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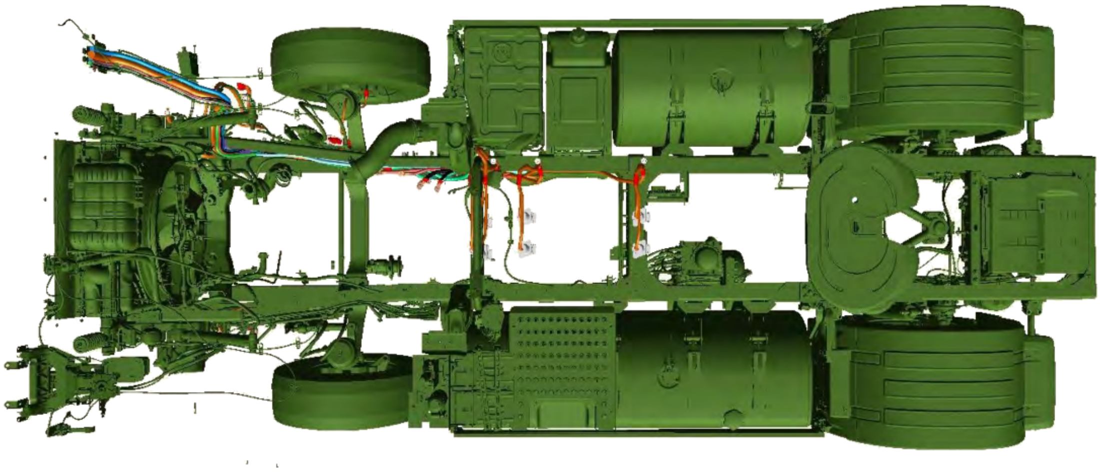

Alternative Harness Routing and Pass-Through

Master's Thesis in Product Development

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
Top view of a Volvo truck chassis with coloured harness route

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Abstract

The number of electronically controlled features on heavy-duty trucks increases constantly nowadays. As a result more and more cable harnesses need to be routed on the chassis of a truck and passed through into the cab. The cab must furthermore be tiltable to reach the engine and other components underneath it. This situation leads to less space in specific areas on the truck for other components and to problems with wear on cables. Alternative solutions for a harness route and pass-through may improve the situation and set a benchmark in the truck industry.

This Master's thesis conducted at Chalmers University of Technology describes the development of new alternative harness routing and pass-through concepts for the application on Volvo's heavy duty trucks. The thesis was conducted as a product development project at Volvo's Gothenburg site. To show feasibility of new concepts, the cabling of the so-called Bodybuilders which mount their attachments on produced trucks was the focus of the development. The application of the acquired methods during the Master's programme Product Development resulted in two final concepts with their according prototypes. The prototypes were tested at Volvo's facilities. The first concept was an expandable routing solution with mechanical links called PseudoPanto. The second concept was a fully automated coupling for electrical contacts called Selfie. In both concepts the back of the truck was the mounting point. Furthermore, a new routing and pass-through on the truck's cab were developed to be used together with either of the developed concepts.

By leaving the electrical circuit closed during tilting of the cab, PseudoPanto poses less problems for error searching during truck maintenance. In contrast, Selfie breaks the electrical circuits during tilting but does not pose a physical obstruction during maintenance.

Keywords: harness, cabling, pass-through, truck, pantograph

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The Authors, Gothenburg, 2014-09-03

Contents

Acronyms

BB Bodybuilder

CAD Computer Aided Design

CES Cambridge Engineering Selector

COE Cab Over Engine

CPT Cab Pass-Through

DL Development Loop

ECU Electronic Control Unit

LHD Left Hand Drive

LHS Left Hand Side

PLM Product Life Cycle Management

RHD Right Hand Drive

RHS Right Hand Side

SLS Selective Laser Sintering

1

Introduction

The complexity of today's trucks continuously rises as truck manufacturers challenge themselves in adding more features to their products in order to sustain competitiveness. Traditional solutions must be replaced to be able to cope with the situation.

One example of this increasing complexity relates to the number of electronic devices situated on the truck. The use of electrical cables are a common means of transmitting electrical signal and power on today's trucks between these components. These cables are usually bundled and packed together in order to save space and better protect them. This assembly of electrical cables is called a cable harness. It is predicted that the functionality will increase in future trucks, which indicates an increasing number of electronic devices (Reiter, 2012). This in turn may indicate that the number of cables in the truck will also increase and thereby the size of existing cable harnesses.

This thesis was proposed by the Electrical Packaging and Installation Group at Volvo Group Trucks Technology (further called Volvo) and concerned Volvo's current solution of the cab-chassis harness routing which connects components located on the chassis to the inside of the cab. It also relates to the pass-through where the harness crosses the cab wall. The current solution is known to pose problems in terms of abrasive wear on the cables and the space available for additional cables.

1.1 Purpose

The authors intended to contribute to the knowledge of product development regarding harness routing of electric cables in trucks. The objective of the thesis is to investigate the possibilities of developing new alternative harness routing solutions by conducting a product development project. The targeted results were concepts developed to a level where physical prototypes for testing purposes could be produced.

1.2 Limitations

The thesis analysed exclusively the harness routes of electric cables and not any other type of cabling on a truck.

The scope was to investigate only a part of the total cab-chassis harness in order to exemplify the possibility to find new alternative harness routing solutions. By re-routing some of the existing cables of the current solution, more space would be available for the rest of the cables. It was assumed that by proving the re-routing of one part of the harness to be possible, the solution could be adapted to hold an increased number of cables in a further development step. The cables to be re-routed are described in more detail in chapter 3.

The parts investigated of the harness routing were the chassis route close to the cab, a new cab-chassis connection, the route on the cab and a new pass-through into the cab. The routing inside of the cab was not part of the development.

The solutions were developed for one specific target truck in Volvo's current series of heavy duty trucks. The solutions delivered by this project should therefore not be considered to be applicable for trucks in general without some modifications, as they are truck specific.

2

Method

This chapter describes the methods and theories used in the course of this thesis. A generic overview of the development process can be seen in Figure 2.2. The development process followed in general the product development methods presented in Ulrich and Eppinger (2012) which are also applied in the Master's programme Product Development at Chalmers University of Technology.

2.1 Information Gathering

In order to grasp the problem posed and to get an overview about related issues and parts on a truck, information was gathered in the beginning. Furthermore, this information was needed to elicit the requirements posed on the new product. This was accomplished by the methods which are described in this section.

2.1.1 Interviews

The first measure to receive information from a primary source was to get in contact with employees at Volvo. Semi-structured interviews were chosen as the pattern of communication as suggested in Bryman and Bell (2003). This method was assumed to lead to a wide bandwidth of information from the interviewee. This bandwidth can be seen as positive since the authors lacked knowledge about trucks in general in the beginning of the thesis and could use any new bit of information.

The people to be interviewed were chosen after their responsibility for parts that could even be remotely related to the new product to be developed. In total over 30 people were chosen for the interviews from different departments and functions at Volvo such as Packaging & Installation, Wiring, Vehicle Architecture, Body-in-White, component owners and technology specialists.

During the interviews the authors first described the goal of their thesis project to the interviewee. In the course of the interview it was tried to discuss about problems with the status quo, difficulties and opportunities of a new product and personal reflections of the interviewee on the thesis goal. To improve the efficiency of communication during the interviews, a Volvo model truck (see Figure 2.1) was used as a **mediating tool**. This truck helped in overcoming barriers regarding exchange of communication which was based mainly on the authors' nescience considering Volvo's products.

Figure 2.1: Model Volvo truck

2.1.2 Internal Document Research

To get a deeper understanding of Volvo's products and processes, internal documents related to the task were reviewed. The research included:

- ISO Standards
- Schematics of cabling on Volvo trucks
- Volvo's internal standards and requirements

2.2 Scope Definition

To set the scope of the time restricted project both a **target truck** model and a **target cabling** were set together with Volvo. The reason a target truck was chosen was to not be influenced by Volvo's wide product variation which could not be fully considered under the given time. To prove feasibility of the product it was also seen as sufficient to show feasibility with the chosen target cabling.

2.3 Software

Certain software was made available to the authors at Volvo to conduct the thesis project. The software used to perform the design of CAD models of the product was DS Catia V5. Certain CAD models had to be edited first in PTC Creo, another CAD software used at Volvo. To study a mockup model of the chosen target truck in detail, PTC DIVISION MockUp was used. To receive detailed product life cycle information Volvo's own software Kola was in use during the project. The main PLM tool used to load finished parts and assemblies into Catia V5 was DS Enovia. To perform simulations of created mathematical models the commercial software MATLAB and the free software Octave were used.

2.4 Function Modelling

To analyse the given problem in a structured way, a functional decomposition was performed. The initial approach was a pure **function tree** as proposed in Ulrich and Eppinger (2012) which split up the top function of the product into main functions and lower level functions. The tree was continuously adapted as development proceeded.

After certain solutions for lower level functions had been created, the function tree was adapted into a mixture of a pure function tree and a function-solution tree which is called function-function-solution tree in this report. This structure helped to visualise all the created solutions for the lower level functions and facilitated the process of combining these into solutions for min functions.

2.5 Concept Development

Concept development mainly comprised concept generation, concept selection and prototype building and testing. The methods used in these phases are described in this section.

2.5.1 Concept Generation

The generation of concepts comprised free, creative as well as structured approaches which are described in the following.

External Research

As suggested in Ulrich and Eppinger (2012), external research was conducted. It consisted of searching any written and photographic documentation related to the problem at hand in the database of Chalmers library and on the Internet. To receive a wide spectrum for benchmarking, also other industries and applications than the automotive yet with similar problems were searched. Especially the research of patents proved to be a good source of inspiration.

Brainwriting 6-3-5

This method is a brainstorming technique that tries to ensure equal participation of the members of a brainstorming group. The idea generation happens in written instead of verbal form. This fact may keep criticism during a brainstorming session on a minimum level. The name is derived from the fact that usually 6 people write down 3 ideas each for the solution of a certain problem in 5 minutes on a prepared piece of paper. Their papers are then passed on to the person sitting next to them. Under the next 5 minutes each participant can build on each of the three ideas which another person had created. This process of circling papers is repeated 5 times so that all participants contribute to each paper. (Silverstein, Samuel, & DeCarlo, 2009)

The 6-3-5 method was adapted to the given group size of the brainstorming sessions at Volvo. The method was used as a rather structured approach for extracting ideas from the participants. Furthermore, the method was seen as a quantitative tool to receive many ideas in a rather short time.

Mind Mapping

Mind mapping was another brainstorming method used to extract ideas from the participants in a rather unrestricted way. Mind mapping is normally an individual brainstorming tool where unstructured thoughts are caught into branches that emanate from a central problem on a piece of paper without criticising them ("Mind mapping: Brainstorming by oneself", 1995). The method was though adapted to work in groups. The authors acted as mediators which caught the thoughts of the participants on a board. A metaphoric story (see Appendix B.3) standing for the actual problem was invented and presented for the participants. The story induced a discussion around the central problem and led to associations with similar problems in real life. The associative chains that emerged were mapped by the authors clearly visible for the participants. Thus the solution space for the central problem could be explored in a rather chaotic yet extensive way.

Solution Combination

To receive solutions for main functions of the product, different solutions for lower level functions were combined as suggested in Ulrich and Eppinger (2012) in combination tables. In most cases all theoretically possible combinations could not be created due to technical impossibility.

2.5.2 Concept Selection

To choose the most viable concepts from the mass of created solutions for different functional levels, screening had to be conducted on several levels. The different screening approaches are described in this section.

Pre-Screening

Before concepts could be created that satisfied the main functions which were identified, a lot of solutions existed for the lower level functions of the product. To diminish their number a simple pre-screening was conducted by cancelling the most irrational solutions considering the gathered requirements on the product. The screening was conducted purely by discussion and common sense. To not lose the positive aspects of the cancelled solutions, they were discussed and tried to integrate into the remaining solutions. From the solutions that were left, combinations for satisfying the main functions could then easily be composed.

Concept Screening

To evaluate concepts for the main functions of the product, a Pugh matrix as proposed in Ulrich and Eppinger (2012) was used; specific criteria of each concept were rated as better, alike or worse (marked by $+$, 0 or $-$) than the respective criteria on a reference concept. The criteria which the concepts were rated by were chosen according to the gathered product requirements. For checking the validity of the results, a second screening was conducted in which the reference concept was changed.

Concept Scoring

Concept scoring is a method for evaluating concepts with increased resolution according to certain criteria which can be rated with dissimilar importance. The rating can be done in absolute values or towards a reference concept. The higher the relative importance of each evaluation criterion the higher the multiplication of the points given during evaluation. The more points a concept gets after the evaluation the better it is. (Ulrich & Eppinger, 2012)

For rating the criteria of each concept a scale of 1-5, with 5 as best, was used. The number of criteria was kept low and focused on those criteria which could be evaluated in most detail.

2.5.3 Prototyping

In the early phases of the project **rough functional prototypes** of certain mechanisms were used to gain knowledge about their behaviour and improve understanding. Furthermore, the prototypes improved the communication of ideas between the authors. The prototypes were produced with the help of Meccano (a mechanical toy) and handicraft work.

During development, the manufacturing and testing of **real-size physical prototypes** of parts of the developed product was used as a method for verification of the design. Prototype testing was conducted on a Volvo heavy duty truck test rig with fully functional components. Testing results served as an input for improvement of the design and as a source of knowledge for possibilities and weaknesses of the product. The prototype furthermore served demonstration purposes to show and prove the functional principle.

To produce the prototypes Volvo's rapid prototyping machines were used. The machines produced the prototype parts, which were provided as 3D CAD files, by the selective laser sintering (SLS) method in the materials polyamide (nylon) and alumide. To build the prototype in layers, the machine spreads a flat layer of powder on the building table, melts the powder in specific areas by scanning them with a laser beam, lowers the building table and iterates the process by spreading powder again (Goodridge, Tuck, & Hague, 2012). The finished parts were assembled by the authors with standard parts provided by Volvo.

2.6 Detail Design

To develop the chosen concept in detail with the given time restrictions the development was partitioned into two **development loops (DLs)**. The first DL focused on the function of the according concept and made it ready to be sent in for prototyping. The second DL used the results from the prototype testing to improve the concept and to integrate more considerations regarding manufacturability, product assembly and aesthetics.

In the second DL also a simple **material selection** analysis was performed for specific parts of the developed products. The selection process was performed according to the proposed methods in Ashby (2011) with the help of the software CES (Cambridge Engineering Selector) which served as an extensive material and manufacturing process database. With the chosen materials and the geometrical information about the created products from the CAD software, a simple estimation about material costs of the products could also be created.

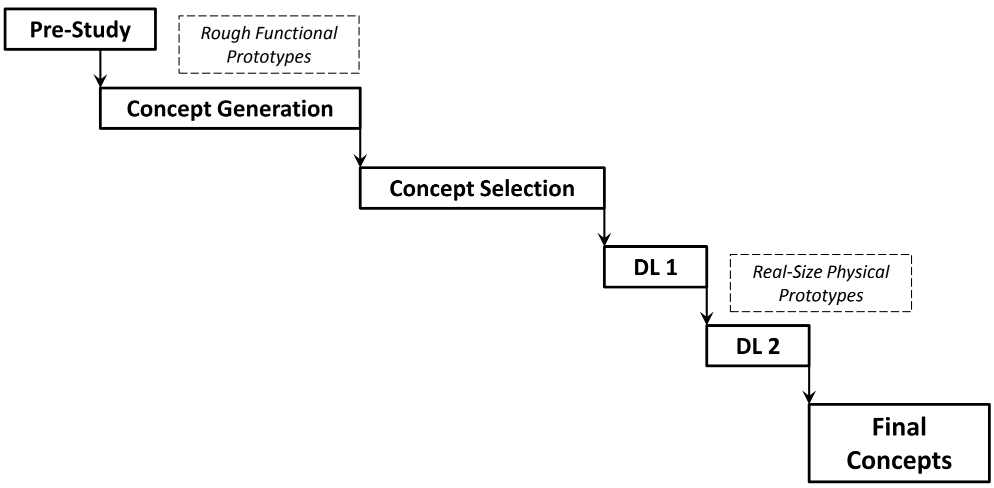


Figure 2.2: Schematic presentation of the development process

3

Pre-Study

The pre-study phase involved gathering, screening and analysis of information related to the problem. The aim of this first phase was to understand the situation of the current solution and its impact on other parts on the truck. Another important aspect was to identify various stakeholders which would be impacted by a new solution and identify which cables to chose for re-routing. The information captured during this phase was vital for understanding what the new solution should do and it resulted in the target specifications, used for the rest of the project (see Appendix B.1). Much of the information was captured from interviewing experts at Volvo, as described in section 2.1.1.

3.1 Current Situation

The current architecture of the truck cabling consists of the cab-chassis harness route which is partly routed on a component called the artificial leg for the transition between chassis and cab. The route is passed through into the cab in a component called cab pass-through. Electrical signals and power are usually transmitted in both directions between electrical components. However, in order to facilitate reading, the electrical connection between cab and chassis components will henceforth be considered to start from the chassis and end inside the cab.

3.1.1 Truck Cables

Cables are responsible for transmitting electrical power and signals between components in an electronic system. Cables are composed of conductors which are usually wires made of copper. Common problems with cables in the truck industry are vibrations and relative movements between parts which expose the cables to abrasive wear when chafing. The chafing damages the wires until malfunction, resulting in a transmission termination of electrical power or signals. Sharp edges and dirt can accelerate the wire degradation. Cables are usually bundled up together in order to mitigate the risk of abrasive wear. Furthermore, these bundles may be protected by a variety of measures such as casings, hoses or sleeves. The bundled cables, protected or not, are collectively called the cable harness.

3.1.2 Cab-Chassis Harness Route

The cab-chassis harness is the cable harness which connects components on the chassis to the inside of the cab. In Volvo's current line of heavy duty trucks, the cab-chassis harness is routed along and inside the RHS (Right Hand Side) frame (see Figure 3.1). This fact holds true for both LHD (Left Hand Drive) and RHD (Right Hand Drive) trucks. The harness contains several different cable bundles which are each encased by a protective corrugated hose. Along the route the cable bundles are clamped together and fixed to the frame with cable ties.

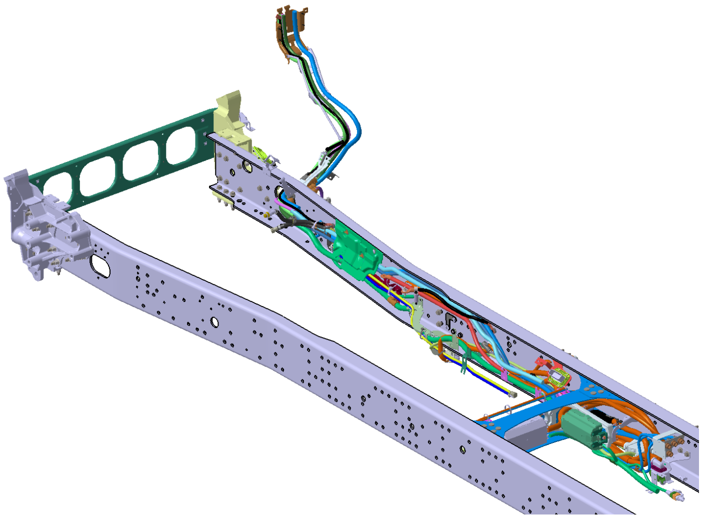
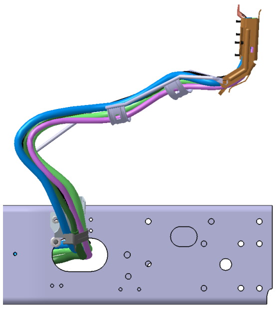


Figure 3.1: Cab-Chassis harness route on the RHS frame

3.1.3 Artificial Leg

The cable harness is fixed to the frame just until the front end of the chassis beams. After the harness has crossed over to the outer side of the frame through a hole, it needs to bridge the gap between the chassis and cab. This is achieved by a component called the artificial leg. The artificial leg provides a support on which the cable harness can be fixed with cable ties (see Figure 3.2a). One important requirement that the artificial leg needs to fulfil is to allow tilting of the cab. Cab tilting occurs on Cab Over Engine-trucks (COE) whenever the engine needs to be accessed, further explained in detail in section 3.2. To assure that the harness will not be damaged during tilting, the artificial leg moves the harness into a different position permitted by its flexible lower part (see Figure 3.2b).



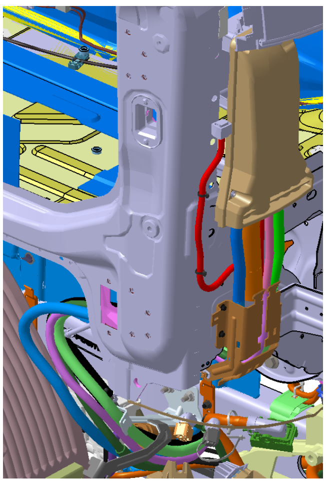
(a) Cable harness fixed with cable ties

(b) Encircled flexible lower part

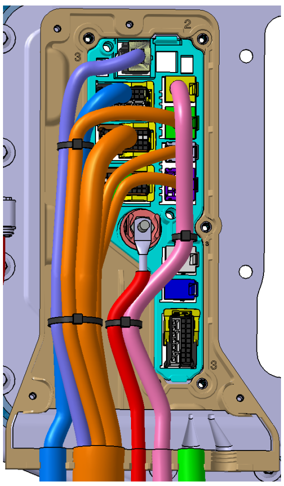
Figure 3.2: Artificial Leg

3.1.4 Cab Pass-Through

The cab pass-through (CPT) is the component which allows the cab-chassis harness to enter the inside of the cab (see Figure 3.3a). Basically the CPT is a box which covers up an opening in the front. As in the case of the harness route, this opening exist only on the RHS front, in both LHD and RHD of the current heavy duty trucks. The CPT provides entry for the cables, but limits the permeation of water, dirt and other undesirable material as much as possible. Therefore, gaskets and other sealing methods seal the lid of the box. The box itself consists of two halves which attached to the cab by clamping them together from both sides of the cab wall. The CPT holds in-line connectors which connect the outer cab-chassis route with the inner cab-route (see Figure 3.3b). The inner cab-route ultimately leads to the electrical central under the centre dashboard where all the Electronic Control Units (ECU) are situated.



(a) Position on RHS



(b) In-line connectors

Figure 3.3: CPT

3.2 Cab-Chassis Movement Analysis

Most of the trucks Volvo manufacturers are COE-trucks where the cab is located above the engine. In order to reach the engine the cab needs therefore to be moved out of the way which is done by tilting the cab. In this thesis the tilting process is divided into two phases; the inclination phase and the reclination phase (see Appendix C.1). The coordinate system of the truck is defined with the point of origin in front of the truck. Its axes are defined by right hand convention with increased positive Z pointing upwards from the truck's undercarriage and increased positive X pointing backwards, against the truck's forward driving direction (see Figure 3.4). The inclination phase starts from the locked state where the cab is securely locked to the chassis by the cab lock. After unlocking, the cab starts to move vertically upwards 50 mm in an initial phase called take-off. After the take-off, the cab starts to rotate around its tilting centre up to an angle of 70° between cab floor and chassis which is called the tilted state. The reclination phase is a reversion of the inclination phase. The reclination starts by rotating the cab from the tilted state, decreasing the angle between the chassis and cab. In the end phase of the reclination the cab enters a downward vertical movement of 50 mm called landing which resembles a reversion of the take-off phase. Finally, the cab lock engages and locks the cab to the chassis.

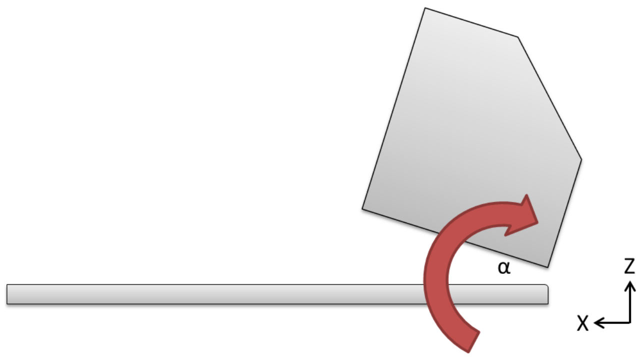


Figure 3.4: Simplified tilting model with coordinate system

The motion described may seem smooth in theory, however in reality there is always some misalignment between cab and chassis. The misalignment is mostly apparent during take-off and landing because there is only one hydraulic cylinder providing the force for the tilting movement which is positioned on the RHS frame. Due to this asymmetrical positioning the tilting movement becomes unbalanced. During take-off this leads to the RHS of the cab lifting earlier than the LHS and during landing the positioning of the cab lock pins differs from their nominal position ±10 mm in X-direction and ±20 mm in Y-direction. Between the cab lock and the chassis a suspension system is located for driver comfort. Therefore cab and chassis are not fixed rigidly to each other which allows relative movements between the two during driving. It is estimated that the cab can move ±50 mm relatively to the chassis in the Z-direction from the nominal position in the locked state.

3.3 Competitor Solution Analysis

Available competitor solutions from other heavy duty truck manufacturers were assessed during the project. CPTs and harness routings of Volvo's competitors DAF, Dongfeng, Eicher, Hino, MAN, Mercedes, Scania and UD were evaluated (see Figure 3.5).

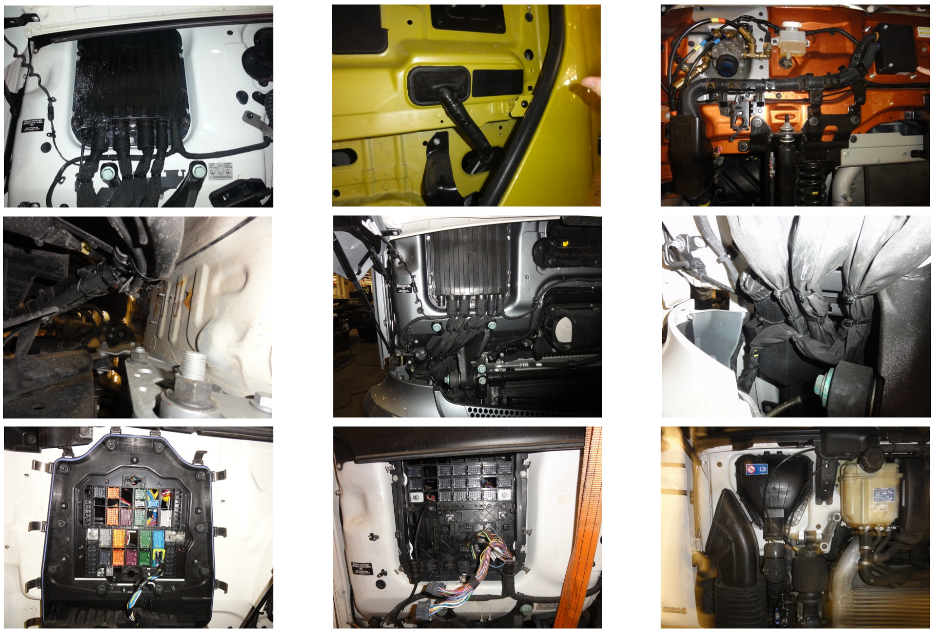


Figure 3.5: Sample of competitor CPT and routing solutions

It was seen that all investigated competitor models had their equivalent CPTs mounted in the vehicle front. The CPTs were located on the RHS on the LHD vehicles and on the LHS on the RHD vehicles. The material of the CPTs could uniformly be identified as plastics. The harness prior to the CPT was routed along the chassis frames on either the RHS, the LHS or both sides of the truck. On all models the harness was routed closely around the centre of rotation for the cab tilting, like on Volvo's models. Some models exhibited a component similar to the artificial leg for bridging the gap between cab and chassis, whereas other models bridged the gap without a supporting structure.

In the Mercedes models it could be observed that the CPT interface offered about twice as many in-line connectors than Volvo's current CPT. The cables entering the CPT were also wrapped in a fabric to seemingly protect the cables from abrasive wear and humidity. Furthermore, Mercedes' CPT was linked directly to the truck's electrical central which was located just behind the CPT. The electric central on Volvo's trucks is located in the middle of the dashboard to be easily accessed on both the RHD and LHD configuration. One drawback of Volvo's configuration is that the climate control unit can not be placed in the middle, aggravating the climate control in the cab.

In the investigated Scania model the cables from the CPT were protected by a curved plastic shell which protected the cables from the CPT about 500 mm in length guiding the harness towards the entry point of the chassis frame. The shell was rigid and fixed on the cab. Its form predefined the bending radius and direction of the harness.

It can be concluded from the study that Volvo's investigated competitors do not offer substantially different solutions for the pass-through into the cab. The current solution can therefore be seen as a dominant design of today.

3.4 Stakeholder and Customer Analysis

The stakeholders were identified by finding those parties that would be affected the most by introducing a new alternative routing/pass-through solution. The interviews conducted with Volvo's employees yielded a comprehensive overview of the stakeholders. A new truck component will impact a considerable number of groups responsible for different areas within Volvo due to the complexity and integrated design of the truck. The two main stakeholders in this project were identified to be bodybuilders and aftermarket service.

3.4.1 Bodybuilders

There are usually 3 kinds of people involved in a truck deal; a customer, a truck manufacturer salesman and a bodybuilder (henceforth called BB). A customer visits a salesman of the chosen truck brand and expresses the intended use of the desired truck. The salesman compiles these needs and sets up an order which is relayed to the manufacturing department of the truck manufacturer starting the production of the truck. The purpose of a truck is usually fulfilled by auxiliary attachments which are provided by the BB after the truck has been produced. Examples of such auxiliary attachments (see Figure 3.6) could be cranes, concrete mixers, rear loaders and more. Even smaller attachments such as lamps can be installed by a BB. This thesis focuses on the larger attachments situated on the chassis behind the cab. These attachments are mechanically and electrically integrated with the truck.

The BB's cabling also needs to be routed into the cab. In Volvo's trucks the BBs route their cables to the BB's electrical central, a separate entity provided exclusively for BB by Volvo.

Current BB-Routing

Since the CPT is only meant to contain the cables which are routed by Volvo, two different options are offered for the BBs to route the cables from the attachments to the inside of the cab.

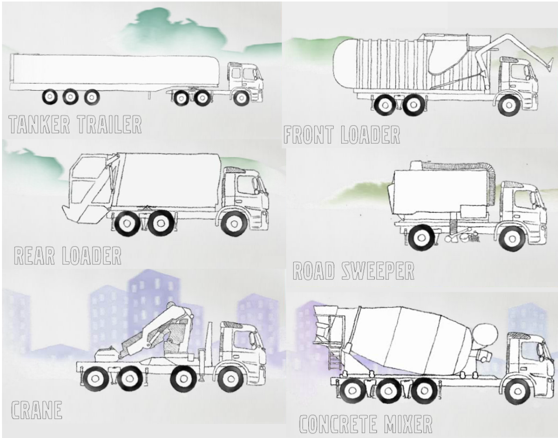


Figure 3.6: Examples of bodybuilder attachments (In Volvo Trucks homepage, retrieved 2014-07-05 from: `http://www.volvotrucks.com/trucks/south-africa-market/en-za/trucks/volvo-fm-euro-3/top10/Pages/flexibility.aspx`)

The first option for the BB is to use a cable harness with chassis connectors pre-routed by Volvo (see Figure 3.7). Three connectors exist on the RHS of the chassis with 7 pins each, which means that 7 wires can be attached. Cables with a maximum of 21 wires are attached to these connectors and routed into the regular cab-chassis harness which follows the RHS frame. Since this option is pre-routed by Volvo, the cables may enter the cab via the CPT.

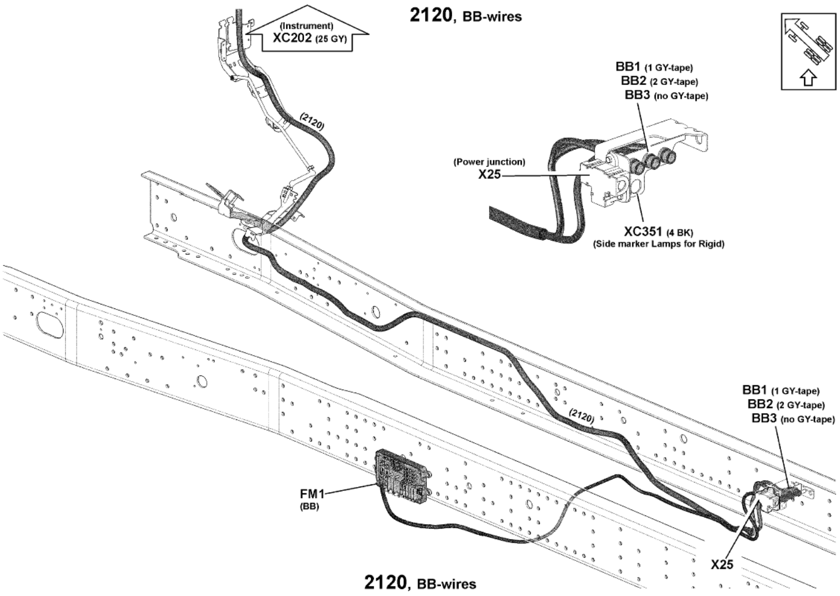
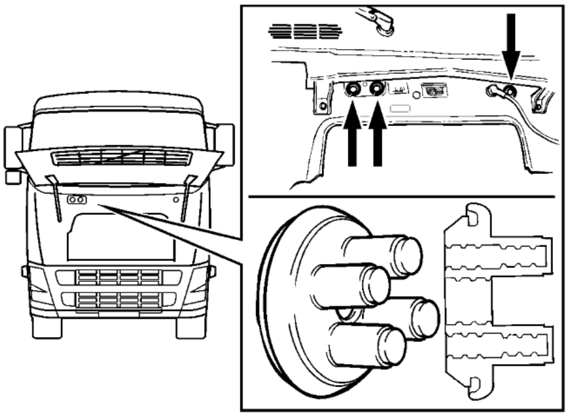
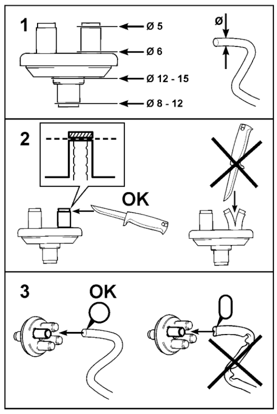


Figure 3.7: Pre-routed BB-cable (retrieved from Volvo (2014))

The second option for the BB is to route their own cables by themselves. As with the previous option the cables are routed along the RHS frame together with Volvo's harness. In order to clamp the cables together with the harness, old cable ties have to be removed and replaced with new ones at the same location. The BB may use grommets made of rubber instead of the CPT to enter the cab. The grommets cover up openings in the cab wall where the BB-wires can pass through. Located close to the CPT, the grommets seal the openings at the front of the truck (see Figure 3.8a). When the truck is delivered to the BB the grommets are completely sealed. The BB has to cut open rubber bushes on the grommets at the correct height in order for the wires to fit and pass through (see Figure 3.8b).



(a) Position on the front (retrieved from Volvo (2014))



(b) Instructions of use (retrieved from Volvo (2014))

Figure 3.8: Grommets

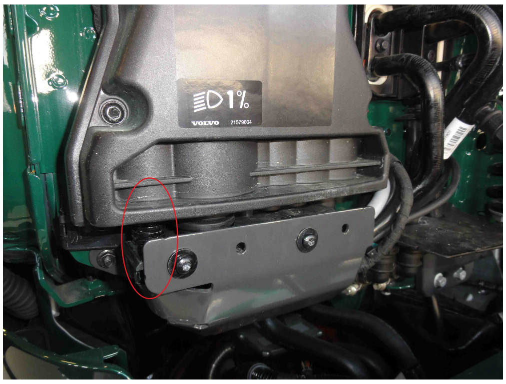
BB Study Visit

To gather more knowledge about BBs and how they route their cables today, a study visit was arranged at the BB JOAB. The study visit included interviews with a senior technical adviser and a tour in the workshop. In the workshop the installation of attachments could be observed and the installation personnel was ready to answer questions. The results of the study visit are presented in the following.

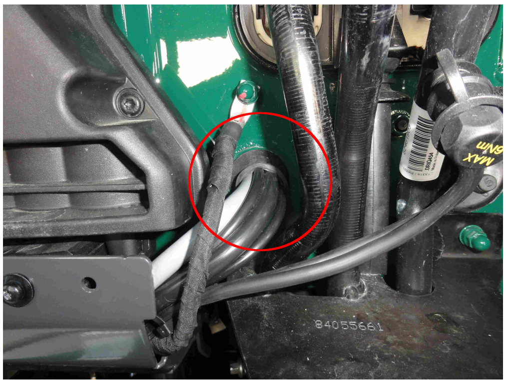
As observed at the BB, the trucks are not prepared for the BB when they arrive from the truck manufacturer. There exists no predefined procedure of cable routing. Since each truck is usually customised, it is often not possible for the BB to use cables which are separately provided by the truck manufacturers. Instead the BB needs to design their own cables. The BB does not make new holes in the cab body and therefore uses only the available pass-through or grommets to enter the cab.

The communication between the BB and the truck manufacturers seems to be inefficient in certain aspects. The truck manufacturers provide an instruction manual informing the BB about the proper procedures during bodybuilding operations. The BB admits though to not fully consider the provided instructions. The BB follows the regulations he is aware of, but the instruction manual does not seem to convey the information as intended. The BB does not have a lot of possibilities to affect truck manufacturers since he is not involved until late in the design phase. Information about new trucks are not usually disclosed to the BB until the final release of the truck.

The BB starts the routing from inside the cab and continues the route towards the chassis. Inside the cab all the switches on the dashboard are installed and the cables are routed from the electrical central to their respective pass-through or grommet. This is one of the most difficult tasks for the BB as it often interferes with the interior which needs to be torn out and reinstalled later. The visited BB handled only the installation of the cabling which had been delivered pre-assembled by their suppliers with a connector fixed at one end. The other end was free in order to thread it through cavities where the cabling should be routed. The attachment to be installed was also delivered fully prepared with the cabling. Basically the BB routed the cables from inside the cab to an interface on the chassis. The attachment was then lifted onto the truck and installed both electrically via the interface and mechanically onto the frame.



(a) CPT with the pre-routed BB-cables encircled



(b) Incorrect use of grommet where too many BB-wires pass through

Figure 3.9: BB-routing in practice

During the study visit one Volvo truck was examined with the pre-routed BB-harness (see Figure 3.9a). The BB however chose not to use the pre-route as he considered the number of pins to be insufficient. The BB could have used the existing 21 pins but needed to route the remaining wires anyway which made it more convenient for the BB to route all wires together at once to the front. The BB thought that the pre-route would maybe prove useful in the future if the customer would decide to add more attachments. In general, the BB considers 20-30 pins to be enough for most trucks and the BB believes that this number will not change considerably in the near future. In the front it was seen that the BB used the provided grommets incorrectly to enter the cab. The grommet had been cut open too much and more wires than intended by Volvo were passed through it. This resulted in a grommet which could not properly seal the inside of the cab from dirt and water (see Figure 3.9b).

From the study visit the following problems with the BB-harness routing were identified:

- The number of pins on Volvo's pre-routed connectors are not enough
- The cab entry provided by Volvo's grommets are not large enough
- Instructions provided by truck manufacturers are not fully conveyed

The decision was taken to develop solutions aimed for the BB-cables in order to solve these existing problems. The idea was to develop solutions which promote the BB-routing by facilitating the routing for the BBs, instead of instructing or restricting them. This possibility would also create more space for other cables and at the same time decrease the BB's impact of the Volvo's own routing.

3.4.2 Aftermarket Service

In order to capture information from the aftermarket service department at Volvo, several interviews were conducted. Most of the time the authors let the interviewee talk freely and occasionally posed appropriate follow-up questions in addition to the prepared questions. The focus was to gain information about the maintenance of the electrical equipment, their needs and problems and how aftermarket service would be affected by a new harness routing and pass-through solution.

Trucks are usually scheduled for maintenance 1-2 times per year after every 100 000 km. Trucks which are bought by a logistics company are usually contracted for 5 years of maintenance. The lifetime of a truck is considered to be 7-8 years but it is not uncommon that the truck is used up to 10 years. (Volvo, 2014)

In order to identify and repair problems with the truck it is necessary for the aftermarket maintenance to diagnose the truck. This is done by connecting measuring equipment into the truck's electric circuit. The principle behind diagnosis is to search for errors first on a system-wide level and then narrow it down to the component level. The malfunctioning component does not need to be the source of the error in which case aftermarket service starts tracing for the source along the circuit. Often, connectors are a possible source of the error. The two nodes of the measuring equipment are coupled into the truck's electric circuit. If the equipment senses a fault, an error exists in the components between the nodes. For the equipment to be able to diagnose, the whole electric circuit must be closed. (Volvo, 2014)

During maintenance, the cab is tilted in order to access the engine. Therefore, one main concern for the aftermarket service is to have easy access to the engine to be able to inspect, reach and use their equipment. Diagnosis should not be obstructed by a new solution for the pass-through. In certain situations it is important to be able to diagnose and at the same time access the engine. After the error has been discovered, the necessary parts are replaced. During replacement the diagnostic equipment does not need to be connected. Volvo's aftermarket service usually only diagnoses Volvo's own cables, but since the BB cabling is interconnected with Volvo's components the BB cabling is still important for the diagnosis process. (Volvo, 2014)

From the analysis it became apparent that the focused BB cabling does not have to be coupled under a standard tilting operation. Under certain circumstances the BB cabling needs though to be a closed circuit for error search purposes. With the gained information a worst-case number of tilting operations was set to 200 on the European market. Error searching does not take place every time the cab is tilted but can be related to the maintenance interval discussed above. It is not possible to give a general estimation about the number of times the BB cabling has to be coupled for error search purposes during a tilted state of the cab.

3.5 System Position Analysis

Positioning of a new pass-through solution on the cab and chassis was split up into two main parts; a connection point and a pass-through point. The connection point is the point on the cab where the cabling route from the chassis first touches the cab in a locked position. The pass-through point is where the cabling is physically entering the inside of the cab. These two points may be the same physical point but they do not have to be.

Figure 3.10: Target truck

Simplified, the cab can be seen as a cube. A picture of the chosen target truck in Figure 3.10 may demonstrate this. Thus it has 6 possible planes for connection and pass-through points for a route from the chassis; front, left and right side, top, floor and back. The front is equipped with a component called firewall which adds protection for the driver in case of a fire. The firewall and special safety regulations put strict requirements on the pass-through in the front. Originating from the front, a routing close to the centre of rotation during tilting may lead to minimal cable movement. The left and right side planes offer possible connection points but they are difficult to reach from the chassis structure due to their remote position. Furthermore, the sides perform potentially larger movements under driving as they are situated furthest from the middle of the truck. The sides do not offer possible pass-through points into the cab as minimal space is available. A pass-through point on the sides of the cab would furthermore lead to asymmetry and thus an aesthetically unpleasant appearance of the truck. Protruding structures at the sides of the cab will also affect the aerodynamic properties. The top does not seem like a sound option for placing a connection point since it is geometrically the most distant part of the cab with respect to the chassis. The top can offer pass-through points, yet with limitations as aerodynamics and aesthetics prohibit certain positions. The floor and the back of the cab seemed to offer large areas for both connection and pass-through points and are furthermore situated in direct proximity to the chassis in the locked position. This is why the investigation was focused on these two areas.

The space on the back of the target truck is restricted by the envelope of all the possible positions of a trailer behind the cab wall. This envelope is called the trailer sweep (see Figure 3.11) and has its minimum distance from the cab wall in the centre of the truck in Y-direction and at the top of the back wall in Z-direction. All components on the truck shall keep a certain safety distance from the trailer sweep.

Discussions with Volvo employees and investigation of the target truck have shown that the back of the cab is more suitable for a connection point than the floor. The following guided the decision to chose the back plane as a location for the cab connection point:

- The movement of take-off and landing is more controlled at the back as the locking mechanism is situated in the corner between cab floor and cab back
- Space is very limited underneath the cab floor in the locked position
- Temperature conditions are worse under the cab floor than on the back
- The environment is harsher under the cab floor as it is more exposed to dirt and water

The placement of the pass-through point does not have to be on the same plane as the connection point. A placement in the same plane might though make mounting easier and could allow for further integration of the product in the future.

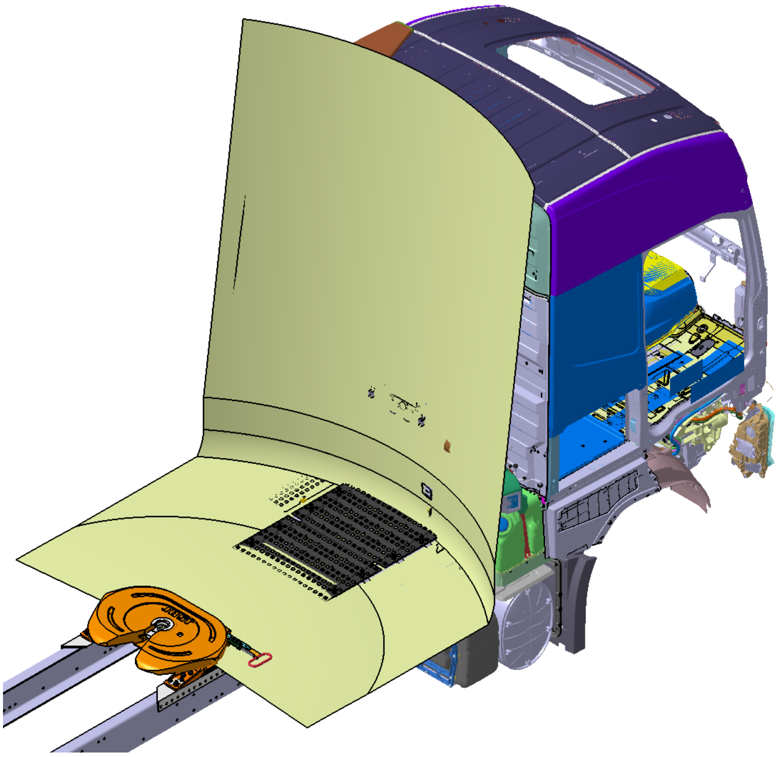


Figure 3.11: Envelope of the trailer sweep on a truck model

Detailed placement of the new product on the chosen plane had to be decided in order to start developing the product, however the choice of placement is in itself dependent on the product design. These two design parameters find themselves in a implicit dependency relationship. To break out of this paradox it was decided to begin with the development of the product which led to input for the positioning. This in turn reinforced the development of the product and the iteration process was followed until the final design was reached.

4

Concept Development

This chapter gives an account of the development process of the concepts. First, the early phase of generating concepts is described which reflects the procedure of creating ideas from scratch. Afterwards the selection process of the concepts is described. Finally the prototyping and testing of concepts is explained.

4.1 Concept Generation

This section describes the process of generating concepts. First different general approaches for development are described, followed by a function analysis. External and internal search for related solutions are described before the concepts are presented that are used as inputs for the concept selection.

4.1.1 Approaches

One of the main problems to be solved by the product was to allow tilting by the electrical connection of the harness route. Five general approaches to accomplish this could be identified from the start of the project which were researched (see Figure 4.1):

- Rigid: The connection is established by a rigid electrical connection which does not change its relative position under tilting
- Prolongable: The connection is capable of expanding and folding an electrical route
- Guided Disconnection: The connection is electrically separable but always keeps a mechanical link
- Plug: The connection is electrically and mechanically separable
- Wireless: The connection is established by devices communicating without wires

After researching and consulting experts at Volvo, the plug and prolongable approach were selected which seemed to have the highest potential of success in the given time frame. In the case of the plug approach, a solution would need to be automatically operated without human interaction.

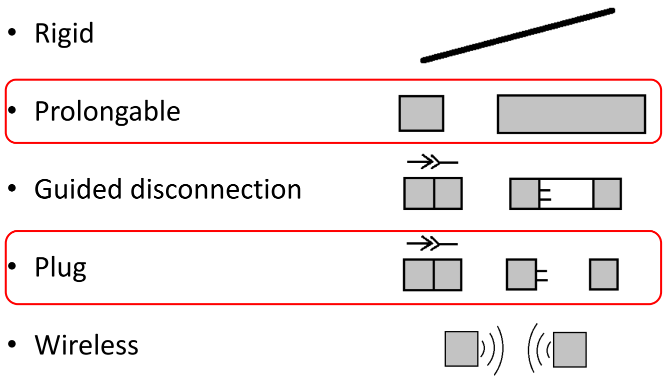


Figure 4.1: Researched approaches, selected encircled

4.1.2 Function Tree

The function tree was established according to the guidelines in Ulrich and Eppinger (2012). The top function was identified to be **Provide Routing Architecture for BB**. Below this top function three main functions could be identified which were **Provide Routing Possibility**, **Allow Driving Situations** and **Allow Tilting** (see Figure 4.3). One of the main functions, Allow Tilting, was identified to be especially important. Therefore, Allow Tilting was assigned to be the critical function which should be developed first. Failing in doing so was assumed to not lead to any success of the development project. Provide Routing Possibility and Allow Driving Situations were assigned to be the secondary main functions which were to be focused on after the critical function had been assessed. The relationship between these main functions may also be depicted as in Figure 4.2 where the critical main function can be seen as the core of the new harness route. Without this core, the surrounding functions cannot be fulfilled. Both complete function trees of the two approaches, plug and prolongable, are very similar (see Appendix B.2). The secondary main functions are identical for both function trees.

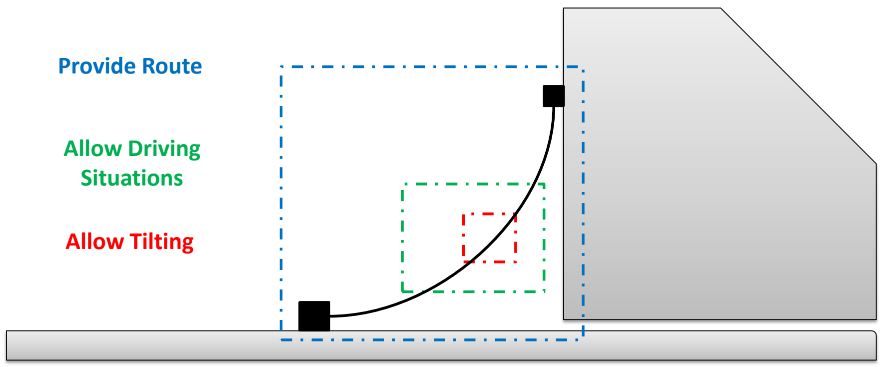


Figure 4.2: Relationships between main functions

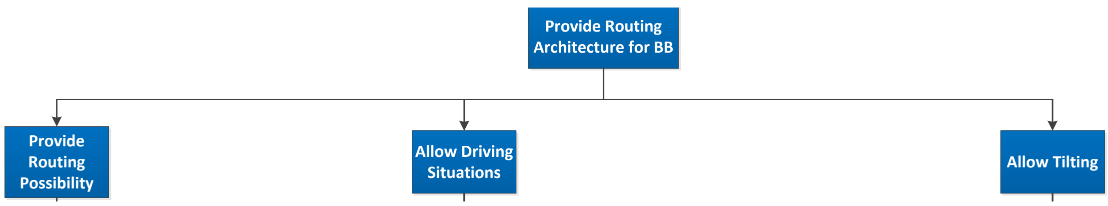


Figure 4.3: Top of function tree

Critical Function

The critical function Allow Tilting is composed by two subfunctions which are Allow Inclination and Allow Reclination, which holds true for both approaches (see Appendix B.2). Starting off with the prolongable approach, Allow Inclination indicates means of extending its reach by unfolding its electrical connection and mechanical link while avoiding sharp corners. Allow Reclination can be seen as the reverse of Allow Inclination with the additional feature to shelter the electrical connection and the mechanical link.

For the Plug approach, Allow Inclination indicates the unmating of the plug and protection of the electrical contacts. The process of unmating the plug can be further divided into the acts of releasing the fixation and the electrical contact and how the loose plug is handled. Allow Reclination contains similarly two subfunctions which are Unprotect Electrical Contacts and Mate Plug. The mating can also be further divided into subfunctions describing how the plug is guided on its path, how the final flush and electrical connection are established, how the fixation is undertaken and how the plugging is protected.

Secondary Main Functions

The secondary main functions are composed by Provide Routing Possibility and Allow Driving Situations for both approaches (see Appendix B.2). Provide Routing Possibility is divided further into three subfunctions which determine how the BB cables are passed through the cab-wall and how routing and transfer points are provided. Allow Driving Situations is composed of two subfunctions, namely the means of allowing the movement between cab and chassis and how vibrations are withstood.

4.1.3 External Research

The external research was conducted as advised in Ulrich and Eppinger (2012). One of the results from the pre-study was the insight that no other competitor had fundamentally different solutions regarding the harness routing and pass-through. Therefore, the main effort was put into researching similar technologies in other industries and applications than the truck industry.

For the plug approach the research was focused on technologies which were associated with a number of connections and disconnections of different kinds of contacts, preferably automatic. Most insight could be gained from technologies containing electrical connections, but also from other connections such as hydraulic and mechanical connections. Notable examples of industries were the train industry with its mechanical connections between waggons and aerospace industry with its automatic guiding of in-flight refuelling and space docking systems. Furthermore, other applications and areas within the truck industry were used as an inspiration, e.g. the fully automated fifth-wheel trailer coupling by JOST (see Figure 4.4). For the prolongable approach the research was focused on mechanisms which extended over a gap by folding and unfolding. Examples of interesting technologies were different cable drums and collapsible bridges (see Figure 4.5).

(a) Trailer mounted interface

(b) Truck mounted interface

Figure 4.4: JOST KKS2 trailer coupling interface (retrieved 2014-08-06 from `http://www.youtube.com/watch?v=V8TKFr3CzDA` at positions 0:42 and 0:54)

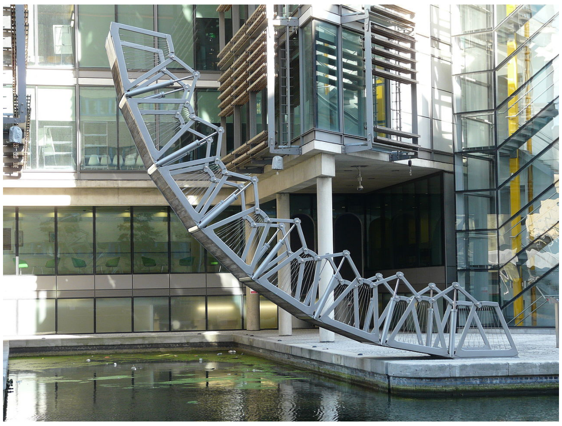


Figure 4.5: The Rolling Bridge in London, example of a collapsible bridge. (in Wikimedia Commons, the free media repository, Retrieved 2014-08-08 from: `http://commons.wikimedia.org/wiki/File:The_Rolling_Bridge_by_Thomas_Heatherwick,_Paddington_Basin2.jpg`)

4.1.4 Brainstorming

The brainstorming consisted of both, individual sessions by the authors and group sessions with invited persons from Volvo. For the individual brainstorming sessions the authors first generated and prepared concepts by themselves followed by a mutual idea exchange on a whiteboard (see Figure 4.6). In this way the authors kept themselves updated about each other's ideas which could be further developed by discussion

There were two group brainstorming sessions with two different groups which were focused on answering the question *How can the electrical connection allow cab movement?*. As previously described in section 2.5 the brainstorming events were divided into two parts, one more structured part comprised of the 6-3-5 brainwriting method and one more unrestricted part comprised of the mind mapping method. The authors chose the participants and divided them into groups with compatible individuals. A mix of theoretical and practical knowledge was desired in both groups. There was an apparent difference between the two group sessions with regards to the two methods. One group

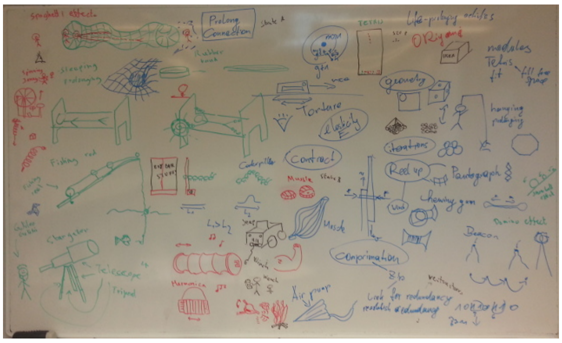


Figure 4.6: Example of the authors' individual brainstorming event

was much more responsive in the structured part than the other which in turn performed better in the unrestricted part. The aim was to have groups of about six people in each group. Due to cancellations the first group consisted of two and the second of five members. In the first group the authors had to participate in the brainwriting method to produce valuable results. The 6-3-5 method was thus adapted accordingly to the number of participants present at each session. Similarly the mind mapping had to be adjusted for each group, since the authors needed to be more or less involved in order to provoke respective group answering. In combination with the methaphoric story representing the difficulty of separating contacts abstractly (see Appendix B.3), a slideshow of stimulating pictures was shown to provoke associations.

4.1.5 Function-Function-Solution Tree

Starting from the input gained from the external research and brainstorming events, many ideas were generated. Each of these ideas were analysed and categorised with respect to the function tree in order to create a function-function-solution tree where only solutions to the lower level functions entered. Each solution was described with a short text, sometimes also together with a picture. The idea was to gather as many possible solution for each of the lower level functions. After a pre-screening (see section 4.2.1), the solutions were assembled into concepts for the main functions by using combination tables. As previously described the focus of these first concepts was to fulfil the critical function Allow Tilting.

4.2 Concept Selection

This section describes how the selection between different concepts for the critical function was carried out. Concepts of the same approach were evaluated with respect to each other in order to maintain concept diversity. A pre-screening was conducted before concepts for the main functions could be created. The concepts were then evaluated after factors based on information gathered during the pre-study phase. Concept screening was performed for both approaches and concept scoring was used whenever the concept screening was not enough to elicit the superior concepts. The screening and scoring matrices can be viewed in Appendix B.4.

4.2.1 Pre-Screening

Prior to creating concepts satisfying the main functions, the most irrational solutions for lower level functions were cancelled out by a pre-screening to lower number of possible combinations. By combining the remaining solutions, concepts for the main functions were created which entered the selection process of screening and scoring.

4.2.2 Feedback

To assist the evaluation process of the concepts, a presentation was held at Volvo in order to capture comments, thoughts and criticism. In this way both Volvo's and the authors' expectations and goals could be matched. Furthermore, the concepts' success probability could be evaluated.

4.2.3 Concept Screening

Concept Screening with a Pugh-matrix was performed as recommended in Ulrich and Eppinger (2012). It was performed twice for both the plug and pronlongable approach in order to secure a non-biased result. The datum concept was changed once in the screening of each approach. For the plug concept, it became apparent that the concept called **Selfie** was superior to the others. The outcome of the prolongable concepts was more ambiguous and a concept scoring had to be performed in order to choose a winning concept.

It follows a list of the concepts that were evaluated during concept screening, briefly described in order to allow the reader to follow the selection process. A more detailed description of the final concepts will be presented later.

Plug Concepts:

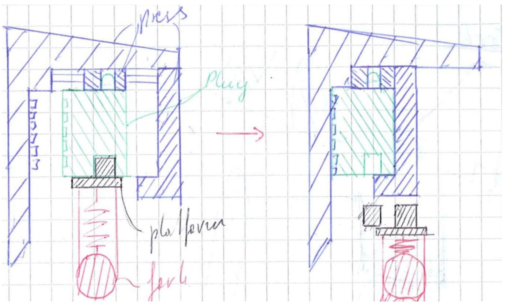


Figure 4.7: Press

Press: A plug is loosely fixed to an interface which holds the plug in position. The connection closes by pulling the plug towards the back of the cab with a third part acting like a press. The interface of the electrical contacts is facing towards the back of the cab. The closing and opening of the Press is operated by rods on a fork which hold the plug. The rods interact with gears inside the Press which operates a screw that pushes the press together.

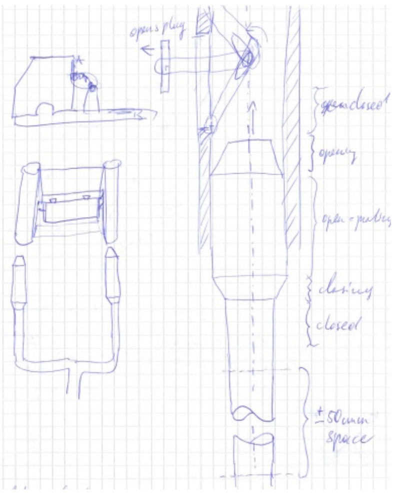


Figure 4.8: Inverted Press

Inverted Press: The Inverted Press also uses a third part which pushes the plug into an interface on the cab wall, like in the regular press concept. The Inverted Press seeks to remain in the closed state. The closing force is provided by a gas spring. The press is opened by a fork that enters the receiving cylinders of the press. The fork is comprised of tapered rods that activate a mechanism during sliding. In the first section of the rod the press is opened and the plug is pre-inserted. In the second section of the rod the press closes itself and mates the plug.

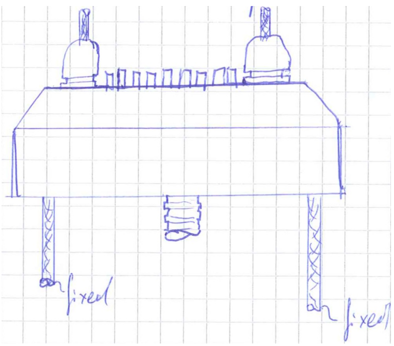


Figure 4.9: Yoyo

Yoyo: The plug is retracted to its mating housing by a rope which is under tension and seeks to mate with the plug. Due to the rope tension the plug is always oriented towards its mating interface during the reclination process.

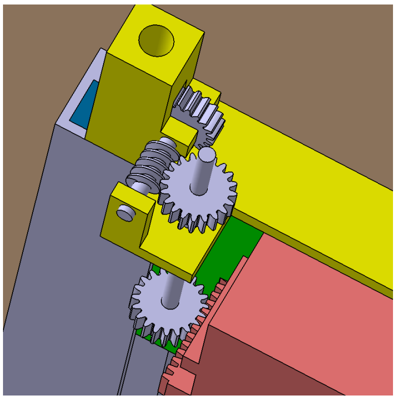


Figure 4.10: Search and Engage

Search and Engage: A plug is guided by extensions on its sides which are connected to a fork of rods which holds the plug up. A shell on the cab wall guides the extension of the plug towards the mating point. At the final mating point the rods of the fork activate a closing mechanism by rack and pinion which pushes the plug towards the mating at the back wall.

Selfie: A plug which is mated in landing direction. The concept comprises a fully automatic coupling that is independent of human interactions. Pictures cannot be shown.

Prolongable Concepts:

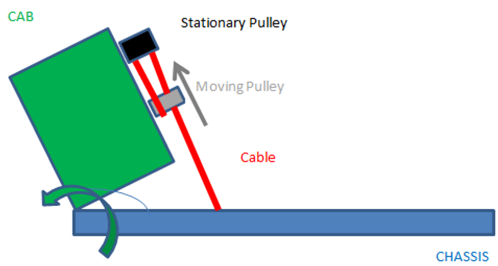


Figure 4.11: Pulley System

Pulley System: The overlength of the electric cables are enough to bridge the gap between chassis and cab during tilting. When the cab is locked the overlength is stored securely inside a shell. The retraction of the cables is performed by a pulley inspired system in which the cables are routed through. The Pulley system is situated at the back of the cab.

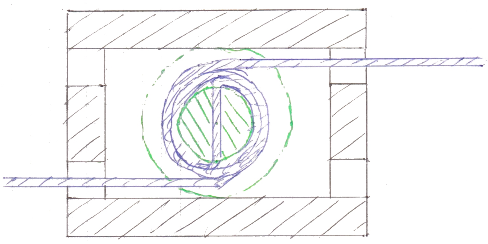


Figure 4.12: Mid-Air Reel

Mid-Air Reel: The Mid-Air Reel rolls up the cabling between chassis and cab from the middle of the connection. The reel rolls up the cabling towards the cab at the same time as it rolls up the cabling towards the chassis. The two reels have a different roll-up direction. In the tilted state the reel hangs in mid-air in the cable connection between cab and chassis.

Figure 4.13: Tubic Spiral

Tubic Spiral: A telescopic cylinder bridges the gap between chassis and cab during tilting. The spiral cables reside inside the cylinder which folds during declination. Rotational joints at each end of the cylinder allows the rotational movement of the cab (x- and y-axis).

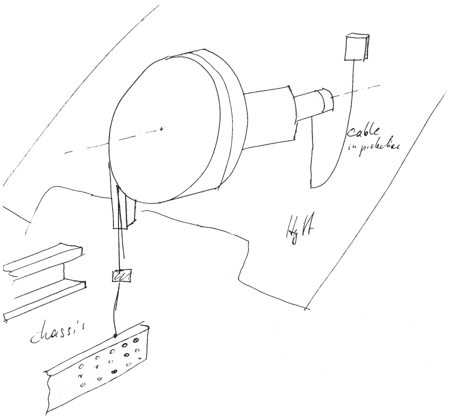


Figure 4.14: Double Reel

Double Reel: The Double Reel rolls up the entire necessary overlength of the cable large cable reel. It has a reel with a smaller diameter attached to its back which is facing the cab. On the smaller reel, less cable length is rolled up and thus the cabling can hang down in a closed compartment at the back of the cab when unreeled. To save the cable from forces an unspecified cable carrier is used to accept all the pulling forces.

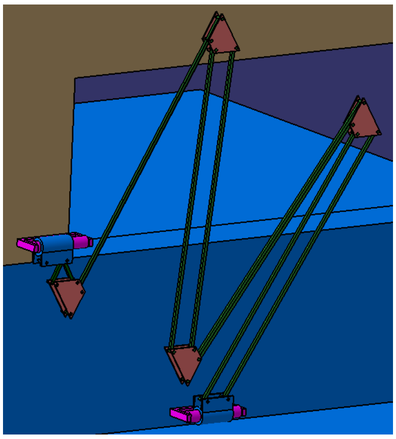


Figure 4.15: Lampy

Lampy: The mechanism of a balanced lamp is used to provide a foldable, force-free linkage between the chassis and the cab. The arms are surrounded by clothes to protect the linkage.

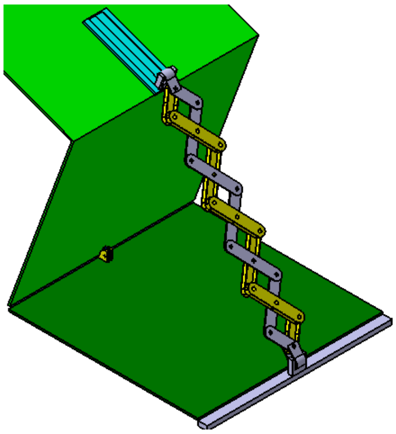


Figure 4.16: Scissor Lift

Scissor Lift: The cable resides inside a structure which unfolds through a pantograph mechanism. The mechanism folds in a zigzag pattern and the cables are folded together inside the pantograph. The cables are winded like in conventional scissor lifts, to increase the number of fixation points for the cables a channel is situated inside the double pantograph.

4.2.4 Concept Scoring

Concept Scoring was performed as recommended in Ulrich and Eppinger (2012). With weighted factors in accordance to their importance the concept scoring made a noticeable difference between the different Prolongable concepts. The winning concept was the **Scissor Lift**. This concept was further developed into **PseudoPanto**.

The positive ideas behind the losing concepts were not lost in either of the concept screening or scoring phases. By merging outstanding aspects of ideas from losing concepts with the winning concepts, valuable inspiration could be used in the concept development phase.

4.3 Prototyping

The development of the chosen concepts was carried out in two development loops. The first loop ended in the production of a physical real-size prototype. The chosen concepts thus had to be developed and prepared in CAD in the first loop to a certain level which allowed prototyping. Thus all joints and interfaces of the concepts had to be set in a way that ensured their functioning. Details such as chamfers or fillets could be omitted. Furthermore, manufacturing aspects were not in focus for the prototype development. The prototypes were tested on a full-size cab-chassis rig. Analysis of the test results revealed design weaknesses which initiated a re-design which ultimately led to the final concepts described in chapter 5.

4.3.1 Prototype Manufacturing

In total there were two prototypes produced, one for each chosen concept. Some finishing work of the prototypes was necessary in order for them to function properly because the SLS process added more material than specified. Mostly the work consisted of grinding, drilling, threading holes and colouring parts. The necessary manual work on the prototypes showed clearly the importance of tolerances for certain parts. Subsequently, the design was adapted to incorporate fewer area contact interfaces and thus fewer specified tolerances.

4.3.2 Assembly

The authors assembled the manufactured prototype together with standard parts such as washers and screws into full prototypes themselves. Through this process even more information regarding the construction was gained and at the same time the possibility of incorrect assembly was reduced. In certain cases the assembly process was observed to be tedious due to a considerable amount of repetitive operations where parts could easily be misplaced.

4.3.3 Prototype Testing

The actual testing was performed on a full-size cab-chassis rig inside a workshop. The physical verification of the critical Allow Tilting function was preferred over a computer simulated verification, due to lower time requirements and increased level of validity. Furthermore, the mounting position of the product on the cab and chassis was evaluated.

The test consisted of one tilting operation (locked position to tilted mode and back again) where the behaviour of the respective concept was observed. The level of deflections of certain parts was documented by notes, pictures and video recording. Subsequently, a damage assessment of the concepts was performed. The documentation of the prototype testing contributed considerably to the following re-design loops. The videos proved to be especially useful as they enabled reviewing of the test over and over again.

5

Final Concepts

This chapter describes the final concepts that have been developed in the course of this thesis. In summary the development has yielded a solution for the alternative harness route that routes the BB cables from the chassis to the bottom edge of the cab's back wall and along the cab floor where they are passed through into the cab. The new pass-through for the cabling may be easily accessed and offers furthermore the possibility to connect cabling from cab-fixed BB components on the cab directly to the new pass-through. The critical part of the route which needs to handle the tilting gap between the chassis and the cab's back wall is solved by two alternative solutions; a prolongation and a disconnection of the route.

In the following, first the concept which satisfies the function Provide Route is presented. Then, the two alternative concepts for the function Allow Tilting are presented, one for the prolongation approach called **PseudoPanto** and one for the disconnection approach called **Selfie**.

5.1 New Route and Pass-Through

This section describes the concept to solve the secondary main function Provide Route. Developing a solution for this function has not been the main focus of the thesis, however it was still done to be able to provide a holistic solution for the product. The development resulted in a new cab pass-through (CPT) and in a new component called Routeway. The final development stage for these parts is described here.

5.1.1 New CPT

The new CPT was designed after the current one which is in use in the front of the truck since its design seemed robust and well-proven. The placement for the new CPT was chosen to be on the right cab floor in the area underneath the passenger seat. The new CPT is composed of three main parts which can be seen in Figure 5.1:

- An inner part (purple) is in contact with the cab floor on the inside of the cab
- A middle part (beige) is in contact with the cab floor on the outside of the cab
- An outer part (dark brown) seals and protects the middle part and can easily be removed

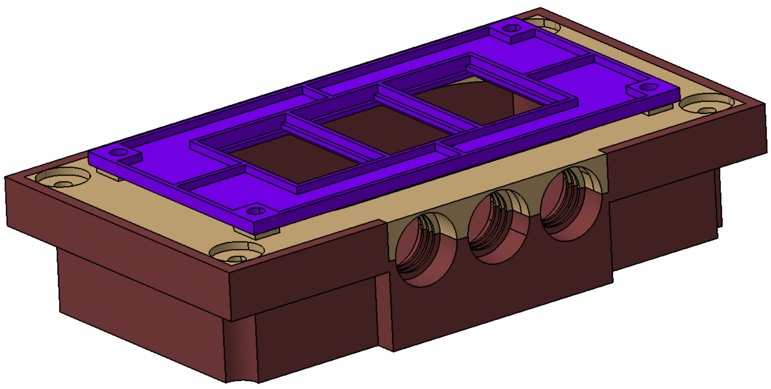


Figure 5.1: New CPT

The inner part has four holes in its corners which are used to fix it with screws through the cab floor to the middle part. Furthermore, the inner part features three rectangular holes where electrical connectors from both the inside and the outside route can be placed in.

The middle part provides holes for the fixture towards the inner part as well as for the fixture towards the outer part. The middle part also features the upper halves of three holes for corrugated hoses which should be used for harnessing the wires on the cab body.

The outer part seals the middle part by its geometry and tight fit towards it (see Figure 5.2). Furthermore, the outer part exhibits the lower halves of the three holes for corrugated hoses. Together with the middle part, a corrugated hose is clamped tightly in the holes which offer three sealing lips (see Figure 5.3).

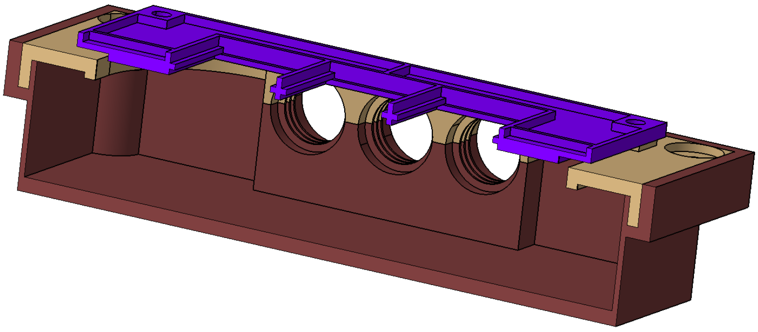


Figure 5.2: Cut through new CPT

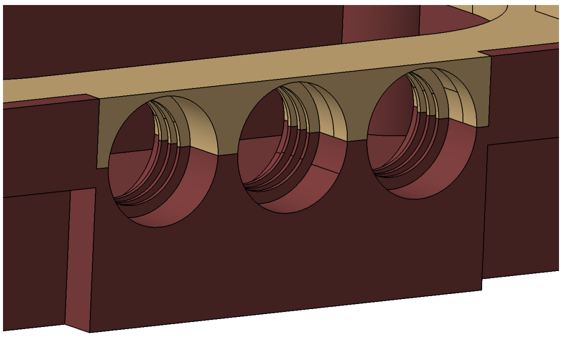


Figure 5.3: Holes for corrugated hose on the new CPT

The position of the new CPT was chosen to be on the cab floor because more space was seen to be available there than on the cab's back wall. On the back wall a lot of components and the envelope of the trailer sweep could interfere with the CPT. Furthermore, the CPT was seen to be more exposed to the environment on the back wall than in the sheltered space underneath the passenger seat. A further consideration was Volvo's fire safety requirements which demand that a specified fire of a certain component on the outside of the cab must not reach the inside of the cab after a specified amount of minutes (see Appendix A.1 for the requirements). The chosen position for the new CPT has the same requirements for fire safety as the current positioning. The cab's back wall has higher requirements in some parts which might be difficult to meet.

5.1.2 Routeway

The Routeway is placed underneath the cab floor and extends from the cab's back wall to the new CPT (see Figure 5.4). This concept embodies a different paradigm towards cable routing than the traditional one. It aims to create space for routing cables instead of routing cables where space is found. The Routeway consists of the following parts:

- A back fastener (dark brown)
- Four flat elements in connection to each other (yellow, pink and green)

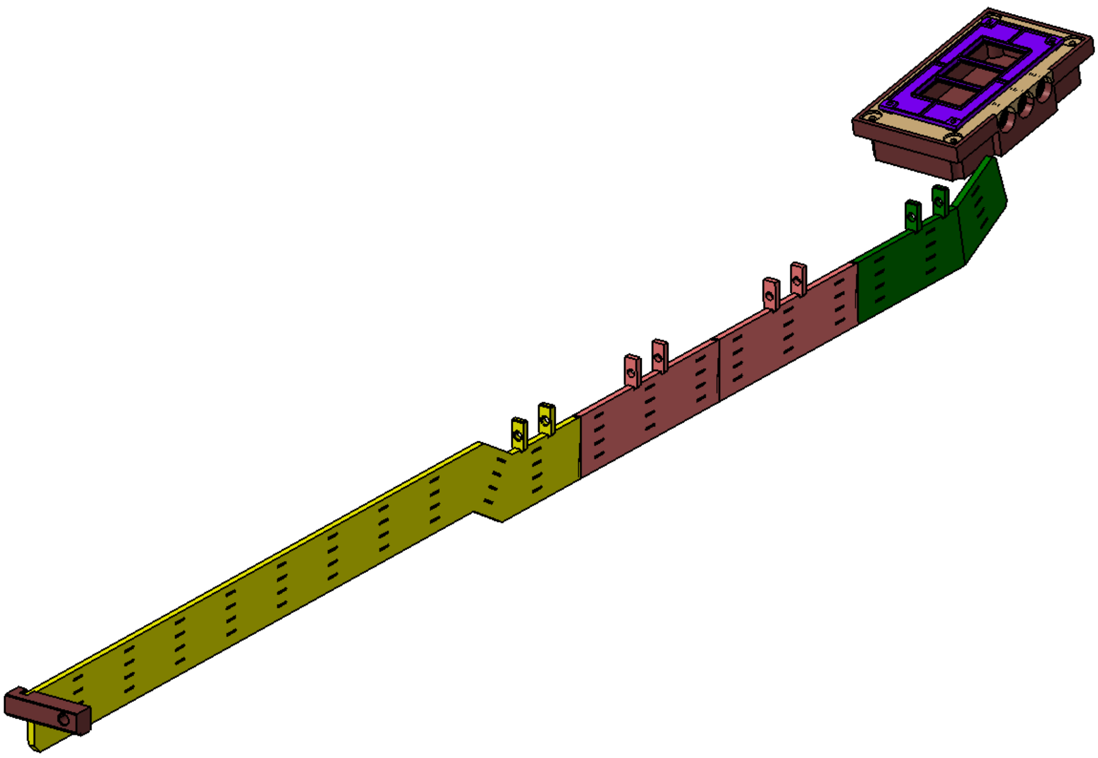


Figure 5.4

The back fastener rests on the bottom fold of the cab's back wall and can be fixed towards the wall by a screw through the fastener's hole. At its back the fastener features an opening where the first flat element of the Routeway can be hooked into (see Figure 5.5).

The flat elements consist of three different but similar parts; a large one in the back, two identical ones in the middle and a small one in the front towards the CPT. All flat elements have loop anchors attached to their tops which fit into the cross beams underneath the right cab floor. The cross beams have holes where the anchors can be bolted to. The flat elements are connected by simple sliding joints to each other (see

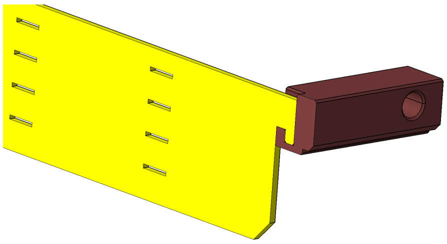


Figure 5.5: Back fastener of Routeway

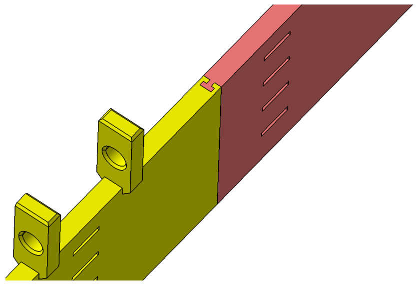


Figure 5.6: Joint between Routeway elements

Figure 5.6). All flat elements feature a raster of elongated slots which serve as mounting possibilities for cable straps which fix a harnessed route towards the Routeway. The large flat element in the back is curved to avoid clash with a storage box in this position. The small flat element in the front is slightly bent upwards to allow a smooth routing towards the entry holes of the new CPT. The middle elements are simple straight elements.

5.1.3 Further Development

Since the focus of the development was not put on the described parts, they need considerable improvement before they reach a mature state. The new CPT and Routeway are pure concepts which have not been prototyped or tested. The design of both needs further refinement before prototypes can be built.

The new CPT needs an adaptation of its surfaces towards the slightly bent surface of the cab floor, the current model only features straight lines and forms. To ensure good sealing also gaskets need to be chosen and integrated in the design. The material of the new CPT has not been chosen but can be assumed to be of the same type as the current CPT.

The Routeway needs evaluation on the possibility of downscaling it to absolute necessary dimensions. The distance between the fixture slots may also be readapted to reach an optimal design. Furthermore, it should be assessed whether physical connections between the single elements are needed or can be omitted. These measures should lead to material savings and a more minimalistic and cost effective design. The material itself needs to be chosen in a further step. Testing with prototypes should examine vibration behaviour of the entire structure during standard driving situations since high vibration amplitudes could damage the routed cabling.

5.2 PseudoPanto

This chapter describes the final development stage of the concept chosen under the prolongable approach, called PseudoPanto. After a description of the general idea a theoretical background about the working principle will be given first, followed by a detailed description of the different parts of the concept. Subsequently, insights from the prototyping and testing will be described and reasons for engineering changes that led to the final concept will be illuminated. Finally, an evaluation of possible material selection for the product will be given.

5.2.1 General Idea

The PseudoPanto builds on two general ideas. First, the idea of folding and unfolding a mechanical link between cab and chassis with the mechanics of a scissor lift, also called a pantograph. The main advantage of a pantograph is its ability to fold most of its maximum length from the extended state into its width in the folded state. The second idea is to harness wires inside a cable channel that protects it from the harsh environment at the back of a truck. The pantograph is used for the mechanical guiding of the prolongable structure. Its characteristics and prolongation movement are analysed in section 5.2.2. To the central axis of the pantograph, 9 cable channels are fixed, 7 long ones in the middle part and 2 short ones in the ends. The channels are fixed in the middle of their back wall rotationally free. The cable channels are meant to guide the wires in a zigzag form over the length of the prolongation. The cable channels are connected in their corners by hinges which restrict and guide the channels in their motion. Since the zigzag form of the cable channels resembles a half pantograph but does not fully behave like a pantograph, its motion can be seen as pseudo-pantographic from which the name of the concept derives.

5.2.2 Pantograph Analysis

The general properties of pantographs in use in this concept are analysed in this section. The pantographic structures are classified first to be able to describe them with a common vocabulary. Then, the kinematics of pantographic motions and the static forces in the structure are analysed. Finally, the necessary lengths of the structure are evaluated.

Classification

Pantographs have been categorised in this report to get an overview of the different variants. The ones treated here have been defined as symmetric pantographs. This means that all of the arms (rigid, smallest entities) of a pantograph have two rotational joints in their extremities and one rotational joint in the middle of the connection line between the joints in the extremities (see Figure 5.7).

A pantographic structure consists of a multiple of single pantographs. A pantograph consists of a number of arms which are holding its structure together by being linked

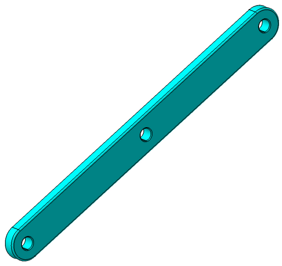
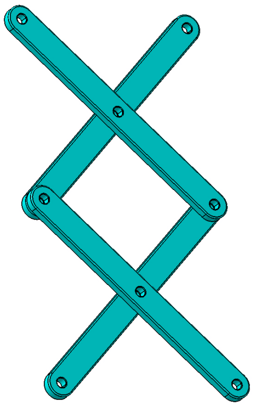
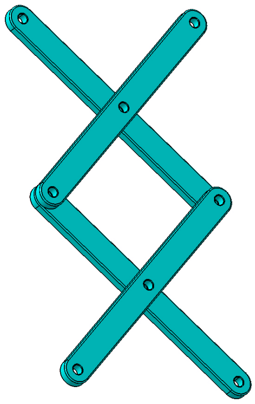


Figure 5.7: Symmetric pantograph arm



(a) Left-oriented pantograph



(b) Right-oriented pantograph

Figure 5.8: Chirality of pantographs

in all their rotational joints to form a repetitive scissor-like movement. Symmetric pantographs can be described by their basic elements since the whole pantograph is just a repetition of these basic elements. The basic element in the symmetric pantographs is the X-formation of two arms, called scissors in this report. If a single pantograph is put in a plane with its extension direction facing upwards (North) in the plane, then looking at a basic element in this position reveals the orientation of the scissors and thus the pantograph; if the arm which is lying upon the other arm is pointing to the upper left (North-West), the pantograph is called left-oriented (see Figure 5.8a). If the arm which is lying upon the other arm is pointing to the upper right (North-East), the pantograph is called right-oriented (see Figure 5.8b). Single pantographs are chiral figures, i.e. a left-oriented pantograph cannot be rotated or translated in any way to become a right-oriented pantograph without disassembling it. This is not true for the basic elements alone which can easily be rotated around their common joint in the middle to become a part of a left or right oriented pantograph.

A single pantograph can furthermore be distinguished into planar-scissor and offset-scissor pantographs. In a planar-scissor pantograph, the arms of the scissors touch each other during the pantographic movement (see Figure 5.9). One of the faces of each arm

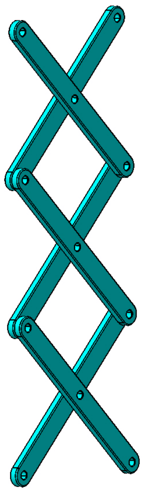


Figure 5.9: Planar scissor pantograph

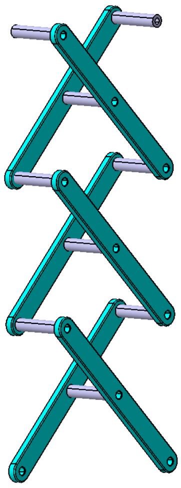
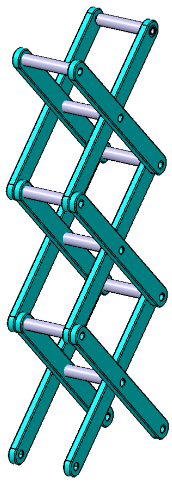
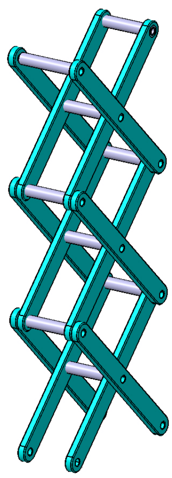


Figure 5.10: Offset scissor pantograph



(a) Homogeneous



(b) Heterogeneous

Figure 5.11: Double pantographs

thus moves in a common plane. An example for this would be an actual scissor which is used for cutting in daily use. In an offset scissor pantograph no faces of the pantograph arms touch each other as they are linked by bridges towards each other (see Figure 5.10).

Single pantographs can furthermore be combined to multiple pantographs. During this thesis only single and double pantographs were analysed. In a double pantograph two single pantographs are linked to each other in parallel with the same extension direction by distancing links (bridges) in at least two rotational joints on their middle axis. Depending on choosing either two pantographs with the same or a different orientation, the double pantographs are either called homogeneous or heterogeneous respectively (see

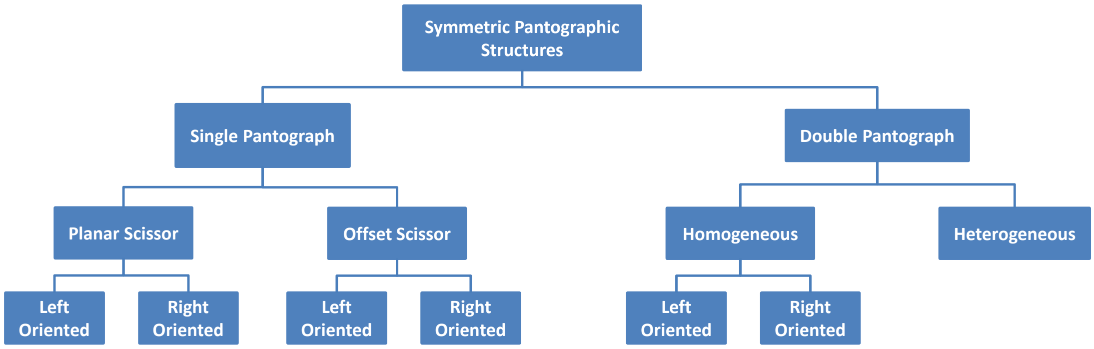


Figure 5.12: Classification of pantographs

Figure 5.11a and 5.11b). A comprehensive overview of the pantograph classification is given in Figure 5.12.

Motion

A simple analysis of the geometry of a single pantograph is conducted to show its prolongation properties. The schematic picture in Figure 5.13 of a part of a pantograph is used to analyse the geometric situation in the structure (used variables in Table 5.1).

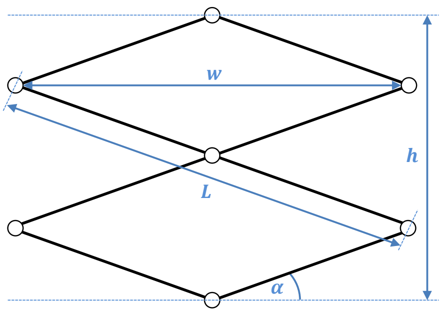


Figure 5.13: Geometrical situation in a pantograph

From Figure 5.13 it follows for a single scissor with two connected half-scissors:

$$h = L \sin \alpha + 2 \left(\frac{L}{2} \sin \alpha \right) \tag{5.1}$$

$$w = L \cos \alpha \tag{5.2}$$

Thus it follows for a pantograph with n scissors and two half-scissors in its ends:

$$h = (n + 1)\, L \sin \alpha \tag{5.3}$$

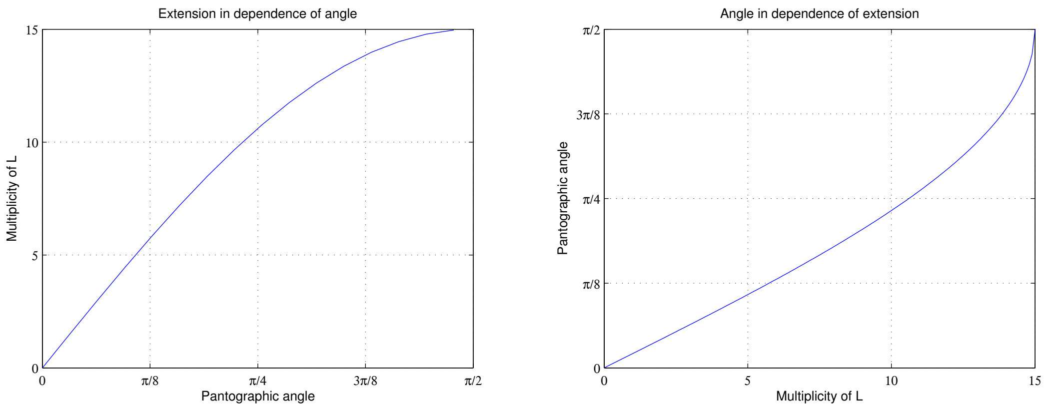
$$w = L \cos \alpha \tag{5.4}$$

$$\alpha = \arcsin \left(\frac{h}{(n + 1)\, L} \right) \tag{5.5}$$

Table 5.1: Variables used for the motion analysis

Variable	Description
L	Main pantograph arm length
h	Height in the pantograph's extension direction
α	Pantographic angle
n	Number of basic elements (scissors)
w	Width of the pantograph

The relationships show that if the pantographic angle grows with constant angular speed, the height of the pantograph first grows quickly and then the extension speed decelerates due to the sinusoidal condition. The pantographic angle in dependence of the extension h first grows with moderate speed and then grows with an accelerating rate towards the end of the extension. The behaviour can be seen in Figure 5.14a and 5.14b where the extension is manifested by multiples of the arm length L.



(a) Extension in dependence of angle **(b)** Angle in dependence of extension

Figure 5.14: Pantograph geometry analysis

Forces

As the pantograph is intended to be a free moving structure without large forces applied, the following force analysis is kept simple. According to a likely scenario, the following load case was chosen; the pantograph is fixed in its ends between two points which allow rotation. On each crossing (middle of the scissors) on the pantograph, a force H is applied (see Figure 5.15). Equilibrium on a pantograph with n scissors leads to:

$$2F - nH = 0 \tag{5.6}$$

$$F = \frac{nH}{2} \tag{5.7}$$

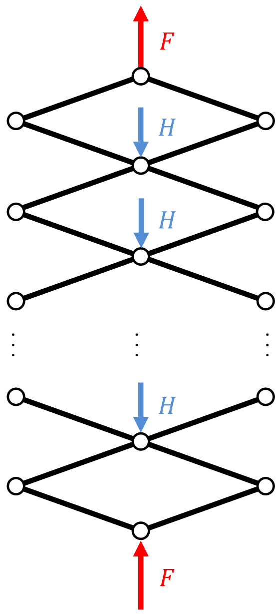


Figure 5.15: Load case of the pantograph

To analyse the crossing arm structure of the pantograph, the structure is cut free in its single arms. To analyse the forces in the joints it is sufficient to look on one half of the scissors due to the inherent symmetry of symmetric pantographs and the symmetric load case. Thus only one free-cut half of the pantograph is analysed. The half will be called a "zig-zag" structure. In this structure it is also sufficient to look at one "zig" (arm extending from top left to bottom right) and one "zag" (arm extending from top right to bottom left) to receive the relationships inside the whole structure as it consists of a repetitive pattern. In the following a zig-arm and a zag-arm are analysed and the general equations derived. The used variables can be seen in Table 5.2.

Table 5.2: Variables used for the force analysis

Variable	**Description**
H	External load on each crossing
F	Reaction force in ends
S	Reaction force in external joints
R	Reaction force in crossing joints
n	number of scissors
i	Index of analysed joint, running top-down

Equilibrium equations (see Appendix C.2) on a free-cut **zig**-arm lead to:

$$R_{xi} = \frac{H}{2\tan\alpha} - 2S_{xi} - \frac{2S_{y_i}}{\tan\alpha} \tag{5.8}$$

$$S_{y_{i+1}} = \frac{H}{2} - S_{y_i} \tag{5.9}$$

$$S_{xi+1} = S_{xi} + \frac{2S_{y_i}}{\tan\alpha} - \frac{H}{2\tan\alpha} \tag{5.10}$$

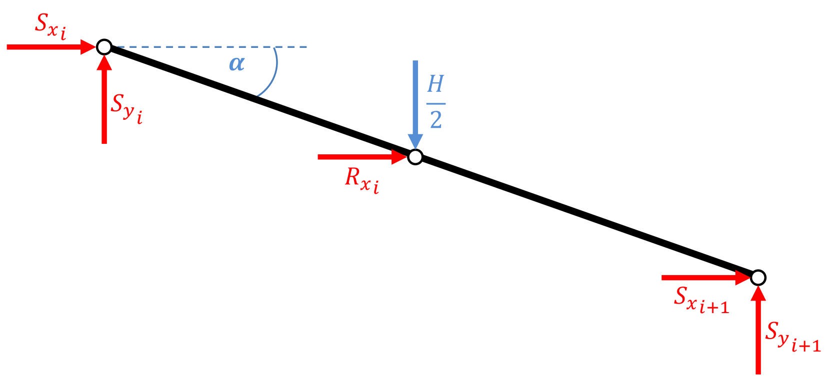


Figure 5.16: Zig-Arm

Equilibrium equations (see Appendix C.2) on a free-cut **zag**-arm lead to:

$$R_{xi} = \frac{H}{2\tan\alpha} - 2S_{xi} + \frac{2S_{y_i}}{\tan\alpha} \tag{5.11}$$

$$S_{y_{i+1}} = -\frac{H}{2} - S_{y_i} \tag{5.12}$$

$$S_{xi+1} = S_{xi} - \frac{2S_{y_i}}{\tan\alpha} - \frac{H}{2\tan\alpha} \tag{5.13}$$

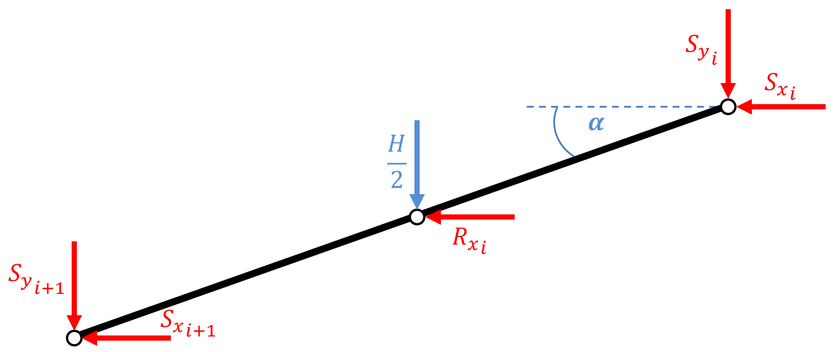


Figure 5.17: Zag-Arm

The pantograph taken in this example also has a top and a bottom, both resembling half-scissors which are like scissors that end in their common joint. This makes mounting easier. The static conditions of the top and bottom half-scissors can be derived (see Appendix C.2) according to Figure 5.18 as:

$$S_{x1} = \frac{F}{2\tan\alpha} \tag{5.14}$$

$$S_{y1} = \frac{F}{2} \tag{5.15}$$

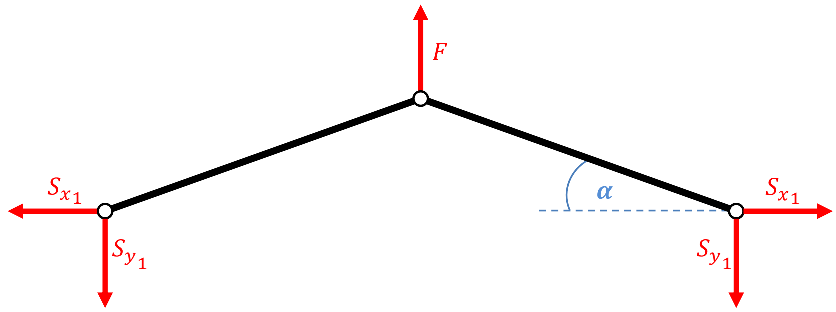


Figure 5.18: First arm pair

A numerical analysis of all the motion equations was conducted with MATLAB. The output of the analysis can be seen in Appendix C.3. The analysis showed that forces in the joints increased the further they were situated from the ends of the pantograph. Thus they were greatest in the middle of the structure. Furthermore, the reaction forces in the crossing joints were seen to be generally higher than the reaction forces in the external joints, which could be expected already from the equilibrium equations. From the analysis it could be seen that the reaction forces in the crossings reach a maximum of 100 times the induced load H at an pantographic angle of 20°. A generic picture of the force distribution can be seen in Figure 5.19. The crossing joint in the middle of the pantograph will thus guide the design for the other joints. Looking at the total pantographic structure, the joint reaction forces showed symmetry around an axis in the middle of the pantograph, parallel to the set truck Y-axis. This could be expected due to the symmetric properties of the pantograph and due to the symmetry in the load case.

It was also observed that the forces in the joints do not depend on the arm length of the pantograph. They solely depend on the number of crossings and the current pantographic angle. Forces can reach extreme values when the pantographic angle approaches zero. Such low or high values near 90° will though never be reached due to the thickness of the pantograph arms. The thicker the arms the smaller the sector the pantographic angle can be in.

To exemplify a load case, the MATLAB programme was run assuming 14 crossings. The crossing load was assumed to be 1. Due to the linearity in the equations regarding the

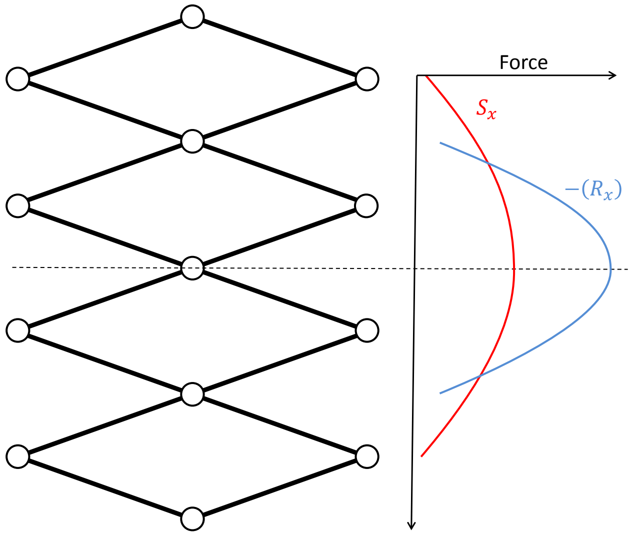


Figure 5.19: Force distribution on a generic pantograph

crossing load H, the resulting forces in the analysis can be seen as a multiplicity of H. Thus, resulting loads can easily be scaled up by multiplying with the actual load value for H.

Length Analysis

To analyse the minimum needed length for a pantograph to bridge the tilting gap, a simplified model of the target truck was created in the CAD software Catia V5 to reproduce a tilted position of the truck. The model can be seen in Figure 5.20. The measures for the model were taken from Volvo's actual Catia model of the target truck which had exact specifications. The main focus in the simplified model was put on the measures between the centre of rotation during tilting and the back of the cab to achieve a rather exact representation of the tilting operation. On the simplified model a tilt angle of 70° was adjusted. The cab lock was taken as a bottom connection point for the bracket holding the bottom of the pantograph (see section 5.2.5). The bracket moves the bottom of the pantograph a certain distance away from the back of the cab in the truck's X-direction. The bottom edge of the back of the cab was taken as the top connection point for the structure which holds the top of the pantograph in the tilted position. The top structure also moves the top of the pantograph a bit away from the back wall and the bottom edge of the back wall. A straight line between the set top and bottom could be placed and measured to receive a geometrical minimum length. The top and bottom of the pantograph in the model could also be varied to test different designs and to see when clashes would occur.

The resulted geometrical length for the chosen design was $L_{\text{min,geom}} = 2578\,\text{mm}$. Additionally, one should bear in mind that the cab overshoots the tilting angle after incli-

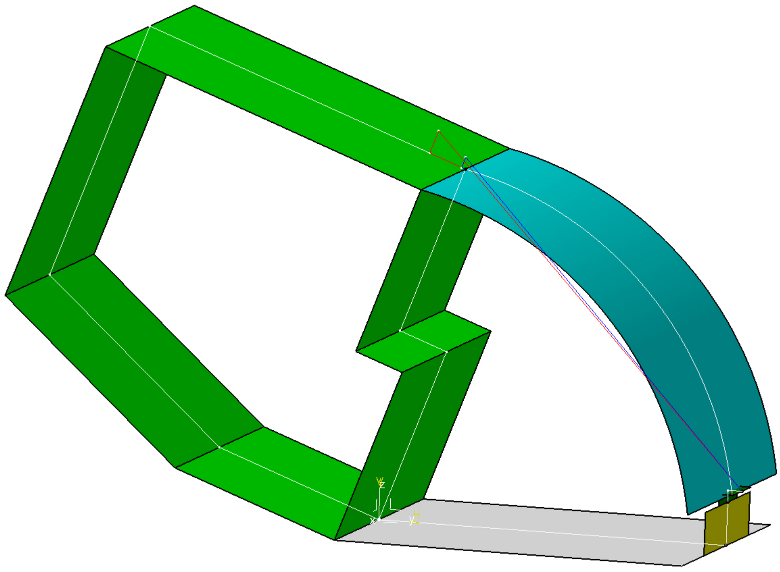


Figure 5.20: Tilting model in Catia

nation since it falls freely into the final position and then swings up and down due to elasticity. Overshooting can be considered by adding 10% to the minimum geometrical length, which results in $L_{\mathrm{min}} = 2846\,\mathrm{mm}$.

For a robust design of the pantograph, its maximum extended length should be more than the calculated value. The more excess length the pantograph has the less the probability that it reaches a self-locking state where the attempt of folding it may lead to a bending of the whole structure due to friction in the joints. A fully extended state of the pantograph should in any case be avoided.

5.2.3 Guiding Pantograph

In the PseudoPanto a symmetric, double, homogeneous, right-oriented, planar-scissor pantograph (see section 5.2.2 for clarification) was chosen to fulfil the function of folding and unfolding the mechanical link of the prolongable solution (see Figure 5.21). The orientation and homogeneity were chosen arbitrarily since their choice did not seem to matter for the result. This structure was seen as an effective way of folding the needed prolongation during the tilting process, since the pantograph is able to fold most if its maximum length into its width. The double pantograph was furthermore assumed to be a stable structure that could give good guidance to a cable route. In the following sections the guiding pantograph and its parts are described in detail.

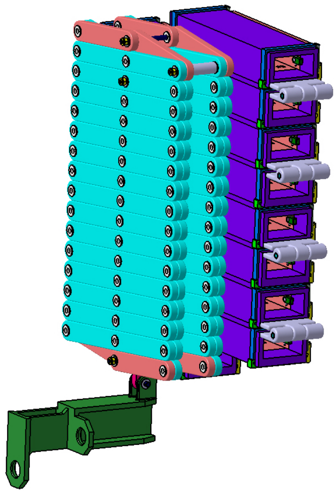


Figure 5.21: PseudoPanto with guiding pantograph (turquoise)

Bending Analysis

Since bending will be the major load case and possible source for incorrect folding during tilting, the guiding pantograph with final specifications is analysed for bending in its main bending plane in this section. The used variables can be seen in Table 5.3.

Since a double pantograph is a highly entangled structure of a certain number of identical elements that are linked to each other, certain simplifications were undertaken to facilitate the bending calculation. Optimally a finite element analysis could have been performed to reach good results, since the pantograph itself already resembles a finite element structure with the arms as elements. This analysis was omitted due to time restrictions. To calculate the bending, the worst case was assumed which would be the total extended state of the pantograph. In this state the structure resembles two parallel beams that are rigidly connection to each other (see Figure 5.22). Thus the following simplifications of the double pantograph were made:

- The extended double pantograph is simplified by two parallel beams with the neutral axis in the middle between the two beams
- The cross-sectional dimensions of each of these beams is set to the cross-sectional dimensions of two arms inside the pantograph
- The length in the bending case is set to the minimum length L_{min}, calculated in section 5.2.2

The second moment of area I_1 of one of the assumed beams (see Figure 5.23) around the axis through its centre of gravity is calculated as in Den Hartog (1977) to:

$$I_1 = \frac{b\,h^3}{12} \tag{5.16}$$

To calculate the second moment of area I_{tot} of the entire assumed cross-section around its neutral axis, the parallel axis theorem is applied to translate the moment of area of the single cross-sections as described in Den Hartog (1977):

$$A_1 = b\,h \tag{5.17}$$

$$I_{\text{tot}} = 2\left[I_1 + A_1\left(D + \frac{h}{2}\right)^2\right] \tag{5.18}$$

$$I_{\text{tot}} = 2\left[\frac{b\,h^3}{12} + b\,h\left(D + \frac{h}{2}\right)^2\right] \tag{5.19}$$

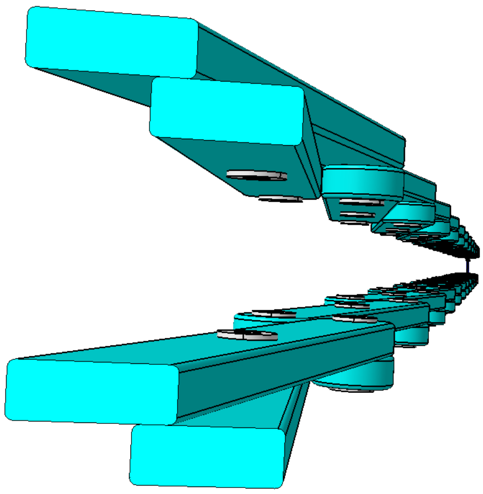


Figure 5.22: Cut of extended guiding pantograph without interlinks

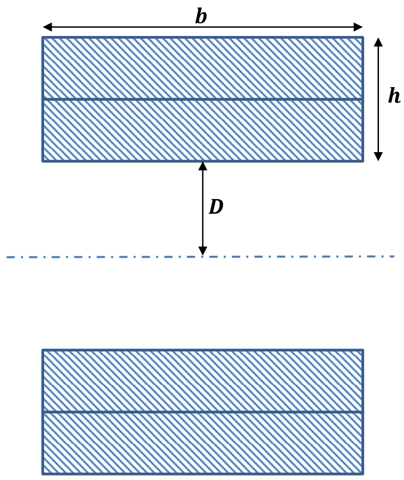


Figure 5.23: Simplified cross-section of the guiding pantograph

To calculate the deflection δ in the middle of the structure, a single force P in the middle is assumed that consists of the assumed structure's weight plus an extra assumed load of 50 N which resembles cable load and weight of other components:

$$P = 2\,L\,A_1\,\rho\,g + 50\,\text{N} \tag{5.20}$$

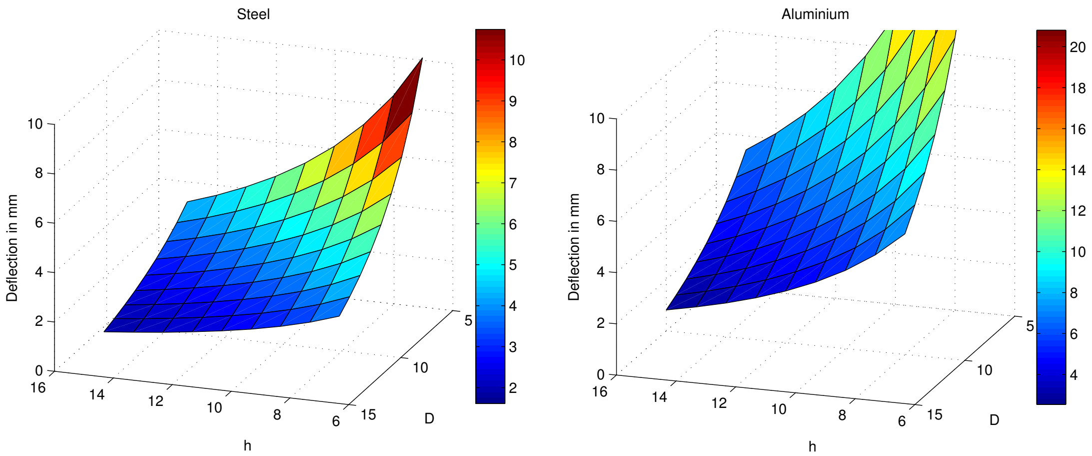
The force P is used to calculate the deflection in the middle as shown for a simple beam on two supports with a single central load in Den Hartog (1977):

$$\delta\,(x)\Big|_{x=\frac{L}{2}} = \frac{P\,L^3}{48\,E\,I_{\text{tot}}} \tag{5.21}$$

The deflection in the middle was calculated with varying h and D for two different materials (steel and aluminium) as an example. The length was set to 2943 mm. The resulting deflections can be seen in Figure 5.24.

Table 5.3: Variables used for the bending analysis

Variable	Description
b	Width of a pantograph arm
h	Height of two pantograph arms
A_1	Cross-section of two pantograph arms
$2\,D$	Distance between two facing pantograph arms
I_1	Second moment of area of the cross-section A_1
I_{tot}	Second moment of area of the total cross-section
L	Length of structure
ρ	Density of material
g	Acceleration of gravity
P	Force of bending in the middle
$\delta\,(x)$	Deflection at position x from structure's end
E	Young's modulus



(a) For steel **(b)** For aluminium

Figure 5.24: Deflection in dependence of D and h of the guiding pantograph

Pantograph Arms

The arms of the pantograph were chosen to be as thin as possible to avoid growing of the structure in the X-direction of the truck and thus interference with the trailer sweep. The cross-section and the geometry were kept rectangular and thus simple to be able to keep production low-cost. The width of the arms was kept as small as possible to achieve a minimal total height of the pantograph when folded. The arm length was set to be able

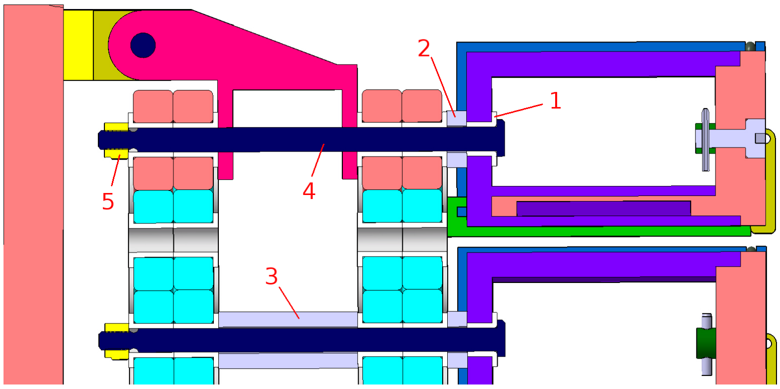


Figure 5.25: Cut of guiding pantograph: 1 bushings, 2 & 3 distancers, 4 bolts, 5 nuts

to provide the total necessary prolongation length without unfolding the pantograph to its maximum extension length. The maximum extension length was avoided since it was considered instable and a probable hinder for folding if friction was considered and because overshooting of the cab after reaching the tilted position had to be assumed. The length of the arms was also restricted by components near the placing of the pantograph which should not be touched during the entire tilting operation. To decide on the total number of arms, considerations concerning the cable channels (see section 5.2.4) were integrated.

Pantograph Joints

The pantograph arms are linked by simple screws or bolts with lock nuts and distance sleeves. The bolts where chosen to be of gauge 5 mm in diameter. The two pantographs are held on distance by the distance sleeves on the bolt. The lock nuts provide a certain force for compression between the arms and the two pantographs so they sit tightly. The compression must not be too high in order to make sliding between the arms possible without any significant resistance.

To allow good gliding of the joints, the bolts are running inside polyamide bushings which are placed inside holes in the pantograph arms. The polyamide bushings thus serve as bearings. In a joint between two arms, one bushing is placed so the faces of two pantograph arms can touch each other to improve bending behaviour in the extended position (explanation is given in section 5.2.7). The flange of the bushings serves as a support for the lock nuts on the outside of the pantograph in the back and as a support for the distance sleeves between the pantographs and between the front pantograph and the cable channel. The assembly of the guiding pantograph can be seen in Figure 5.25.

5.2.4 Cable Channel Pantograph

To guide the cabling on the guiding pantograph, cable channels (see Figure 5.26) are used. The cable channels are mounted on the pantograph in the geometrical centre of gravity of their back wall. The channels are connected by special hinges which link the movements of the channels together. The cable channels fold and unfold in a zigzag in a pseudo-pantographic manner, i.e. their movement is kinematically linked to the actual pantograph. Thus the cable channels fold just like a pantograph but geometrically they are not a pantograph.

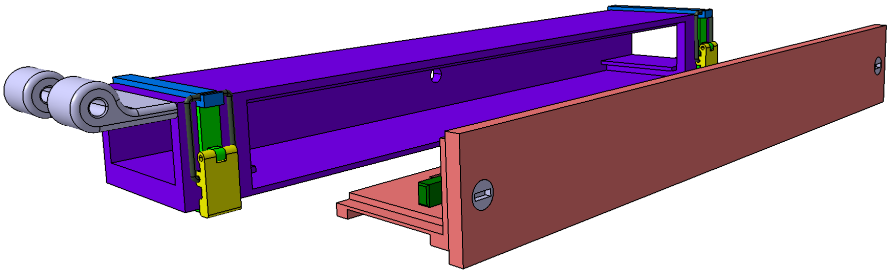


Figure 5.26: Normal size cable channel with retracted drawer

The kinematics of the linked cable channels build on the observation that a pantograph which is an integer multiple in size of a second pantograph geometrically shares certain common intersections of the scissors with the second pantograph, i.e. if the first pantograph is n times larger than the second, the second pantograph shares each n-th scissor crossing with the larger pantograph. These common intersections find themselves always in the same positions towards each other, independent of the current pantographic angle and thus extension. This principle can be seen in Figure 5.27.

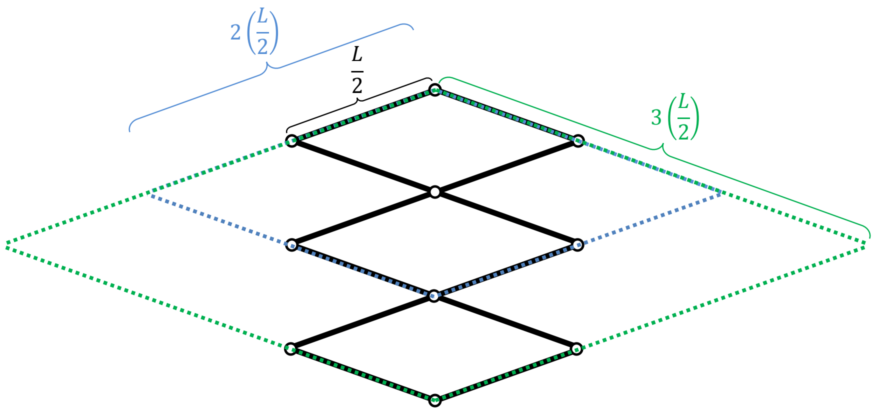


Figure 5.27: Relationship between pantographs of integer multiple size

In the PseudoPanto this fact is used by designing the cable channels a factor of 2 longer than the arms of the guiding pantograph. The cable channels are thus connected in their middles to each second scissor on the behind pantograph (see Figure 5.28). As the guiding pantograph ends in single joints, i.e. the ends of the pantograph are comprised of half-length arms, smaller cable channels are connected to the end joints. Together with the design of the hinges that connect all channels and just leave rotation around the hinges' axis free, the zigzag structure of the cable channels becomes kinematically linked towards the guiding pantograph if weight is ignored. The movement of the guiding pantograph thus determines the movement of the cable channel, which is desirable to be able to predict the motion. The cable channels consist of three main parts which are described in the following sections.

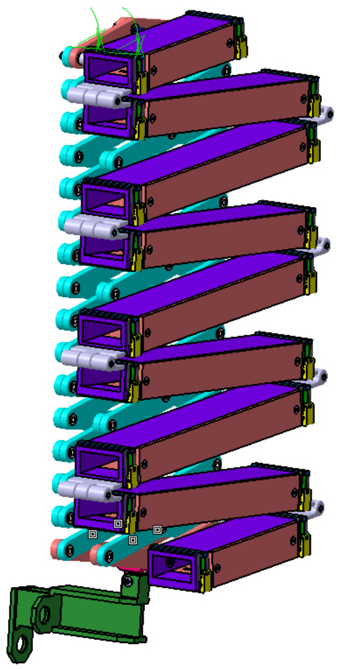


Figure 5.28: Cable channel pantograph on the guiding pantograph

Cable Channel

There are two types of cable channels, the normal ones and the shorter ones for the ends. Their design is almost the same and can be exemplified by looking at the normal ones first and then pointing out the differences of the smaller ones.

The cable channels are fixed rotationally free towards the guiding pantograph. It has a hole in the geometrical centre of the its plane facing the pantograph in which another polyamide bushing is inserted like in the joints of the pantograph arms. In the small channels this hole is located close to the end of the channel (Figure 5.29). The hole and the bushing are aligned with the crossing joint of the scissor behind it and are connected by one and the same bolt and lock nut. To keep a certain distance between the back wall of the main channel and the pantograph arms and to keep contact pressure, a distance sleeve is used.

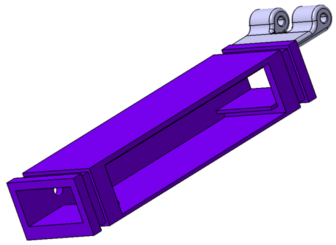
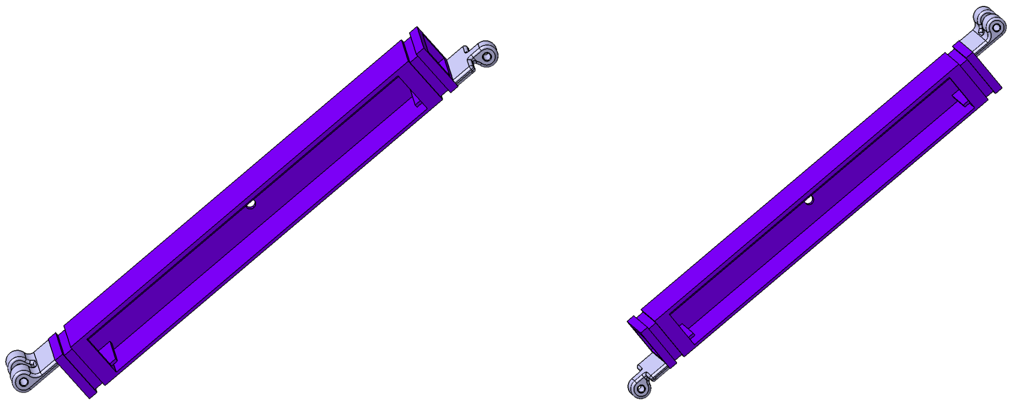


Figure 5.29: Small cable channel

At their ends, the large channels have two disparate hinges. The hinges are located in the upper or lower diagonal corners of the channel. Since a large channel is always linked to a channel above and below itself, there are two variants of the placing of the hinges, i.e. either top-right with bottom-left or top-left with bottom-right (see Figure 5.30a and 5.30b). The small cable channels only have one hinge which is connected to a large channel. The hinges are designed so that in the folded position the cable channels all lie parallel to each other with 5 mm space between them (see Figure 5.31). The front of the channels has a cut-out to insert the drawers that are described later.



(a) Form A **(b)** Form B

Figure 5.30: Normal size cable channels

To choose an adequate length of the cable channels and the pantograph arms accordingly, a desired total length of all channels was set to 2900 mm. The folded cable channel pantograph could be seen as a structure of rows which are comprised of a cable channel's height and the vertical distance to the next channel (see Figure 5.31). In the chosen design this row height is 40 mm. The structure is one cable channel wide in folded position. It has to be considered that the two small channels together stand for one channel when

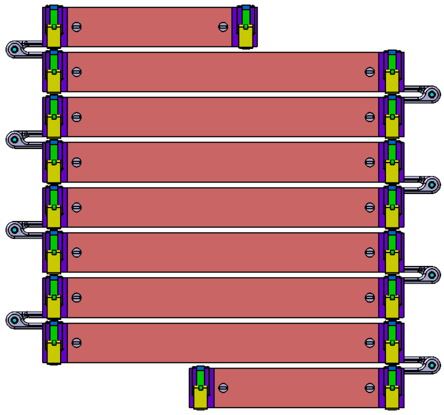


Figure 5.31: Folded cable channel pantograph with parallel channels

looking at the length, but they must be seen as two channel rows when looking at the height since they are not located in the same plane.

The maximum space available on the back wall of the cab in Z-direction of the truck was measured to be 405 mm. The maximum number of channel rows thus becomes:

$$\frac{405\,\text{mm}}{40\,\text{mm}} = 10{,}1$$

This means that 10 channel rows can be used at maximum. This means that 9 channel lengths is the maximum, which leads to 10 channel rows as explained above. The resulting arm length would be:

$$\frac{2900\,\text{mm}}{9} = 322{,}2\,\text{mm}$$

The maximum space available in the width (Y-direction of the truck) is restricted by a component behind the cab back wall called trailer arch. With leaving some extra space of 11 mm to the trailer arch, the channel length may be 430 mm at maximum. The number of necessary channels thus becomes:

$$\frac{2900\,\text{mm}}{430\,\text{mm}} = 6{,}7$$

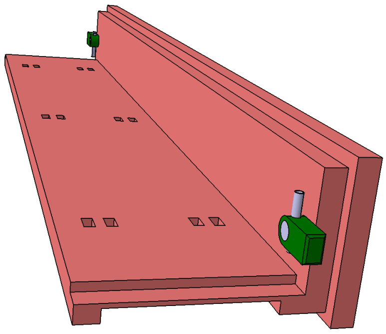
7 channels lengths must thus be used under these conditions, which leads to 8 channel rows in height. To keep away from these extremes the design was set to 8 channel lengths which means 9 channel rows in height. In this case not too much space in the Y-direction is used which means a safe distance from components like the trailer arch. Also, the total height is not too large which means fewer possibilities to clash with components on the back of the cab. With 8 channel lengths the arm length must be at least:

$$\frac{2900\,\text{mm}}{8} = 363\,\text{mm}$$

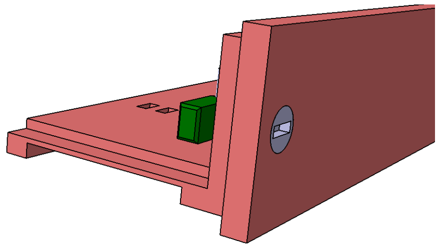
The arm length was chosen to be 370 mm to be able to compensate for not totally stretched arms in the final position.

Drawer

The drawer is an insert that is put inside the predefined slot in the cable channel. It can be taken out for mounting wires inside the cable channel. The insert incorporates slots in its bottom which allow fixing of the routed wires with cable ties to the bottom. Furthermore, slots along the insert's contacting surface provide a possibility for better sealing. There are two different drawers, one for the big and one for the small cable channels. Their design is alike and can be seen in Figure 5.32.



(a) Normal size



(b) Locking mechanism on drawers

Figure 5.32: Cable channel drawer

To prevent unwanted opening of the drawers under driving they are equipped with a simple locking mechanism on both of their ends. A pin with a slot for a screwdriver can be operated from the outside to rotate the attached locking pin to a closed or open position (see Figure 5.32).

Edge Protection

The transitions from one cable channel to the other are the exposed parts of a cable route on the product. Since these edges bend a lot during the pantographic motion they have to be protected by a flexible layer that keeps away water and dirt. The exact material for this purpose was not chosen during this project. Ideally it is a fabric that is impenetrable by water and other liquids and endures rough environments. It should also be able to be glued to rigid bodies.

To tightly fit such a fabric over the edge of the cable channels, a simple clamping mechanism (see Figure 5.33) was developed. The tightening bars of the clamp form a rectangle which fits in prepared grooves on the cable channel. The chosen fabric should be glued with sealing glue inside these grooves. Then the clamp is put in the grooves as well with the fabric between the clamp and the channel. The clamp has a simple lever like on old jam jars which is pushed down into a locked position and thereby pulls a metal shackle which clamps the whole structure together.

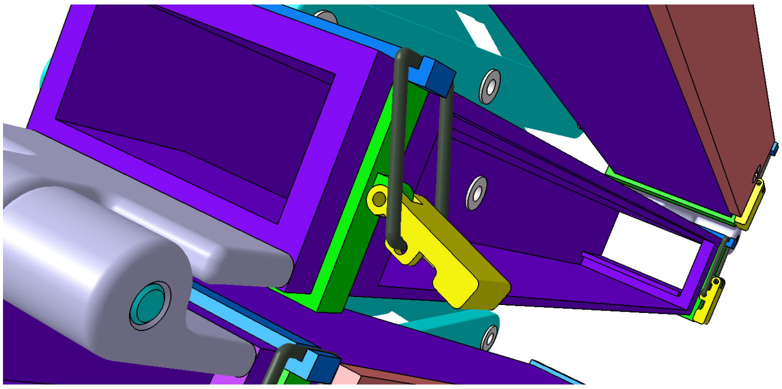


Figure 5.33: Opened clamping mechanism on the cable channel

5.2.5 Bottom Support

For the positioning on the bottom it was chosen to take the right cab lock as a connection point. The right side offered the most space on the target truck and furthermore the air intake posed an obstruction on the left side. The cab lock was chosen as the preferred positioning because it does not execute any relative motion towards the cab in the locked position under driving. This leads to less movement of the whole product and thus the cabling under driving. Relative movement only arises below the cab lock where the suspension system is located.

The guiding pantograph is fixed with a rotational joint to a bracket which acts as a support for the pantograph on the chassis. The bracket consists of an arm and an angle which has two holes. The angle is adapted to the geometry of the cab lock and the two holes are the interface for the two cab lock bolts. The bolts can be removed and reinserted in the cab lock with the bracket between them. The bracket is designed for stiffness to be able to always hold the PseudoPanto in the same bottom position.

The end of the bracket's arm is connected to a fork which is linked to the bottom tip of the guiding pantograph. This fork is rotationally free around the Y-axis in a 90° sector towards the back of the cab (see Figure 5.34).

The bottom support positions the bottom point of the guiding pantograph. The positioning of the bottom point is almost in the middle of the cab lock in Y-direction, a certain length away from the back wall of the cab in the X-direction and approximately in flush with the top of the cab lock in Z-direction to avoid clashes under the tilting process.

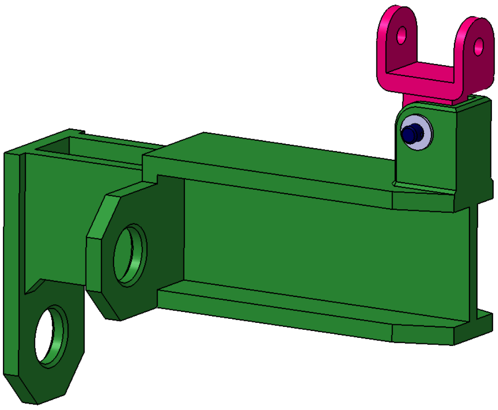


Figure 5.34: Bottom support

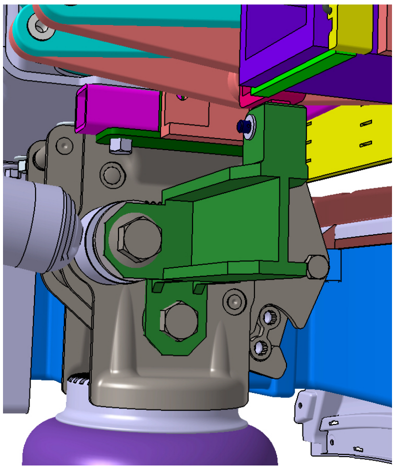


Figure 5.35: Mounted bottom support

5.2.6 Top Support

To connect the top of the pantograph to the cab, the problem of the pantograph's height in folded position had to be overcome. When folded and fixed to the bottom connection, the pantograph's top still resides above the cab's back corner in substantial distance. Since unfolding and remaining with this overlap would result in a clash between the cab's back edge and the pantograph before reaching the tilted position, a solution for moving the pantograph's top towards the cab's back edge under tilting had to be found.

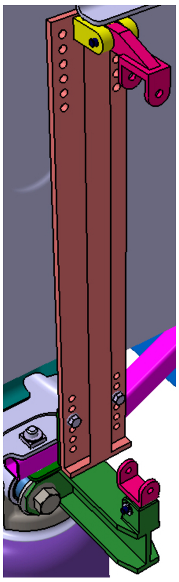


Figure 5.36: Swallowtail interface without pantograph

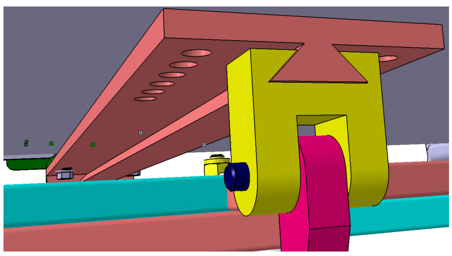
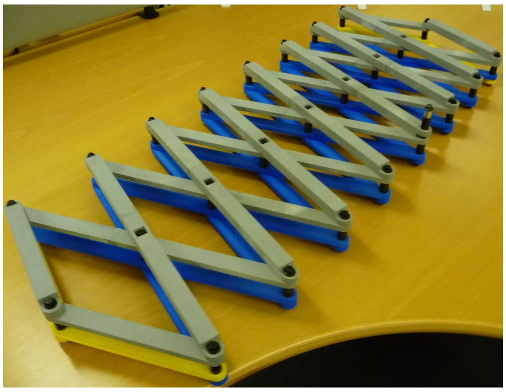


Figure 5.37: Swallowtail interface with pantograph

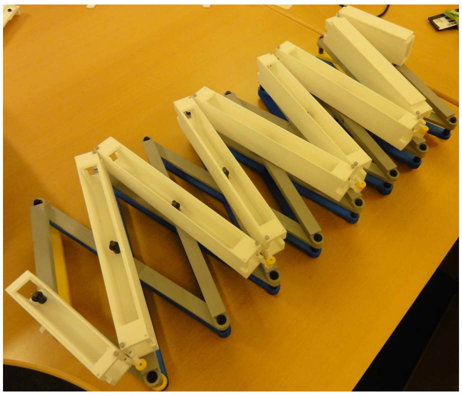
This difficulty was overcome by a simple sliding rail with a swallowtail interface (see Figure 5.36); by using a vertical rail mounted on the back of the cab (see Figure 5.37), the connection point of the pantograph automatically moves to the cab's back edge under inclination. When reclining the cab, the connection point moves upwards on the rail until the locked position is reached again. The rail can be mounted on the back of the cab with screws and a bracket on its bottom that also fixes it towards the right main cab beam.

5.2.7 Prototype Testing

Before development could proceed to DL2, a full, real-size prototype from DL1 (parts visible in Figure 5.38) had been created and tested. Certain design decisions were taken after the testing which highlighted design flaws. In this section the insights from prototyping and testing are described and the design changes explained and justified.



(a) Guiding Pantograph

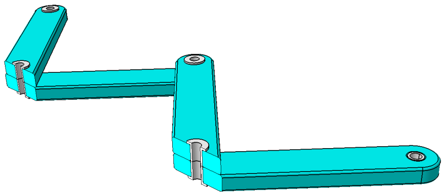


(b) Cable Channels mounted

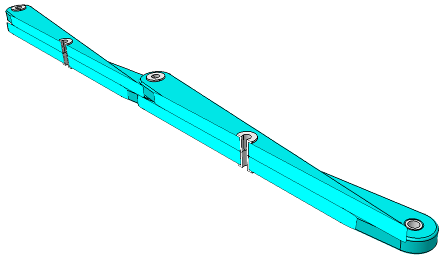
Figure 5.38: PseudoPanto Prototype

Prototypes Insights

By testing the movement of a single pantograph it could be seen that if the pantograph arms consisted of planar scissors, i.e. two arms of a scissor touched each other on their facing planes during the movement, their bending deflection was improved. In a previous design the flanges of the polyamide bushings were meant to keep a distance between two facing pantograph arms. Removing this feature showed clearly less deflection under self-weight in the maximum extended and the maximum folded position. It is assumed that substantial shortening of the effective bending length for the cross section of a single arm in these positions is the reason for this behaviour (see Figure 5.39); if the faces of the arms can touch each other, they can also support each other. The greater the area of the one arm that is projected on the other, the higher the overall stiffness of the considered section. This will be called the **area support effect** in this report.



(a) Low effect



(b) High effect

Figure 5.39: Area support effect

Testing a single pantograph also showed that bending under self-weight in the extended state was so substantial that trying to push it back into the folded position only resulted in even more bending due to friction. On a reclining cab this would have inevitably led to plastic deformation and destruction.

Furthermore, the pantograph was seen to unfold first on its top when mounted on the truck. The lower scissors of the structure followed later. This behaviour can be explained by the elasticity in the structure, the non-perfect fit of the bolts in the holes of the pantograph arms and weight force pushing on the lower scissors. In some cases this even led to a negative pantographic angle of the bottom arms which could have damaged the structure if the extension was not reversed and the error fixed.

Mounting the prototype on the truck appeared to be easy. The stiffness of the bottom support was seen to not be sufficient though as substantial bending occurred already in the static locked position when mounted. It was concluded that the design of the bending cross-section of the bottom support was inadequate.

Adding Stiffness

The lack of stiffness in the prototype led to the conclusion to choose a double pantograph as the guiding mechanical structure. This increases stiffness of the structure but leads to larger outer dimensions of the product. Furthermore, the discovered area support effect was used in the current design by designing the pantograph arms to be parts of planar scissors.

Hinges

The new hinges build on the paradigm of linking the guiding pantograph kinematically to the cable channels as explained in section 5.2.4. The previous hinges allowed one more axis of rotation to be free, in parallel to the current. These hinges restricted the hinging angle between certain values though. This concept did not work as folding of the cable channels exposed a chaotic movement which was hard to predict.

Top Support

Two concepts were tested to act as a top support; the swallowtail rail as described in section 5.2.6 and an extender mechanism (see Figure 5.40). The extender should extend from a folded position by rotating around a fixed point on the cab under inclination. This rotation should lower the top point of the pantograph and prevent clash with the cab. This concept proved not to work as a folded position could not be sustained in the locked position. The swallowtail rail however proved to work perfectly under testing.

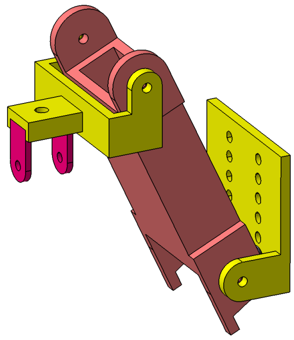


Figure 5.40: Discarded extender mechanism

5.2.8 Material Considerations

A simple analysis on material choice for most of the parts of the PseudoPanto was conducted with the help of the CES software. The material selection process followed Ashby (2011). The used variable can be seen in Table 5.6. Certain base requirements were set on all parts; low flammability and high durability in humid and wet environments.

Pantograph Arms

The arms of the double pantograph can be seen as beams loaded in bending with stiffness, length, width specified and height as a free parameter. This is a standard problem in Ashby (2011) and including costs this leads to the material index

$$M_1 = \frac{E^{\frac{1}{3}}}{C_m \rho} \tag{5.22}$$

Table 5.4 shows the results of the material selection in CES (see Appendix C.6).

Table 5.4: Material selection of the pantograph arms

Material	ρ	σ_f	C_m
Stainless steel austenitic, AISI205 wrought, annealed	7850 $\frac{\text{kg}}{\text{m}^3}$	425 MPa	11 - 12 $\frac{\text{SEK}}{\text{kg}}$

Bottom Support and Top Support

The material requirements for these components were seen to be alike; high stiffness and yield strength. As a secondary factor, cost was tried to be kept low. An analysis in the CES software led to the same material choice as for the pantograph arms above.

Cable Channels

The cable channel was seen to be an exposed structure that may had to tolerate sudden hits by other bodies, which requires low brittleness (high K_{1c}). Furthermore, it should not fail under static load (high σ_f). The analysis in CES (see Appendix C.6) yielded the following material recommendation in Table 5.5.

Table 5.5: Material selection of the cable channels

Material	ρ	σ_f	C_m	K_{1c}
Magnesium, commercial purity	1740 $\frac{kg}{m^3}$	65-100 MPa	21-23 $\frac{SEK}{kg}$	50-70 MPa $m^{\frac{1}{2}}$
Polyester SMC (25% glass fiber, self-extinguishing)	1750 $\frac{kg}{m^3}$	55-83 MPa	22-29 $\frac{SEK}{kg}$	15-37 MPa $m^{\frac{1}{2}}$

Table 5.6: Variables used in the material selection

Variable	**Description**
E	Young's modulus
C_m	Price per kg in SEK
ρ	Density
σ_f	Failure strength (yield, fracture)
K_{1c}	Fracture toughness

5.2.9 Summary & Further Development

A summary can be drawn in Table 5.7 which assumes PseudoPanto to be realised in the recommended materials. The summarised data is taken from the bill of materials see Appendix C.5).

Since the PseudoPanto has been created from scratch, it still needs further development with the input of specialists at Volvo to reach an adequate state of maturity. Certain details still need to be decided and further testing with prototypes in the target material is advised.

Table 5.7: Summary of PseudoPanto

Total number of parts	547
Number of different parts	36
Total material cost	328 SEK
Total weight	25 kg

The bracket of the bottom support needs better geometrical fitting to the cab lock and may need a redesign to ensure minimal deflection with minimal material input.

The material and type of the edge protection needs to be chosen to fulfil the requirements of protection in these areas. The design of the cable channels in their edges may also need a redesign to facilitate mounting of a cable route. The current design demands that one end of the cable route is put through all the openings of the cable channels. An optimal solution would allow that the cable route can just be put into all cable channels at the same time. This could be reached by designing clip closers on the edges that can be closed easily after putting the route in all cable channels.

It should furhtermore be made possible to route the wires in the edges in a manner that mostly moves and loads the wires rotationally around their long axis. This load case is to prefer to pure bending for copper wires which might lead to fatigue due to the cyclic loading.

To facilitate maintenance and replacement of parts on the tilted truck, the bottom connection point of the guiding pantograph should be made detachable. Thus the whole structure of the PseudoPanto could be moved out of the way in order to reach certain components underneath it.

Further development should also strive to minimise the number of fixing elements (screws and bolts) in the concept and maybe reach a more integrated design. The current number of parts seems unproportionally high for this concept.

5.3 Selfie

This section describes the final development stage of the chosen concept under the plug approach, called Selfie. In the following sections the general idea of the concept will be described. Detailed designs cannot be presented in this report since Volvo decided to proceed with the concept and aims for patenting certain parts of the mechanism. Publishing details about the solution in this report would make a patent impossible. Therefore pictures of the final version of this concept cannot be shown. However, certain insights from the prototyping and testing will be described and material considerations will be discussed.

5.3.1 General Idea

The main goal in the plug approach was to satisfy the main function Allow Tilting by a coupleable solution for the electric contacts. Furthermore, the focus was set on achieving a fully automatic unplugging of the contact under inclination and a fully automatic plugging under declination of the cab. Selfie is a concept that satisfies all these requirements. It works fully mechanical and is independent of external energy sources as it uses the potential energy of the cab's weight to operate its own coupling and locking mechanism. The solution does not need human interaction under the entire operation. This is made possible by a fully reversible movement of the mechanism in Selfie.

In the next sections first the theoretical issues around plugging concepts on a truck are discussed, followed by a description of how certain challenges were overcome on a general level.

5.3.2 Plugging Challenges

During development certain obstacles had to be overcome which are generally inherent in plugging mechanisms. Separating electrical circuits in a contact implies the exposure of electrical contact surfaces. This leads to issues with corrosion, wear and signal quality. Furthermore, a plug poses additional requirements on contacting force, contact protection in an open state, sealing against the outside conditions, locking and holding the plugged contact in position and ensuring a correct guiding of the plug before it reaches the contacting point. A short description of these challenges is given in the following.

Connector Design

The main function of electronic connectors is to transmit power or signals between two units. The transmission should comprise only acceptable losses in power or signal quality. In order to reach this, a connector should have as little impact as possible on the electrical properties of the circuit, i.e. its contact resistance should be low and invariant. (Mroczkowski, 1992)

Figure 5.41: Example of a coupled connector with the contact spring visible (in Wikimedia Commons, the free media repository, Retrieved 2014-07-15 from: `http://commons.wikimedia.org/wiki/File:Jack-plug--socket-switch.jpg`)

Standard connectors commonly consist of a housing called plug on the one side which contains the male pins and a housing called receptacle which contains female sockets on the other side of the connection (Christ & Wernli, 2014). To achieve the signal or power transmission the connector must provide and sustain a metal-to-metal interface between the contact points which is mostly achieved by a contact spring (example provided in Figure 5.41 which provides the necessary force for the interface (Mroczkowski, 1992). The contact spring is often comprised by the electrical contact itself. In general, the higher this contacting force on the individual pins the higher also the needed mating/unmating force of a separable connector.

The pins and sockets of a connector usually consist of a base material (in most cases copper) which is coated by a protective metal layer that prevents exposure of the base metal to the environment. There are many coating variants, the most used in the automotive industry are gold, silver, nickel and tin. (Volvo, 2014)

Corrosion and Wear

Connectors on a heavy duty truck are particularly sensitive to corrosion by fretting. Fretting arises from small amplitude movements up to 100 μm between the contacting surfaces of electronic connectors. These movements can be induced by external mechanical and electromagnetic vibrations or temperature changes. Fretting alone leads to wear and metal transfer between the contact partners. In case base metal contacts are used this leads to oxidation of the surface or the wear debris that has been built up during the movements. This situation is then called fretting corrosion. The debris may accumulate in the contact zone and leads to increased contact resistance. (Antler, 1985b, 1985a)

Especially separable connectors that are mated at relatively low forces are prone to fretting (Antler, 1985a). Flowers, Xie, Bozack, and Malucci (2004) have shown that fretting corrosion seems to have a threshold behaviour, i.e. degradation of the contact materials by fretting seems to be insignificant at different frequencies below a certain excitation level. In the case of a heavy duty truck, the necessary vibrations for fretting corrosion are omnipresent during truck operation due to excitations by the engine and the suspension system during driving (Volvo, 2014). To minimise the extent of fretting, vibration between the contacting members should be impeded and high contacting force should be provided (Volvo, 2014).

Wear on separable connectors is mainly induced by friction during inserting and withdrawing the pins in the connection. The amount of friction is linked to the contacting force provided by the contact springs. The friction when sliding the contact has the positive effect of removing surface particles, for instance oxides from the debris of fretting, and thus achieve good electrical contact (Moran, Sweetland, & Suh, 2004; Volvo, 2014). On the other hand wear sets a limit to the number of plugging/unplugging cycles as it degrades the coating metal gradually which leads to exposure of the base material.

Guidance

One big challenge that has to be overcome in the design of a fully automated contact at the back of a truck is to ensure correct guiding of the plug into the receptacle under reclination. Since no human interaction should be needed in this coupling process, a guidance has to achieve first a catching of the opposing contact onto the guidance system itself and a subsequent controlled movement of the contacts towards each other until the mated state is reached. The mechanism of catching the opposing contact has to be able to compensate for position misalignments between the cab and the chassis during the landing phase. The controlled movement of the contacts towards each other has to be able to cope with the almost vertical but in practice unpredictable landing motion of the cab on the chassis (see section 3.2). Vice versa the guidance should ensure a controlled unmating of the contacts during inclination.

Locking, Sealing and Protection

The coupled connection needs to be locked in position when the mated state has been reached. This inhibits unintended opening of the connection and adds to the wanted rigidity of the bond. Conversely, unlocking has to occur automatically during the inclination operation before the connection can hinder the movement of the cab.

In the locked state, an automatic connection should furthermore provide sealing against the harsh environment on a truck. Under driving, the sides and the back of a truck can be enfolded by fine spray of water, oil and other aerosols which are able to reach even small gaps and cracks (Volvo, 2014).

In both an open and closed state a connector needs protection from external forces and impacts. The protection should furthermore be insulating for electric current and electromagnetic fields to ensure low signal perturbation and thus noise.

5.3.3 Selfie Parts

Selfie consists generally of one chassis-mounted (lower) and one cab-mounted (upper) part. The lower part embodies the plug which possesses certain degrees of freedom. The upper part embodies the receptacle which is rigidly fixed and enwraps the plug in the locked state. A description of these two parts is given in the following sections.

Chassis-Mounted

The lower part of Selfie is mounted on its bottom to the chassis by a bracket that consists of an arm and an angle. The bracket is fixed to the cab lock with the locking screws in the same manner as the PseudoPanto's bracket which was described in section 5.2.5. Also here, the cab lock serves as a connection point which does not move relative to the cab under driving. This fact eases the requirements posed on Selfie.

The arm of the bracket holds a system of sliders and rotational joints which give the structure built upon them the needed degrees of freedom in the required magnitude. This results in a limited free movement in the X- and Y-direction and rotation around the Y- and Z-axis of the truck to cope with position variations between cab and chassis.

On top of the lower part, upon the system that permits the movement, the plug and the locking system are mounted. The plug is a symmetric structure that contains a commercial electrical connector in its centre. The plug possesses a specific geometry on its outside which supports the mating operation. Wires are routed from the commercial connector on the inside through the bottom of the plug from where they can be harnessed by a standard corrugated hose on the chassis.

The locking system is located slightly below the plug to which it is rigidly fixed. Locking and unlocking is performed by physical insertion and retraction of specific parts of the lock into the corresponding part. The locking process is designed to begin when the reclining cab has entered the landing phase during reclination and thus majorly moves vertically towards the ground. Conversely, unlocking of the mechanism is completed slightly before the end of the take-off phase during inclination.

Cab-Mounted

The upper part of Selfie is mounted at the back wall of the cab centred above the cab lock in the locked position of the cab. The part consists mainly of a shell-like component called Outer Shell that can be opened on its top for mounting wires. The Outer Shell comprises an opening on its bottom which is directed towards the lower part in the locked position of the cab. The opening is designed to correspond to the specific geometry of the plug and the allowed position variation between cab and chassis. Above the bottom opening the Outer Shell features a short tunnel in which the plug is meant to glide up towards the mated position. The Outer Shell thus provides the required guidance and protection for the plug by its structure.

At the end of the tunnel in the Outer Shell a component called Antiplug is mounted. The Antiplug resembles a negative of the plug in its geometry which facilitates a perfect mating between their outer surfaces and thus provides sealing. The Antiplug contains the opposing electrical connector in its centre. Wires are routed from this connector through the top (removable) part of the Outer Shell from where they are harnessed by a standard corrugated hose on the cab.

Electrical Connectors

The commercial connectors used in Selfie are a Deutsch DRC12-40PA in the plug coupled to a Deutsch DRC16-40SE in the Antiplug, with capacities for 40 pins and sockets (drawing see Appendix C.4). The fully equipped connectors alone can be seen in Figure 5.42. The adequate pins and sockets are nickel coated and are suited for a wire gauge of up to 2,5 mm^2. The connector normally includes a screw which ensures a tight fit of the connection. The screw has been removed for the application in Selfie where other components take over the same function.

Figure 5.42: Deutsch DRC connectors in Selfie

The connectors are well-suited for harsh environments since they are mostly used in military applications. The connectors are designed to endure frequent coupling. The design of the pins with a chamfer allows a certain misalignment towards the sockets. Crimping of the pins and sockets towards the copper wires is relatively easy and fast. The nickel coating provides a relatively hard surface which is beneficial for the wear resistance.

5.3.4 Prototype Testing

By the end of DL1 a prototype of Selfie was created with SLS in alumide and some parts in polyamide. Alumide is polyamide with aluminium components which adds more stiffness to the prototypes.

For the prototype the electrical connectors Han 40D-HMC-F-c and Han 40D-HMC-M-c from Harting were used (see Figure 5.43). The contact contained 40 silver plated pins and sockets. The necessary mating and unmating force for the fully equipped connector was measured to be approximately 100 N. The connector was not used in the final concepts because the pins and sockets generally seemed rather fragile. Furtermore, silver plated pins tend to form unwanted silver coating in the atmosphere around a truck (Volvo, 2014).

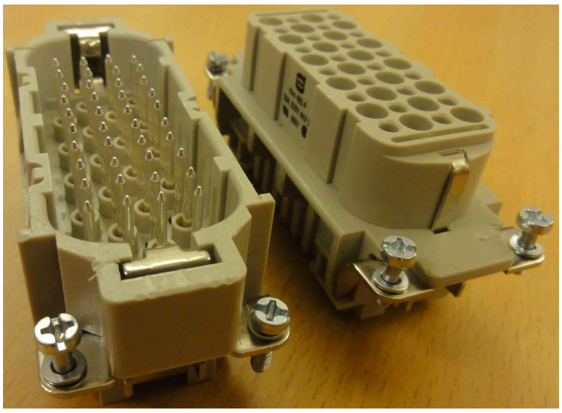


Figure 5.43: Harting Han D connector in prototype of Selfie

During testing of Selfie it was observed that too many contact constraints were present in the design which led to self-locking during plugging due to the imperfect precision of the SLS method. To reach robustness in design certain contact constraints were removed or adapted to fit the tolerances of regular machining processes.

The prototype of the Outer Shell exhibited considerable weight which was seen to mainly origin from its unnecessary thickness in certain parts. The design was thus adapted and ribs were used instead to reach the same stiffness.

5.3.5 Material Considerations

A simple analysis on material choice for some of the parts of Selfie was conducted with the help of the CES selector. The material selection process followed Ashby (2011). The used variables are the same as in section 5.2.8 (see Table 5.6). Certain base requirements were set on all parts; low flammability and high durability in humid and wet environments.

Outer Shell

The Outer Shell can be seen partly as a panel structure with stiffness, length and width specified and thickness as a free parameter. This is a standard problem in Ashby (2011) and yields the material index

$$M_1 = \frac{\sigma_f^2}{\rho} \tag{5.23}$$

Furthermore, K_{1c} was required to be high to achieve resistance against sudden impacts by material from the environment. The analysis in CES (see Appendix C.6) yielded the material recommendation in Table 5.8.

Table 5.8: Material selection of the Outer Shell

Material	ρ	σ_f	C_m	K_{1c}
Stainless steel, martensitic, AISI403 wrought, annealed	$7700\,\frac{\text{kg}}{\text{m}^3}$	245-550 MPa	7,1-7,9 $\frac{\text{SEK}}{\text{kg}}$	37-156 MPa $\text{m}^{\frac{1}{2}}$

Plug and Antiplug

The requirements set on these parts were a minimum level of stiffness and good insulation properties since they comprised the electric connectors. The search in the material database then aimed for low price and high strength. Furthermore, good insulation properties for low noise induction and good gliding properties of the material against the material of the Outer Shell were considered. The selection yielded thermosets or thermoplastics as a material recommendation (see Appendix C.6 for chart). Table 5.9 shows one viable example of each group.

Table 5.9: Material selection of the Plug and Antiplug

Material	ρ	σ_f	C_m
Thermosets: Phenol fromaldehyde (PF) (cotton filled, impact modified, molding)	$1400\,\frac{\text{kg}}{\text{m}^3}$	33 - 55 MPa	15 - 16 $\frac{\text{SEK}}{\text{kg}}$
Thermoplastics: Polyphenylene oxide / polystyrene alloy (30% glass fiber)	$1300\,\frac{\text{kg}}{\text{m}^3}$	95 - 105 MPa	23 - 34 $\frac{\text{SEK}}{\text{kg}}$

5.3.6 Summary & Further Development

A summary can be drawn in Table 5.10 which assumes Selfie to be realised in the recommended materials.

Table 5.10: Summary of Selfie

Total number of parts	117
Number of different parts	35
Total material cost	193 SEK
Total weight	20 kg

Like the PseudoPanto, Selfie was created from scratch. Selfie needs further development and especially testing to become a mature concept. The mechanism itself seems to work, downscaling might though be possible with more knowledge about locking mechanisms.

Testing of a prototype in the target material is advised to observe the actual behaviour and gliding properties of the locking mechanism and the plug inside the Outer Shell. Different material pairings and tolerances might be examined and tested to reach optimal gliding behaviour and to make self-locking impossible.

Some parts of Selfie are not or not fully developed but needed before the concept can be implemented:

- A protection mechanism for the electric connector of the plug in the open state has not been designed but would be needed to prevent exposure to the environment
- An extension cable should be designed and provided for maintenance staff to be able to close the circuit in the tilted position for tests
- The design of the bottom system that provides the lower part of Selfie with its degrees of freedom is rather simplistic and should be improved to reach a smooth and robust movement
- Generally, steps to reach an integrated design of the parts should be taken to minimise the number of different parts

6

Conclusions

The goal of the thesis has been fulfilled as two new alternative harness routing concepts have been developed. The concept created following an approach to prolong the connection is called PseudoPanto. It has been tested and the working principle has been confirmed. The other concept created followed an automatic coupling approach and is called Selfie. A fully working prototype for Selfie could not be tested under the development time. The developed concepts show that alternative routing solutions are technically possible, however the question remains how much of the cabling can be rerouted. PseudoPanto is more mature in its development than Selfie, yet the adaptability of PseudoPanto for more cabling is seen more problematic than in Selfie. One should be clear about the objectives during a selection of one of the presented concepts.

Considering aftermarket circuit diagnosis for error searching, both concepts exhibit advantages and disadvantages; Selfie needs an extra extension cable in the tilted state because the circuit of the cabling must be closed for error search purposes. As error search is not needed under every tilting operation, the extent of this disadvantage depends on the frequency of error search actions on the truck which is unknown at this state. PseudoPanto on the other hand does not pose any problem for circuit diagnosis as its circuit is always closed. It might though cause a problem by inducing a physical obstruction if large components close to PseudoPanto have to be replaced. In those cases the PseudoPanto might be in the way of special tools and machines which need to reach those components. Therefore the PseudoPanto needs to be detachable at certain points to be able to move it out of the way. The extent of this disadvantage depends on the frequency replacing such components which is also unknown. To draw sound conclusions, both the frequency of the error searching and component replacement have to be assessed. A way to circumvent both problems in future concepts could also be a combination of the two approaches, i.e. a prolongable solutions which can furthermore be coupled.

It was observed that direct contact with employees at Volvo led to good results in gathering information. Indirect contact (e.g. mail) did not lead to the same quality of information. The use of a mediating object (truck model) was a great way to communicate a subject which was hard to describe. The truck model helped to manifest an abstract idea of the authors on a physical artifact which was familiar to the interviewees. It seemed as the recognition of a well-known object led also to a higher willingness of the interviewees to respond and describe their thoughts.

A considerable amount of time was put into the pre-study to set the scope of the thesis project which stole time from a more extensive detail development of the concepts in the end. In retrospect it can be said that the time used in the pre-study should have been compressed as much as possible to start a focused development earlier in the process.

The situation of working in the borderland between two different CAD systems (ProE on chassis and Catia V5 on cab) was seen as a time consuming obstruction. Time had to be spent on finding and converting CAD data in question to be able to work. Furthermore, working in an area of the truck which involves a lot of different area responsible groups increased the time needed for information gathering. Most area responsible groups were usually fully aware of their own situation but unaware of others.

Regarding the process of concept screening it should be noted that the authors held limited knowledge about how the created concepts would perform in real life due to a general nescience about trucks. Therefore, many assumptions had to be made during the concept evaluations. The gathered knowledge from Volvo employees helped to overcome this obstacle partly.

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A

Volvo Documents

A.1 Burn Through Requirements

The following four pages provide an excerpt of Volvo's own standard for burn-through on the cab. They were retrieved from Volvo (2014).

Figures 1-4 Shortest permissible burn-through time / Kortast tillåtna genombränningstid

Fig. 1 Front view/Front

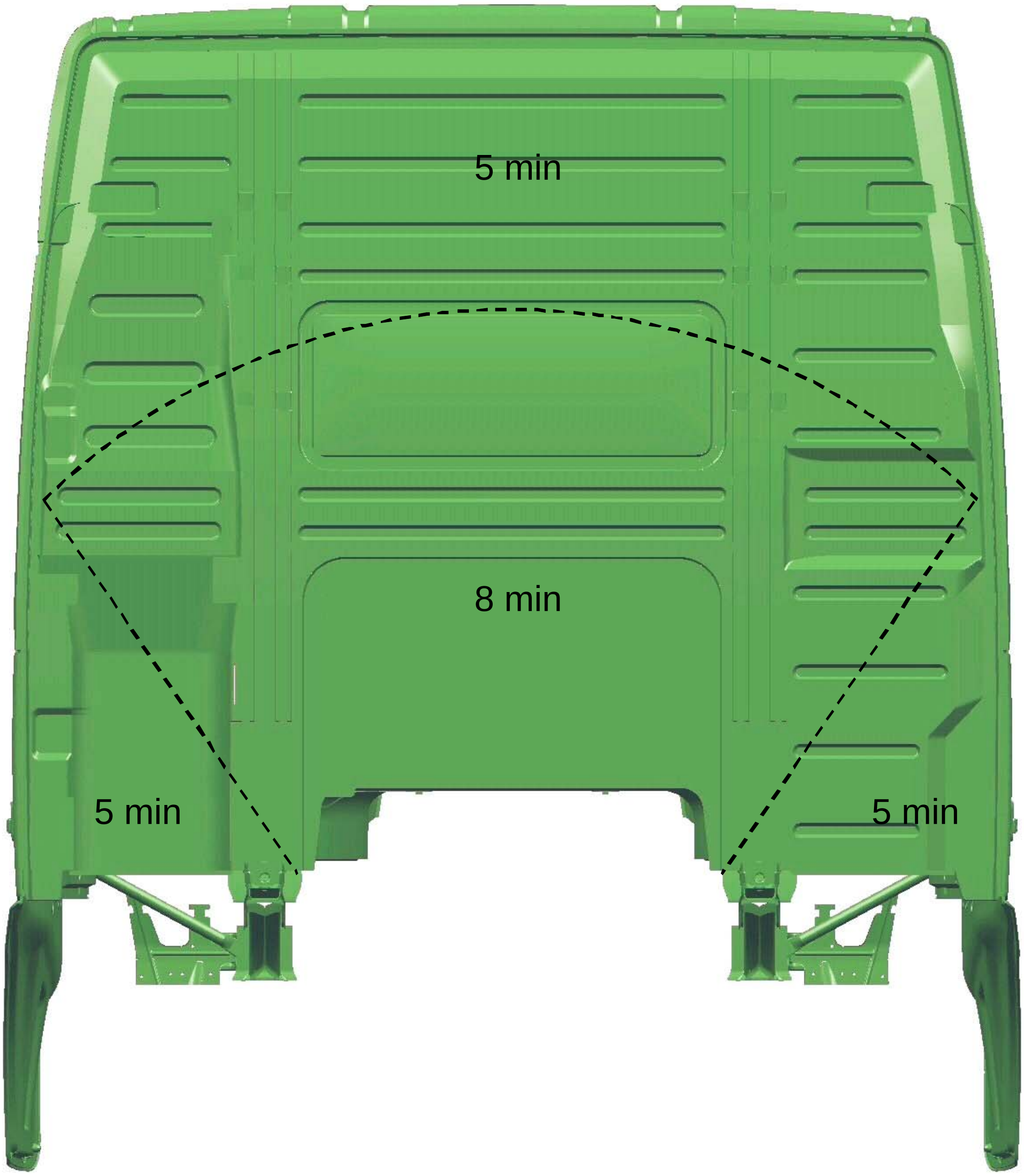


Fig. 2 Rear view/Baksida

Fig. 3 Side view/Sida

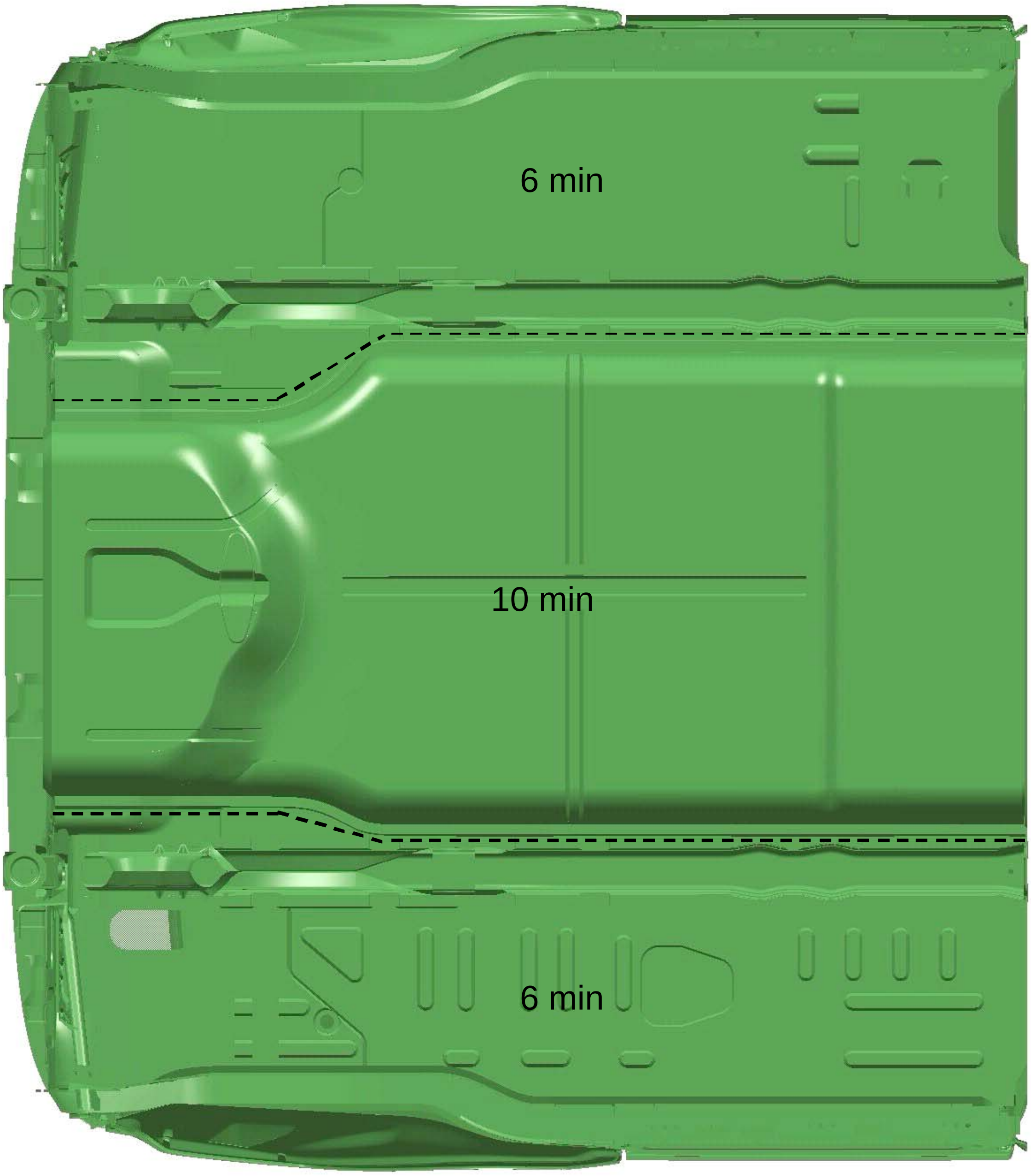


Fig. 4 Floor view/Golv

B

Development Process

B.1 Target Specifications

Target Specifications

Metric No	Need Nos.	Metric	Importance (1-5)	Units	Marginal Value	Ideal Value
1	1, 7	Clash with other components	3	Boolean		TRUE
2	2	Tilting possibility	5	Boolean	TRUE	TRUE
3	3	Difference in total number of bottlenecks on the truck	2	Int	<= 0	
4	4	Number of Bodybuilder's cables integrated	5	Int	> 0	21
5	8	Temperature resistance of chassis route	5	C	> x	
6	8	Temperature resistance of connection	5	C	> x	
7	8	Temperature resistance of cab route	5	C	> x	
8	8	Temperature resistance of pass-through	5	C	> x	
9	10	Exposure time in dirty environment without malfunctioning	5	Days	> x	
10	11	Absolute X Position variation tolerance btw. Chasis-cab from the nominal	5	mm	>= 10	
11	11	Absolute Y Position variation tolerance btw. Chasis-cab from the nominal	5	mm	>= 20	
12	11	Absolute Z Position variation tolerance btw. Chasis-cab from the nominal	5	mm	>= 50	
13	11	The simultaneous combination of the tolerances in all directions can be reached	5	Boolean		TRUE
14	12	Number of tolerated cycles with maximum variation between cab and chassis as an amplitude	5	Int	> 10^7	
15	13	The engine can be started when the cab is tilted	4	Boolean		TRUE
16	15	Change in Eigenfrequency of the suspension system between cab and lock	4	Hz	< x	0
17	16	Number of endured tilting operations	4	Int	> x	3000
18	18	Absolute X Landing/Takeoff position tolerance from the nominal	5	mm	>= 10	
19	18	Absolute Y Landing/Takeoff position tolerance from the nominal	5	mm	>= 20	

20	18	Absolute Z Landing/Takeoff position tolerance from the nominal	5	mm	>= 50	
21	18	Simultaneous combination of all Landing/Takeoff position tolerances is possible	5	Boolean		TRUE
22	19	Number of added human interactions to reach the tilted state from locked state	4	Int		0
23	20	Number of added human interactions to reach the locked state from tilted state	4	Int		0
24	21	Weight of cumulated alien material inside the system after X testdrives in dirty conditions		g	< x	0
25	22	Time in atmosphere with oil and lubricant aerosols before failure	5	s	> x	
26	23	Time in 100% humid atmosphere before failure in normal state	5	s	>x	
27	23	Time in 100% humid atmosphere before failre in tilted state	5			
28	24	Depth of the deepest abrasive wear in cables after X usage hours	5	mm	< x	0
29	24	Number of abrasive wear points in cables after X usage hours	5	Int	< x	0
30	25	Time to change all components	3	h	< x	
31	26	Signal to noise ratio between system boundaries	5	dB	<= X	
32	27	Minimum transfer rate	5	bit/s	> 0	
33	28	Assembly time	3	min	< x	
34	28	Mounting time	3	min	< x	
35	29	Manufacturing cost	2	SEK	< x	
36	30	Power against cab opening power	3	W	< x	0
37	31	Time under constant X l/min with turbulent water flow before malfunctioning in normal state	5	s	> x	
38	31	Time under constant X l/min with turbulent water flow before malfunctioning in tilted state	5	s	> x	
39	32	Maximum allowable angle between truck and floor where declination and inclination is still possible	4	deg	> x	90

B.2 Function Trees

The function trees are displayed on the following page.

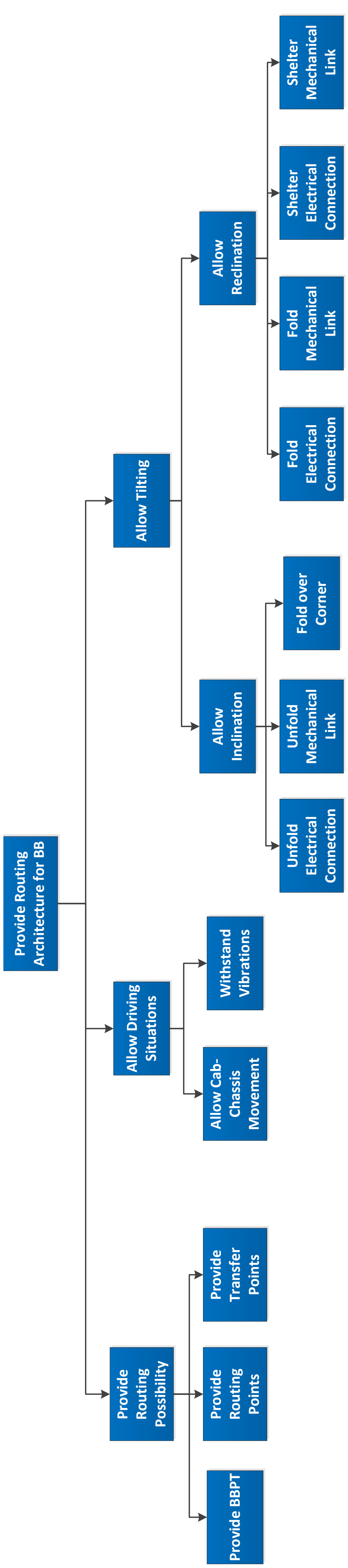


Figure B.1: Function tree Prolongable

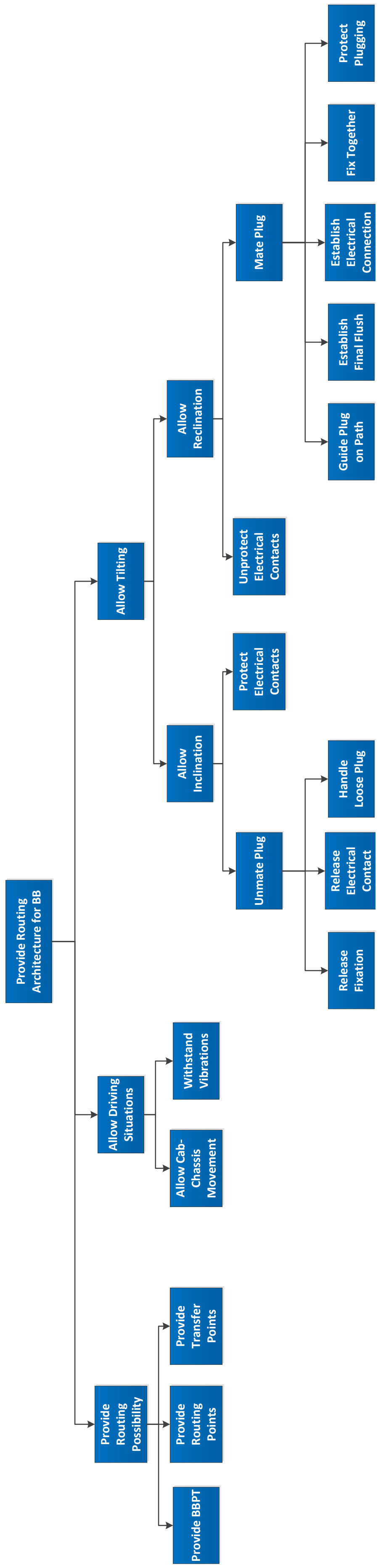


Figure B.2: Function tree Plug

B.3 Brainstorming

The metaphoric story used during brainstorming can be seen in Figure B.3. The story splits up in the middle into two different outcomes representing a prolongable and a plug solution.

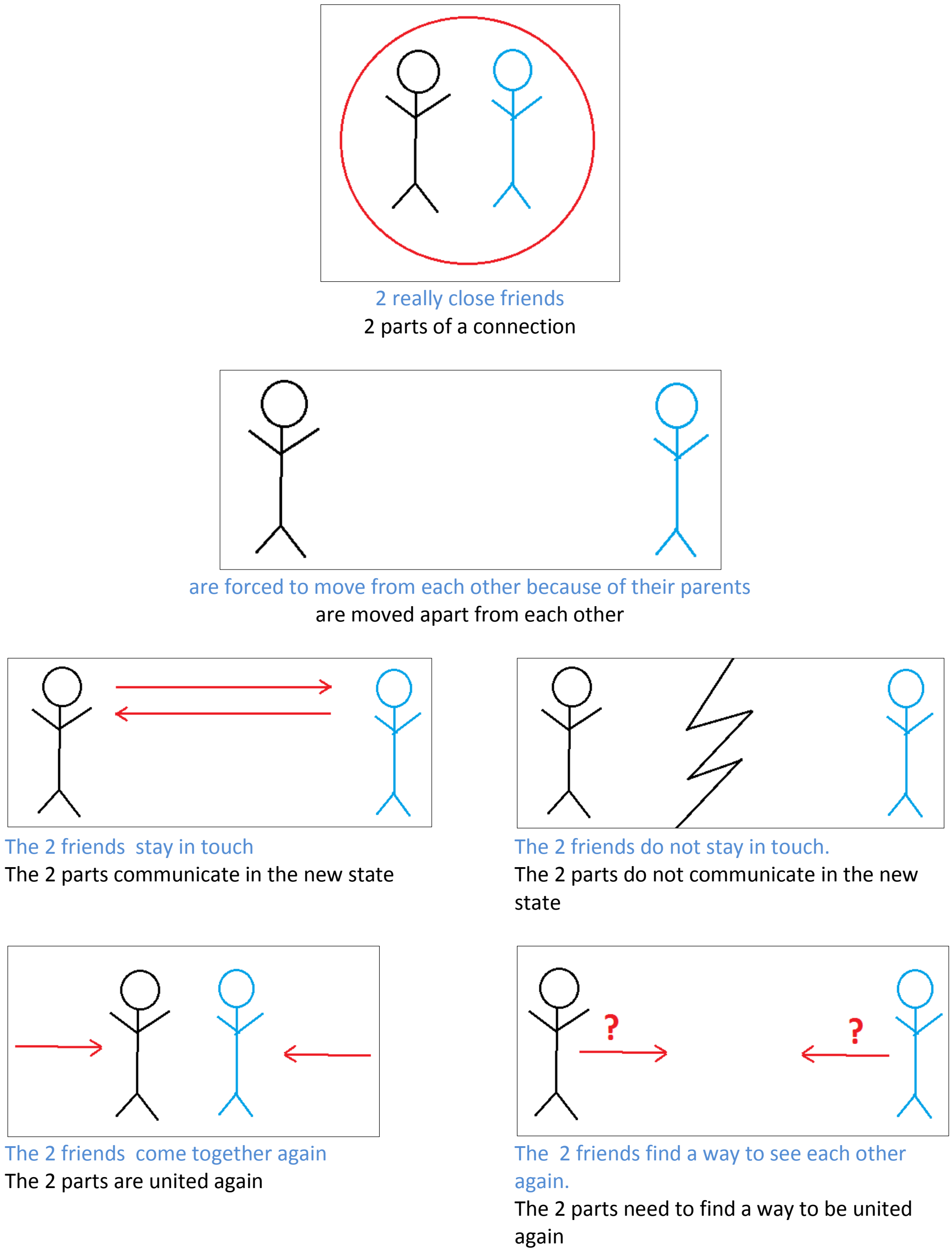


Figure B.3: Metaphoric story

B.4 Evaluation Matrices

Selfie

Table B.1: Plug Screening Matrix 1

Factor	The Press	Inverted Press	Selfie	Yo-Yo	Search and Engage
Dirt entry possibilities	DATUM	0	-	-	0
Water entry possibilities		0	-	-	0
Assumed plugging robustness		0	+	-	-
Parasitic suspension		0	0	+	0
# of added human interactions for inclination		0	0	0	0
# of added human interactions for declination		0	0	0	0
number of parts		0	+	+	-
volume		0	+	+	0
possibility for increased number of cables		0	-	-	0
Assumed loading on inclination movement		0	+	+	0
assumed loading on declination movement		0	+	+	0
Contacting rigidity		+	+	+	0
Applied closing force		-	0	-	0
Neccessary mating force		0	-	-	0
# of volution parts		0	+	0	-
ability for circuit to be prolonged		+	+	+	0
Sum +		2	8	7	
Sum 0					
Sum -		1	4	6	3
Score		1	4	1	-3

Table B.2: Plug Screening Matrix 2

Factor	The Press	Inverted Press	Selfie	Yo-Yo
Dirt entry possibilities	0	0	0	DATUM
Water entry possibilities	0	0	0	
Assumed plugging robustness	+	+	+	
Parasitic suspension	-	-	-	
# of added human interactions for inclination	0	0	0	
# of added human interactions for declination	0	0	0	
number of parts	-	-	0	
volume	-	-	0	
possibility for increased number of cables	+	+	+	
Assumed loading on inclination movement	-	-	+	
assumed loading on declination movement	-	-	-	
Contacting rigidity	-	-	0	
Applied closing force	+	+	+	
Neccessary mating force	+	+	0	
# of volution parts	-	-	0	
ability for circuit to be prolonged	-	-	-	
Sum +	4	4	4	
Sum 0				
Sum -	8	8	3	
Score	-4	-4	1	0

PseudoPanto

Table B.3: Prolongable Screening Matrix 1

Factor	Tubic Spiral	Pulley System	Double Reel	Scissor Lift	Mid-Air Reel	Lampy
Dirt entry possibilities	+	+	+	+		+
Water entry possibilities	+	+	+	+		+
Assumed folding robustness	+	0	0	+		-
Parasitic suspension	-	0	0	-		-
# of added human interactions for inclination	0	0	0	0		0
# of added human interactions for declination	0	0	0	0		0
number of parts	-	-	0	-		-
volume	-	-	-	-		-
possibility for increased number of cables	0	+	+	+	Datum	0
Assumed loading on inclination movement	+	0	0	+		+
assumed loading on declination movement	+	0	0	+		+
volume of the envelope	-	0	0	-		-
cable mounting complexity	0	0	0	-		-
difference between bending radii of cabling in locked and tilted position	0	-	0	-		-
axial load on cabling	+	0	0	+		+
cable length	-	0	-	-		-
able to modify to be pluggable	-	0	0	-		-
Sum +	6	3	3	7		5
Sum 0	5	11	12	2		3
Sum -	6	3	2	8		9
Score	0	0	1	-1	0	-4

Table B.4: Prolongable Screening Matrix 2

Factor	Tubic Spiral	Pulley System	Double Reel	Scissor Lift	Mid-Air Reel
Dirt entry possibilities		-	-	0	-
Water entry possibilities		-	-	0	-
Assumed folding robustness		-	-	0	-
Parasitic suspension		+	+	0	+
# of added human interactions for inclination					
# of added human interactions for declination					
number of parts		-	0	-	0
volume		-	-	0	+
possibility for increased number of cables	Datum	+	+	+	-
Assumed loading on inclination movement		-	-	0	-
assumed loading on declination movement		-	-	0	-
volume of the envelope		-	+	0	+
cable mounting complexity		0	0	-	0
difference between bending radii of cabling in locked and tilted position		0	0	-	0
axial load on cabling		-	-	+	-
cable length		+	+	0	+
able to modify to be pluggable		+	+	0	+
Sum +		4	5	2	5
Sum 0		2	3	10	3
Sum -		9	7	3	7
Score	0	-5	-2	-1	-2

Table B.5: Prolongable Scoring Matrix

Factor	**Importance**	**Tubic Spiral**		**Scissor Lift**		**Mid-Air Reel**	
		Rate	Weighted Rate	Rate	Weighted Rate	Rate	Weighted Rate
Feasibility	4	2	8	4	16	3	12
Space requirements	3	1	3	2	6	3	9
Adaptability for plugging	3	2	6	4	12	5	15
Cable load	4	3	12	4	16	2	8
contamination possibility	4	4	16	2	8	3	12
Robustness of the movement	5	3	15	5	25	3	15
Failure possibilities	5	2	10	4	20	3	15
Expandability of wires	4	2	8	4	16	2	8
Sum			78		119		94

C

Technical Analysis

C.1 Tilting Analysis

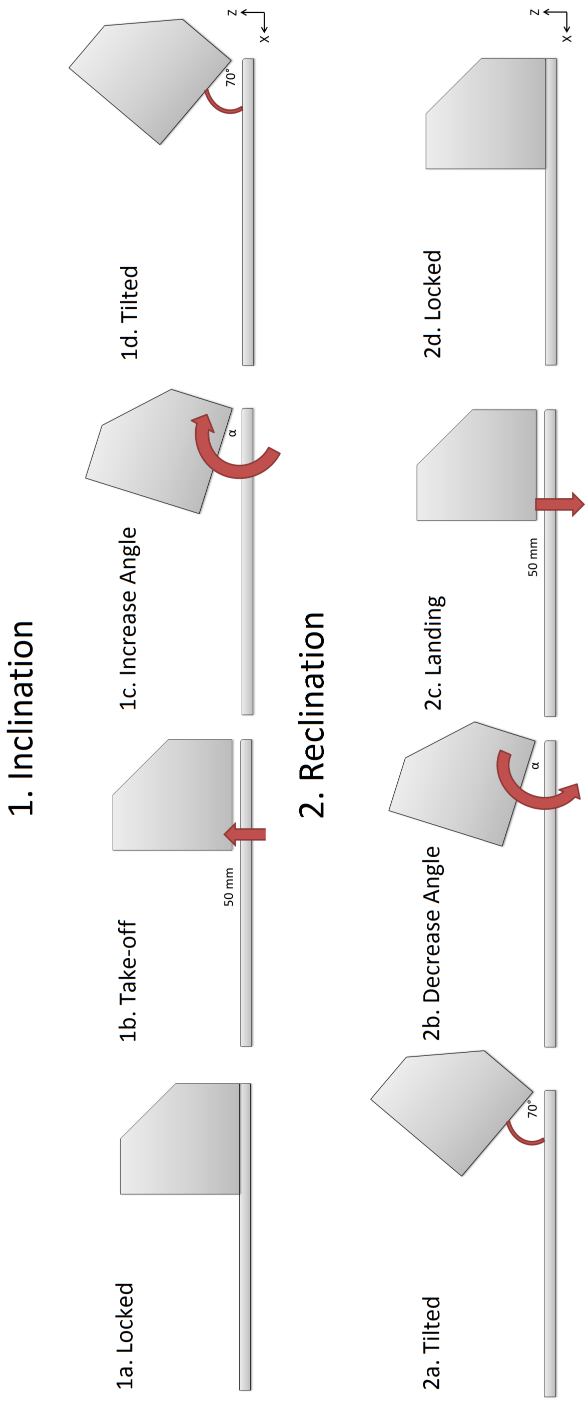


Figure C.1: The tilting operation sequence

C.2 Derivations

Equilibrium equations on a zig-arm

Moment equilibrium around the $i+1$ joint with arm length L:

$$\frac{H}{2}\frac{L}{2}\cos\alpha - S_{xi}\,L\sin\alpha - S_{y_i}\,L\cos\alpha - R_{xi}\frac{L}{2}\sin\alpha = 0 \tag{C.1}$$

$$\frac{H}{2}\cos\alpha - 2\,S_{xi}\sin\alpha - 2\,S_{y_i}\cos\alpha - R_{xi}\sin\alpha = 0 \tag{C.2}$$

$$\frac{H}{2} - 2\,S_{xi}\,\frac{\sin\alpha}{\cos\alpha} - 2\,S_{y_i} - R_{xi}\frac{\sin\alpha}{\cos\alpha} = 0 \tag{C.3}$$

$$\frac{H}{2} - 2\,S_{xi}\,\tan\alpha - 2\,S_{y_i} - R_{xi}\tan\alpha = 0 \tag{C.4}$$

$$\frac{H}{2\tan\alpha} - 2\,S_{xi} - \frac{2\,S_{y_i}}{\tan\alpha} = R_{xi} \tag{C.5}$$

Vertical equilibrium:

$$S_{y_i} + S_{y_{i+1}} - \frac{H}{2} = 0 \tag{C.6}$$

$$-S_{y_i} - \frac{H}{2} = S_{y_{i+1}} \tag{C.7}$$

Horizontal equilibrium:

$$S_{xi} + R_{xi} + S_{xi+1} = 0 \tag{C.8}$$

$$S_{xi} + \frac{H}{2\tan\alpha} - 2\,S_{xi} - \frac{2\,S_{y_i}}{\tan\alpha} + S_{xi+1} = 0 \tag{C.9}$$

$$-S_{xi} + \frac{H}{2\tan\alpha} - \frac{2\,S_{y_i}}{\tan\alpha} + S_{xi+1} = 0 \tag{C.10}$$

$$S_{xi} - \frac{H}{2\tan\alpha} + \frac{2\,S_{y_i}}{\tan\alpha} = S_{xi+1} \tag{C.11}$$

Equilibrium equations on a zag-arm

Moment equilibrium around the $i+1$ joint with arm length L:

$$-\frac{H}{2}\frac{L}{2}\cos\alpha + S_{xi}\,L\sin\alpha - S_{y_i}\,L\cos\alpha + R_{xi}\frac{L}{2}\sin\alpha = 0 \tag{C.12}$$

$$-\frac{H}{2}\cos\alpha + 2\,S_{xi}\sin\alpha - 2\,S_{y_i}\cos\alpha + R_{xi}\sin\alpha = 0 \tag{C.13}$$

$$-\frac{H}{2} + 2\,S_{xi}\,\frac{\sin\alpha}{\cos\alpha} - 2\,S_{y_i} + R_{xi}\frac{\sin\alpha}{\cos\alpha} = 0 \tag{C.14}$$

$$-\frac{H}{2} + 2\,S_{xi}\,\tan\alpha - 2\,S_{y_i} + R_{xi}\tan\alpha = 0 \tag{C.15}$$

$$\frac{H}{2\tan\alpha} - 2\,S_{xi} + \frac{2\,S_{y_i}}{\tan\alpha} = R_{xi} \tag{C.16}$$

Vertical equilibrium:

$$-S_{y_i} - S_{y_{i+1}} - \frac{H}{2} = 0 \tag{C.17}$$

$$-S_{y_i} - \frac{H}{2} = S_{y_{i+1}} \tag{C.18}$$

Horizontal equilibrium:

$$-S_{xi} - R_{xi} - S_{xi+1} = 0 \tag{C.19}$$

$$-S_{xi} - \frac{H}{2\tan\alpha} + 2\,S_{xi} - \frac{2\,S_{y_i}}{\tan\alpha} - S_{xi+1} = 0 \tag{C.20}$$

$$S_{xi} - \frac{H}{2\tan\alpha} - \frac{2\,S_{y_i}}{\tan\alpha} - S_{xi+1} = 0 \tag{C.21}$$

$$S_{xi} - \frac{H}{2\tan\alpha} - \frac{2\,S_{y_i}}{\tan\alpha} = S_{xi+1} \tag{C.22}$$

Equilibrium equations on the first arm pair

Vertical equilibrium:

$$F - 2\,S_{y_1} = 0 \tag{C.23}$$

$$S_{y_1} = \frac{F}{2} \tag{C.24}$$

As the direction of the force S_1 is predefined by the direction of the arms, it follows:

$$\tan\alpha = \frac{S_{y1}}{S_{x1}} \tag{C.25}$$

$$\tan\alpha = \frac{F}{2\,S_{x1}} \tag{C.26}$$

$$S_{x1} = \frac{F}{2\tan\alpha} \tag{C.27}$$

C.3 Pantograph Analysis

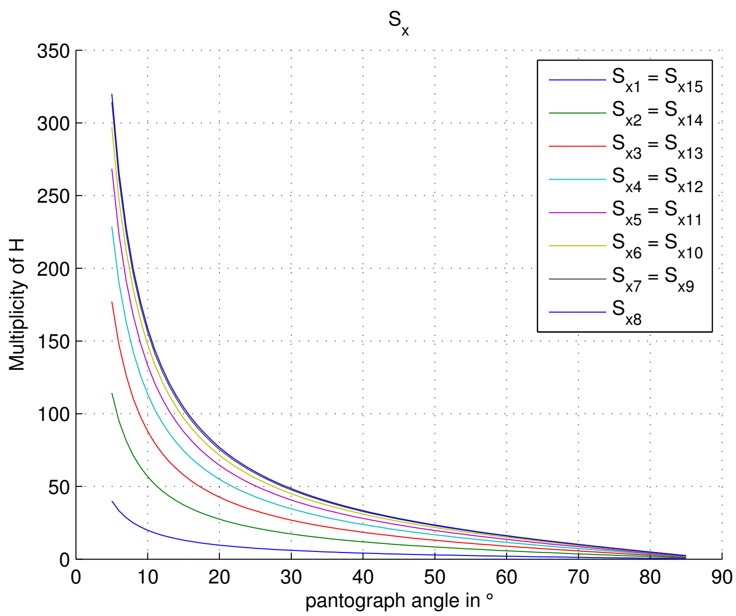


Figure C.2: S_x in dependence of pantographic angle

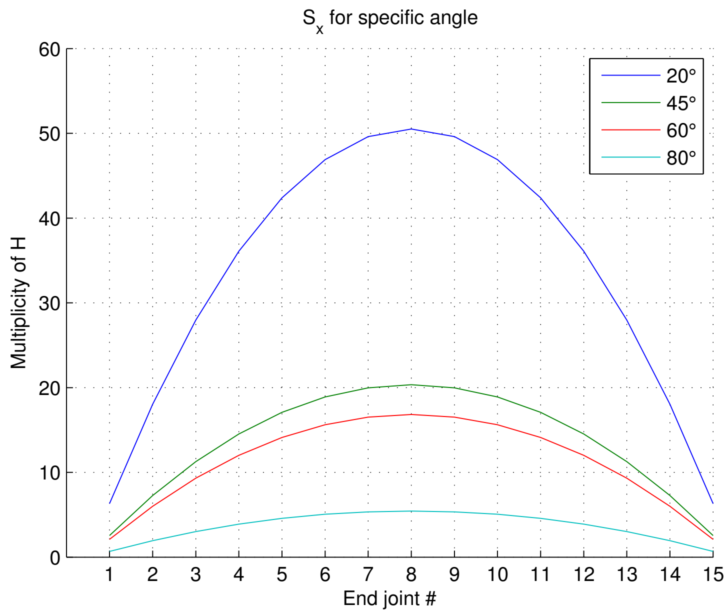


Figure C.3: S_x in dependence of joint number

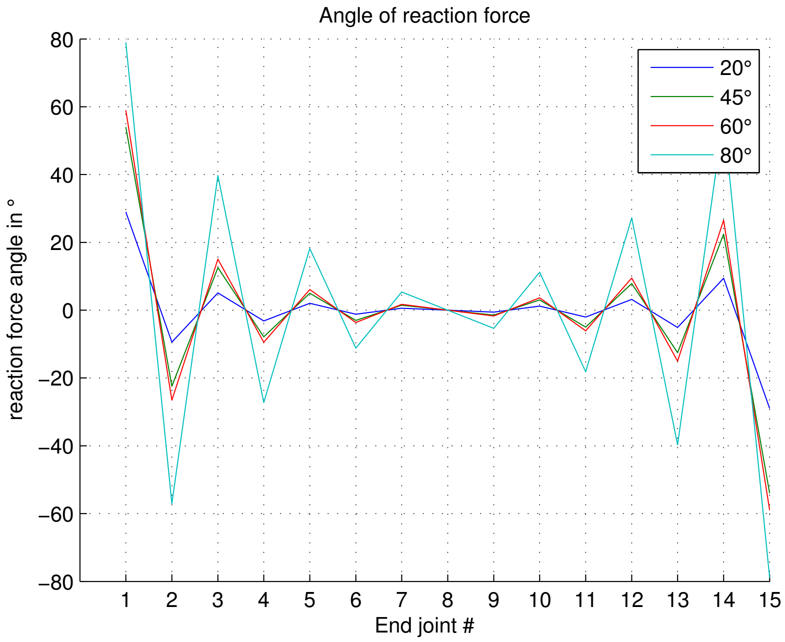


Figure C.4: Angles of reaction force S

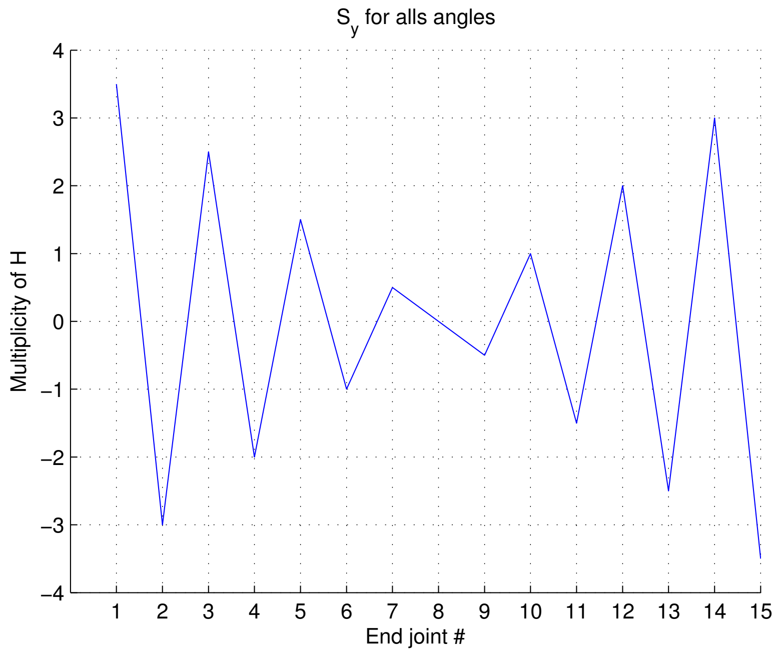


Figure C.5: S_y in dependence of joint number

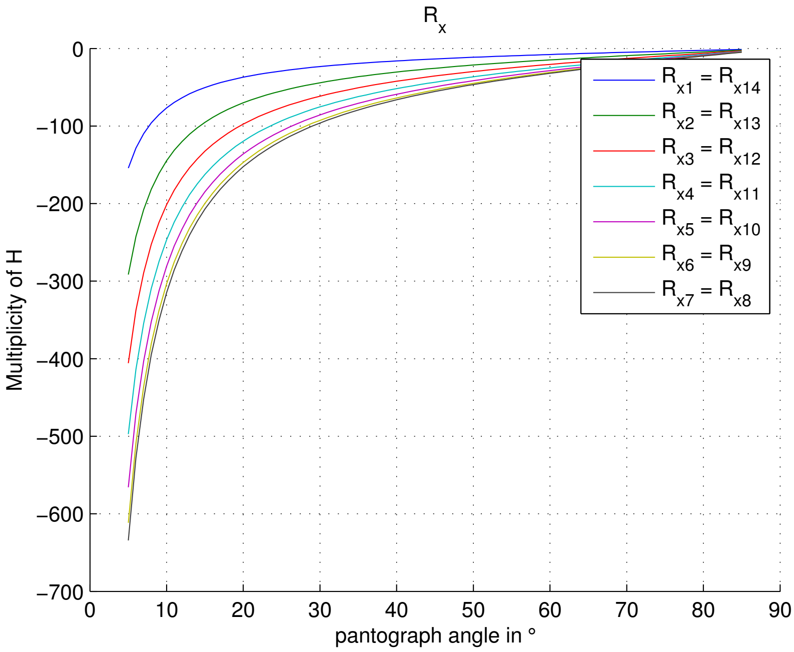


Figure C.6: R_x in dependence of pantographic angle

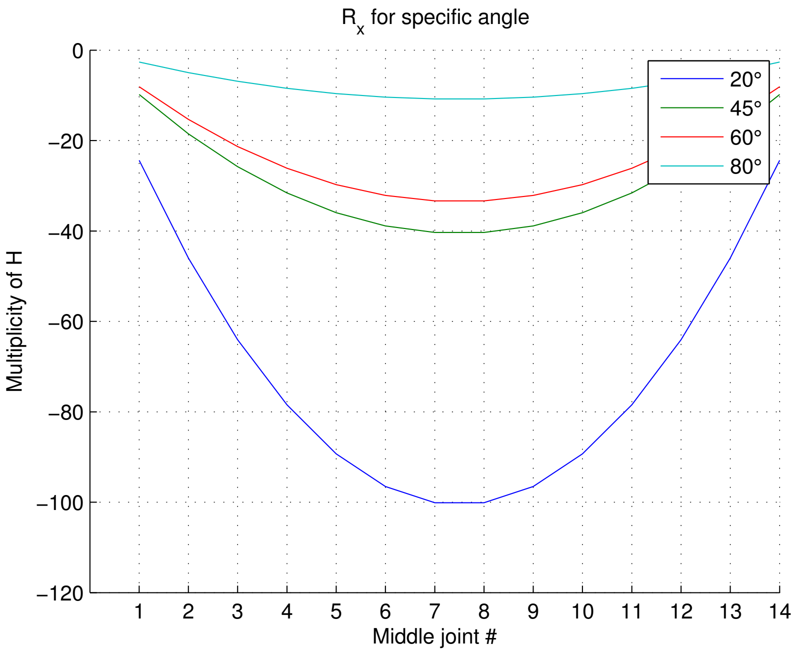
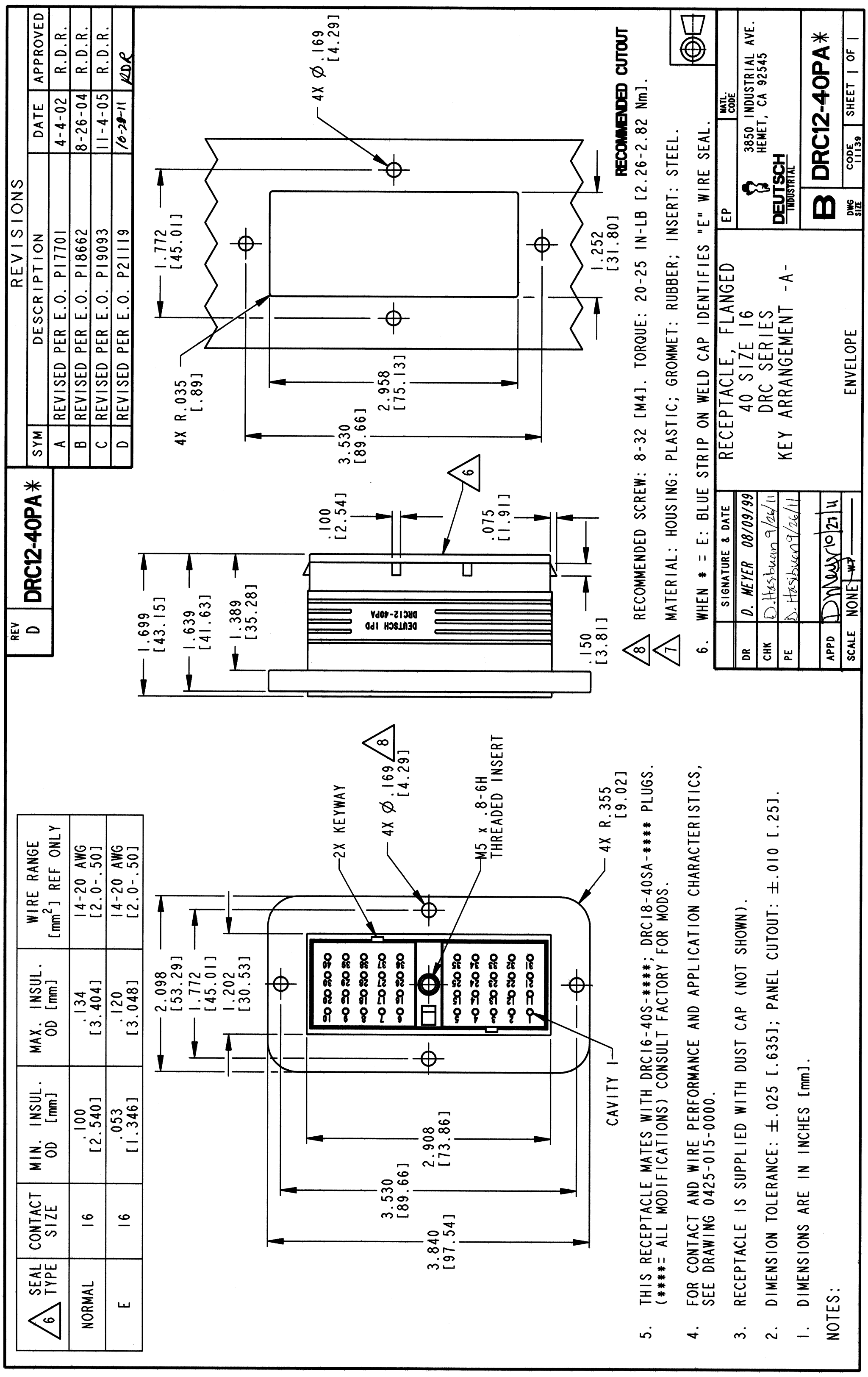


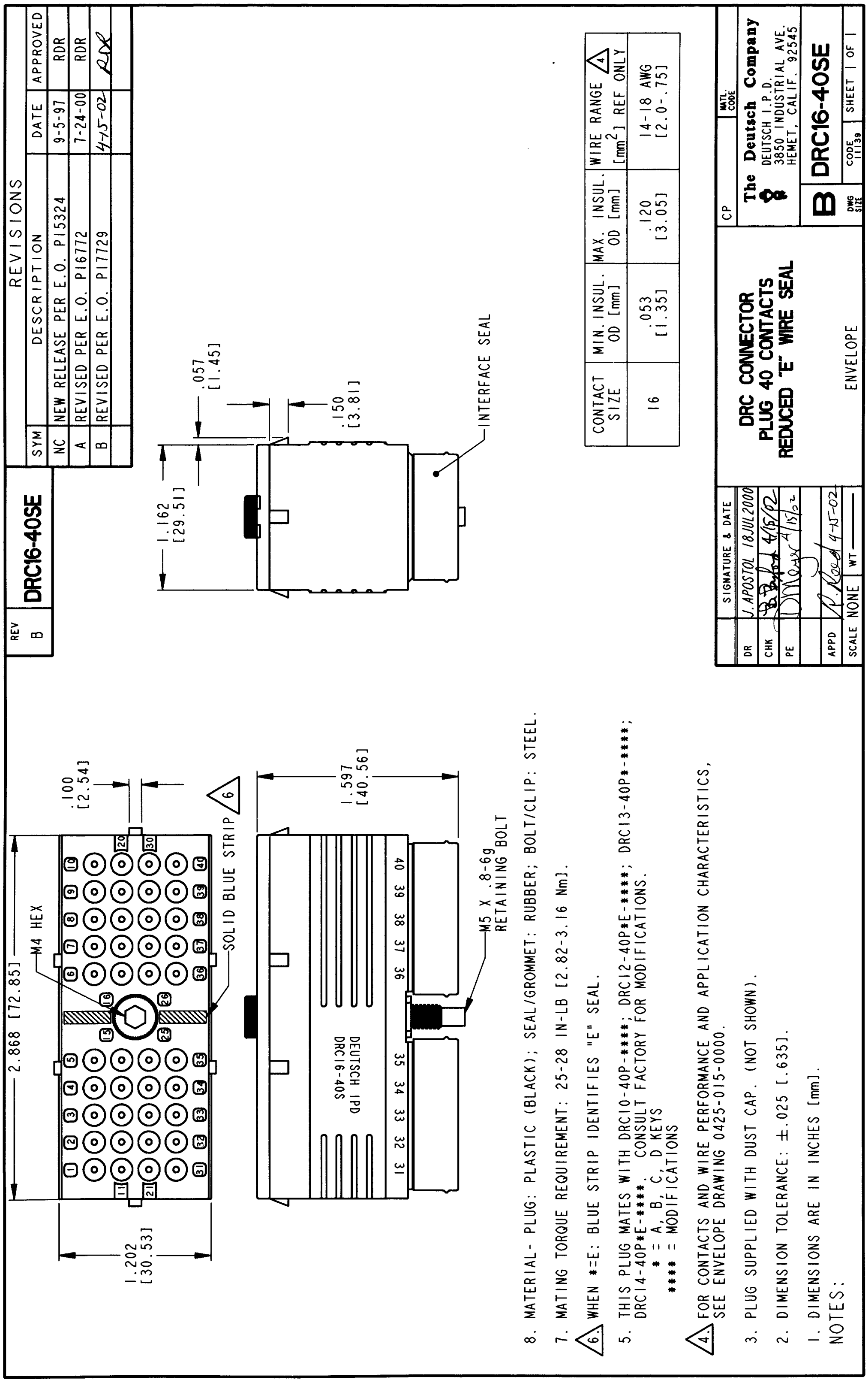
Figure C.7: R_x in dependence of joint number

C.4 Drawings

Technical drawings DRC12-40PA of and DRC16-40SE on the next two pages. The documents were retrieved 2014-08-06 from:

- http://www.te.com/commerce/DocumentDelivery/DDEController?Action=showdoc&DocId=Customer+Drawing%7FDRC16-40SE%7FB%7Fpdf%7FEnglish%7FENG_CD_DRC16-40SE_B.pdf%7FDRC16-40SE
- http://www.te.com/commerce/DocumentDelivery/DDEController?Action=showdoc&DocId=Customer+Drawing%7FDRC12-40PAX%7FD%7Fpdf%7FEnglish%7FENG_CD_DRC12-40PAX_D.pdf%7FDRC12-40PA


REVISIONS
SYM DESCRIPTION DATE APPROVED
A REVISED PER E.O. P17701 4-4-02 R.D.R.
B REVISED PER E.O. P18662 8-26-04 R.D.R.
C REVISED PER E.O. P19093 11-4-05 R.D.R.
D REVISED PER E.O. P21119
REV D DRC12-40PA*
SEAL TYPE / CONTACT SIZE / MIN. INSUL. OD [mm] / MAX. INSUL. OD [mm] / WIRE RANGE [mm²] REF ONLY
NORMAL 16 .100 [2.540] .134 [3.404] 14-20 AWG [2.0-.50]
E 16 .053 [1.346] .120 [3.048] 14-20 AWG [2.0-.50]
2X KEYWAY
4X Ø.169 [4.29]
M5 x .8-6H THREADED INSERT
4X R.355 [9.02]
CAVITY 1
4X R.035 [.89]
RECOMMENDED CUTOUT
DEUTSCH IPD DRC12-40PA
NOTES:
1. DIMENSIONS ARE IN INCHES [mm].
2. DIMENSION TOLERANCE: ±.025 [.635]; PANEL CUTOUT: ±.010 [.25].
3. RECEPTACLE IS SUPPLIED WITH DUST CAP (NOT SHOWN).
4. FOR CONTACT AND WIRE PERFORMANCE AND APPLICATION CHARACTERISTICS, SEE DRAWING 0425-015-0000.
5. THIS RECEPTACLE MATES WITH DRC16-40S-****; DRC18-40SA-**** PLUGS. (****= ALL MODIFICATIONS) CONSULT FACTORY FOR MODS.
6. WHEN * = E: BLUE STRIP ON WELD CAP IDENTIFIES "E" WIRE SEAL.
7. MATERIAL: HOUSING: PLASTIC; GROMMET: RUBBER; INSERT: STEEL.
8. RECOMMENDED SCREW: 8-32 [M4]. TORQUE: 20-25 IN-LB [2.26-2.82 Nm].
RECEPTACLE, FLANGED
40 SIZE 16
DRC SERIES
KEY ARRANGEMENT -A-
ENVELOPE
DEUTSCH INDUSTRIAL
3850 INDUSTRIAL AVE. HEMET, CA 92545
B DRC12-40PA*
CODE 11139
SHEET 1 OF 1
SCALE NONE
DR D. MEYER 08/09/99


REV B DRC16-40SE
REVISIONS
SYM DESCRIPTION DATE APPROVED
NC NEW RELEASE PER E.O. P15324 9-5-97 RDR
A REVISED PER E.O. P16772 7-24-00 RDR
B REVISED PER E.O. P17729 4-15-02
2.868 [72.85]
M4 HEX
.100 [2.54]
1.202 [30.53]
SOLID BLUE STRIP 6
1.597 [40.56]
DEUTSCH IPD DRC16-40S
M5 X .8-6g RETAINING BOLT
1.162 [29.51]
.057 [1.45]
.150 [3.81]
INTERFACE SEAL
8. MATERIAL- PLUG: PLASTIC (BLACK); SEAL/GROMMET: RUBBER; BOLT/CLIP: STEEL.
7. MATING TORQUE REQUIREMENT: 25-28 IN-LB [2.82-3.16 Nm].
6. WHEN *=E: BLUE STRIP IDENTIFIES "E" SEAL.
5. THIS PLUG MATES WITH DRC10-40P-****; DRC12-40P*E-****; DRC13-40P*-****; DRC14-40P*E-****. CONSULT FACTORY FOR MODIFICATIONS.
* = A, B, C, D KEYS
**** = MODIFICATIONS
4. FOR CONTACTS AND WIRE PERFORMANCE AND APPLICATION CHARACTERISTICS, SEE ENVELOPE DRAWING 0425-015-0000.
3. PLUG SUPPLIED WITH DUST CAP. (NOT SHOWN).
2. DIMENSION TOLERANCE: ±.025 [.635].
1. DIMENSIONS ARE IN INCHES [mm].
NOTES:
CONTACT SIZE | MIN. INSUL. OD [mm] | MAX. INSUL. OD [mm] | WIRE RANGE 4 [mm²] REF ONLY
16 | .053 [1.35] | .120 [3.05] | 14-18 AWG [2.0-.75]
SIGNATURE & DATE
DR J. APOSTOL 18JUL2000
CHK
PE
APPD
SCALE NONE WT
DRC CONNECTOR
PLUG 40 CONTACTS
REDUCED "E" WIRE SEAL
ENVELOPE
CP
MATL. CODE
The Deutsch Company
DEUTSCH I.P.D.
3850 INDUSTRIAL AVE.
HEMET, CALIF. 92545
B DRC16-40SE
DWG SIZE CODE 11139 SHEET 1 OF 1

C.5 Bill of Materials

Bill of materials of Pseudo Panto on following two pages.

PseudoPanto
Bill of Materials

Total weight: 24,559 kg
Total cost: 328,31 SEK
Total # of parts: 547

Bottom

File name	Quantity	Volume [m^3]	Material	Density [kg/m^3]	Weight [kg]	Price [SEK/kg]	Material Cost [SEK]	Description
BottomFix_V3	1	8,37E-05	Stainless Steel austenitic	7860	0,658	12,00	7,89	Bracket that holds up the pantograph
BottomFork_V2	1	5,41E-06	Stainless Steel austenitic	7860	0,042	12,00	0,51	Connection to bottom end of pantograph
WasherBolt_5mm	4	5,89E-08	Steel	7860	0,002	5,00	0,01	
Bolt_5mmx24mm	1	5,42E-07	Steel	7860	0,004	5,00	0,02	

Middle

File name	Quantity	Volume [m^3]	Material	Density [kg/m^3]	Weight [kg]	Price [SEK/kg]	Material Cost [SEK]	Description
ccBox_A_V4	4	1,82E-04	Magnesium	1740	1,265	23,20	29,34	Cable Channels middle
ccBox_B_V4	3	1,82E-04	Magnesium	1740	0,948	23,20	22,00	Cable Channels middle
ccBox_END_A_V4	1	1,15E-04	Magnesium	1740	0,200	23,20	4,63	Cable Channel end
ccBox_END_B_V4	1	1,15E-04	Magnesium	1740	0,200	23,20	4,63	Cable Channel end
ccLid_V4	7	1,31E-04	Magnesium	1740	1,600	23,20	37,13	Lid for Cable Channel
ccLid_END_V4	2	6,78E-05	Magnesium	1740	0,236	23,20	5,47	Lid for Cable Channel end
LidLockBlock_V1	18	2,37E-07	Steel	7860	0,034	5,00	0,17	Lock for Lids
LidLockScrew_V1	18	2,88E-07	Steel	7860	0,041	5,00	0,20	
SpringPin_2mm	18	1,34E-08	Steel	7860	0,002	5,00	0,01	
Clamp_Inner	18	2,55E-06	Steel	7860	0,360	5,00	1,80	Clamp for edge protection
Clamp_Outer	18	2,71E-06	Steel	7860	0,384	5,00	1,92	Clamp for edge protection
ClampSpring	18	2,23E-07	Steel	7860	0,032	5,00	0,16	Spring for clam
Lever	18	8,75E-07	Steel	7860	0,124	5,00	0,62	Lever for clamping

ParallelPin_5mmx55mm	8	1,08E-06	Steel	7860	0,068	5,00	0,34	Pin for hinges
Bolt_threaded_5mmx70mm	40	1,39E-06	Steel	7860	0,437	5,00	2,18	
Bolt_threaded_5mmx80mm	9	1,59E-06	Steel	7860	0,112	5,00	0,56	
BushingFlapped_D7xL5	9	1,70E-07	Polyamide	1140	0,002	33,60	0,06	Bearings for cable channel
BushingFlapped_D7xL8	196	2,26E-07	Polyamide	1140	0,051	33,60	1,70	Bearings for arms
Distancer_28mm	47	2,24E-06	Steel	7860	0,829	5,00	4,14	
Distancer_4mm	9	3,20E-07	Steel	7860	0,023	5,00	0,11	
LockNut_M4		1,49E-07	Steel	7860	0,000	5,00	0,00	
PantografArm_2Point_back_V2	4	1,66E-05	Stainless Steel austenitic	7860	0,521	12,00	6,26	Pantograph end arm
PantografArm_2Point_front_V2	4	1,66E-05	Stainless Steel austenitic	7860	0,521	12,00	6,26	Pantograph end arm
PantografArm_3Point_back_V2	30	3,10E-05	Stainless Steel austenitic	7860	7,307	12,00	87,69	Pantograph middle arm
PantografArm_3Point_front_V2	30	3,10E-05	Stainless Steel austenitic	7860	7,307	12,00	87,69	Pantograph middle arm

Top

File name	Quantity	Volume [m^3]	Material	Density [kg/m^3]	Weight [kg]	Price [SEK/kg]	Material Cost [SEK]	Description
Bolt_5mmx30mm	1	6,60E-07	Steel	7860	0,005	5,00	0,03	
CabFixtureBracket_Swallow_V2	1	1,47E-05	Stainless Steel austenitic	7860	0,116	12,00	1,39	Bracket to fix rail on bottom
HexScrew_M5x14	4	5,89E-07	Steel	7860	0,019	5,00	0,09	
InvSwallowJoint_V2	1	6,35E-06	Stainless Steel austenitic	7860	0,050	12,00	0,60	Swallowtail running on rail
InvSwallowRail_V2	1	1,35E-04	Stainless Steel austenitic	7860	1,057	12,00	12,69	Rail on wall
Nut_M5	2	2,59E-07	Steel	7860	0,004	5,00	0,02	
TopFork_V2	1	6,66E-06	Stainless Steel austenitic	7860	0,052	12,00	0,63	Top connection to pantorgraph

C.6 Material Database Charts

PseudoPanto

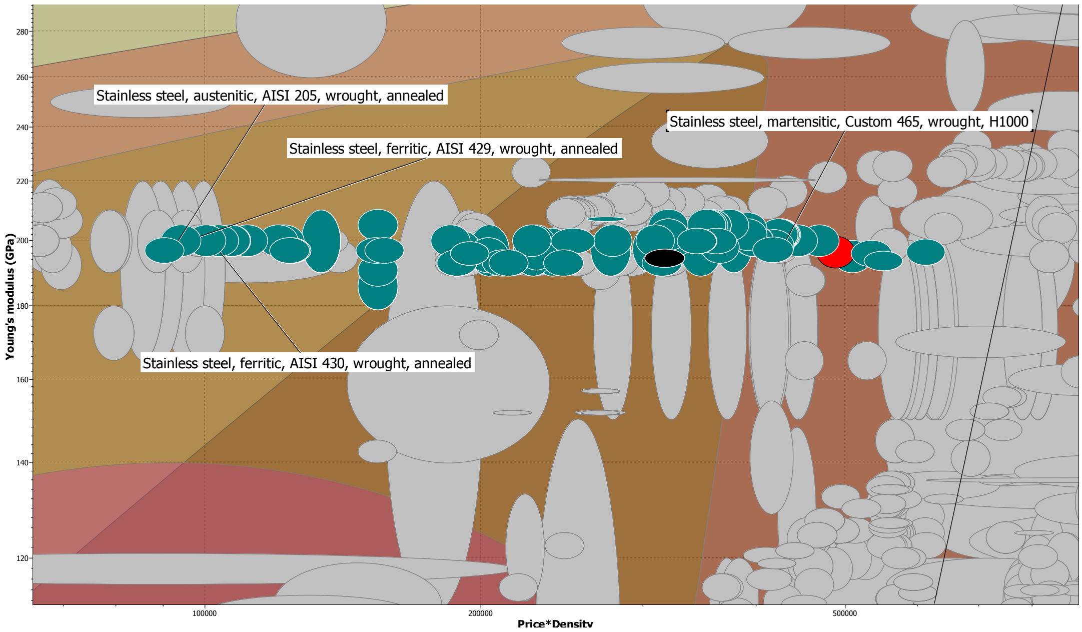


Figure C.8: Pantograph arms: Young's modulus over price*density

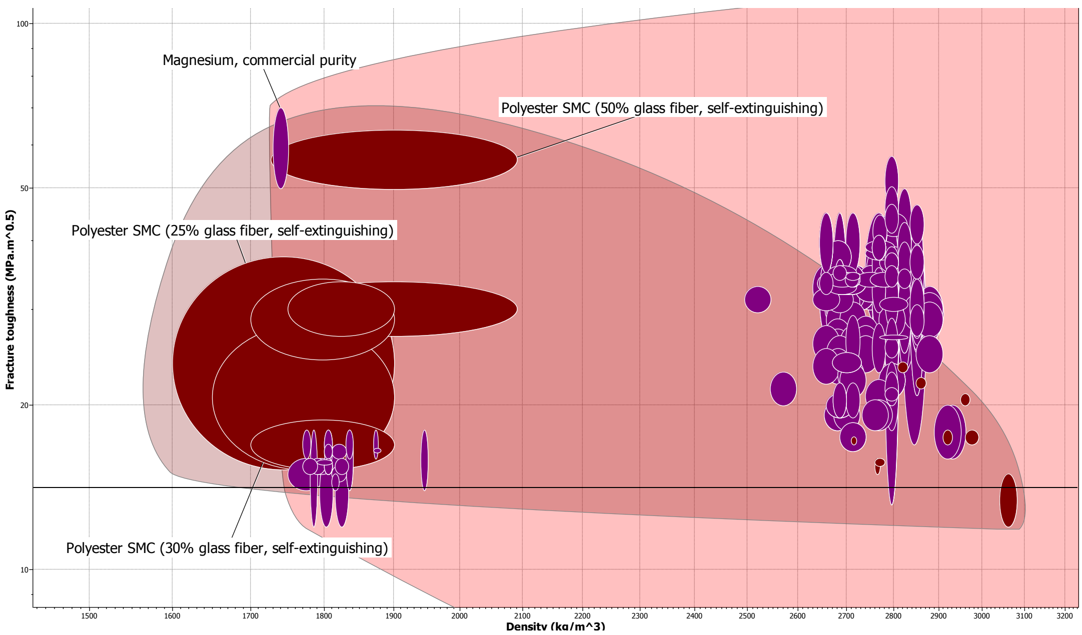


Figure C.9: Cable channels: Fracture toughness over density

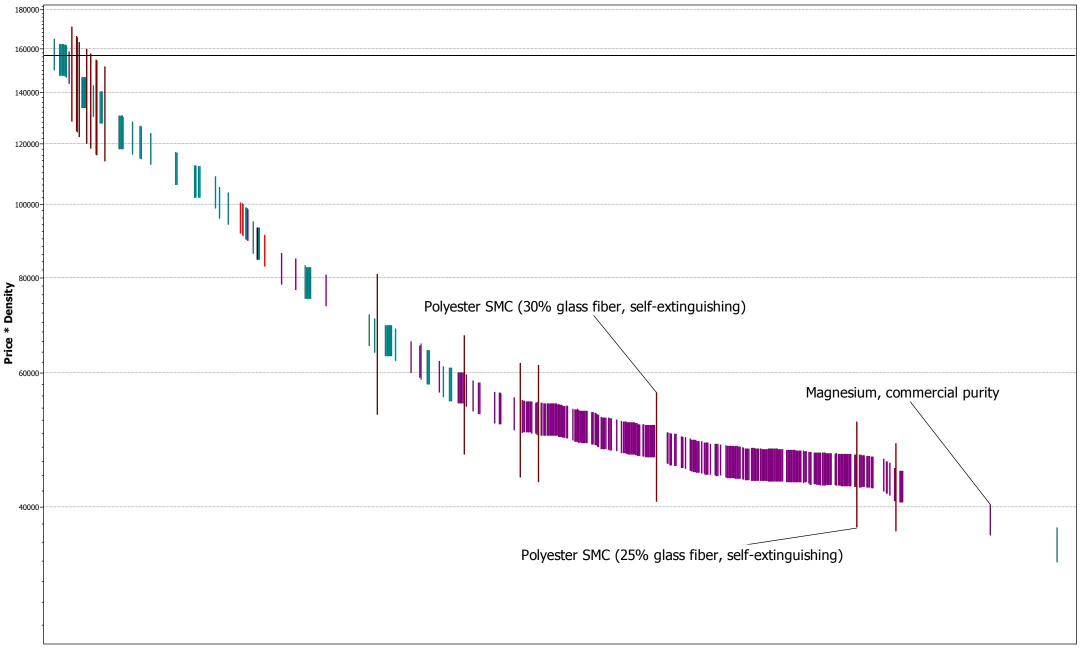


Figure C.10: Cable channels: Price*density

Selfie

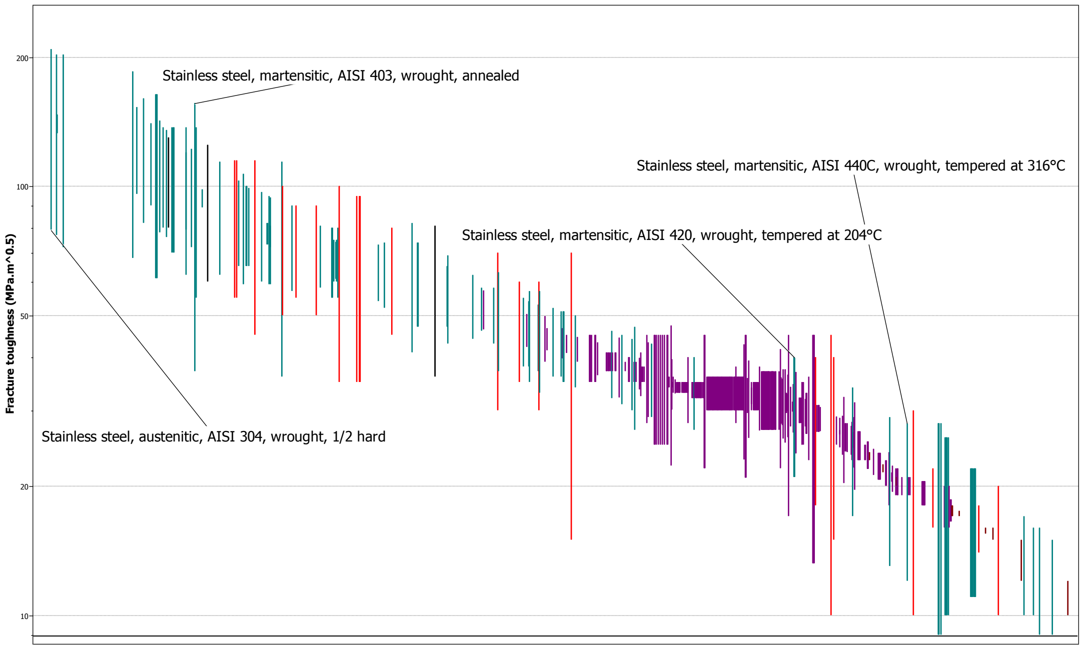


Figure C.11: Outer Shell: Fracture toughness

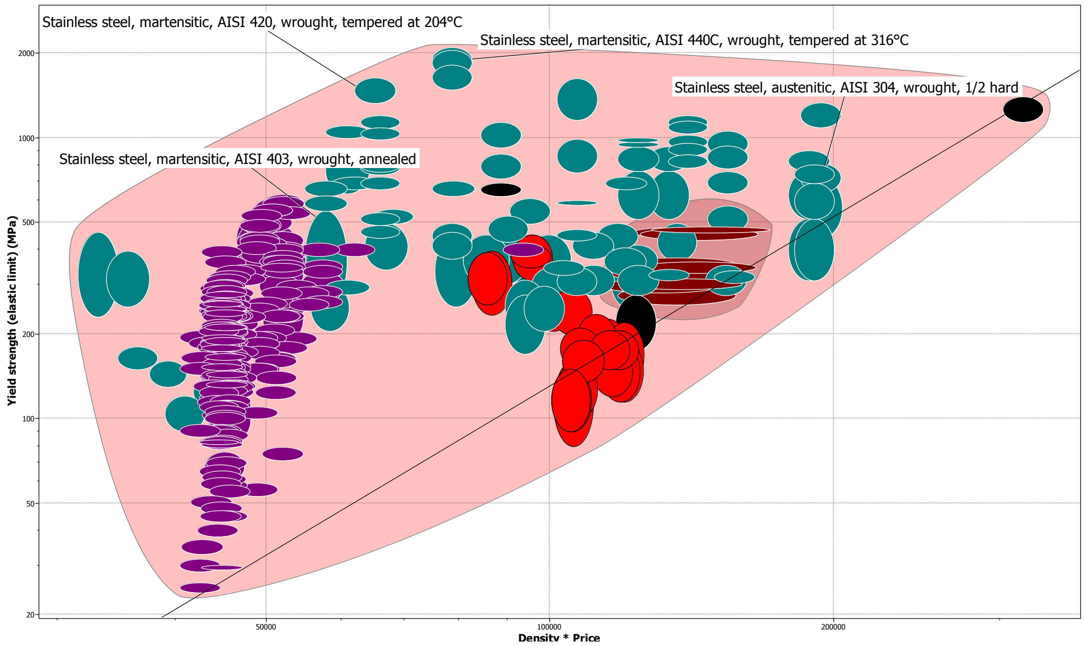


Figure C.12: Outer Shell: Yield strength over density*price

Figure C.13: Plug and Antiplug: Density*price