shown and briefly explained in Section 4.4.1. The first phase leads to understanding that the concepts can be categorized into three subfamilies depending on how they are attached to the truck: inner damper-integrated, outer damper-integrated, and independent module. The first screening phase leads to the screening of two concepts. In Phase 2, further development such as CAD models and verifications of these two remaining concepts are presented in Section 4.4.2. One concept was kept after the second screening phase. Further subconcepts of this concept are explained in Section 4.6.1. The final chosen concept is also shown and then refined in Section 4.5.

4.4.1 Phase 1: Idea Generation and Screening

The first concept, Figure 15, is based on a lead screw driven by a motor, as can be seen at the bottom in Figure 15a. The concept works by driving the motor to rotate the lead screw and thus compressing the concept. The concept operates by being attached to the truck's frame at one end, and to the truck's axle on the other end. When compressing the axle is lifted. The concept also includes a housing with grooves and a connection ring with protruding knobs, as can be seen in Figure 15b. The idea behind the grooved housing and knobs is to allow the concept to handle bumps during a lifting session, i.e., if crossing a road bump occurs whilst lifting rather than all the force going into the lead screw, motor and other components, the concept would allow for free sliding within the groove.



(a) Suspension screw based concept, drawing 1 (b) Suspension Screw based concept, drawing 2

Figure 15: Drafts of the concept 1. This concept is based on a lead screw, connection ring with protruding knobs, and a grooved housing

The second concept, as seen in Figure 16, consists of a splined shaft clamped on the damper or an independent rod to lift the axle once requested. A gear connected to the frame lifts a splined shaft connected to the axle.

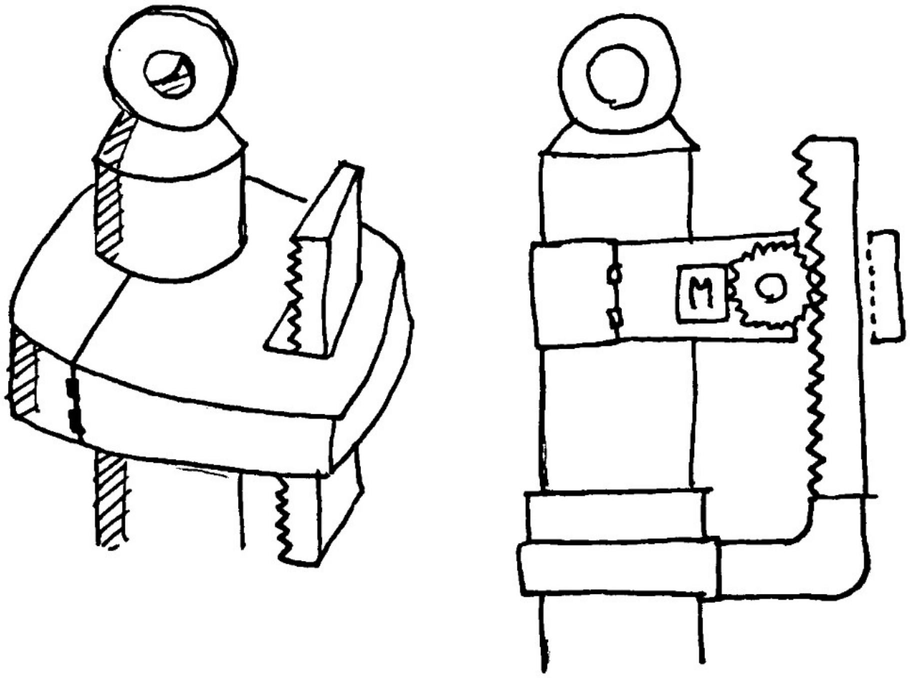


Figure 16: Drawings of concept 2. This concept is based on a splined shaft connected to the axle that can be driven to lift the truck's axle

The third concept, Figure 17, uses a pulley system with motor-driven wire ropes to pull the axle. The idea behind the pulley system is to yield two separate benefits. First it reduces the driving motor's required force, secondly it allows flexibility in compression, which makes so that the concept can freely compress should crossing a road bump during a lifting session occur. The top of the pulley system concept is where the motor is located and also a collection point for pulled rope, as can be seen in the right part of Figure 17. The top is connected to the frame of the truck. The bottom of the pulley system concept is connected to the axle of the trucks. The system can connected to the damper, or it can be entirely independently attached elsewhere.

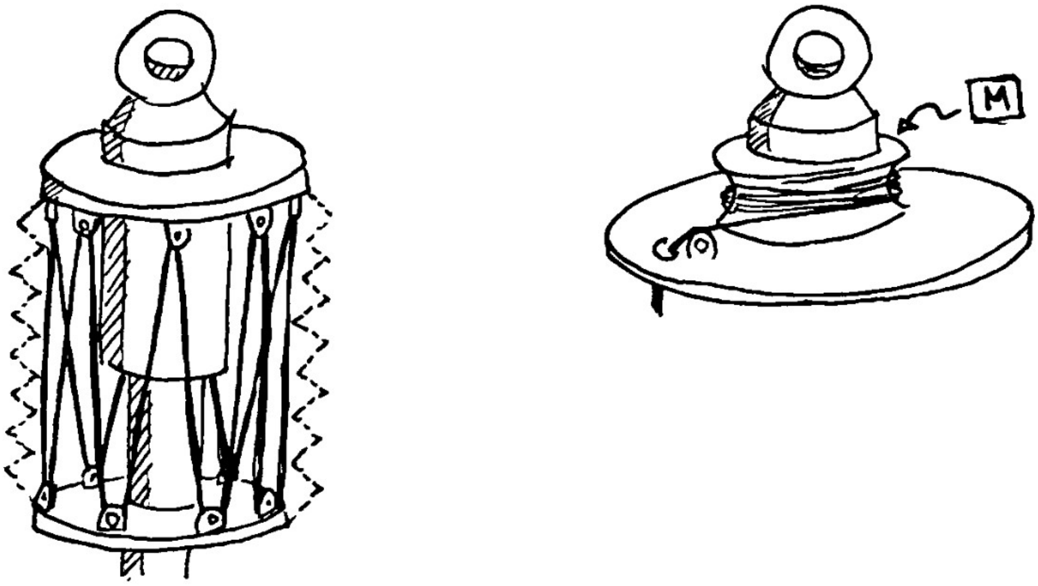


Figure 17: Drawings of third concept. This concept is based on a pulley system

The fourth concept is integrated inside the damper. It consists of an inner movable unit that can pull the bottom part of the damper from the inside. It can sequentially clamp to the bottom part of the damper connected to the axle and then push against the top part of the damper to lift the axle. This concept can climb freely inside the top part of the damper.

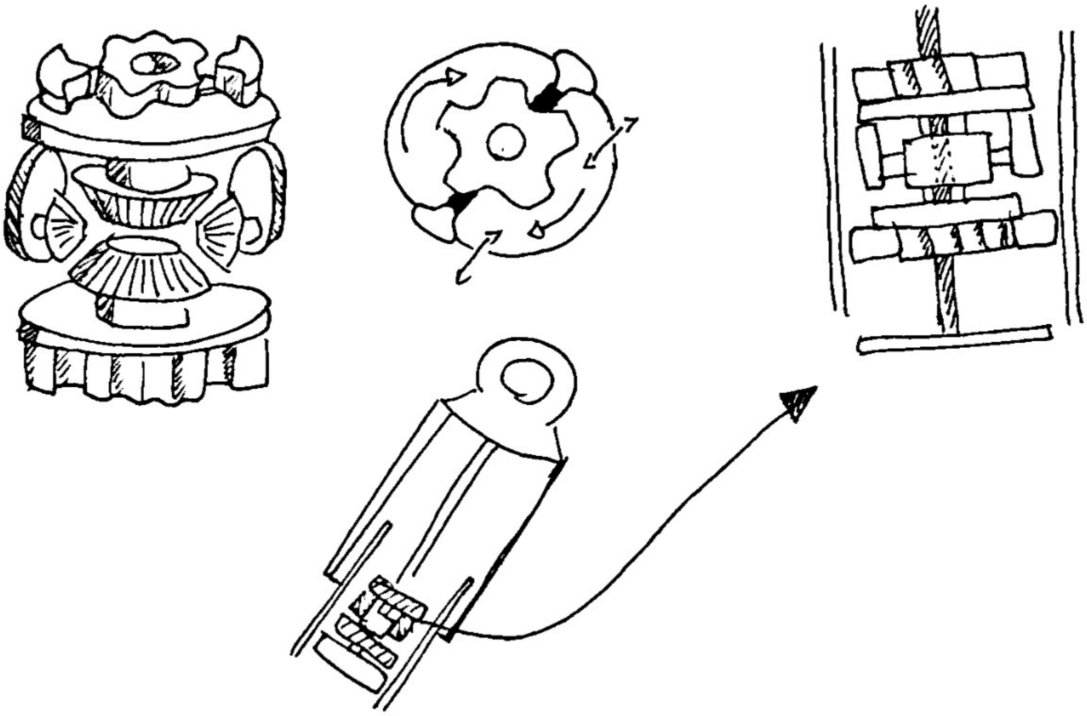


Figure 18: Drawings of the fourth concept. This concept is based on an internal unit that can pull the axle from the inside of the damper

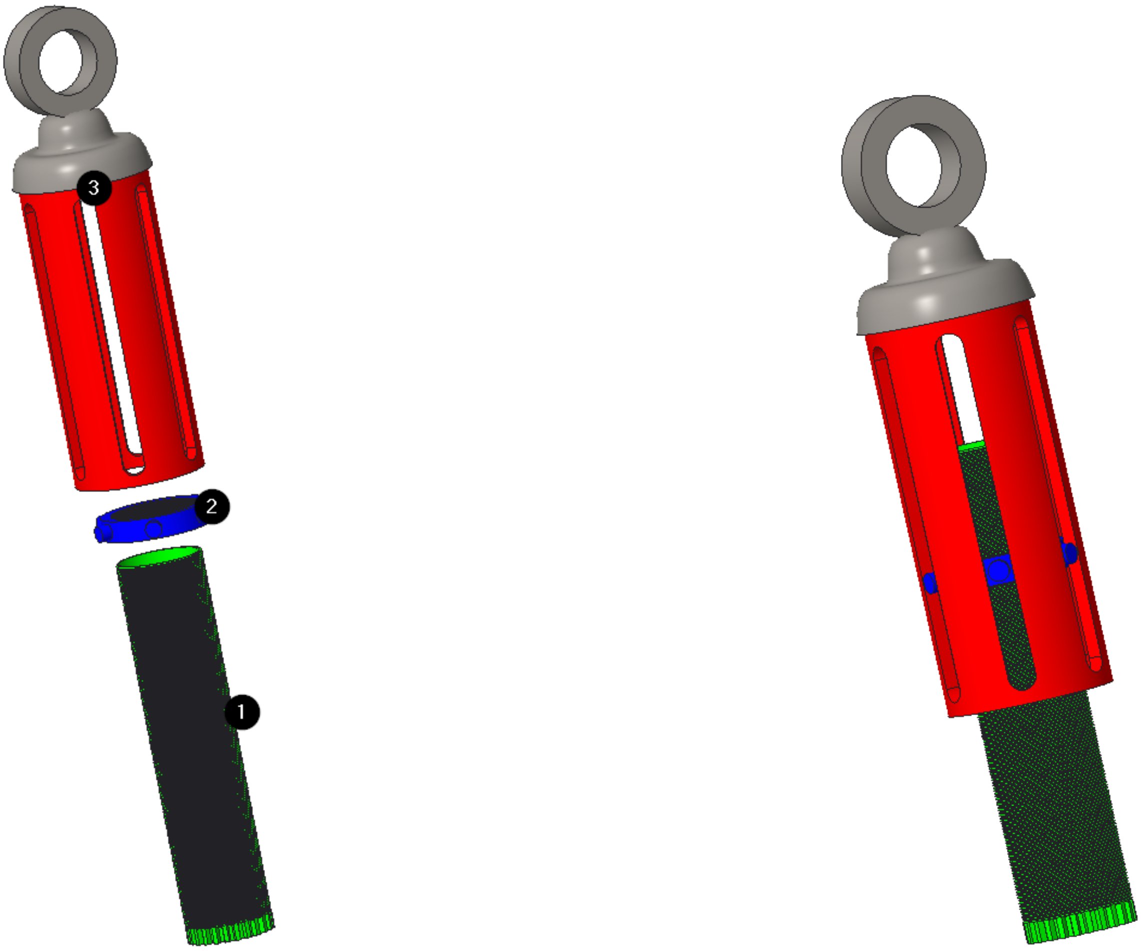
Screening

Phase 1 ended with a screening session. This session resulted in two concepts being screened out and two concepts remaining. The two concepts screened out were Concept 2 and Concept 3, The spline shaft concept and the pulley rope system. The spline shaft concept was screened out due to its inability to handle external environment forces, such as bumps (*Requirement R.4*). The pulley rope system concept was screened out after Volvo experts' verdict due to its lack of quality in visual robust design (*Requirement R.8*)

4.4.2 Phase 2: Concept Refinement and Screening

In this phase, two concepts were made into CAD assemblies to provide insights on size, manufacturability, and cost. CAD models pictures can be seen below.

The suspension screw concept is made of 3 essential parts. It works by rotating part 2 in part 3 and lifting part 1 and thus the axle. Parts 1 & 2 are free to translate, following the grooves in part 3.



(a) Exploded view of the concept 1

(b) Unexploded view of the concept 1

Figure 19: CAD model of the suspension screw based concept

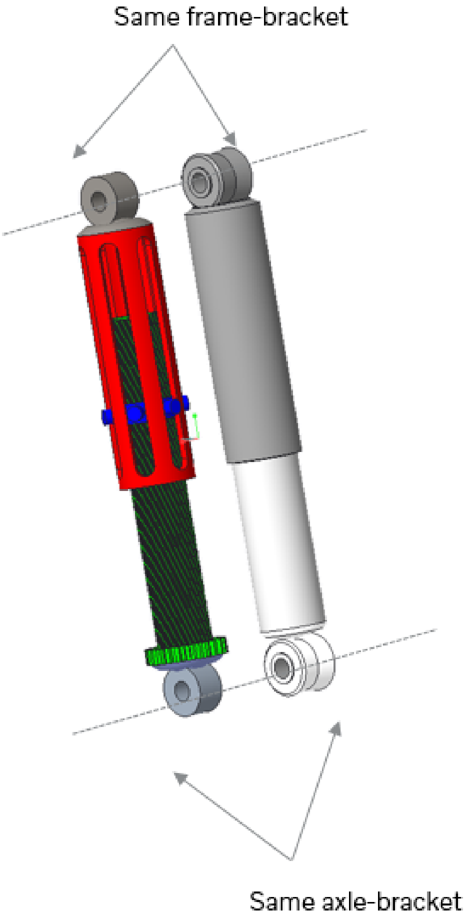
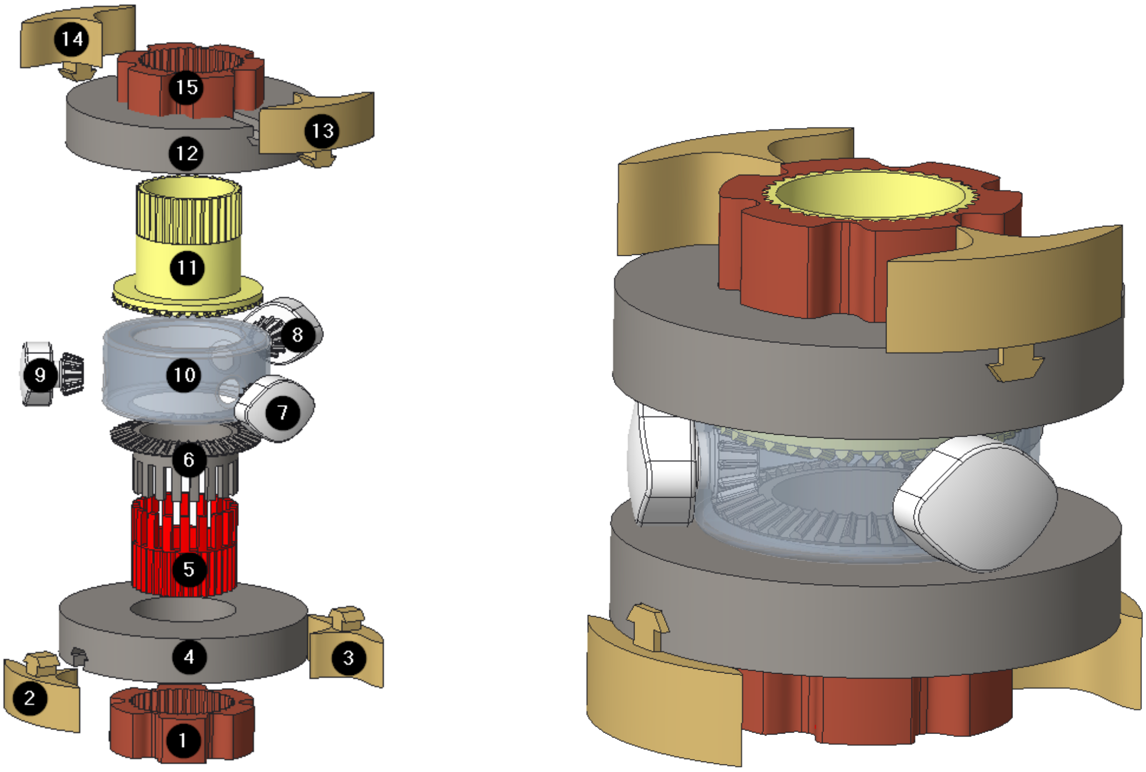


Figure 20: Example of Modular suspension screw in context

The inner concept (3), called the crawler concept, is made of 15 parts, as can be seen in Figure 21. This concept works by using sequential cam mechanisms to clamp the bottom part of the damper and pull it by pushing against the top part of the damper. The vertical rotation of part 11 is transferred as rotation to part 15 and part 1, at the top and bottom, respectively. In the middle of the concept, the rotation of part 11 also transferred into a horizontal rotation to parts 7, 8 & 9. The rotation of parts 7, 8 & 9 expands and contracts the middle of the crawler. During the expansion, the rotation of part 15 expands the top of the crawler by cams connected to parts 13 & 14 and thus grips the outer walls inside the damper. The crawler works by sequentially gripping and then expanding to move up or down through the damper.



(a) Exploded view of the concept (b) Unexploded view of the concept

Figure 21: CAD model of the inner family

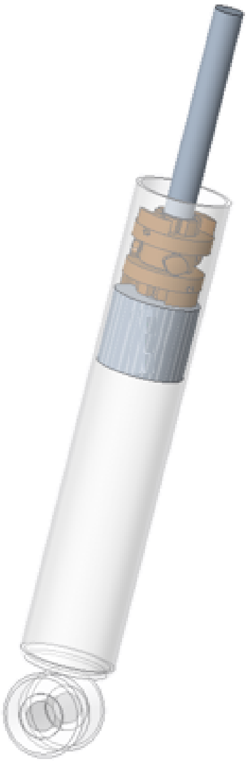


Figure 22: Crawler in context

Screening

Phase 2 resulted in the elimination of the crawler concept. The reason was the existence of too many complicated interactions with the damper. The concept was seen to require parts that would be too big to fit inside the damper, e.g., no motor with the required specifications of power and volume exists. The concept would also consist of many parts, and the needed preassembly would be extensive.

4.4.3 Phase 3: Concept Refinement and Concept Selection

During Phase 3, the remaining concept, the suspension screw concept (see Figure 19), was looked at. Different versions containing different system placements on the truck, different order of the components, and different component specifications were generated. Every possible arrangement of the components was looked at during meetings with the Volvo Trucks department. Implementation of the concept as a custom damper versus as an independent module was also considered. The equations used are Equations 2- 5, and the full order of calculations can be seen in Appendix B.

The motor in any other position than at the top, connected to the frame, was ruled out as infeasible due to different force profiles near the axle.

The lead screw was changed into a ball screw bearing to reduce friction, which increased the motor's power requirement (and thus cost and weight). Figure 23 shows the difference in lifting time for the two different components in different positions on the truck. Lead screw does not fulfill the lifting time requirement, (**R.1**), for any position.

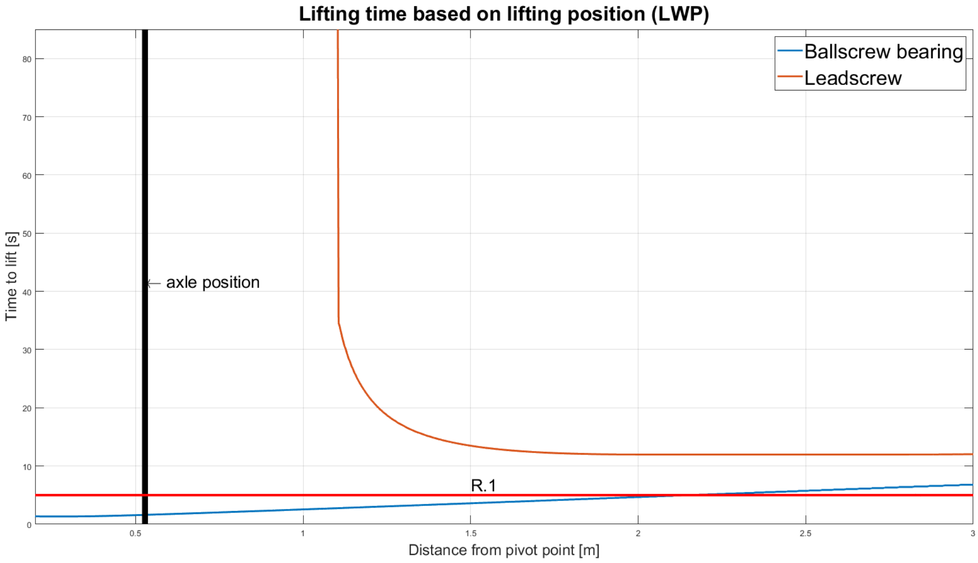
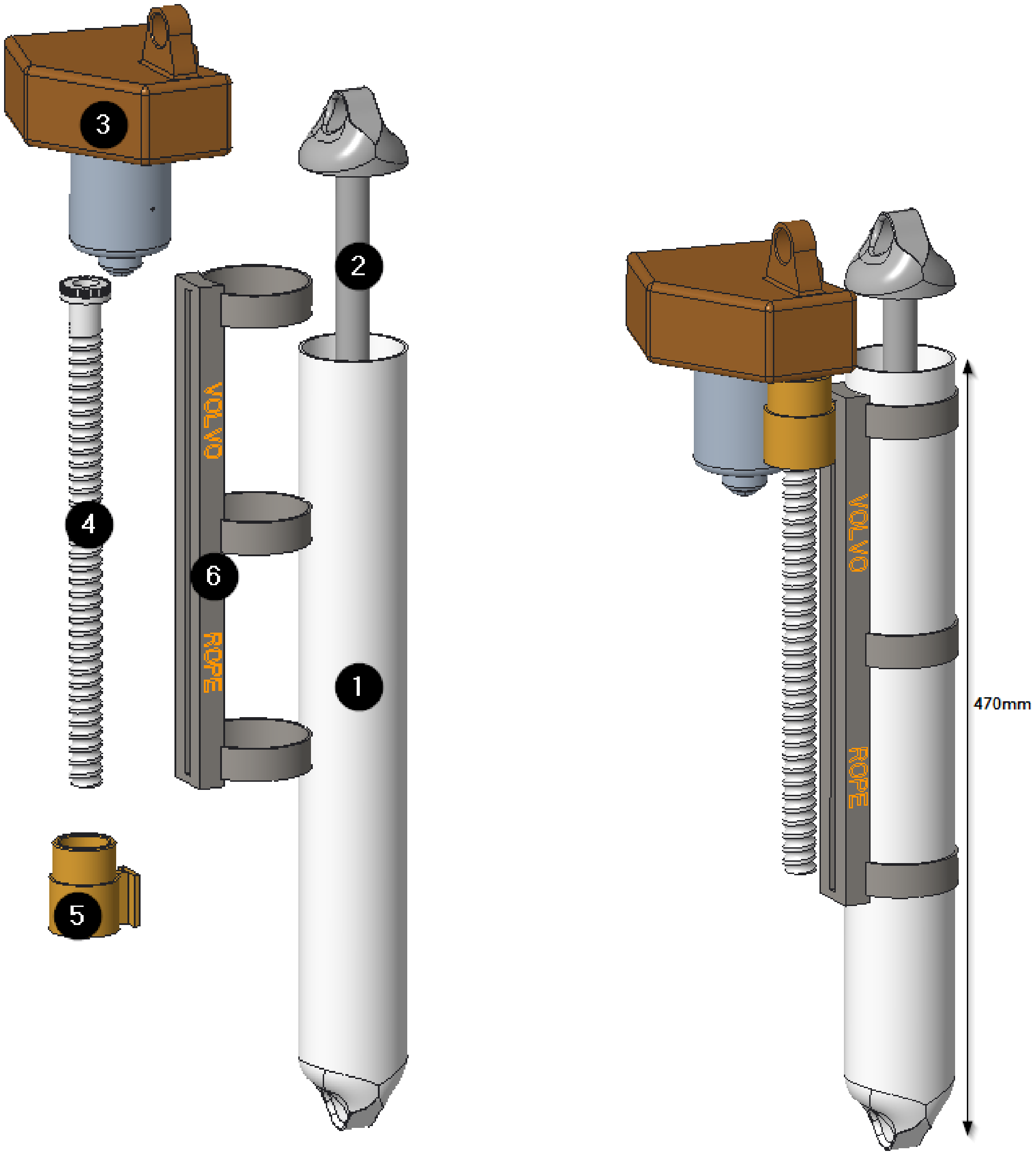


Figure 23: Efficiency study between a lead screw and a ball screw bearing. This graph shows the lifting time for different positions on the truck for this two different components

The ring with protruding knobs was changed into a slider to reduce preassembly steps.

A final version of the concept was chosen and can be seen in Figure 24. The concept relies on part 4 rotating, thus linearly moving part 5, inside the groove of part 6. Part 4 is driven by a motor contained in part 3, the gearbox. The gearbox is connected to part 2 and the truck's frame. Part 6 is clamped to the bottom tube of the damper, part 1. The bottom of the damper is connected, via a screw joint, to the truck's axle .

Part 5 can move freely inside the groove of part 6 until it is lifted to the top of part 6. Once part 5 connects to the top of part 6, any further lifting of part 5 will raise the whole bottom part of the damper, thus lifting the axle. Even when lifting, the connection between part 5 and part 6 is not fixed in compression, and therefore if a bump occurs, the parts can disconnect - allow free compression of the system.



(a) Final Selection design, exploded view

(b) Final Selection design, unexploded view

Figure 24: Isometric views of the final selection concept

Table 3: Part number and description

Subsystem	Number	Material
Bottom link	*1*	Steel
Top link	*2*	Steel
Motor+gearbox	*3*	Aluminium
Threaded rod	*4*	Steel
Ballscrew bearing	*5*	Steel
Slider groove	*6*	Steel

4.5 Detailed Design

This section aims to explain the concept, show the different generations of refinements of the final concept, and finally showcase the values from the dimensioning of the individual parts.

The dimensioning of the individual parts is based on the volume available, the motor's power requirements (based on Equation 6) and dynamic forces that the system had to be able to handle.

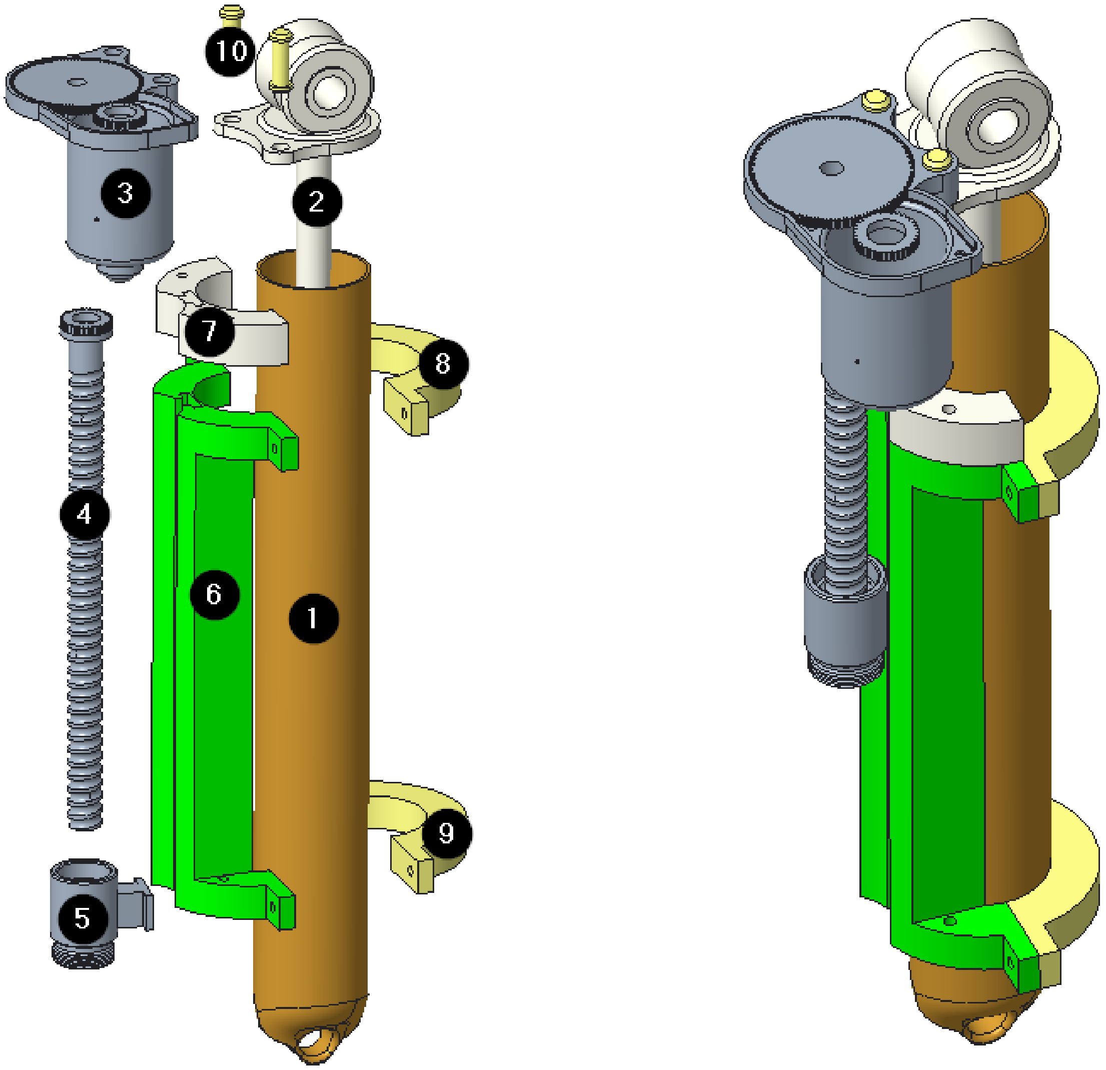
Using Equation 6, an absolute lifting force of 4.6 kN, a stroke of 90 mm and a lifting time of 5 seconds, the ideal minimum power requirements for the motor was set to 82.8 W.

The magnitude of the force is to account for the forces during the vehicle dynamics and axle weight during the most extreme conditions, being set to 7.5 kN.

This dynamic force is connected to the maximum forces that the system could endure and is not directly related to the required lifting force to lift the axle.

4.5.1 First Iteration

The first iteration of the detailed design can be seen in Figure 25; this figure includes both views of the exploded and unexploded assembly. The concept's cost, weight, and amount of parts can be seen in Table 4. Figure 26 showcases a sequence of how the system works during a lifting session. Descriptions of the part's function and material can be seen in Table 5.



(a) First step Detailed Design exploded view

(b) First step Detailed Design unexploded view

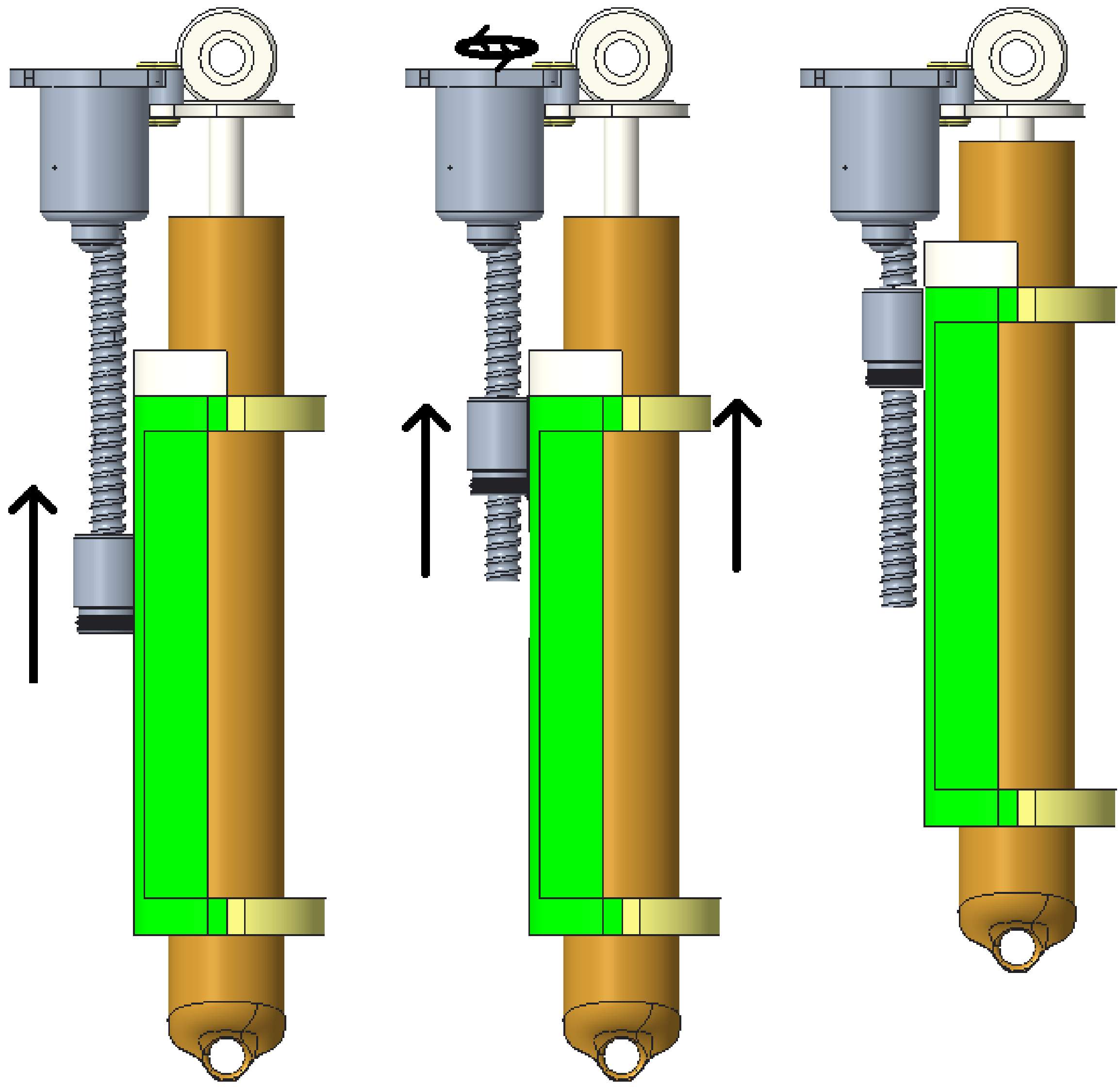
Figure 25: Isometric views of the first version concept

Table 4: Key values of the main concept first version

	Values
Cost	Confidential
Weight	4.9kg
Number of parts	31

Table 5: Subsystem numbers and material descriptions

Subsystem	**Number**	**Material**
Bottom link	*1*	Steel
Top link	*2*	Steel
Motor+gearbox	*3*	Aluminium
Threaded rod	*4*	Steel
Ballscrew bearing	*5*	Steel
Slider	*6*	Steel
Clamping part top 1	*7*	Steel
Clamping part top 2	*8*	Steel
Clamping part bottom	*9*	Steel
Screw connection	*10*	Steel



(a) Bottom link can move freely up and down

(b) The system starts to lift

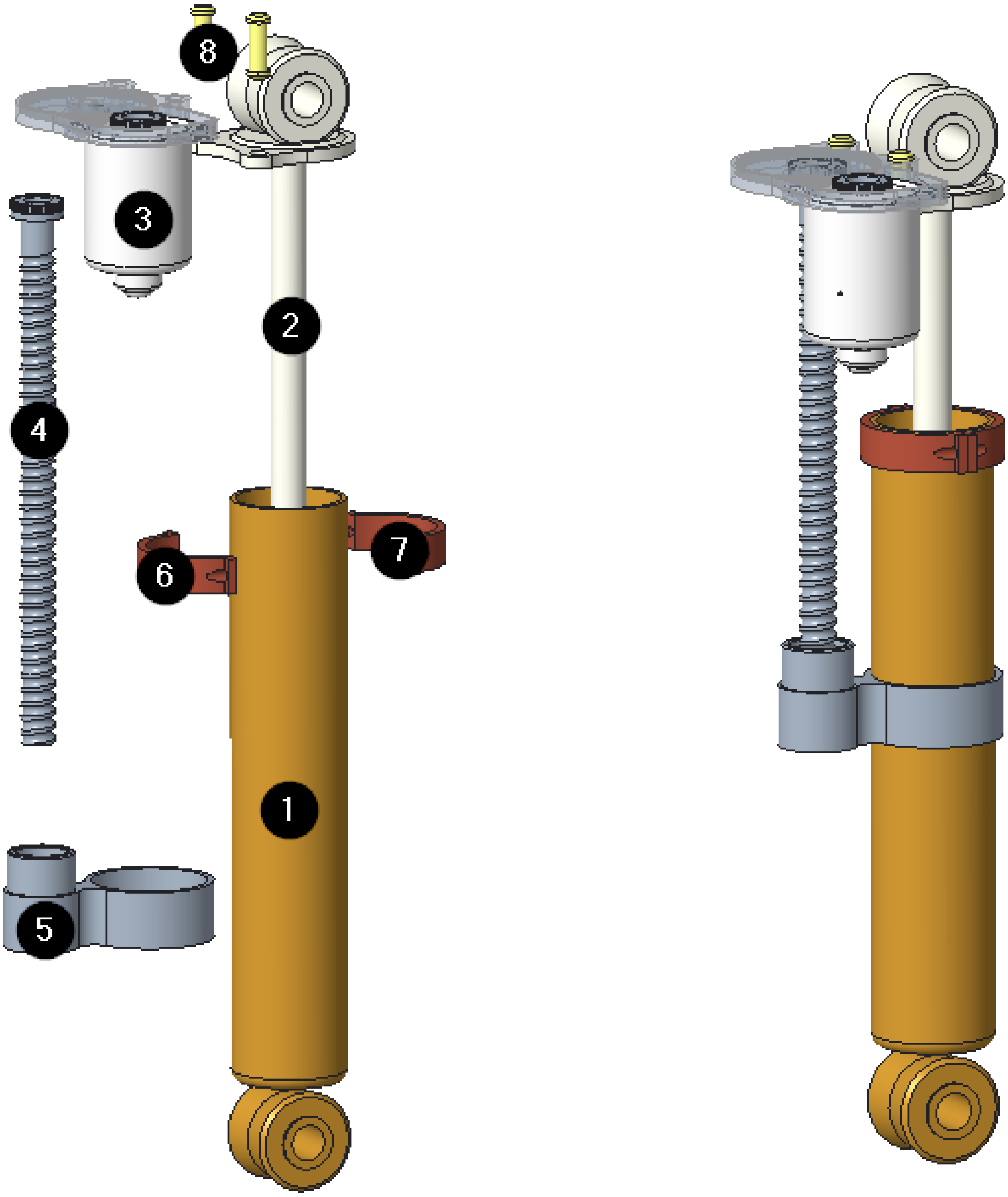
(c) Bottom link is lifted

Figure 26: Sequence of a lifting session

4.5.2 Second Iteration

The second iteration of the detailed design can be seen in Figure 27; this figure includes both views of the exploded and unexploded assembly. The concept's cost, weight, and amount of parts can be seen in Table 6. Descriptions of the part's function and material can be seen in Table 7.

This version works similarly to the previous version; however, the slider part is removed in favor of a ring connection. This adjustment keeps the same function as before but with less material and fewer parts.



(a) Second step Detailed Design exploded view (Confidential)

(b) Second step Detailed Design unexploded view (Confidential)

Figure 27: Isometric views of the second version concept

Table 6: Key values of the main concept second version

	Values
Cost	Confidential
Weight	3.1kg
Number of parts	23

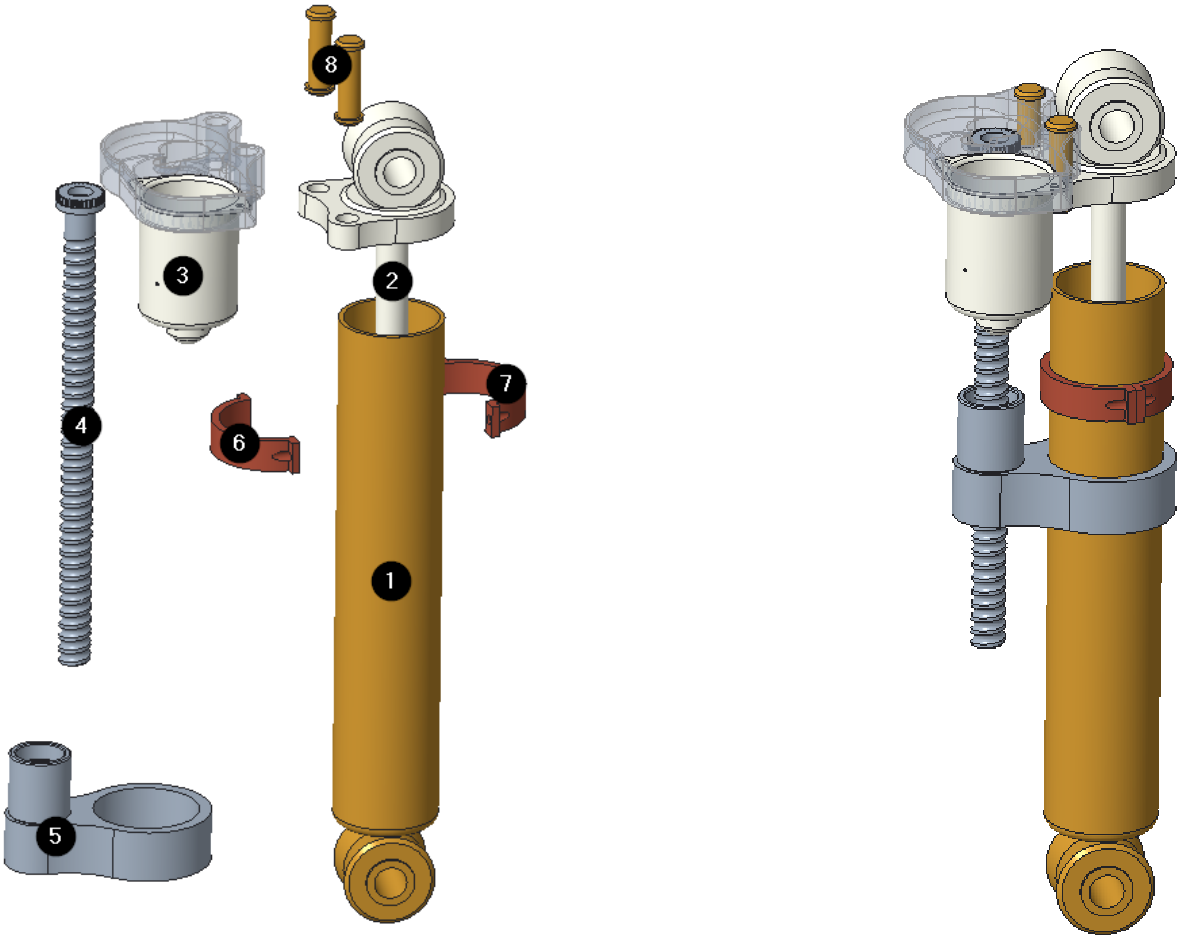
Table 7: Subsystem number and material descriptions

Subsystem	**Number**	**Material**
Bottom link	*1*	Steel
Top link	*2*	Steel
Motor+gearbox	*3*	Aluminium
Threaded rod	*4*	Steel
Ballscrew bearing + sliding ring	*5*	Steel
Clamping part top 1	*6*	Steel
Clamping part top 2	*7*	Steel
Screw connection	*8*	Steel

4.5.3 Third Iteration

The third iteration of the detailed design can be seen in Figure 28; this figure includes both views of the exploded and unexploded assembly. The concept's cost, weight and amount of parts can be seen in Table 8. Descriptions of the part's function and material can be seen in Table 9. Figure 29 showcases a sealing proposal to fulfill R.6 and Figures 30a & 30b show the concept on the truck environment.

During this iteration the focus was mechanical integrity. This iteration included changes in topology and thicknesses of parts to better handle the forces during its intended use. This resulted in increased weights of certain parts, and the system as a whole.



(a) Third step Detailed Design exploded view (Confidential)

(b) Third step Detailed Design unexploded view (Confidential)

Figure 28: Isometric views of the third version concept

Table 8: Key values of the main concept second version

	Values
Cost	Confidential
Weight	3.87 kg
Number of parts	23

Table 9: Subsystem number and material descriptions

Subsystem	Number	Material
Bottom link	*1*	Steel
Top link	*2*	Steel
Motor+gearbox	*3*	Aluminium
Threaded rod	*4*	Steel
Ballscrew bearing + sliding ring	*5*	Steel
Clamping part top 1	*6*	Steel
Clamping part top 2	*7*	Steel
Screw connection	*8*	Steel

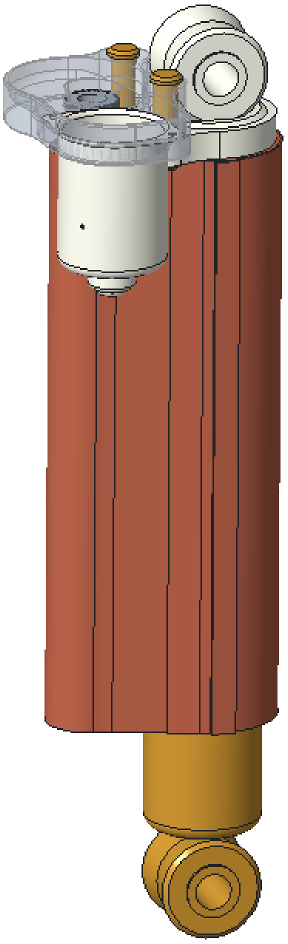
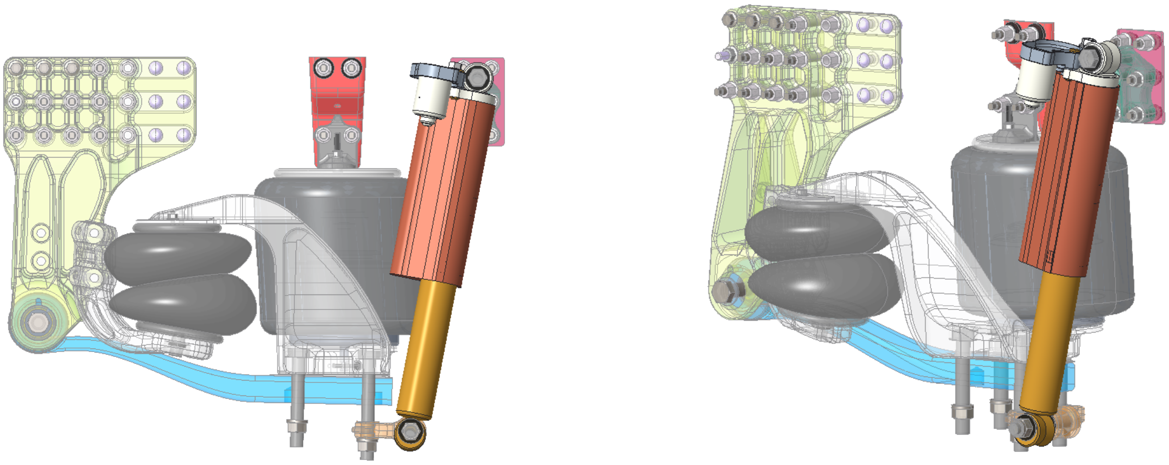


Figure 29: Third version concept of the concept, with added dust cover for sealing



(a) Front view of the concept on a part of a pusher axle installation. The air bellow lifting system is kept to show the volume that can be saved

(b) Isometric view of the concept on a part of a pusher axle installation. The air bellow lifting system is kept to show the volume that can be saved

Figure 30: Front and isometric view of the concept on a part of a pusher axle installation

4.6 Verification and Refinement

The purpose of this chapter is to assess the proper fulfillment of the requirements of the product. This process has been done continuously throughout the project and more intensively during and after *Detailed design* phase.

4.6.1 System-level Verification - Calculations

Following are the results from the calculations of the lifting times for different positions on the truck by using the same method as in Section . The results can be seen in Figures 31-33 for three truck variants.

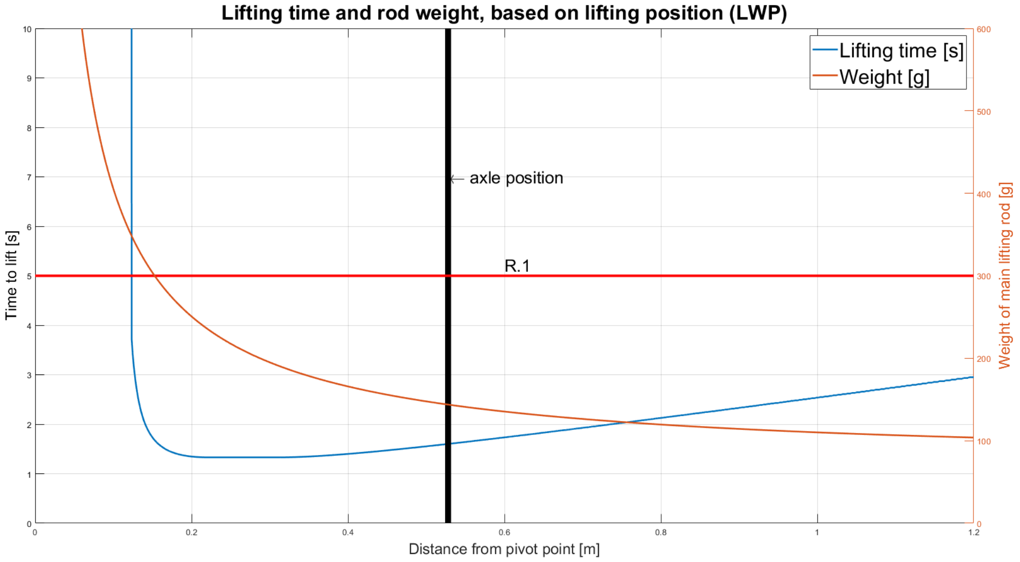


Figure 31: Lifting time and weight **LWP**

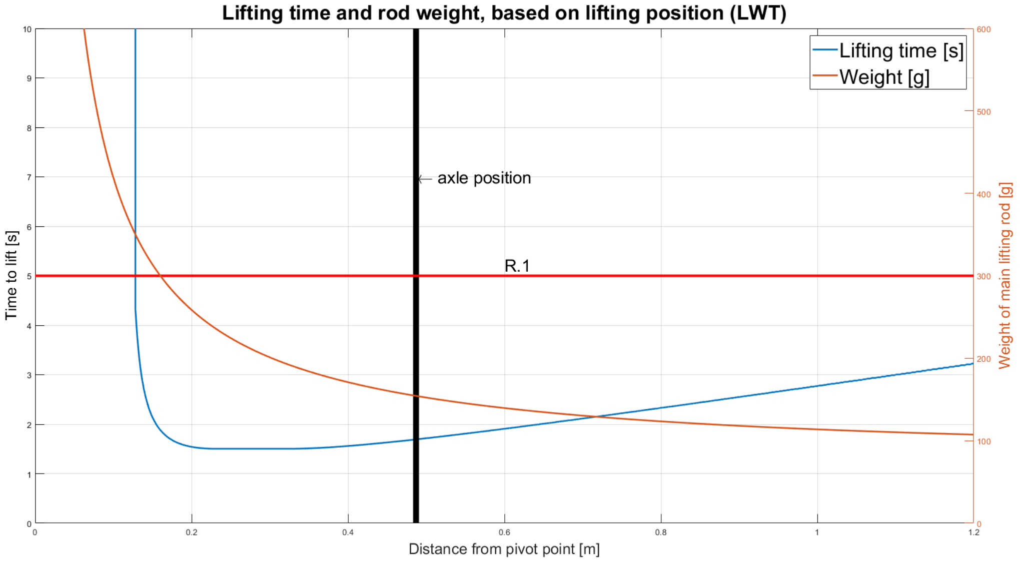


Figure 32: Lifting time and weight **LWT**

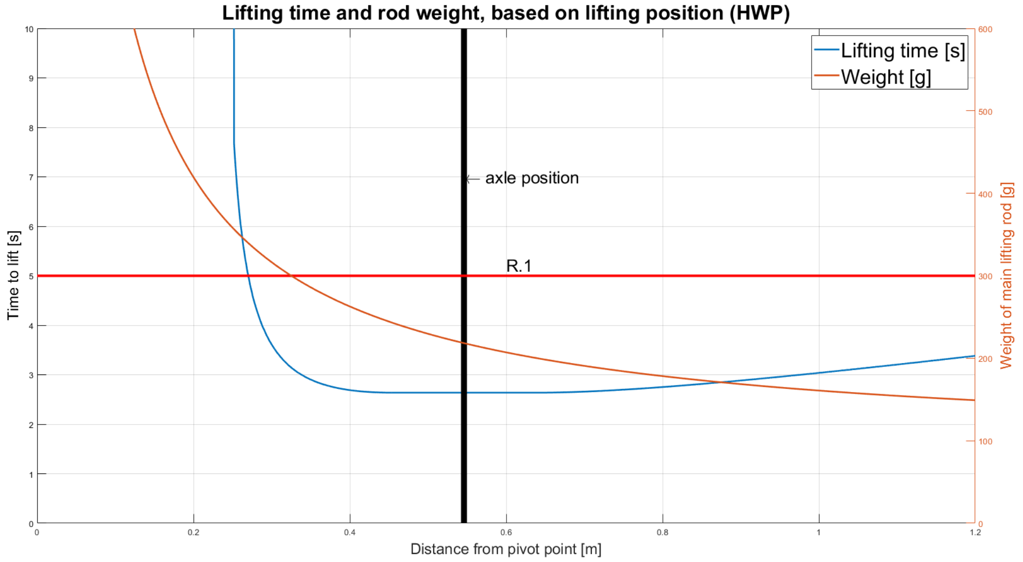


Figure 33: Lifting time and weight **HWP**

So, the closer to the rotating point the concept is, the higher the force required is: this leads to an infinite increasing lifting time since the motor has a peak torque it can not exceed, torque providing the lifting force. Similarly, the further the concept from the rotating point the more stroke it has to travel. However, the motor also has a maximal rotational speed, and not every lead for lead screws is available, leading to an increasing lifting time. It can be seen that the R.1 is fulfilled for every truck's variants in many positions. Furthermore, the weight estimation assumed using a rod to handle the screwing. The rod has to handle the lifting force, varying depending on the position. The rod will then have a varying cross-sectional area to support the corresponding stress, but also a varying length depending on the required stroke. So, the closer to the rotating point the concept is, the higher the force required is and thus the higher the cross-sectional area, but also the shorter the rod due to a shorter stroke.

The last detailed design characteristics were implemented in the calculations and the optimized gear ratios and thus lifting time can be read in Table 10.

Table 10: Results of the analysis on the optimized gear ratios thus lifting time

	LWP	**LWT**	**HWP**
Lifting time	1.8s	1.9s	2.6s
Screw lead	5mm	5mm	5mm
Gear ratio	4	4	4

4.6.2 System-level Verification - Prototype Analysis

The CAD model for the printed physical prototype can be seen in Figure 34. Adjustments to the model were made to fit with the available standard components and to account for the change in the material of the parts. These changes include an altered interface to the motor, a direct connection to a printed damper top, and a thicker connection nut between the screw rod and the damper bottom.

A photograph of the printed parts can be seen in Figure 35. Photographs of the individual parts can be seen in Figure 35.

A photograph of the assembled physical prototype can be seen in Figure 36. This assembled prototype was later installed on a truck master rig to test the following requirements: R.8, R.9, R.13 & R.14. No photographs of the full installation can be shown due to confidentiality issues.

The prototype was also used to establish the number of steps that would be required in the main, and preassembly line (R.13 & R.14). It was counted up to be 1 step for the main assembly line - the electrical connection to the lifting system's motor. There would be no further steps on the main assembly line since the product would be directly assembled to the damper during the preassembly line. In the preassembly line, the total steps would be 7.

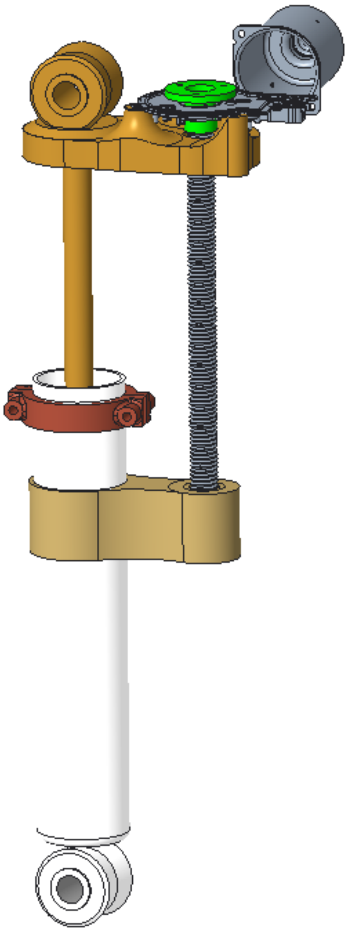


Figure 34: ISO view of the CAD model used to print the physical prototype

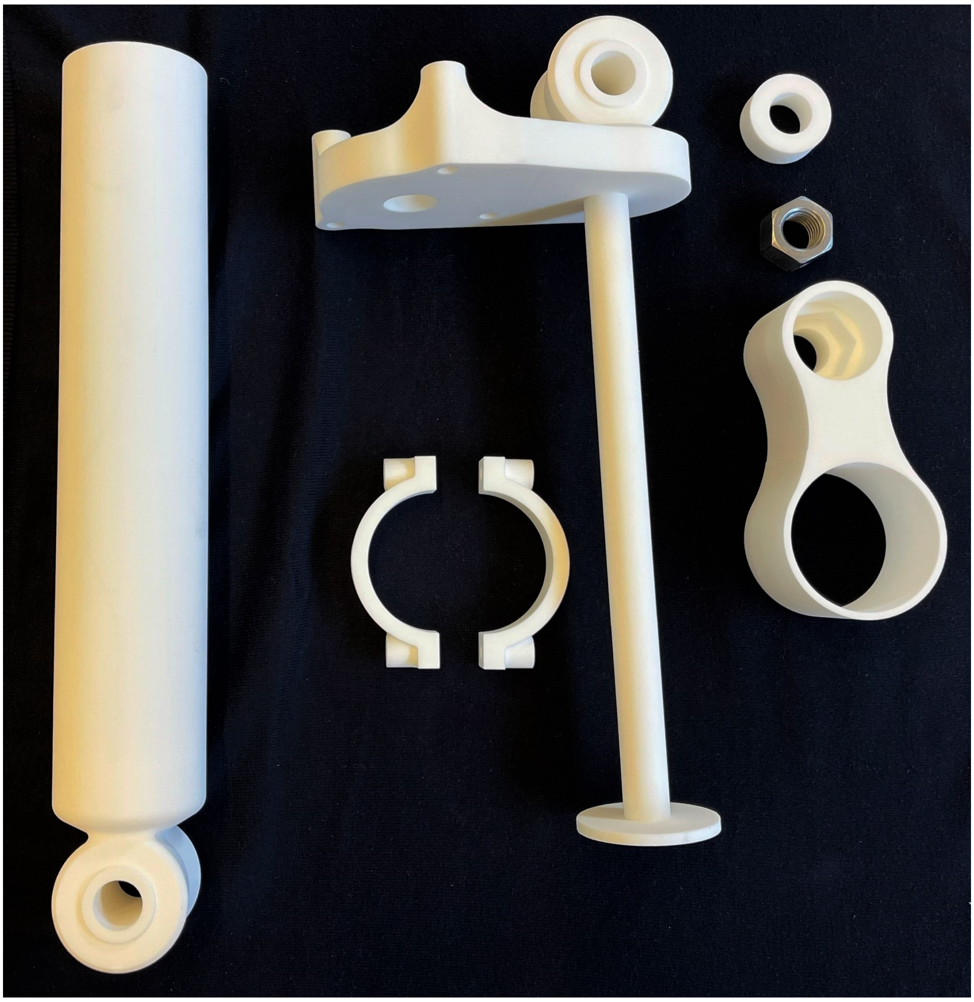


Figure 35: Photograph of the 3D printed parts, before assembly of physical prototype

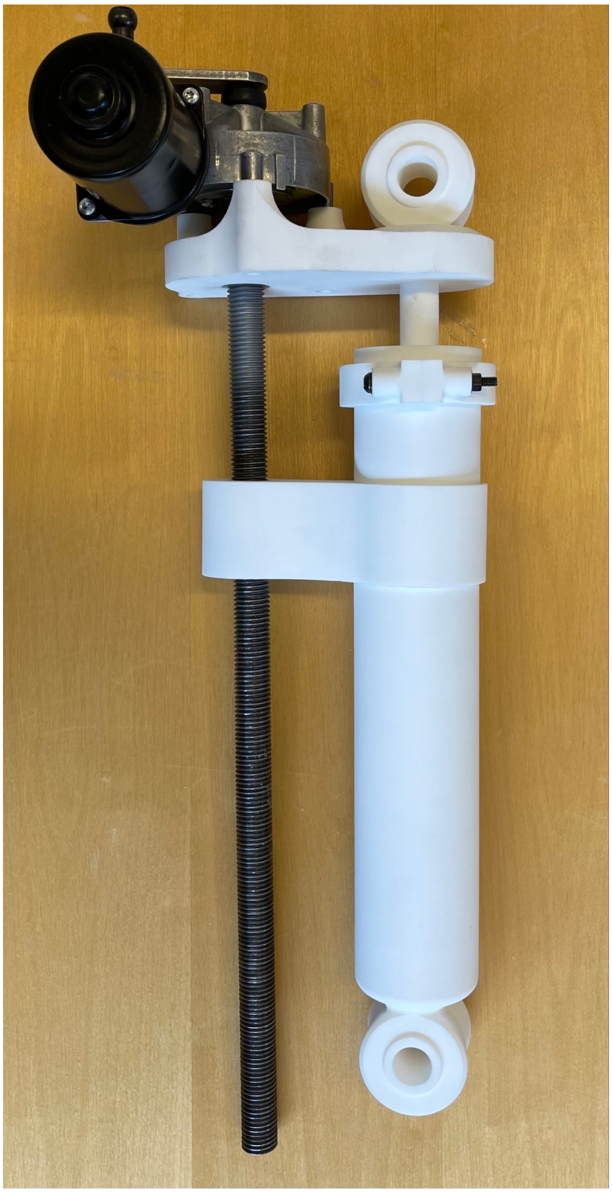


Figure 36: Photograph of the assembled physical prototype

4.6.3 Part-level Verification

Following are the results from the FEM analyses done on the first, and later the second, detailed design CAD. Zones that are red in the figures mark where the parts would not withhold a safety factor of 2 during extreme dynamic conditions. The colors of the FEM analysis areas are set to display on a scale going from blue to green to red. Fully red areas represent areas where the stress would be higher than a preset maximum allowed stress. The preset peak depends on the intended material for the part and is set to 200 MPa for aluminum parts and 500 MPa for steel parts.

The load condition is set to a vertical force of 15 kN, in the position marked by the orange arrows in Figure 37. The same load condition is kept through all the FEM studies conducted, but only displayed once so as to not overfill the figures.

In the FEM analysis of the first detailed design version, as seen in Figures 37-38, there are many areas where the stress peaks to values higher than the maximum allowed stress, i.e., the mechanical structure of the part would fail at these areas. The final detailed design version was done with the aid of the previous FEM analysis, to ensure good mechanical integrity for the system. As can be seen in Figure 39-40, the structure is refined by increasing the thickness and radius on the corresponding areas, and no red spots are seen, meaning that the parts would hold. There is an exception, though, the bolts used for the interface between the suspension top plate and the gearbox cover. This result, and its implications, is discussed further in the Chapter 5; *Discussion*.

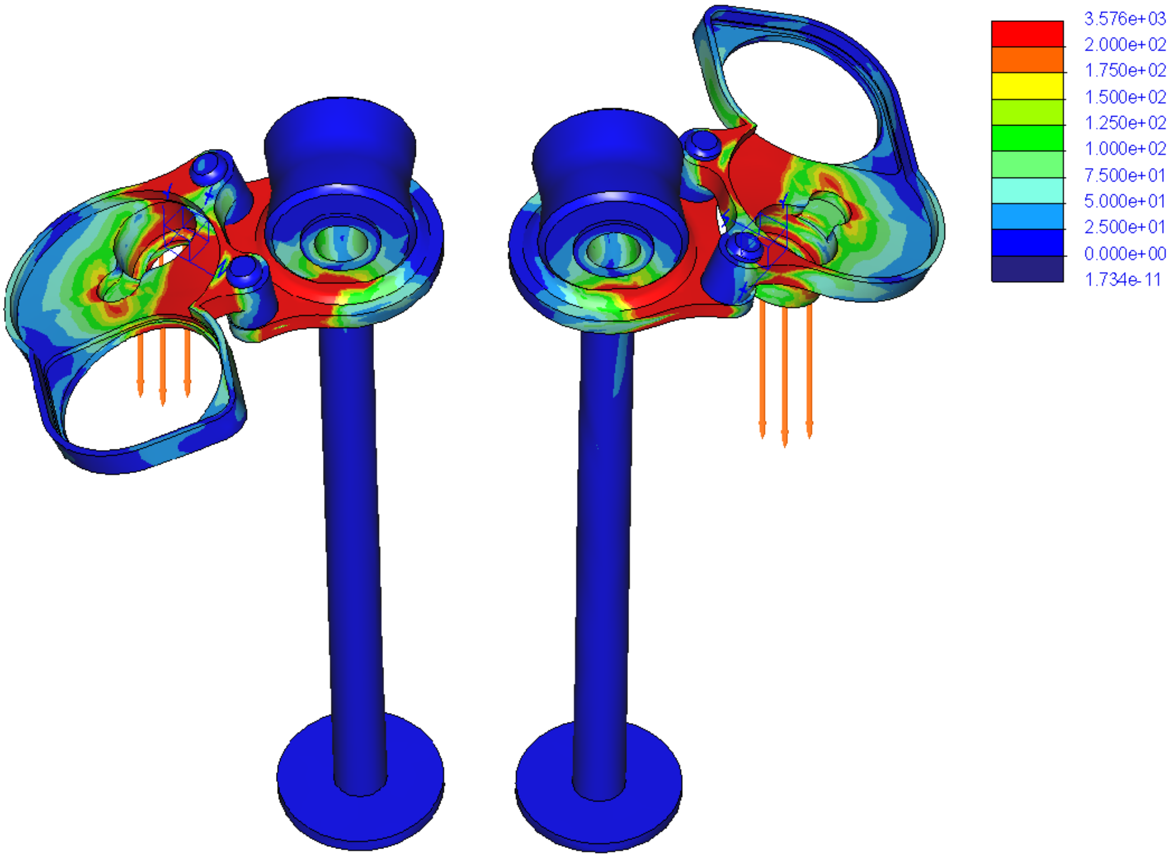
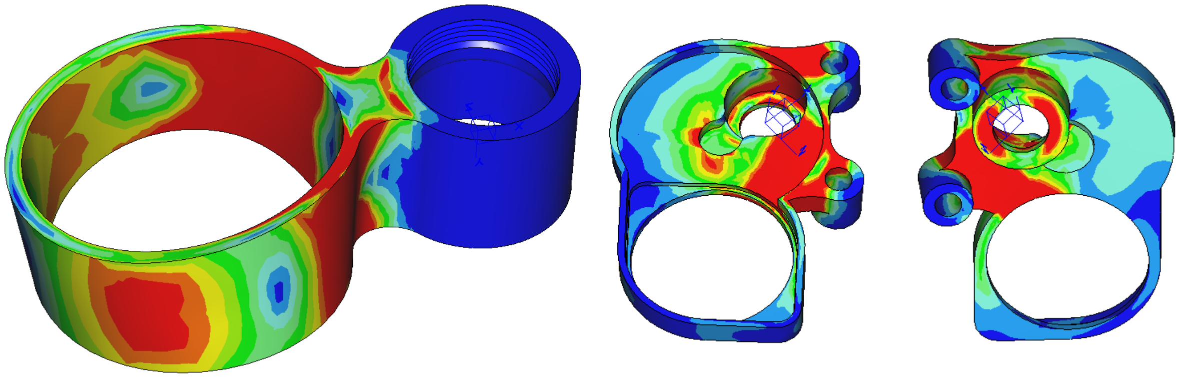
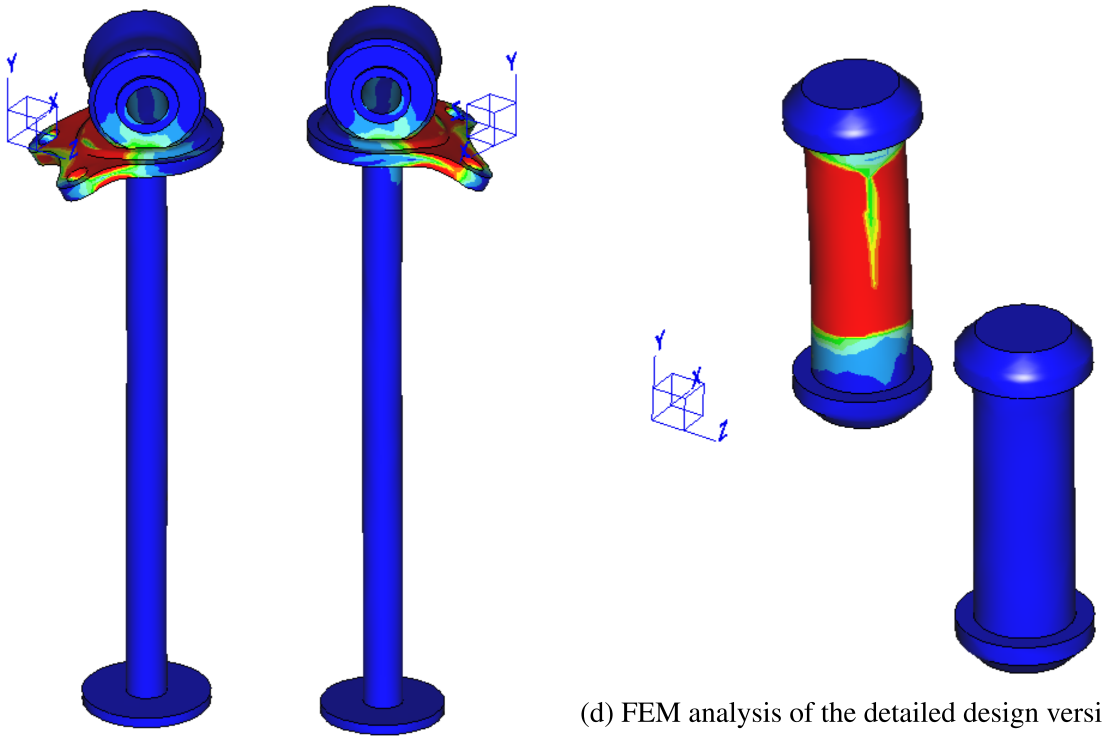


Figure 37: FEM analysis of the detailed design version 1 - Interface between the suspension top plate and the gearbox cover analysis. The maximum allowed stress is set to 200 MPa. The materials in this view are mixed and the meaning of the zone's color changes between parts



(a) FEM analysis of the detailed design version 1 - Ball screw bearing nut analysis. The maximum allowed stress is set to 500 MPa

(b) FEM analysis of the detailed design version 1 - Gearbox cover analysis. The maximum allowed stress is set to 200 MPa



(c) FEM analysis of the detailed design version 1 - Suspension plate analysis. The maximum allowed stress is set to 500 MPa

(d) FEM analysis of the detailed design version 1 - Bolts used for the interface between the suspension top plate and the gearbox cover analysis. The maximum allowed stress is set to 500 MPa

Figure 38: FEM analysis of the subparts of the system

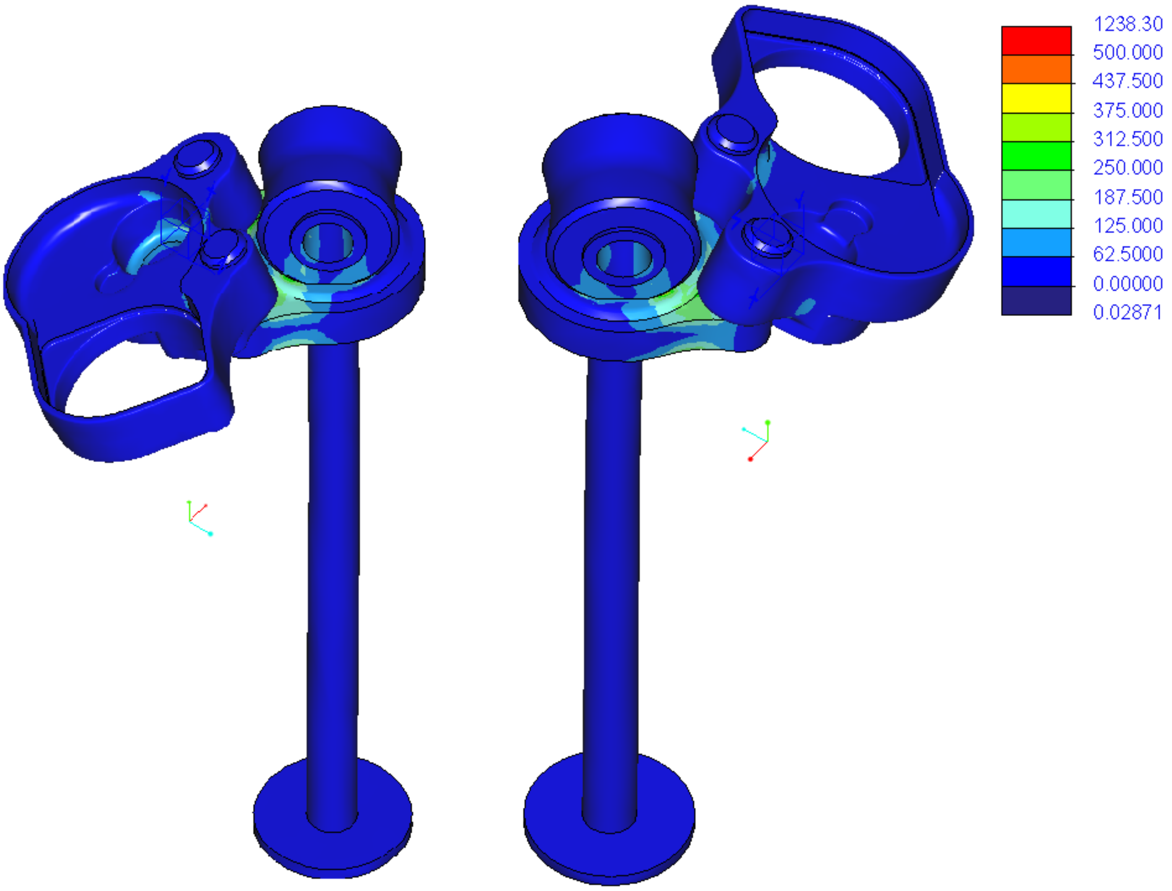
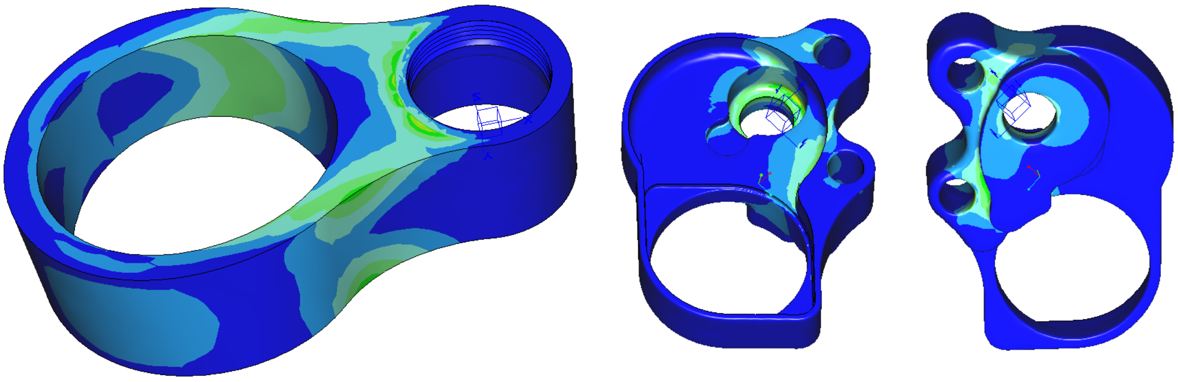
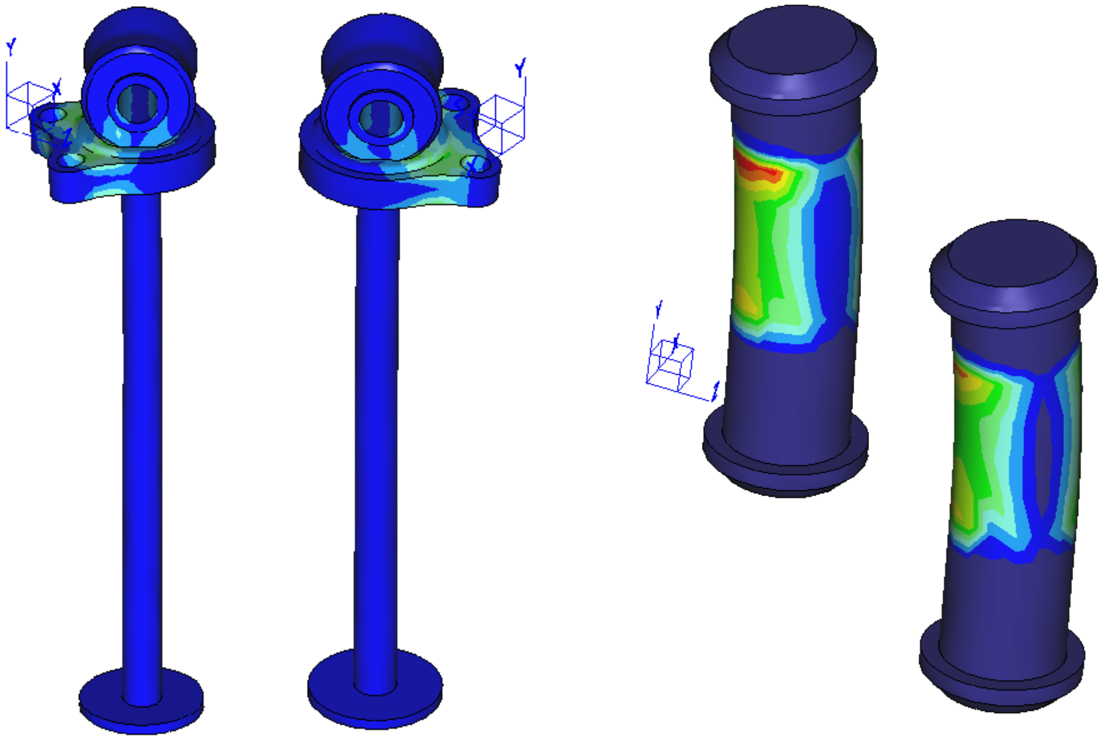


Figure 39: FEM analysis of the detailed design version 2 - Interface between the suspension top plate and the gearbox cover analysis. The maximum allowed stress is set to 500 MPa. The materials in this view are mixed and the meaning of the zone's color changes between parts



(a) FEM analysis of the detailed design version 2 - Ball screw bearing nut analysis. The maximum allowed stress is set to 500 MPa

(b) FEM analysis of the detailed design version 1 - Gearbox cover analysis.The maximum allowed stress is set to 200 MPa



(c) FEM analysis of the detailed design version 2 - Suspension plate analysis. The maximum allowed stress is set to 500 MPa

(d) FEM analysis of the detailed design version 2 - Bolts used for the interface between the suspension top plate and the gearbox cover analysis. The maximum allowed stress is set to 500 MPa

Figure 40: FEM analysis of the subparts of the system

4.6.4 Environmental Impact

Using Equation 7-11 the following environmental impact results were acquired:

- **Material impact, MI**

  By using Equation 7;

$$Emission_{product} = \sum_{i=1}^{n} Weight_{part_i}[kg] * ME_{part_i}[\tfrac{SEK}{kg}],$$

  we get the air bellow axle lift's and the newly developed system's total production emission.

  The values are summarized in Table 11 and Table 12.

Table 11: Table summarizing weight, material emission and total emission of type of material of the air bellow axle lift system. The air bellow axle lift system's total emission is also displayed at the end

Materials & Processes		Pre-Use			Use			**Sum**
		Production			Life			
		Index	Amount	Impact	Index	Amount	Impact	
	Unit	*SEK/kg*	*kg*	*SEK*	*SEK/kg*	*kg*	*SEK*	
Cast Iron	Kg	8.1	26.468	214.4	0	26.468	0	214.4
Rubber	Kg	28	6.8	190.4	0	6.8	0	190.4

Materials & Processes		Disposal						
		Reuse - Material			Landfill			
		Index	Amount	Impact	Index	Amount	Impact	
	Unit	*SEK/kg*	*kg*	*SEK*	*SEK/kg*	*kg*	*SEK*	
Cast Iron	Kg	0	26.468	0	4.21E-6	26.468	0.0001	0
Rubber	Kg	0	6.8	0	0	6.8	0	0
TOTAL								**404.8**

Table 12: Table summarizing weight, material emission and total emission of type of material of the developed concept. The developed concept's total emission is also displayed at the end

Materials & Processes		Pre-Use			Use			Sum
		Production			Life			
		Index	Amount	Impact	Index	Amount	Impact	
	Unit	*SEK/kg*	*kg*	*SEK*	*SEK/kg*	*kg*	*SEK*	
Aluminium casted	Kg	17.48	0.722	12.62	0	0.722	0	12.62
Steel casted	Kg	22.8	7.0298	160.27	0	7.0298	0	160.27

Materials & Processes		Disposal						
		Reuse - Material			Landfill			
		Index	Amount	Impact	Index	Amount	Impact	
	Unit	*SEK/kg*	*kg*	*SEK*	*SEK/kg*	*kg*	*SEK*	
Aluminium casted	Kg	-9.46	0.722	-6.84	1E-4	0.722	4E-06	-6.84
Steel casted	Kg	-11.8	7.0298	-82.56	4.21E-6	7.0298	1E-05	-82.56
TOTAL								**83.1**

Using Equation 8:

$$\begin{aligned} Emission_{difference} &= Emission_{new}[SEK] - Emission_{airbellow}[SEK] \\ &= 83.1[SEK] - 404.8[SEK] \\ &= -321.7[SEK] \end{aligned}$$

Using Equation 9:

$$\begin{aligned} Emission_{ratio} &= \frac{Emission_{new}[SEK]}{Emission_{airbellow}[SEK]} \\ &= \frac{83.1[SEK]}{404.8[SEK]} \\ &= .205 \end{aligned}$$

- **Weight impact, WI**

  Using Equation 10:

$$\begin{aligned} WI_{ratio} &= \frac{Weight_{new}[kg]}{Weight_{airbellow}[kg]} \\ &= \frac{7.082[kg]}{33.268[kg]} \\ &= .116 \end{aligned}$$

  Using Equation 11:

$$\begin{aligned} Cargo_{increase} &= A \cdot (Weight_{airbellow} - Weight_{new})[kg] \\ &= A \cdot (33.268 - 7.082)[kg] \\ &= A \cdot 26.186[kg] \end{aligned}$$

This study shows that estimated emission cost reduction went down to 20.5 % of the initial emission cost, meaning a reduction of 79.5 %. The weight impact study on the improved cargo is not discussed due to confidentiality issue on the scaling factor A.

4.6.5 Final Verification

This section provides an updated list of requirements, see Table 13. The list of requirements is updated with a column for the real values of the system developed during the course of this project. There is a column for whether the feature has been tested or not, since some features were not tested within the time limit of the project.

This section is also followed by an updated chart of the cost-weight budget trade-off curve, Figure 41. The figure now including the position of the system developed during the course of this project, using the products real values from the requirements list.

Table 13: Verified requirements

Feature	**#**	**Required value**	**Unit**	**Verified**	**Realized value**	**Unit**
Lifting time	R.1	5	s	Yes	2.6 [1]	s
Lifting force	R.2	4.6	kN	Yes	4.6	kN
Lifting stroke	R.3	90	mm	Yes	90	mm
External environment adaptability	R.4	Yes	[Y/N]	Yes	Yes	[Y/N]
Locking mechanism	R.5	Yes	[Y/N]	No	Not verified	[Y/N]
Sealed	R.6	Yes	[Y/N]	No	Not verified	[Y/N]
Fatigue resistance	R.7	x	n	No	Not verified	n
Robust-looking design	R.8	Yes	[Y/N]	Yes	Yes	[Y/N]
Packaging	R.9	Yes	[Y/N]	Yes	Yes	[Y/N]
Cost	R.10	x	SEK	Yes	$0.66 \cdot x$	SEK
Weight	R.11	33	kg	Yes	7.74	kg
Cost-weight budget	R.12	x	SEK	Yes	$0.49 \cdot x$	SEK
Assembly steps (MAL)	R.13	3	n	Yes	1	n
Assembly steps (PAL)	R.14	3	n	Yes	7	n

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[1] This value is derived from calculations based on the lifting force, stroke and motor power available

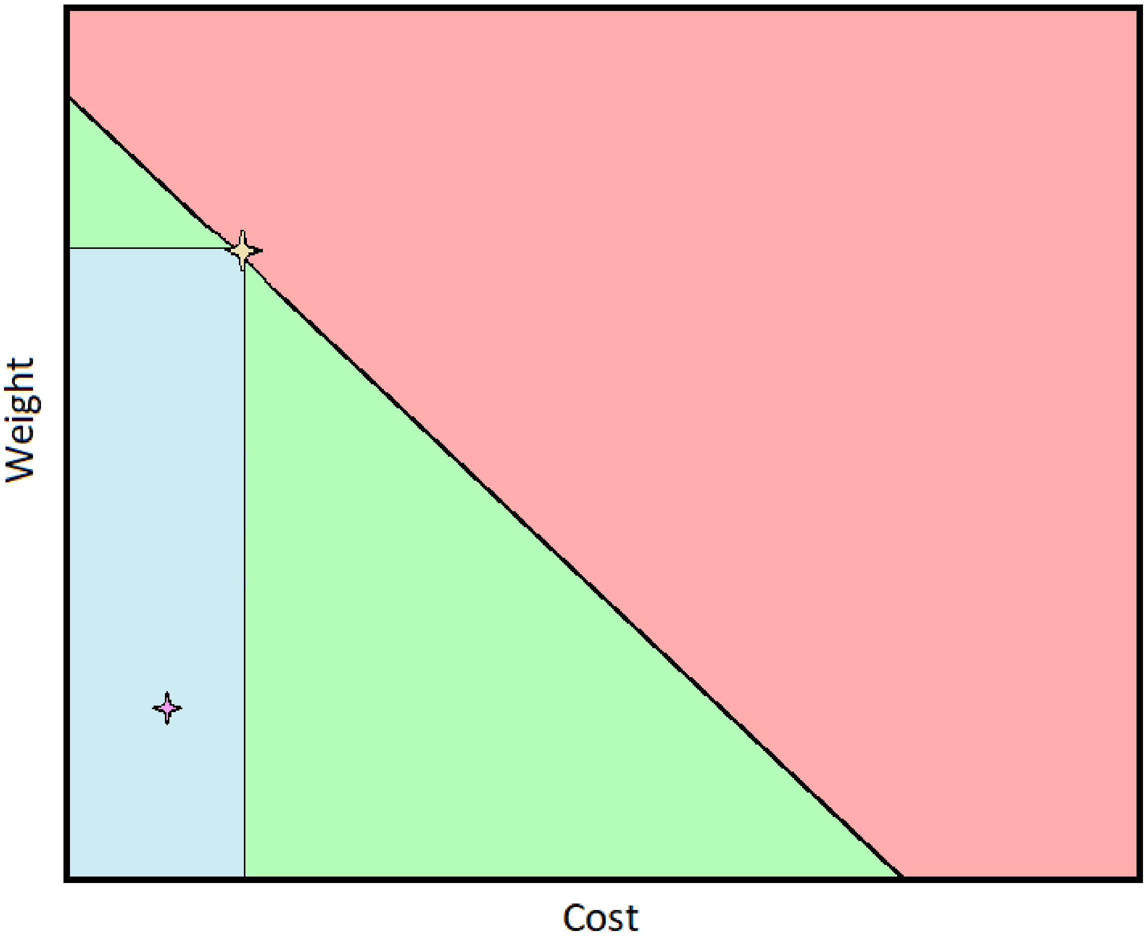

Figure 41: Cost-weight budget area graph. In the figure the air bellow axle lift system can be seen, marked by the yellow star-symbol, as well as the system developed in this project marked by the magenta star-symbol. As can be clearly seen, since the solution is slightly cheaper to produce and remarkably lighter it is within the blue zone

4.7 Prestudy for further Development

After the final verifications, the requirements list was looked at for missing items, resulting in the following items:

- *Locking mechanism*, **R.5**
- *Sealed*, **R.6**
- *Fatigue resistance*, **R.7**

When looking at the parts, it was identified that the gearbox is underdeveloped and would require better development. The gear ratio was calculated as optimally (for the lifting speed) at the value of 4:1. However, since the lifting time is 2.6 seconds, the gear ratio (and consequently the gear sizes) could be optimized for packaging instead - since there is room for lifting time increases in favor of packaging.

Also, control systems will need to be implemented to manage the lifting since this concept is implemented twice, on both sides of the truck for one axle and to also signal that the axle has successfully been lifted.

5 Discussion

This report shows the development of a new truck axle lifting device, from the start to a detailed design version backed up by FEM simulations and tests on a physical prototype. The tests and calculations show that replacing the current air bellow axle lift system with this new system can save a good amount of weight. The cost of the new system would also be at a lower price than the air bellow axle lift system. The project's mission was to reach a concept that would have a lower score on a cost-weight budget, which it has, having simultaneously both a lower cost and weight.

After verifying the project's final version of the concept, the system is estimated to have a total weight of 7.74 kg, compared to the air bellow axle lift system, which weights 33 kg. The cost is also seen as significantly reduced. However, both the air bellow axle lift's and the new system's costs are confidential and are not showcased. The results show that the concept can, theoretically, lift the axle in less than 5 seconds, which matches the lifting speed of the air bellow axle lift system. This system allows to get rid of the heavy iron-casted parts of the previous solution. No alternative material were looked upon by Volvo due to the tough lever arm requirement and to the cheap cost of cast iron. It can also be seen that the product contains more parts than the previous technology; this would mean that the new concept requires more steps to preassemble than the air bellow axle lift. However, the assembly on the axle frame (i.e., at the main assembly line) consists only of 1 connecting point compared to previously 3; this is a beneficial trade-off since the main assembly line is more time-sensitive than preassembly lines. Reducing the main assembly line steps means more flexibility for future installations on the main assembly line.

The FEM analyses could show how the final version managed the force applied to it. After the final refinement, we can see that the integrity of each analyzed part is good. There is an exception, though, the bolts used for the interface between the suspension top plate and the gearbox cover. Using bolt stress calculations, we could, however, see that the bolts should withstand the forces without being remotely close to failure. We believe the discrepancy in the results between the FEM and the bolts calculation because of all load passing through the screw and not through the clamped part. So in the FEM analysis model it does not simulate a screw joint. We have concluded that this should not affect the accuracy of the other parts' FEM analysis results.

All the requirements that can be verified in an early stage within a quick prototype have been conducted. The requirement R.5 *Locking mechanism* has not been fulfilled and requires a more mature design stage. In the end, it was deemed by the Volvo Trucks department that there can be plenty of solutions for the locking mechanism and that it should be developed at a later stage. It was not assumed to be critical for the integrity of the design of the concept at an early stage. The requirements R.6 - *Sealed* and R.7 *Fatigue resistance* have not been tested due to the need of using the proper materials, tooling, and test environments, which have not been within the scope of this thesis. A FMEA study on the system has not been done and could have been relevant to better assess the integrity and robustness of the concept.

The method throughout the project has been structured around the product development method by Ulrich et al. (Ulrich et al., 2019). This method relies on splitting the process into different areas such as Identifying Customer Needs, Product Specifications, Concept Generation, Concept Selection, Concept Testing, Product Architecture, and Industrial Design (Ulrich et al., 2019). Some methods had to be revised to fit better the project's context and environment. During Phase 2 of the concept generation, we assumed that creating only one CAD model for each family was enough. If we had focused on concept development at the expense of detail design, the design space could have been explored more extensively, potentially revealing other promising concept candidates. The mature problem definition and the high level of maturity asked for the concept required in the scope of the thesis led us working this way. Also, the method used during the conceptualization phase, i.e., sketching and iterating the sketches followed by continuous supervision and team design review meetings, was a somewhat unstructured and resource-heavy (in terms of availability of experts' knowledge) way of conducting an early phase product development project. This method worked good considering the amount of tacit knowledge needed to be acquired while developing the product but might not have been optimal in many other product development projects. Working this way required a lot of available supervision, which can not be expected in every product development project. That said, given the circumstances of this project, the method used for conceptualization worked well and led to an efficient early development phase giving us ample time to work on detailed design. There are still areas left to develop before a product like this could go into production. These steps are described in Section 5.1, *Development plan*.

The environmental impact of the concept is discussed in section 5.2.

5.1 Development Plan

This section aims to describe the necessary steps required to take the concept developed in this project into production. The steps mainly consist of validating the final requirements and sizing the individual concept parts.

- **Develop gearbox** that will be used. This is still necessary but was regarded as its own project (due to the sheer size of designing a new high-standard) gearbox, so it was left outside of the scope of this project - to put focus on more critical holistic problems. It was decided the design of the gearbox would not be critical at an early stage, and its future development of it would not come with any design-breaking.
- **Develop final locking mechanism**.
- **Develop sealing of the product**, and verify by conducting tests in a weather simulation chamber.
- **Add control systems** to manage the lifting.

5.2 Environmental Impact

The potential environmental impact of changing the air bellow axle lift system of the trucks to a system based on the product developed during this project is substantial. The estimates calculated show that the material impact of production can be reduced by as much as 80 %, going from a total material emission cost of 404.8 to 83.2 SEK. Also, the reduced weight itself gives a better fuel consumption efficiency of the vehicle and potential for more transported cargo - these values are more difficult to accurately calculate. However, it's safe to say that a reduced weight on the truck would yield a better efficiency of it, even if marginal.

6 Conclusions

During this project, a new axle lifting system was conceptualized and developed into a detailed design CAD and an early functional prototype.

The project followed a typical product development setup with the following steps:

- **Problem formulation**

  The problem formulation was done to specify the intended outcome of the project and was set as *"Our goal is to develop a new axle lifting system that has the same features as the currently available air bellow axle lift system, while also having a lower weight - within a cost-weight based budget"*.

- **Requirements**

  The requirements of the product were summarized into a requirements list strongly based on the qualities of the currently used air bellow system.

- **Prestudy**

  The prestudy section gave a base for inspiration before initializing the concept development of the project. The technology of a linear actuator was used as inspiration for the concept that ended up becoming the final concept.

- **Concept development**

  The concept development was conducted in iterative steps, and in 3 separate phases - each with an increased level of detail. The concept development was ended with a single final concept.

- **Detailed design**

  The detailed design phase was done to refine the concept chosen after the previous step. This phase was done in parallel with "verification and refinement", to both verify and then fix items where verification showed lackluster results.

- **Verification and refinement**

  Verification for every feature on the requirements list was the goal of this phase. Some features were not feasible to test at the current stage. Every verification yielded positive results.

The results show that a promising opportunity to significantly reduce the weight, cost, and size of the axle lifting system exists, as well as reducing the number of main assembly line steps. Validation tests and calculations have indicated the following:

- **Weight reduction** of 75 %.

  Compared to the currently used air bellow axle lifting system, the newly developed axle lift weights less. The weight reduction stems from two factors. The new concept is made out of aluminum and steel parts. Also. the new concept has a large reduction in volume. These two factors together lead to a concept that weights 75 % less compared to the air bellow axle lift system. This weight reduction will save hundreds of thousands of kilos of material every year in production. Also, a lighter truck will be loadable with more cargo while still meeting regulation limitations.

- **Cost reduction** of 34 %.

  The production cost is reduced by 34 %. The cost reduction comes from the reduced amount of produced material.

- **Material emission cost reduction** of 80 %.

  The reduced material also yields, outside of reduced production cost, a lower amount of material emission costs. This stems from the reduced mass of material, but also that the new system avoids the use of rubber, which as a material has a very high material emission cost.

- **Main assembly line steps reduction** of 66 %.

  The product is designed in such a way that all assembly steps, but one, can be completed in preassembly. This results in a product that has a higher number of assembly steps, for the preassembly steps - but a lower amount of steps in the main assembly line. This is a very beneficial trade-off since the main assembly line is very time-sensitive while the preassembly lines aren't.

  By reducing the number of steps in the main assembly line, more flexibility is created for the installment of future products.

The product is still in need of development before it is ready for production, but the results of this report show a promising concept that could yield great benefits to the truck industry if further developed.

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Appendices

A Idea Generation 1

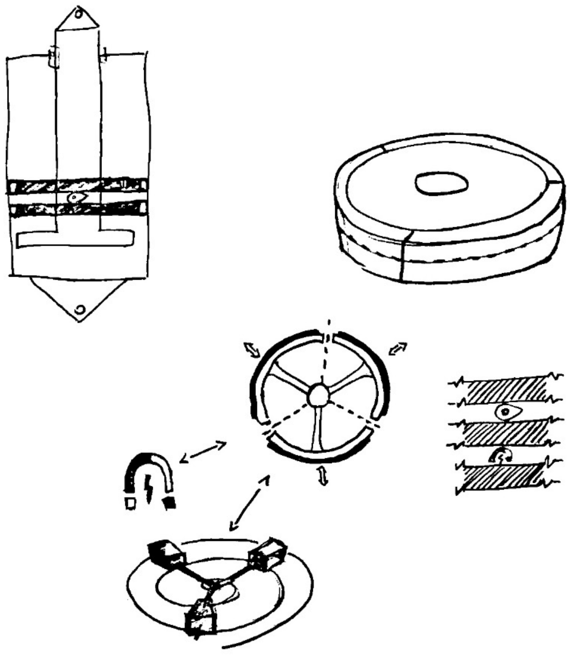

Figure 42: Brainstrom 15 feb 7

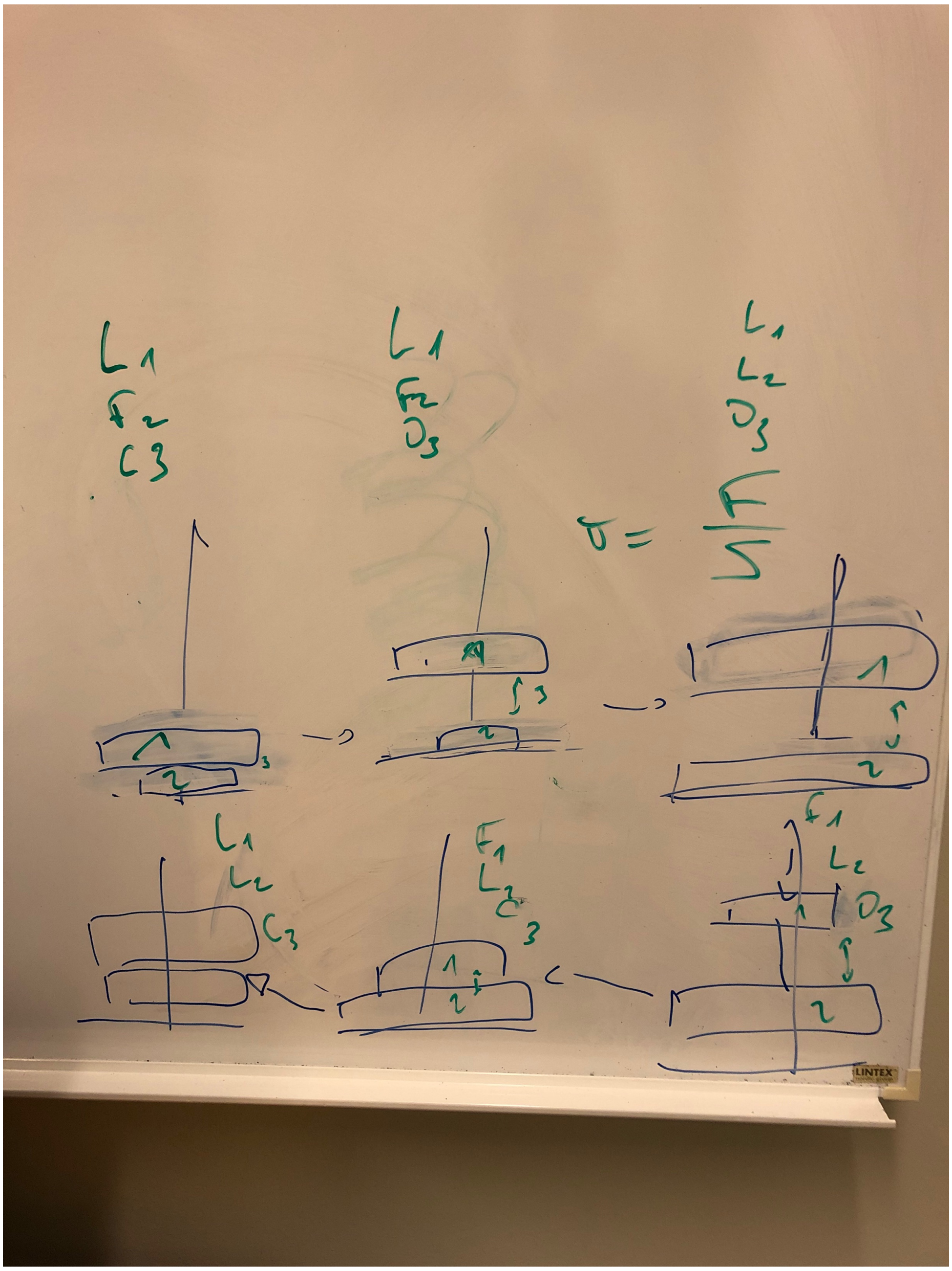

Figure 43: Brainstrom 15 feb 8

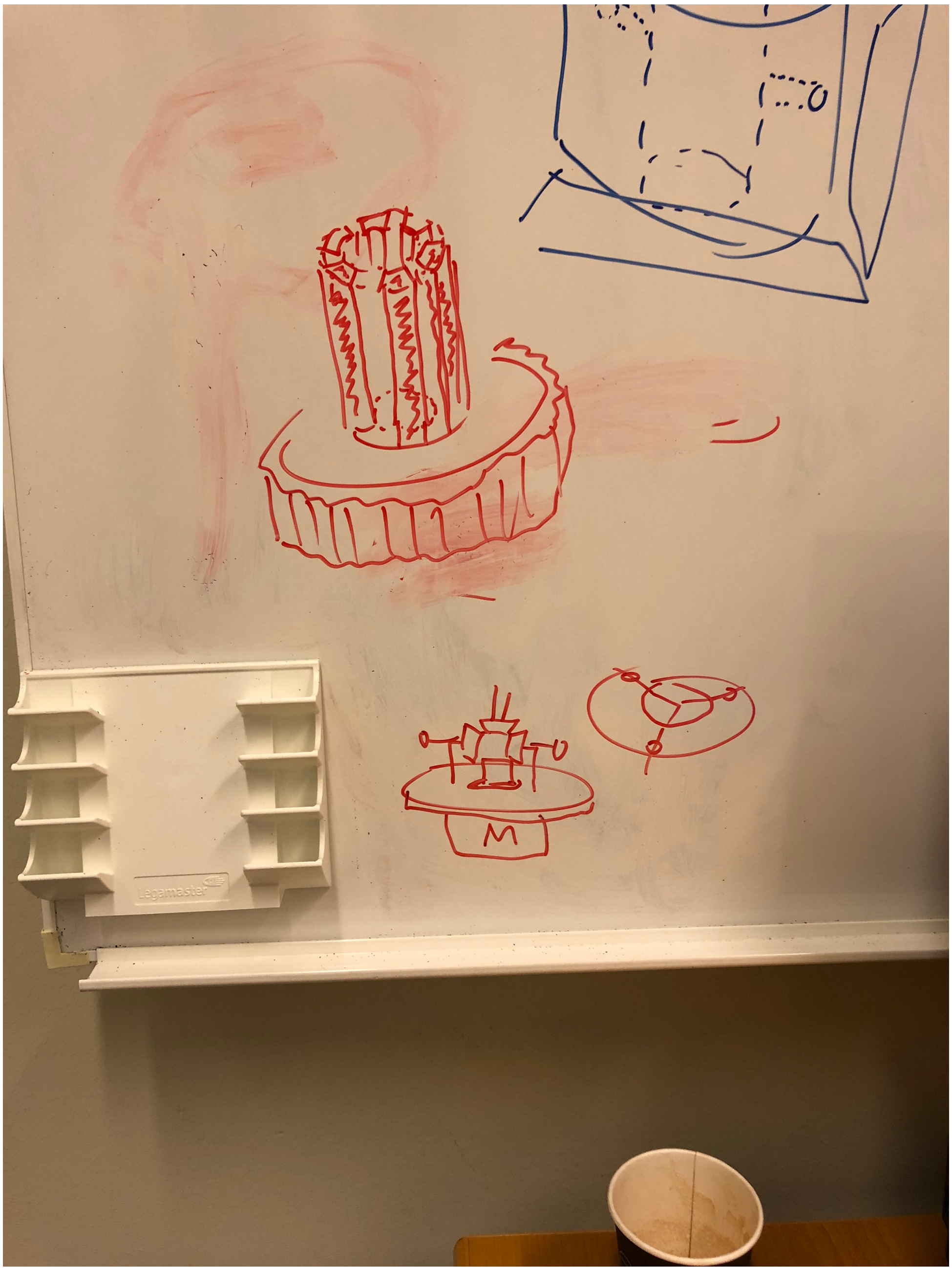

Figure 44: Brainstrom 15 feb 9

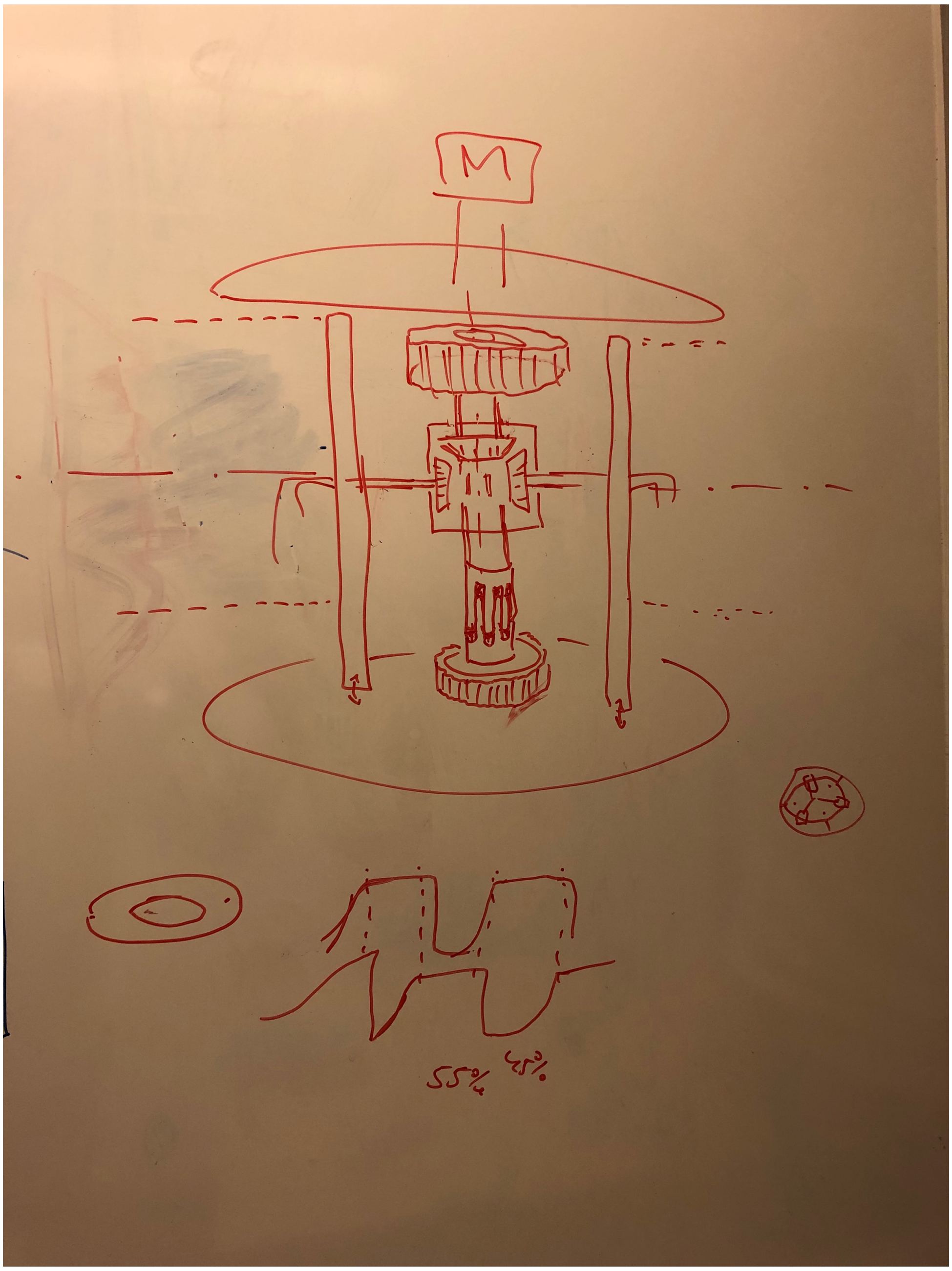

Figure 45: Brainstrom 15 feb 13

A.1 Brainstorming 8th February

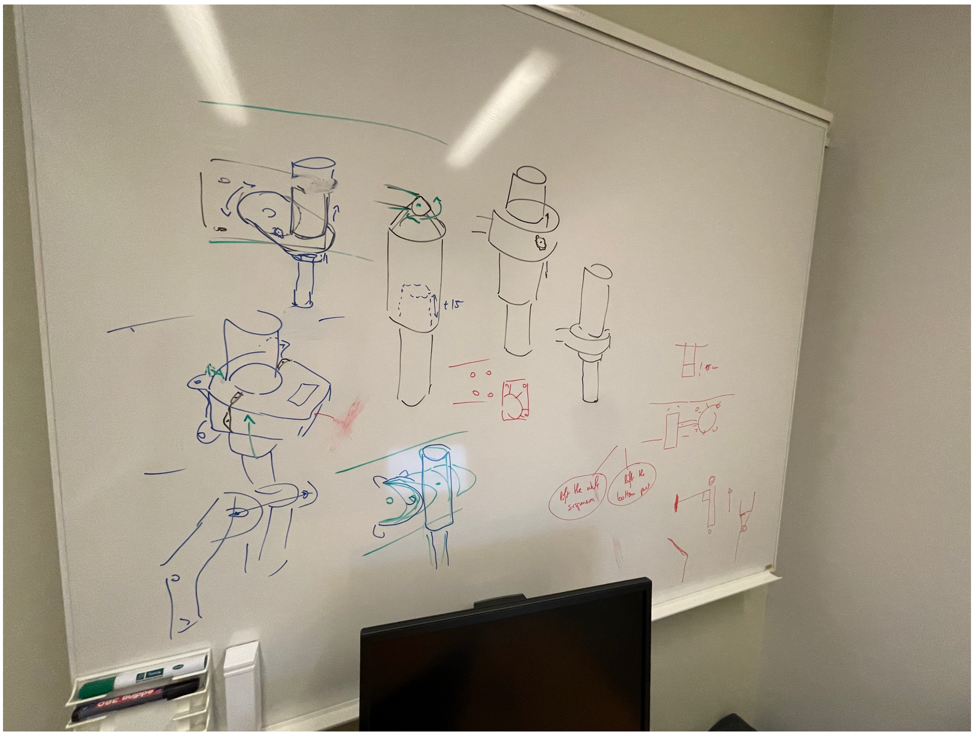

Figure 46: Brainstrom 8 feb 2

A.2 Brainstorming 10th February

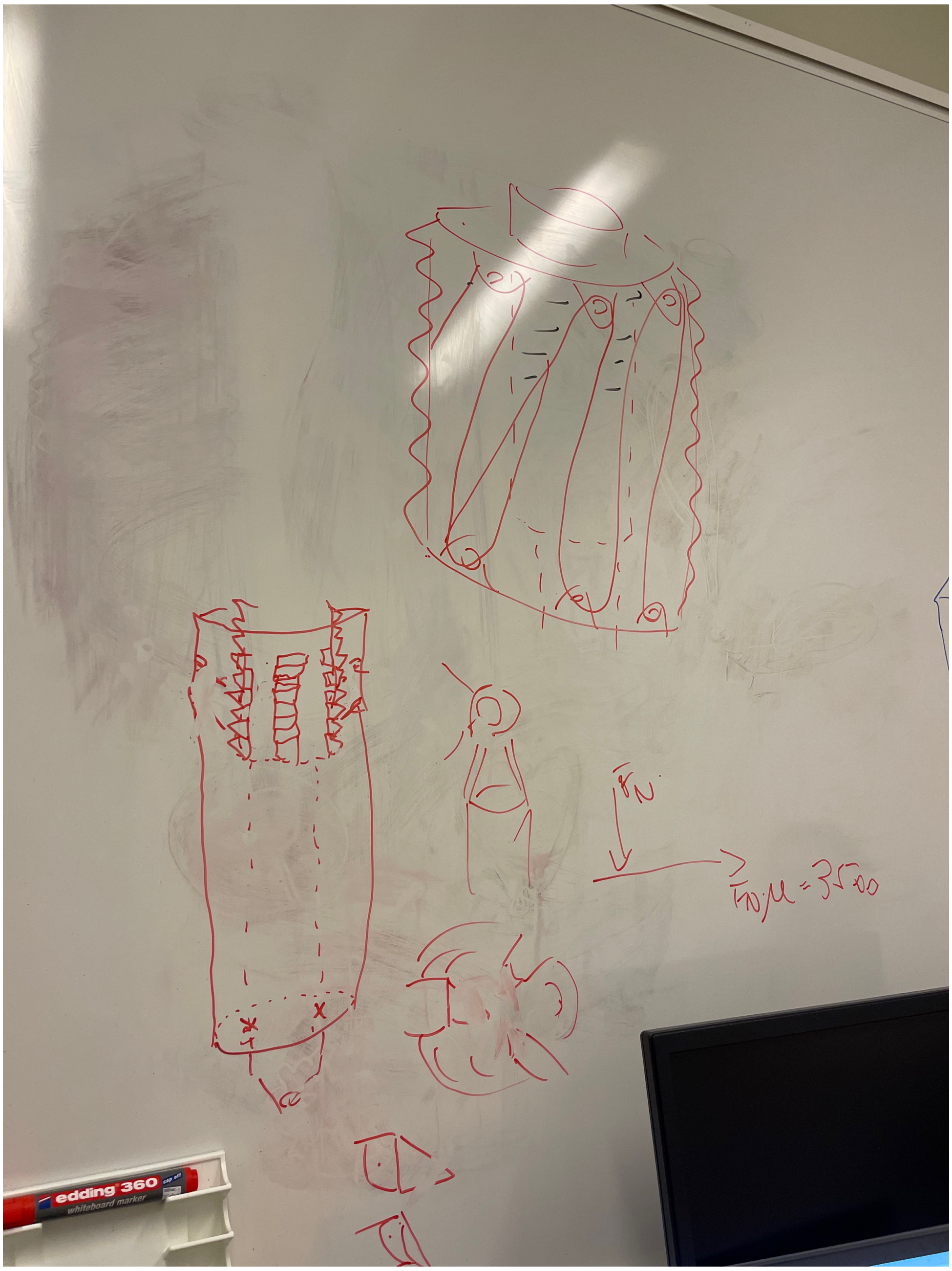

Figure 47: Brainstrom 10 feb 2

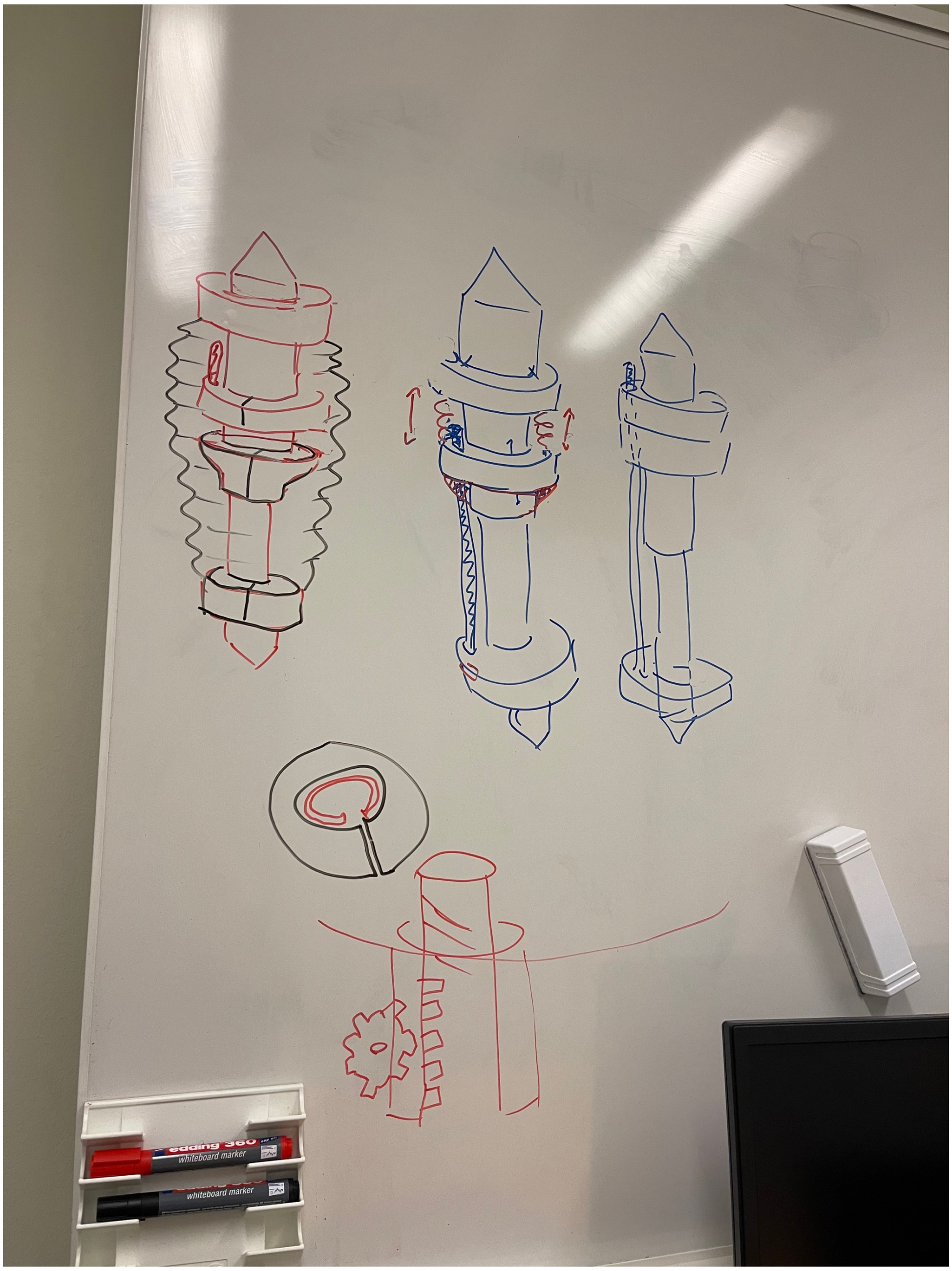

Figure 48: Brainstrom 10 feb 3

A.3 Brainstorming 15th February

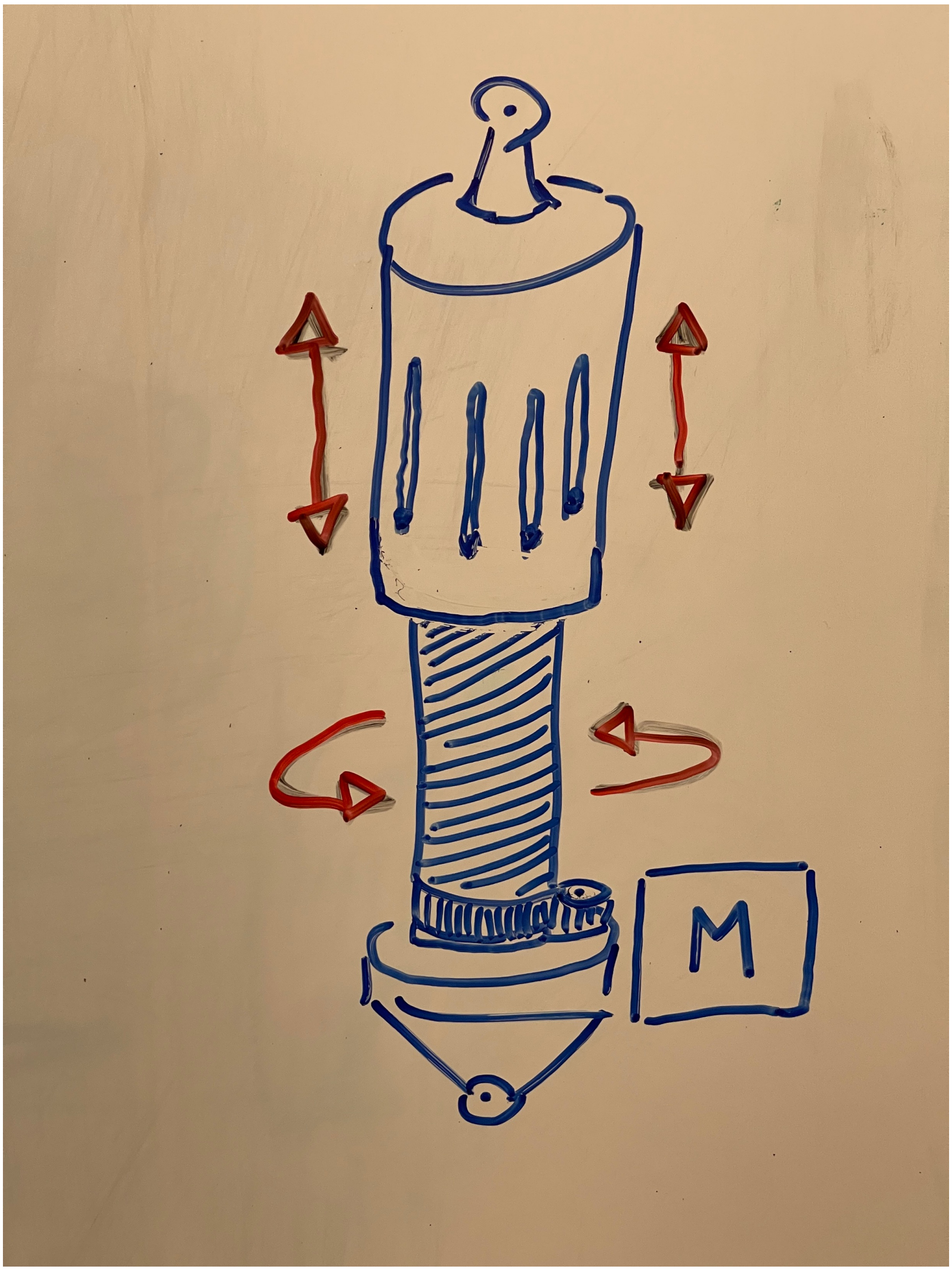

Figure 49: Brainstrom 15 feb 1

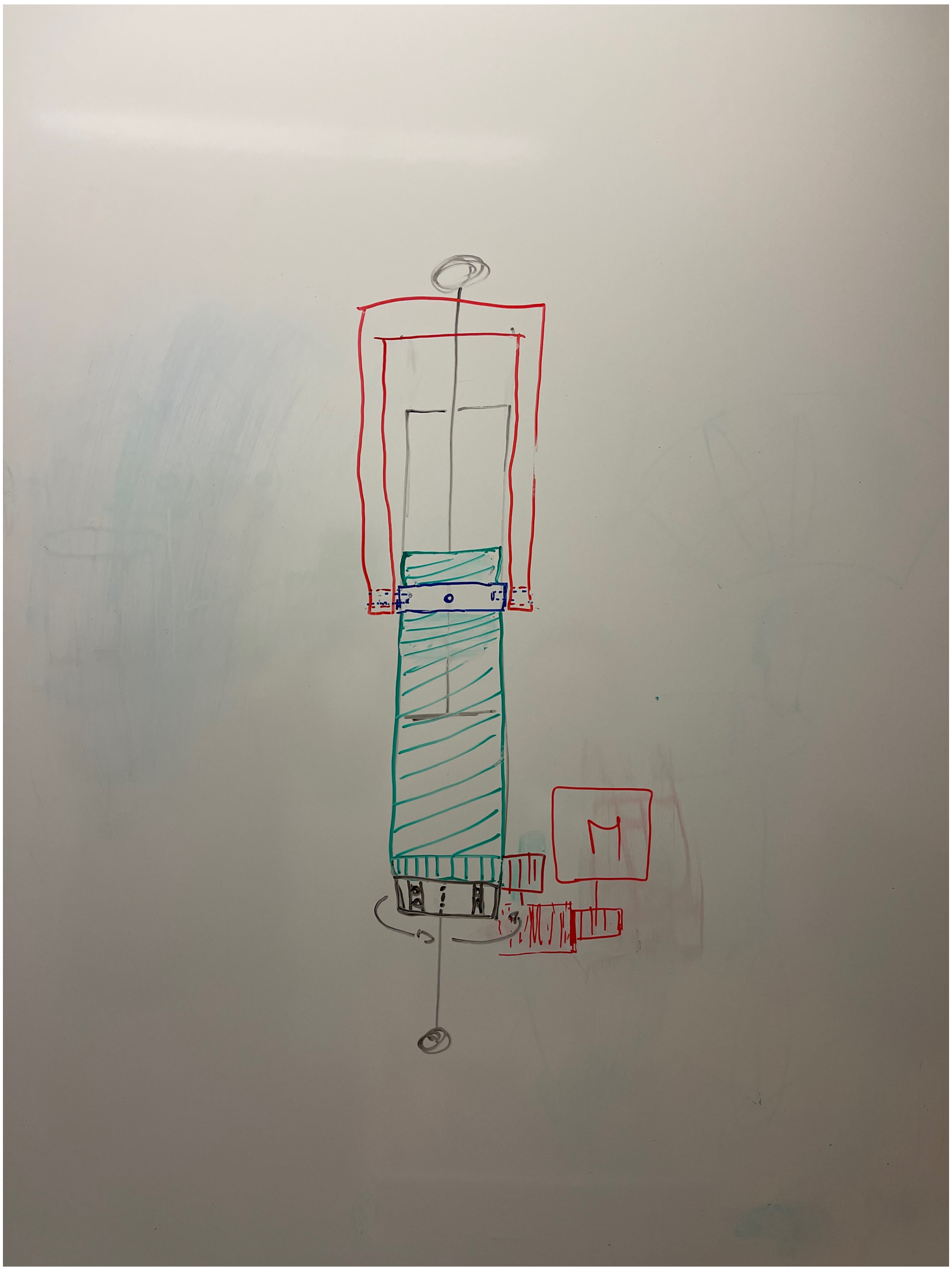

Figure 50: Brainstrom 15 feb 2

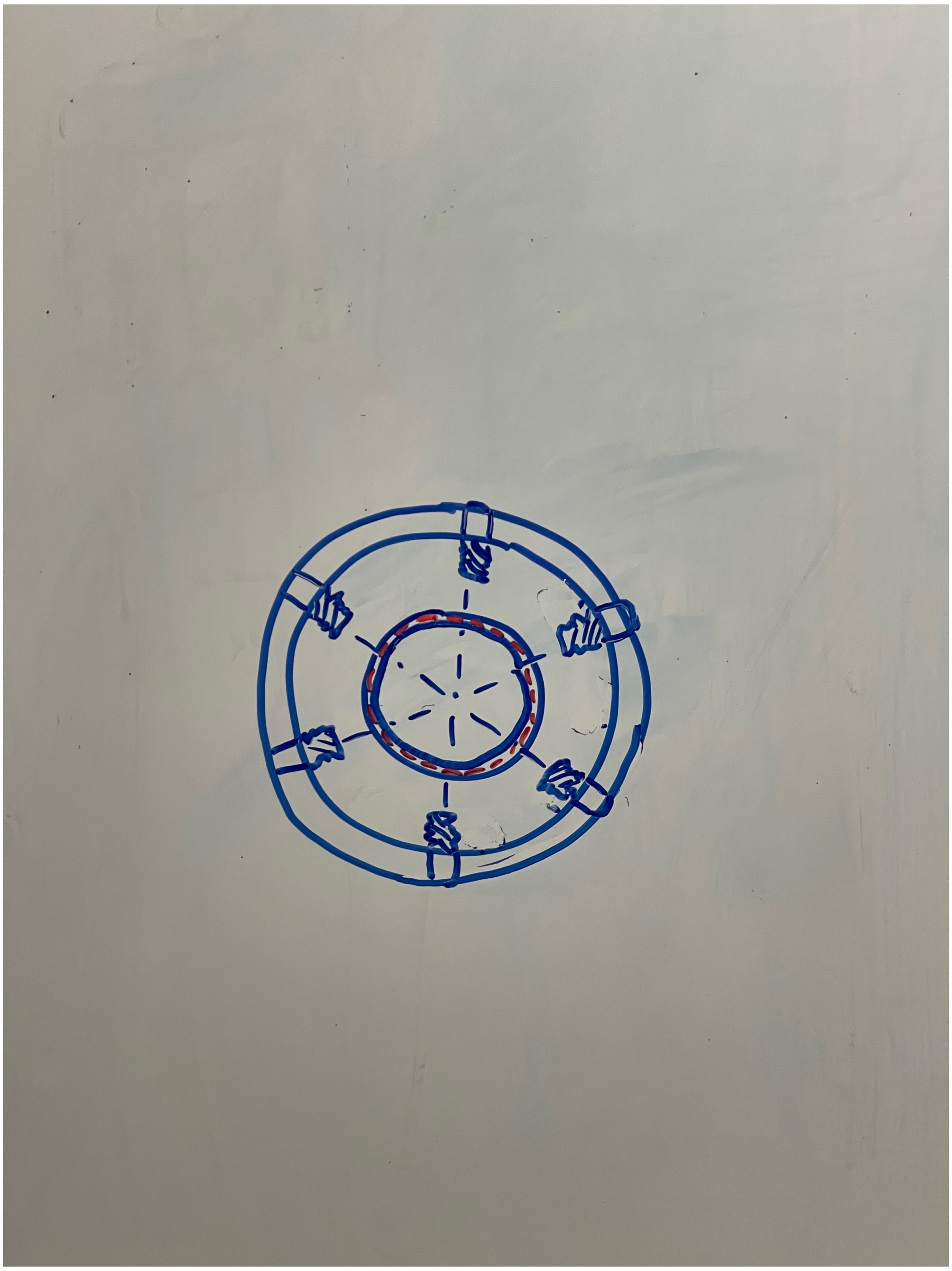

Figure 51: Brainstrom 15 feb 3

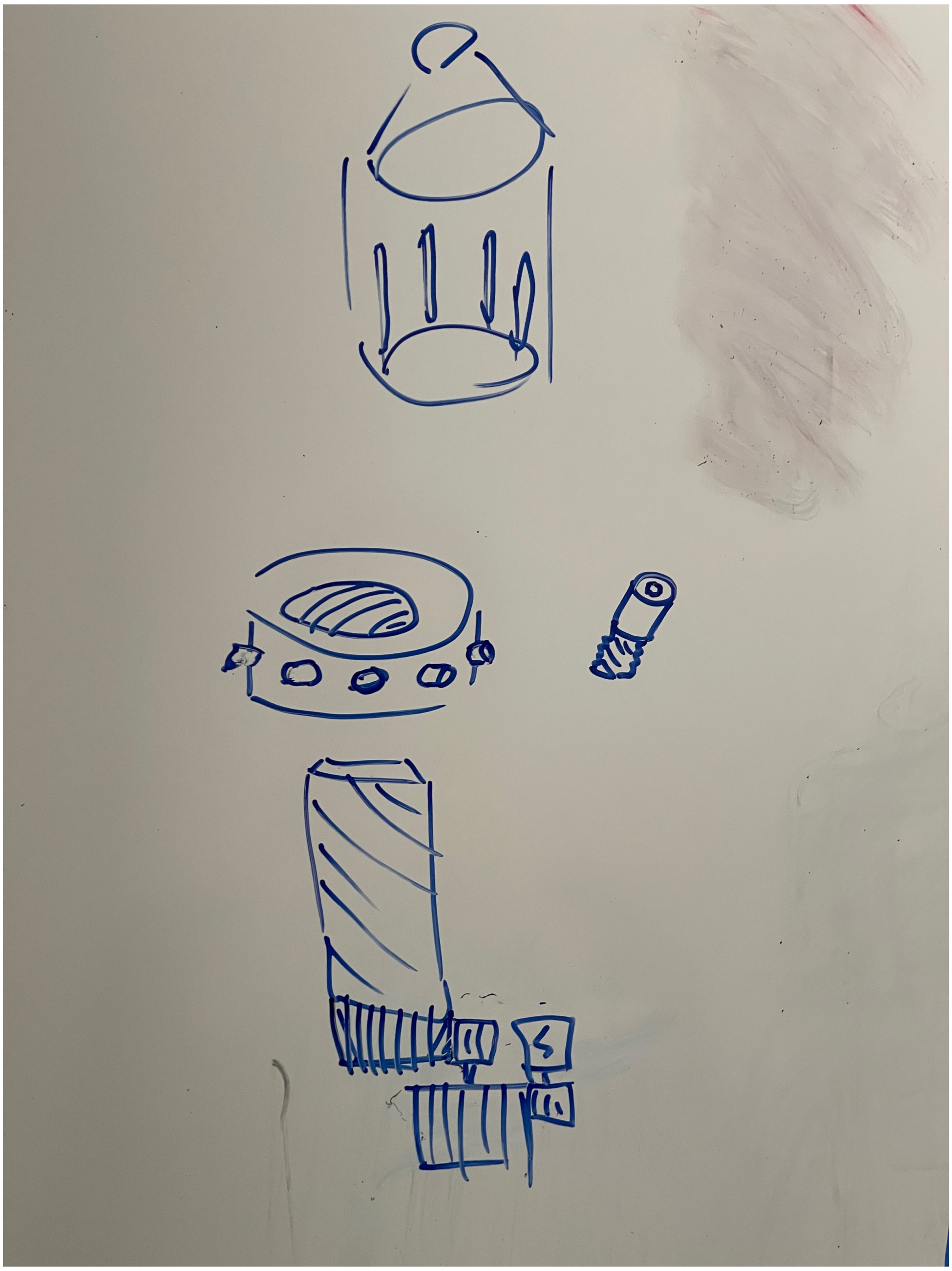

Figure 52: Brainstrom 15 feb 4

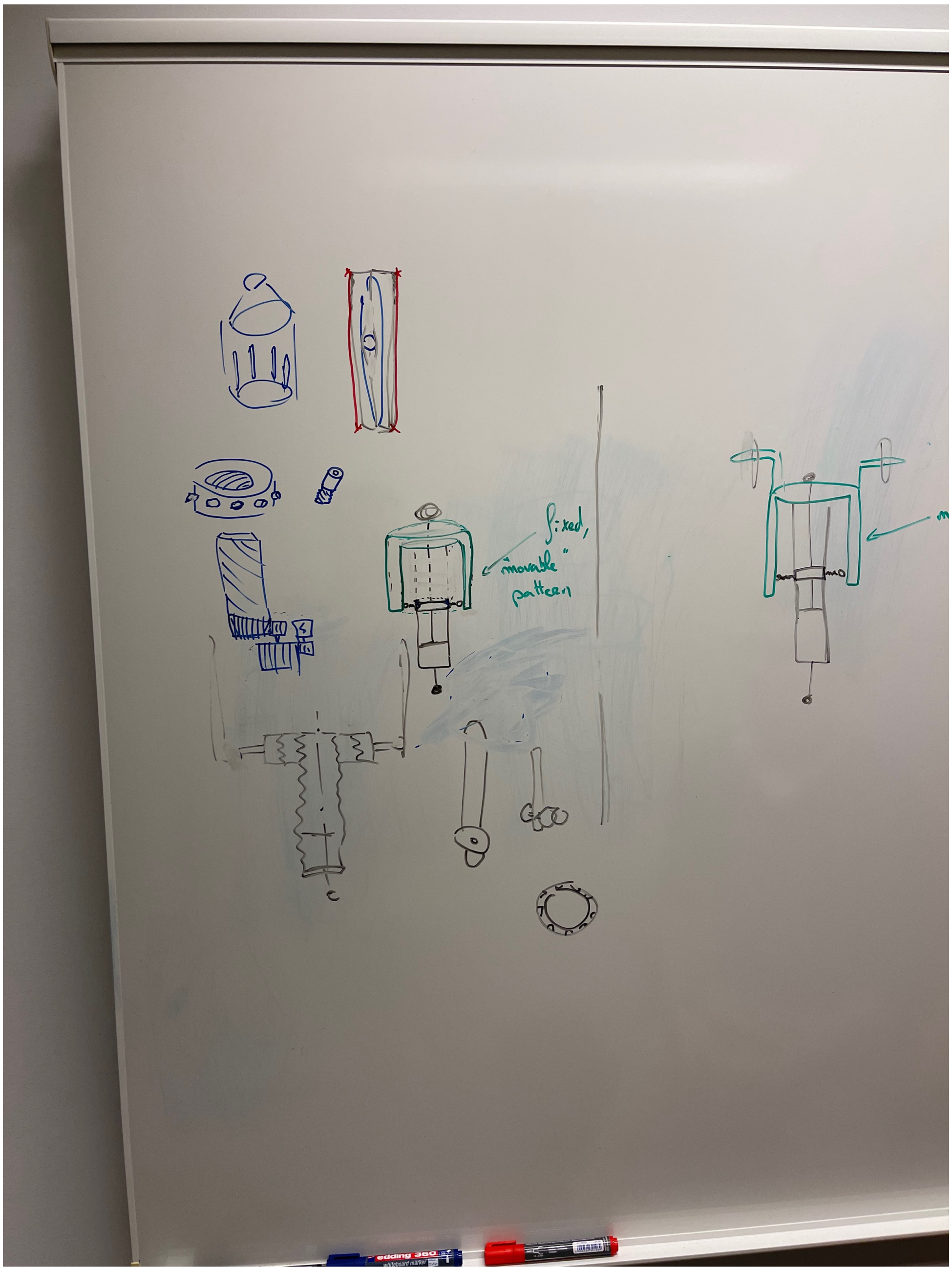

Figure 53: Brainstrom 15 feb 5

Figure 54: Brainstrom 15 feb 6

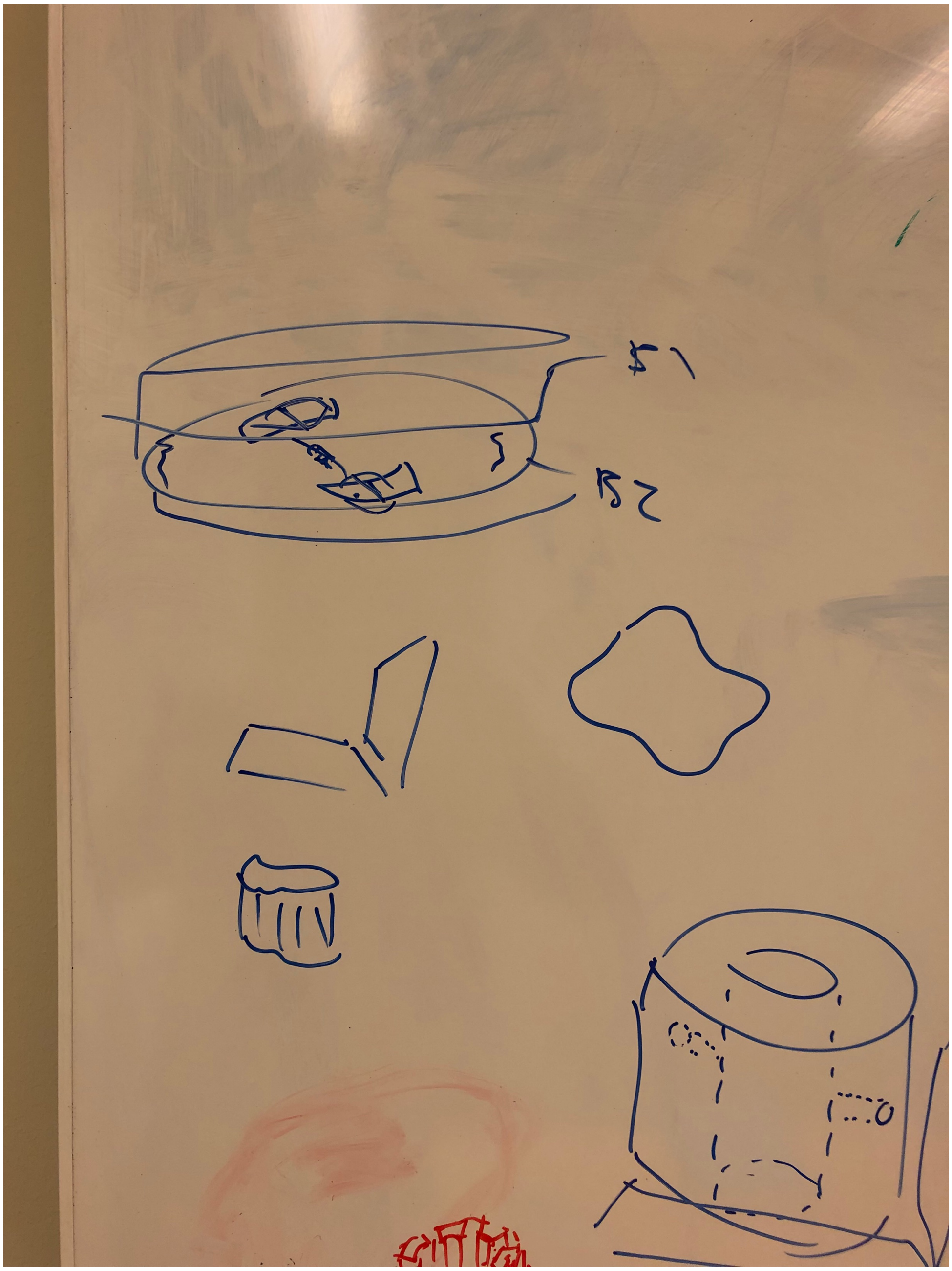

Figure 55: Brainstrom 15 feb 10

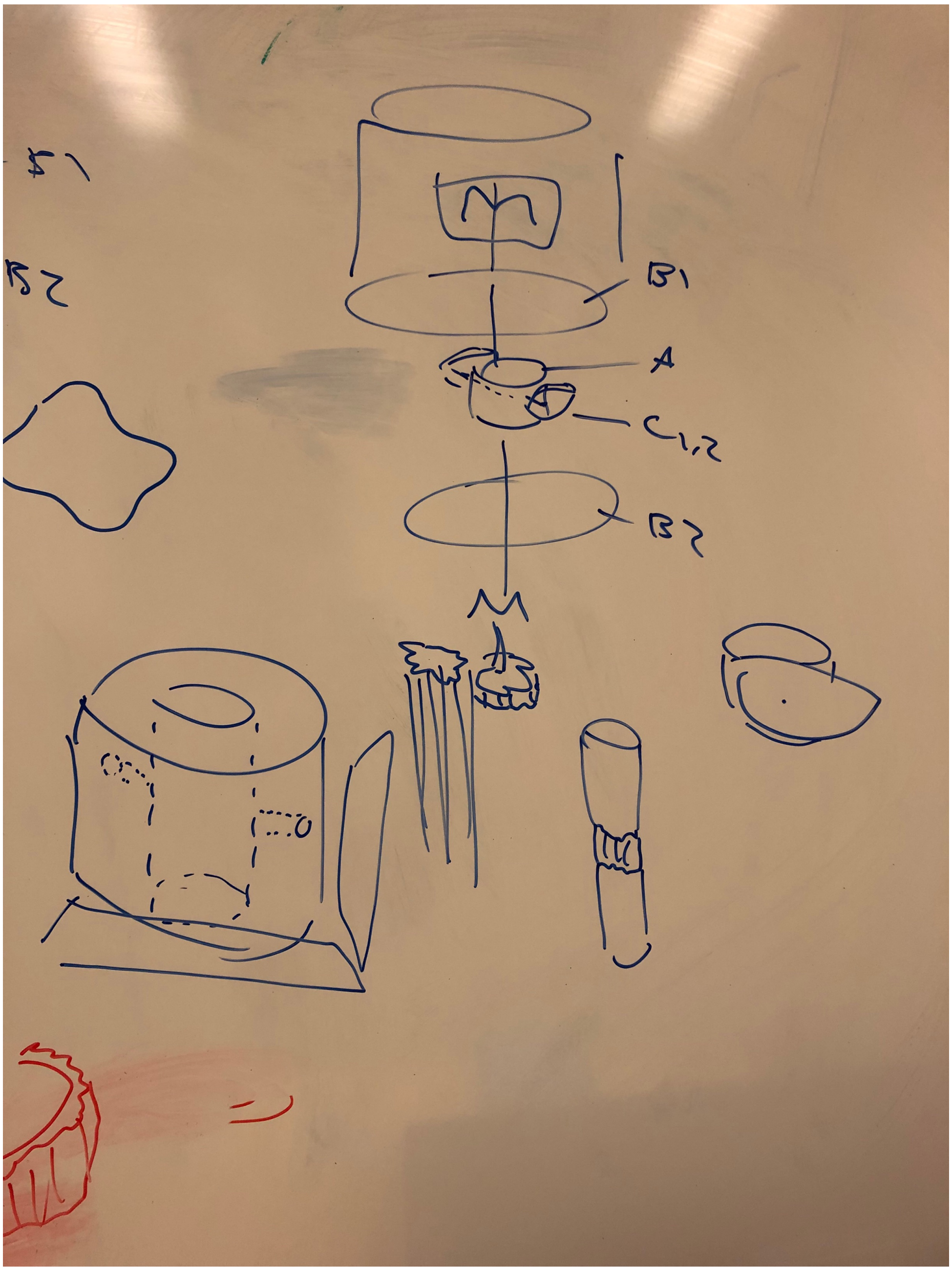

Figure 56: Brainstrom 15 feb 11

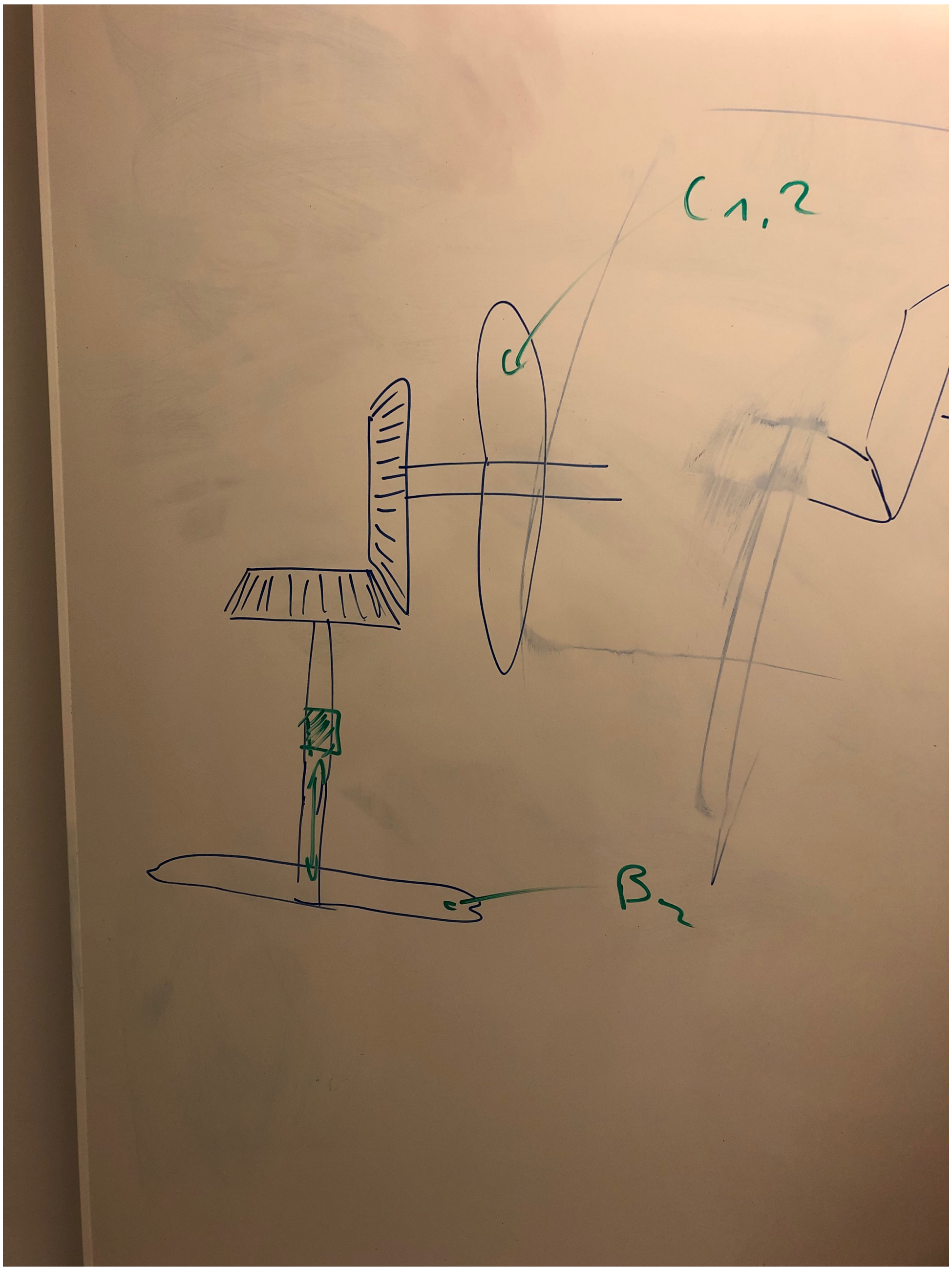

Figure 57: Brainstrom 15 feb 12

A.4 Brainstorming 23th February

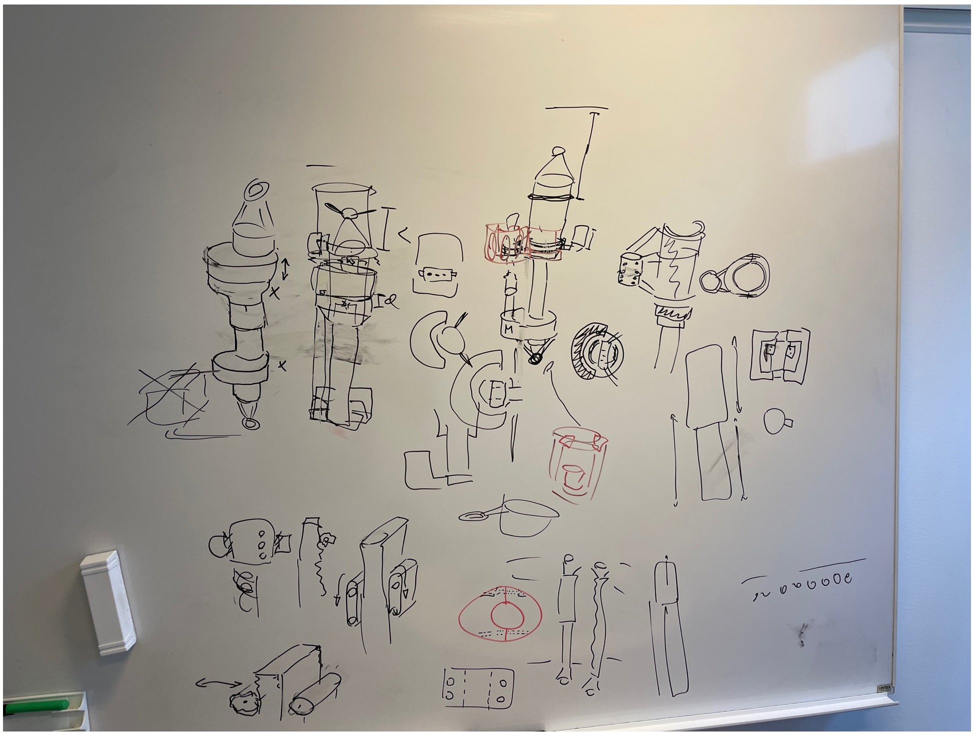

Figure 58: Brainstrom 23 feb 1

A.5 Brainstorming 31st March

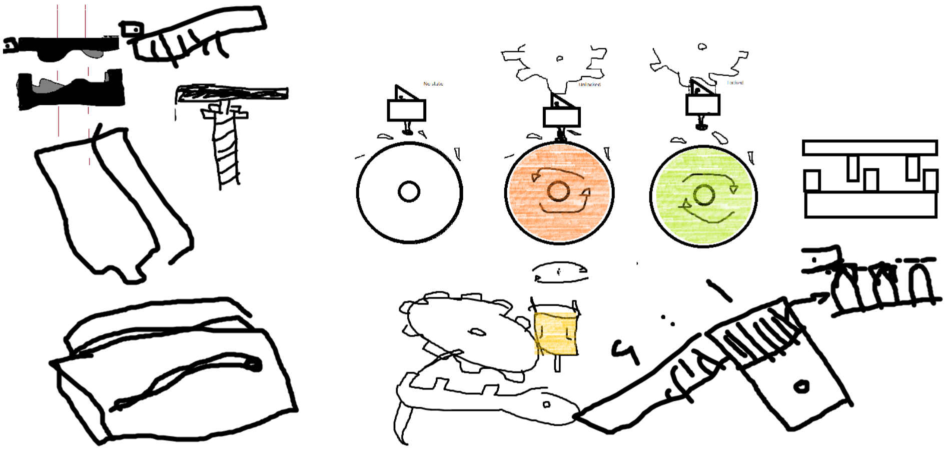

Figure 59: Brainstrom 31 march 1

B Source code listing

```
function [pos,Forces,Strokes] = fpos(n1,truck)
%obtaining different positions, forces and strokes for
%the corresponding truck

pos=linspace(0.001,1.2,n1);
Forces=zeros(n1,1);
Strokes=zeros(n1,1);

alpha=asin(0.09/truck.lever_CG);
Forces=truck.force.*truck.lever_CG./pos;
Strokes=pos.*sin(alpha);

end
```

```
%Power characteristics of the motor used
clc



Torque=linspace(2,50,1000); %Nm
A=linspace(2.5,15,1000);
rpm=linspace(50,5,1000)*pi/30; %rad.s

mechanical_power=Torque.*rpm; %W
efficiencies=Torque.*rpm./(A.*24);

%Plot
figure
yyaxis right
plot(Torque,mechanical_power, "--")
yyaxis left
plot(Torque,efficiencies)
legend(["Efficiency","Mechanical Power (W)"])
title("Motor Characteristics vs Torque")
```

```
function [qq] = position_time(Positions,Forces,Strokes,motor,
my,sigma,maxLead,minLead,n1,n2,lever,frame_height,ylimit)
%% Function computing the lifting time (and other parameters)
%%of the device depending on
%%its position compared to the CG and to
%%the motor used




%%Variables
L = zeros(n2,1); %lead of the screw
```

```
t = zeros(n2,1); %lifting time
min_t=zeros(n1,1);
opt_rpm=zeros(n1,1);
opt_L=zeros(n1,1);
opt_Torque=zeros(n1,1);
Torque=motor.torque;
rpm=motor.rpm;
diameters=sqrt(4*Forces/(pi*sigma))+0.002;
weight=7800*pi*(diameters.^2).*(Strokes+frame_height)./4

%looping through all positions
%and computing lifting time for every operating point of the
%%motor
for i=1:n1
    for j=1:n2
        L(j) = (Torque(j) * 2 * pi * my) / Forces(i);
        if L(j)>maxLead
            t(j) = 100;
        elseif L(j)<minLead
            t(j) = 100;
        else
            t(j) = Strokes(i)/(L(j)*rpm(j)/60);
        end
    end

Idxmin = find(t == min(t)); %finding the index of the best
min_t(i) = min(t);       %%lifting time
opt_rpm(i)=rpm(Idxmin(1));
opt_L(i)=L(Idxmin(1));
opt_torque(i)=Torque(Idxmin(1));
end
Strokes = Strokes';
Weights = weight';
table(Positions', min_t, opt_rpm, opt_L,Strokes,Weights,
diameters')


%Plot
plot(Positions,min_t,'LineWidth',2)
title('Lifting␣time␣and␣rod␣weight,␣based␣on␣lifting
position␣(HWP)', 'FontSize', 24)
ylabel('Time␣to␣lift␣[s]', 'FontSize', 18)
hold on
ylim([0 ylimit])
yyaxis right
xlabel('Distance␣from␣pivot␣point␣[m]', 'FontSize', 18)
```

```
plot(Positions,weight.*1000,'LineWidth',2)
%plot(Positions,opt_torque,'LineWidth',5)
ylabel('Weight␣of␣main␣lifting␣rod␣[g]', 'FontSize', 18)
ylim([0 600])
legend('Lifting␣time␣[s]','Weight␣[g]', 'FontSize', 24)
legend('AutoUpdate','off')
yyaxis left
plot([lever lever],[0 ylimit],'-k','LineWidth',7)
text(lever,ylimit/2,'\leftarrow␣axle␣position',
'VerticalAlignment','middle','FontSize',20)
grid on
qq=1;
end
```

```
clear
clc
clf

%%%Inputs
n1=1000; %number of steps for the positions
n2=1000; %number of steps for the motors points
liftingHeight=0.09;
liftingTime=5;
my=0.9;
sigma=420000000;
maxLead=0.005;
minLead=0.0045;
ylimit = 10;
emotor = 0.50*0.7;

%Truck definition
trucks.LWP.lever_CG=xxx;
trucks.LWP.force=xxx;


trucks.LWT.lever_CG= xxx; %Confidential
trucks.LWT.force=xxx; %Confidential

trucks.HWP.lever_CG=xxx; %Confidential
trucks.HWP.force=xxx; %Confidential


%Motor definition
ratio=5;
motor.wiper.torque=linspace(2*ratio,emotor*100*ratio,n2);
motor.wiper.rpm=linspace(50/ratio,5/ratio,n2); %rpm
motor.wiper.amp=linspace(2.5,15,n2); %amp
```

```
motor.wiper.mechanicalpower=motor.wiper.torque.*motor.wiper.rpm
.*pi./30; %W
motor.wiper.efficiency=motor.wiper.mechanicalpower./
(motor.wiper.amp.*24); %no unit




%Efficiency
max_eff=max(motor.wiper.efficiency)
motor.wiper.torque=motor.wiper.torque./(72*max_eff);
motor.wiper.rpm=motor.wiper.rpm.*72;


%Getting positions,forces and strokes
[pos,Forces,Strokes] = fpos(n1,trucks.HWP);
[qq] = position_time(pos,Forces,Strokes,motor.wiper,my,sigma,
maxLead,minLead,n1,n2,trucks.HWP.lever_CG,1,ylimit)




%%
```

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