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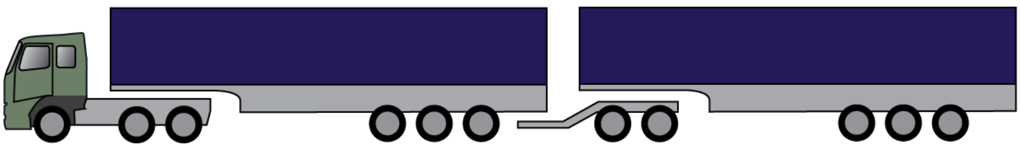

Development of a dolly trailer

Designing a dolly for large-volume goods

Master of Science Thesis in the Master's Degree Programme in Product Development

CARL DAVIDSSON
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Department of Product and Production Development
Division of Product Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2011

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Abstract

Fierce competition, high fuel prices, and ever-increasing environmental awareness and concern make efficient road transport solutions more relevant than ever. Using longer vehicle combinations than the current standard allows for fuel consumption and emissions to be reduced drastically. Duo^2 is a joint research project studying environmental and safety aspects of longer vehicle combinations. Current EU regulations define a European-wide module-based system for trailers called the European Modular System (EMS). This Master's thesis studies design possibilities of one of these modules – the dolly trailer.

A dolly trailer is basically a small trailer, allowing for a coupling between a towing vehicle lacking a fifth wheel (horizontal coupling plate), such as a truck, to tow a trailer with a fifth wheel coupling, such as a link or semi-trailer. Investigations have been made regarding the possibility of design improvements to the dolly, with a large focus on reduction of the overall height. Reducing the height of the dolly would in turn mean that semi-trailers could be designed with more cargo space – increasing transport efficiency. This report documents the design process, from pre-studies and concept generation, through concept elimination and selection. Further redesign possibilities are also taken into consideration, especially in the form of adapting Volvo truck chassis components and design principles into trailer design. Two viable production concepts are presented, as well as a design study in extremely low chassis design.

Keywords: Volvo, trailer design, low chassis, Dolly, Duo^2, European Modular System (EMS), trailer, large-volume, Epsilon.

Nomenclature

Fifth wheel	A horizontal plate pivoting around a towing vehicle's transversal axis with a hole to which the kingpin of the towed vehicle can be mounted.
Fifth wheel coupling	A coupling between a trailer and a towing vehicle consisting of a fifth wheel and a kingpin.
Kingpin	Solid steel rod protruding vertically from the bottom of a semi-trailer. Connects to a fifth wheel to form an articulated joint in a vehicle combination.
Ride height	Vertical distance between wheel axle centre and chassis mounting point of the suspension.
Tare weight	Weight of unladen vehicle

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1 Introduction

This report presents the process and results of a product development project concerning the construction of a dolly trailer (Figure 1) used in the commercial vehicles industry. The project was carried out at Epsilon Utvecklingscenter i Väst AB (henceforth referred to as Epsilon) in Gothenburg, Sweden, as a part of a research project.

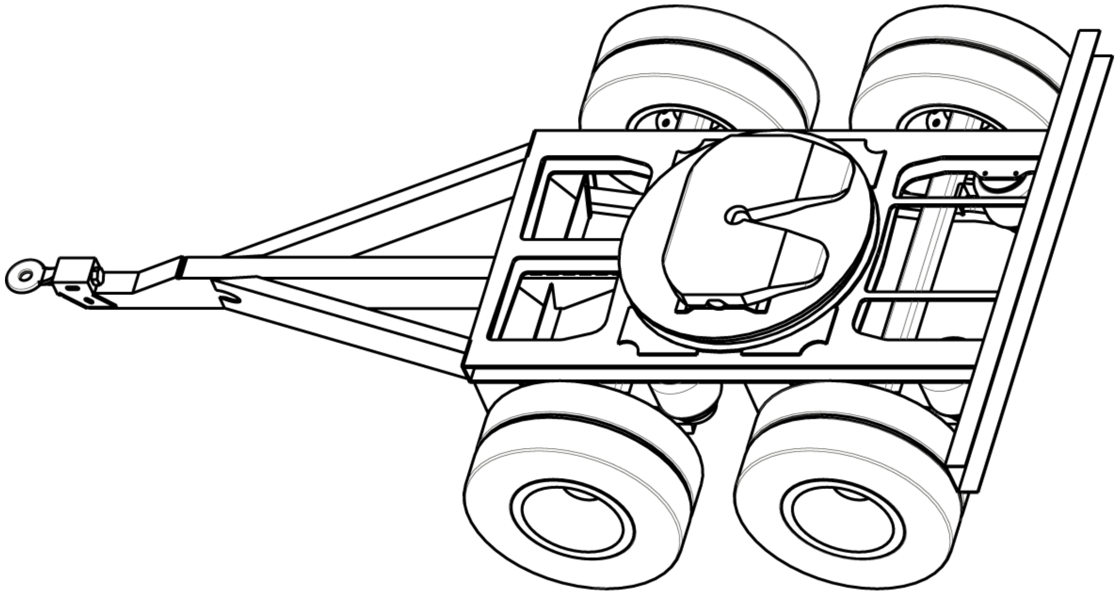

Figure 1 Dolly trailer

1.1 Background

The present legal requirements of today allow for vehicle combinations on Swedish roads to be up to 25.25 metres long, and weigh up to 60 tonnes (Swedish National Road and Transport Research Institute, 2008). This is both longer and heavier than most other countries allow, but is it possible to safely go even bigger?

Studies have shown that longer and heavier vehicles do not only increase the efficiency of transportation with respect to fuel consumption per transported distance and goods (l / (tonnes × km)), but also increases the traffic safety due to a reduction of the total number of vehicles on the road. (Löfroth & Svensson, 2010; Swedish National Road and Transport Research Institute, 2008) It is not uncomplicated to build longer and heavier vehicles, consequently manufacturers invest in research and development efforts to improve structural strength, driving characteristics and safety. Furthermore, in order to achieve equal competitive opportunities, a European Union agreement called the European Modular System (EMS) has been signed by all member states. The system is based on a fixed set of modules that make up all different vehicle combinations. Within this system, the dolly is a vital module that enables couplings between trailers and trucks.

1.1.1 The European Modular System

The European Modular System was introduced as a result of Sweden and Finland joining the EU. Traditionally, the two countries had allowed for much longer vehicle combinations than EU regulations would allow for commercial vehicles. As longer combinations were seen as both economically and environmentally superior, Sweden and Finland refused to comply with the EU regulations, while other member states argued that allowing longer vehicle combinations in some countries would create an unfair competitive advantage. This led to the development of a new agreement – the European Modular System – that allowed membership states to allow longer or heavier vehicles on parts of the road network as long as they adhered to a set of standardised modules outlined by the EU. One should note that neither the 25.25 metre length limit nor the 60 tonne mass limit are specified in the European Commission directive, but in Swedish regulations as the Commission directive allow member states to individually regulate these parameters. (EMS Informal Platform Group, 2009; The Council of the European Union, 1996)

Definitions of modules in EMS

The intent of the EMS is to standardise vehicle combinations. Hence, a finite set of vehicle modules are defined and outlined by the directive. All modules compliant with the regulations are to be considered road legal within the entire EU, although regulations governing vehicle combinations may vary between member states. (EMS Informal Platform Group, 2009)

Truck

A truck (Figure 2) is a motor vehicle with space for a swap body or load area. The axles of the truck configuration most often consist of one front axle and two rear axles, but configurations with three or more rear axles exist as well. The driven axles are commonly one or more of the rear ones, but special cases exist where the front wheels are also driven. (Aurell & Wadman, 2007)

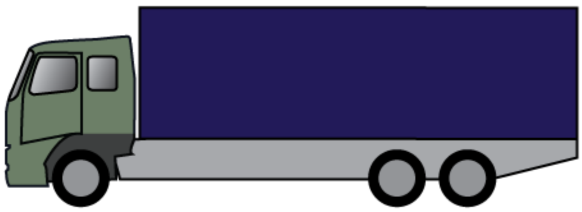

Figure 2 Truck

Tractor

A tractor (Figure 3) is a motor vehicle used to tow trailers. Instead of a swap body or load area it includes a fifth wheel coupling for attaching a semi-trailer or link. The tractor has a similar axle configuration as a truck, but is usually shorter. (Aurell & Wadman, 2007)

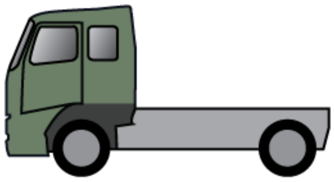

Figure 3 Tractor

Dolly

A dolly (Figure 4) is a towing trailer with a fifth wheel coupling that is designed to tow a semi-trailer or link. For a more comprehensive description of a dolly see section 3.7. (Aurell & Wadman, 2007)

Figure 4 Dolly

Semi-trailer

A semi-trailer (Figure 5) has no front axle, but is instead supported by a fifth wheel coupling on the towing vehicle. The rear is supported by a tandem or triple axle. The semi-trailer has a kingpin that is either attached to the fifth wheel coupling on a dolly, link or tractor. The EMS specifies the standard length of a semi-trailer to 13.6 metres. Semi-trailers with a lowered bed height (to increase cargo volume) are called mega-trailers. (Aurell & Wadman, 2007)

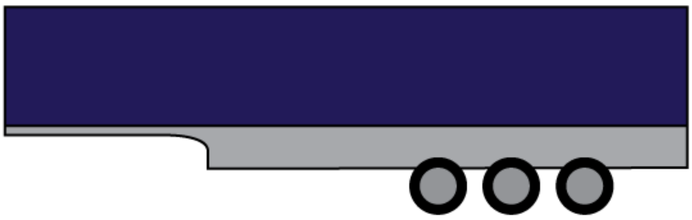

Figure 5 Semi-trailer

Link

A link (Figure 6) has a loading area or swap body in the front and a fifth wheel in the back. It attaches to a dolly or a tractor via a kingpin and has the ability to act as a towing trailer to a semi-trailer. As with the semi-trailer it has no axle in front, but a tandem or triple rear axle configuration. (Aurell & Wadman, 2007)

Figure 6 Link

Centre axle trailer

A centre axle trailer (Figure 7) has a tandem axle located in the centre of the chassis and is attached to a vehicle in front using a drawbar for stability. The drawbar used on a centre axle trailer is commonly rigid. (Aurell & Wadman, 2007)

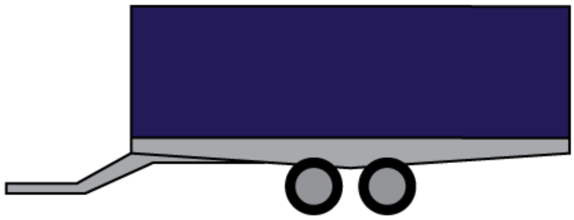

Figure 7 Centre axle trailer

Swap body

A swap body (Figure 8) is a storage area that is used together with a centre axle trailer, a truck or a link. The length of a swap body is specified to 7.82 metres in EMS. (Aurell & Wadman, 2007)

Figure 8 Swap body

Full trailer

This module is not part of the EMS, but is an old Swedish standard. A full trailer (Figure 9) has both a front axle and a rear axle, in some cases tandem axles, and is connected to a vehicle in front with a drawbar, which is normally hinged, i.e. pivoting around the transversal axis. (Aurell & Wadman, 2007)

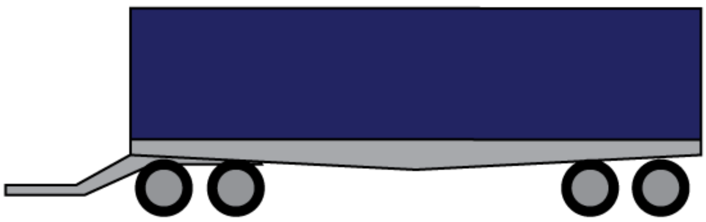

Figure 9 Old Swedish trailer

1.1.2 The Duo² project

Duo² is a research project that is partially funded by the Swedish government agency Vinnova, within their transport efficiency programme, with the overall aim to reduce the carbon dioxide equivalent emissions and the number of vehicles on Swedish roads. Volvo Technology, a subsidiary company of the Volvo Group, is the project owner and work in close cooperation with a number of subcontractors to achieve these goals. (Vinnova, 2010)

During the project, vehicle combinations are going to be evaluated concerning their traffic safety, emissions and load capacity. Vehicle tests are to be performed on a predetermined route between Gothenburg and Malmö in Sweden. The goal set for reductions in carbon dioxide emissions is 15 % per m^3×km, while the vehicle efficiency aim is to increase the m^3×km per vehicle by 40 % and decrease congestion by 30 %. (Vinnova, 2011)

The vehicle combinations used in the project are based on the European Modular System and could thus potentially be used in the entire European Union. However, the initial focus is to legalise longer vehicle combinations in Sweden.

Field test

During the summer of 2011 field tests will commence using two different vehicle combinations. The tests are performed to provide data regarding traffic safety, transport efficiency, driving characteristics and mechanical properties.

Field test configuration 1

The first combination consists of a tractor, two mega-trailers (large semi-trailers) and one dolly. This configuration is illustrated in Figure 10, with lengths and axle pressures. Note that the sum of the individual allowed axle pressures is 92 tonnes, while the maximum allowed pressure is 80 tonnes for the entire combination.

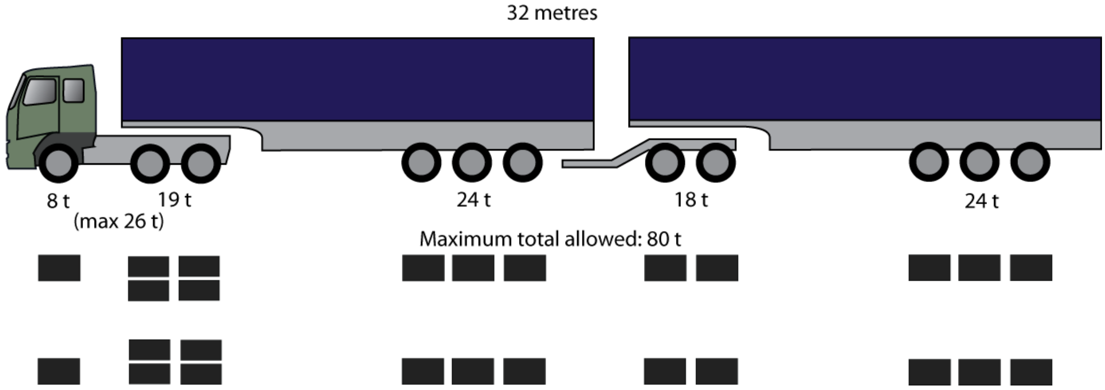

Figure 10 Tractor - Semi-trailer - Dolly - Semi-trailer, including wheel configurations

Field test configuration 2

The second combination does not include a dolly, but is a truck combined with two centre axle trailers. This configuration is shorter than the first configuration, and the length and axle pressures may be seen in Figure 11.

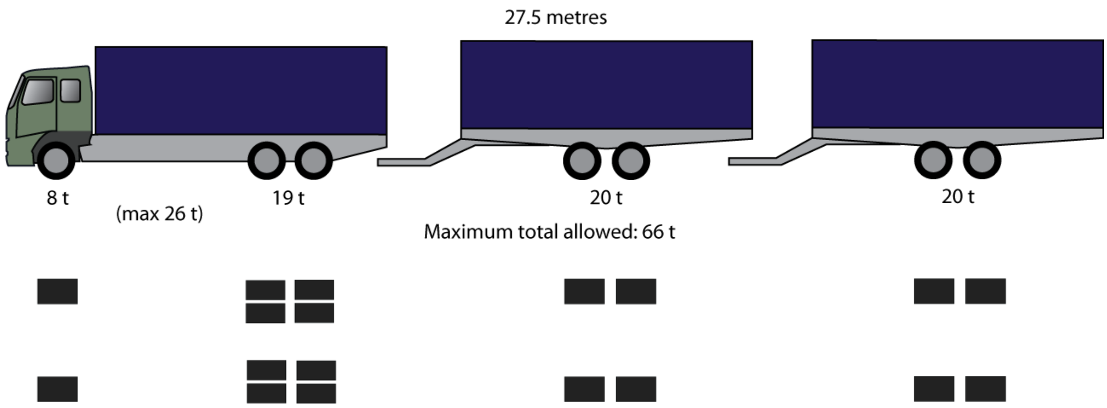

Figure 11 Truck - Centre axle trailer - Centre axle trailer, including wheel configurations

Companies involved

Volvo Technology is the project owner and receives the grant from Vinnova. Volvo Technology and Volvo 3P, both part of the Volvo Group, together develop the new trucks. Their responsibility is primarily to develop the truck and the tractor, but they also contribute with input and expertise to other stakeholders such as trailer manufacturers and the Swedish Transport Administration. Epsilon is a consulting company that has a good relationship with the Volvo Group and is intimately involved in the project.

The dolly and the other trailers in the Duo^2 project are designed and manufactured by Norrborns Industri AB in Bollnäs, Sweden, under the brand name Parator. Norrborn Industri AB is a small business and therefore has little time and resources for research and new product development. Most of their designs are based on previous experience and the mentality is rather to over-dimension than to optimise.

Other companies and government agencies involved are: DB Schenker, SSAB, Sveriges Åkeriföretag (Swedish haulage trade organisation), The Swedish Motor Vehicle Inspection Company, The Swedish National Road and Transport Research Institute, The Swedish Transport Agency, Team Kallebäck, The VBG Group and Wabco.

1.2 Problem description

As mentioned, the trailer manufacturer Parator is a small business with limited new product development. Many of their new products are designs based on existing products and years of experience. Therefore, the dolly is assumed to have unexplored areas of potential improvements. This is also the reason why the Duo^2 project group initiated this project; their knowledge about dollies and the potential improvements of them was limited.

Today the dolly is a mainly welded design, which is both expensive and unsatisfactory from a maintainability viewpoint. Welding is not only expensive but introduces heat to the steel alloy, and thereby changes the material properties, and also requires a high degree of manual labour. A truck chassis has a more standardised manufacturing method and application of some of the manufacturing techniques from Volvo to the dolly could perhaps make the production of it more efficient.

The current dollies from Parator have robust designs, and there have been no actual calculations or investigation to find out what dimensions are needed to withstand the forces applied to a dolly during use. Instead, the design is based on experience of what works, and what does not. A more thorough investigation of the design parameters can create better understanding of which parts of the dolly that are most exposed to high stresses, and which parts that can have reduced dimensions. This information may also help to validate different concepts of reducing the ride height.

The never-ending rationalisation of the haulage industry nowadays prioritises, to a large extent, research on how to accommodate larger transported volumes (Löfroth & Svensson, 2010). In this research it is found that one of the bottle-necks in the system is the dolly. Decreasing the height of the dolly provides a larger volume available for the trailer, hence increasing cargo volume. Nevertheless, the dolly needs to be safe, robust and able to cope with the dynamic forces.

1.3 Purpose

This project was initiated as an exploratory project within the Duo^2 research project. The scope is to investigate possibilities of improving the dolly design with respect to manufacturability and operational performance. Duo^2 strives to make the haulage industry more efficient, in terms of the volume of transported goods per vehicle. Hence, much focus is directed towards exploring potential concepts of producing very low dollies.

1.4 Aim

The objective of this project is to develop concepts that facilitate low dolly chassis, with improved manufacturability, and with potential for a future market introduction. Within twenty working weeks, final concepts are to be presented with detailed CAD drawings.

1.5 Delimitations

The Duo^2 project is a partly government funded project. This in combination with the fact that laws and regulations differ between countries, one limitation of the project is that the dolly designed will only be taking laws and regulations applicable in Sweden into consideration.

Only such components and modules that directly affect the chassis design will be considered. Hence, pressure tanks, braking system, electronics, lightings etc have been excluded from the design part of this project. Furthermore, due to the early stage in the development, material selection issue is not part of the project. All chassis are assumed to be made of the same steel alloy.

1.6 Environmental aspects

The main environmental impact of the haulage industry is of course carbon dioxide emissions. As in society as a whole, there is a growing environmental awareness within the industry. This is perhaps not only due to an increasing awareness of the industry’s environmental impact, but an ever-present concern of the increasing price of fuel (This is money, 2011). The Duo^2 project as a whole has the potential to greatly reduce the fuel consumption for long-haul operations, which in turn reduces carbon dioxide emissions (Löfroth & Svensson, 2010). The dolly has the potential to contribute by allowing for even larger cargo volumes to be transported. Other life-cycle aspects could be considered, such as manufacturing waste and energy consumption, servicing, tyre wear etc., but as a component of a vehicle combination, these aspects have minimal contribution to the emissions.

2 Methodology

The project structure mainly adheres mainly to the product development principles found in the books "Product design and development" (Ulrich & Eppinger, 2000) and "Revolutionizing product development" (Wheelwright & Kim, 1992). Hence, a standardised structure for the product development process has been applied, combining elements from both books. The process used can be described as a funnel approach, as illustrated in Figure 12. The funnel structure implies that the process starts off with a plethora of ideas, covering a broad range of concepts and possibilities. As the project progresses, the funnel narrows. Concepts are discarded; others are combined or improved, resulting in a convergence towards a final solution.

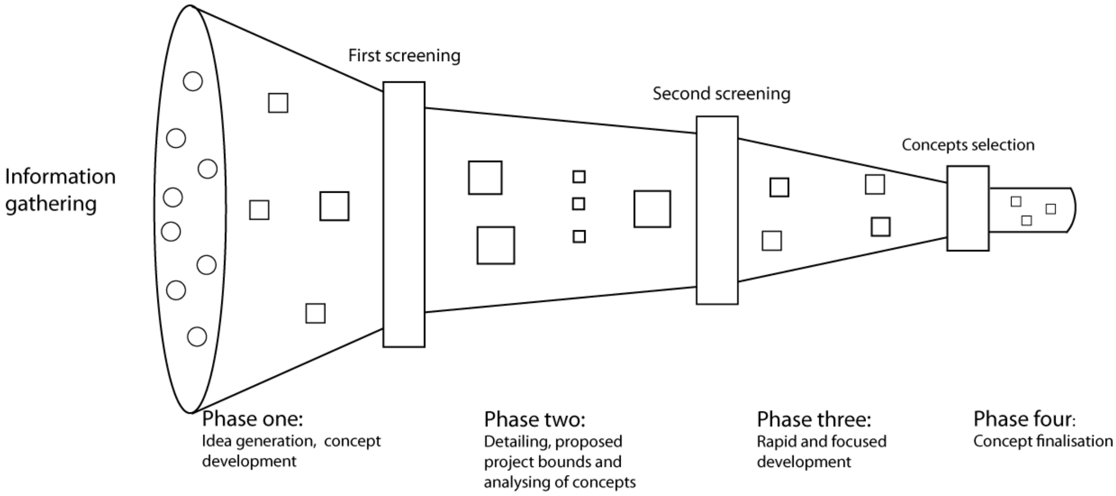

Figure 12 The development funnel, inspired by Wheelwright and Clark (1992, pages 119 & 124)

2.1 Pre-study

After establishing the project scope and delimitations, as well as planning the project using a Gantt-chart, a literature study was carried out in order to gather the necessary information. Focus was largely directed towards establishing a solid requirements specification for future reference in the project. Hence, national and international regulations, legislations and directives were researched in order to determine all legal requirements that had to be met. The European Modular System, as well as trucks in general, was studied in order to gain an understanding of different vehicle combinations and the function of each component.

The primary research method was literature studies of European Council regulations and directives, ISO standards, and regulations from the Swedish Transport Agency. Interviews were also carried out with representatives from ISO, a trailer manufacturer, and a hauling company. To encourage an open and free discussion, the interviews were held in a quite informal manner, but with some standardised questions asked to all participants. Study visits were also arranged; one to a manufacturer of high-strength steel, and one to a trailer manufacturer in order to observe the facilities and the current production methods.

Since optimisation of the chassis structure was an important part of the project, a reference model was needed for structural calculations. This was created by receiving 2D drawings of an existing dolly trailer from a manufacturer, creating a reference 3D CAD model, and then carrying out FEA stress- and stiffness calculations to be used as a benchmark. Different concepts regarding the construction of a dolly were sought out from manufacturer websites and catalogues, as well as study visits to truck parking lots and a trailer rental company.

2.2 Concept generation

Concepts for improvements in the dolly design were generated based on the pre-study, benchmarking and the requirements specification. Both unstructured and creative methods, such as brainstorming sessions and sketching random ideas, as well as more systematic methods, such as morphological matrices, were used during this stage.

2.3 Concept evaluation and selection

For evaluation of basic design ideas and concepts, quick sketches were used as visual aids in discussion regarding the strengths and weaknesses of different concepts. For further analysis basic CAD mock-ups were used in order to evaluate compatibility with other components as well as design constraints imposed by different concepts. For evaluation of the final alternatives in the concept selection process, fully detailed CAD models were produced and FEA was carried out in order to evaluate chassis stiffness and stress distribution for different design concepts.

To evaluate the different concepts relative to each other, in order to make informed decisions when selecting what concepts to develop further, Elimination- and Pugh matrices were used together with expert discussions. When evaluating concepts, possibilities of combining two or more concepts into one superior concept were also explored.

2.4 Detailed design

Detailed design was performed using the Pro/Engineer 3D CAD modelling software from PTC. This was done for the concepts deemed the most viable contenders for a production model. 3D modelling allowed for subcontractor components to be packaged on the chassis structure, and for different suspension assemblies to be evaluated for compatibility with the chassis designs. The design phase involved refining the basic design concepts for chassis structures into full assemblies incorporating all necessary sub-systems. FEA calculations were also performed iteratively for the detailed chassis models, and design adjustments were done in order to optimise the structure and minimise stress concentrations.

More detailed design of the basic chassis design concepts highlighted issues and strengths previously not considered, such as compatibility with different sub-systems and manufacturing issues arising from design constraints. This, as well as more in-depth FEA studies, provided additional information for the final concept selection.

3 Theory

In this chapter, theories that are fundamental to the understanding of this report are presented. For a more comprehensive explanation of the theory it is suggested to read the cited references.

3.1 D- and V-values

International standards (The Council of the European Union, 1994) specify the minimum forces that a coupling must be able to resist in order to be considered safe, and the Swedish Transport Agency refers to these standards in their regulations. The values obtained from the ISO standards are called D- and V-values respectively.

The D-value is defined as the theoretical reference value of the horizontal force between a towing vehicle and a trailer, while the V-value is the theoretical amplitude of the vertical force in a coupling. (VBG Group, 2005) How to calculate these values vary between different vehicle modules and combinations. Currently there are no actual standards on how to calculate combinations using a dolly; however, it is common to use the same equations as for a centre axle trailer with a rigid drawbar combination. Svensson[1] explains that a review of the standards is in progress, where guidelines for calculations regarding combinations including dollies are specified. The following equations are relevant to dollies and are derived from the current standards of Swedish Transport Agency directives. (Swedish Transport Agency, 2003; VBG Group, 2005)

$$V_{drawbar} = a \cdot \frac{X^2}{L^2} \cdot C[kN] \tag{1}$$

$Note: L \geq X, else\ the\ value\ of\ \frac{X^2}{L^2} = 1$
$a = 1.8; 2.4\ [m/s^2]$[2]
$X = length\ of\ trailer\ [m]$
$L = length\ of\ drawbar\ (drawbar\ eye\ to\ bogie\ centr\ )\ [m]$
$C = axle\ load\ [tonnes]$

$$D_{hinged\ drawbar} = g \cdot \frac{T \cdot R}{T + R} [kN] \tag{2}$$

$$D_{rigid\ drawbar,} = g \cdot \frac{T \cdot C}{T + C} [kN] \tag{3}$$

$$D_{fifth\ wheel} = g \cdot \frac{0.6 \cdot T \cdot R}{T + R + U} [kN] \tag{4}$$

$$V_{fifth\ wheel} = g \cdot U\ [kN] \tag{5}$$

T= Technically permissible maximum mass in tonnes of the towing vehicle
R= Technically permissible maximum mass in tonnes of the full trailer

[1] Bolennarth Svensson (Business Engineer, Coupling equipment, VBG Group, interviewed by authors 2011, March 15)
[2] 1.8 m/s^2 for vehicles with air suspensions, 2.4 m/s^2 for other vehicles.

U= Fifth wheel coupling imposed vertical load in tonnes.

The new ISO standard presents how to calculate D- and V-values for vehicle combinations within the European Modular System. The following equations are ordained for the first vehicle combination mentioned in section 1.1.2 (ISO/TC 22/SC 15N 579 Rev1, 2011)

$$D_{fifth\,wheel} = \frac{1}{2} \cdot g \cdot \frac{(T + R_{1b} + W_d) \cdot \left((U_d + R_{2b}) + 0.08 \cdot (T + R_{1b} + W_d)\right)}{T + R_{1b} + W_d + U_d + R_{2b} - U_d} \quad (6)$$

$$V_{fifth\,wheel} = g \cdot U_d \quad (7)$$

$$D_{drawbar} = \frac{13}{20} \cdot g \cdot \frac{(T + R_{1b}) \cdot (C_d + R_{2b})}{T + R_{1b} + C_d + R_{2b}} \quad (8)$$

$$V_{drawbar} = Max\left(\frac{54}{L}; 5 \cdot \frac{C_d}{L}\right) \quad (9)$$

T= Technically permissible maximum mass of the tractor
R_{1b} = Technically permissible maximum mass of first semi-trailer's rear axles.
R_{2b} = Technically permissible maximum mass of second semi-trailer's rear axles.
W_d= Tare mass of dolly.
U_d= Mass of semi-trailer that affects fifth wheel coupling on dolly.
C_d= Technically permissible maximum mass of dolly.
$L = length\ of\ drawbar\ (drawbar\ eye\ to\ bogie\ centre)$

(ISO/TC 22/SC 15N 579 Rev1, 2011)

The testing of the couplings in a system is performed as both static and dynamic tests, where the forces corresponding to the computed values are applied individually to the coupling. This means that tests are never performed with more than one D- or V-force applied at the same time. (The Council of the European Union, 1994)

3.2 Beam theory

Beams are widely used as a construction element, and are used by Volvo in their truck chassis design. Hence, it is important to have some rudimentary knowledge of the basics of beam theory. A beam is defined as a straight body, with one dimension in the Cartesian coordinate system greatly exceeding the two other measures, and which is primarily exposed to transversal forces. These forces will lead to bending of the beam. (Lundh, 2002)

Application of transversal forces to the beam will cause internal stresses. They may either be acting as normal stresses in the beam's longitudinal direction or shear stresses in the cross-sectional area. The mechanical behaviour is different between beams with symmetric cross sections and those with asymmetric cross sections (Figure 13 illustrates both symmetric and asymmetric cross sections). A beam with a symmetric cross section, exposed to transversal forces acting in the symmetry plane will only bend in one plane while a beam with an asymmetric cross section will bend in two planes. (Lundh, 2002)

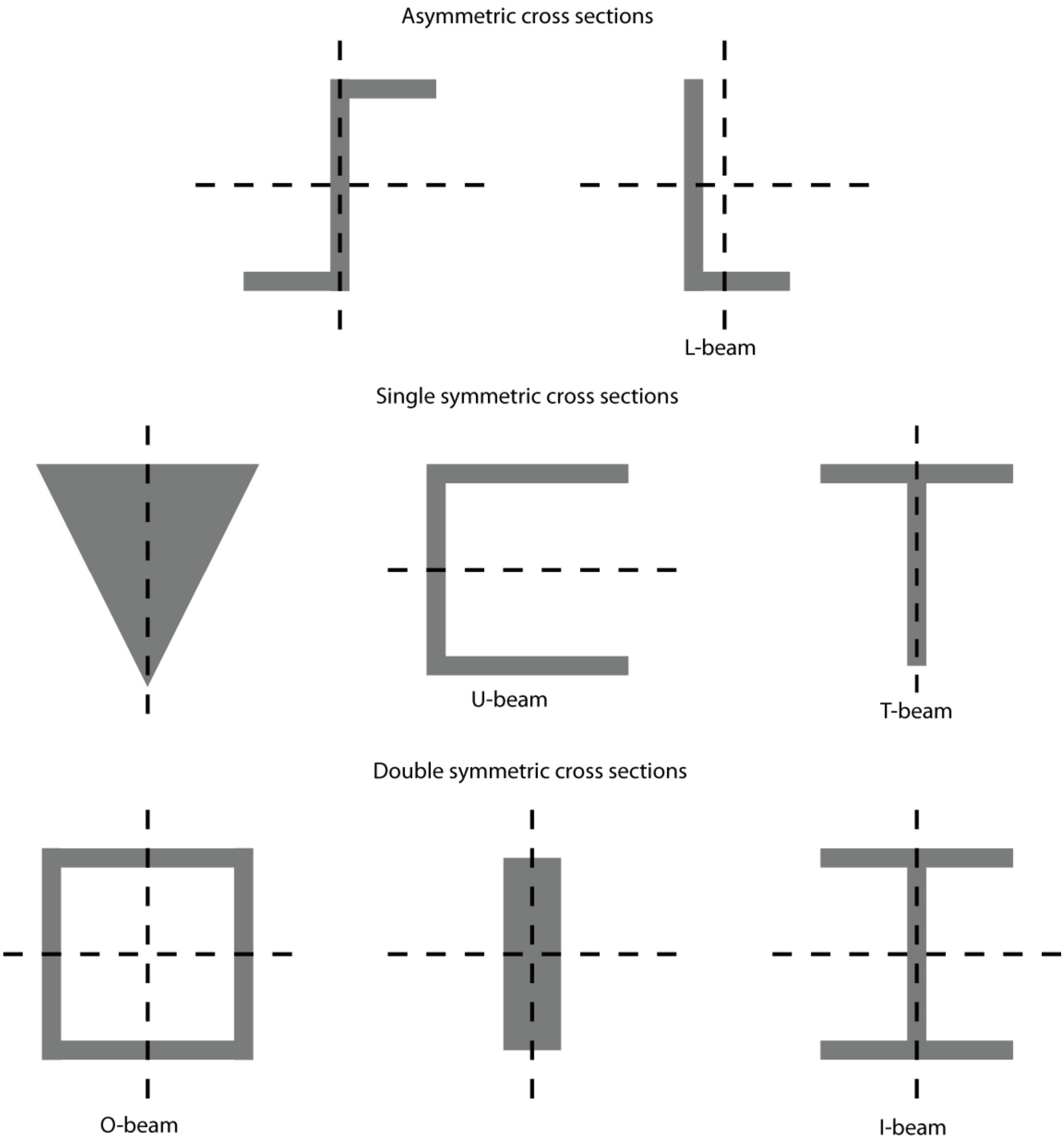

Figure 13 Cross sections of beams

The beam's ability to withstand bending and deflection depends on the Young's modulus for the material and the second moment of area (area moment of inertia) of the cross-sectional area. The area moment of inertia for all cross sections is defined in a Cartesian coordinate system placed in the centre of gravity (*xyz*) as:

$$I = I_y = \int_A z^2 dA \tag{10}$$

Calculations on a beam with asymmetric cross-sectional area are more complex, but follow the same basic rules. The cross section is divided into several double-symmetric sections and their respective area moments of inertia are added. (Lundh, 2002)

3.3 Finite Element Analysis

Finite element analysis (FEA) is a method for solving structural calculations using the finite element method. Essentially, the finite element method is a way of finding approximate solutions to partial differential equations. When applying the finite element method to structural analysis, the geometry is represented by finite elements whose mechanical properties are described by shape functions. The elements are connected by nodes, where boundary conditions such as constraints for rotation and translation, forces or couples are applied. The resulting equations are solved with respect to the given boundary conditions and an approximate solution is obtained.

3.3.1 FEA vs. analytical solution

For geometries with well-known mechanical properties, and with fairly simple boundary conditions, analytical solutions are possible by mere hand calculations. Consider, for example, a simple case of a steel cantilever beam with a square cross-section fully constrained at one end, and with a vertical force applied at the other end. The beam's area moment of inertia is derived from equation (10):

$$I = \frac{w \cdot h^3}{12} \tag{11}$$

$w = width\ of\ the\ cross\ section$
$h = height\ of\ the\ cross\ section$

The displacement of the outer end of the beam is given by:

$$\delta = \frac{P \cdot L^3}{3EI} \tag{12}$$

$L = length\ of\ beam$

Since the force (P) is given, Young's modulus (E) is a material property, and width, height and length are known properties of the geometry, the remaining variable is the displacement (δ) which can easily be found using the above equations. (Sundström, 1998)

Utilising finite element analysis on the same case would mean that the beam is divided into a number of elements joined at the ends at nodes. Each element will have properties such as; area (A), length (L) and Young's modulus (E). From these properties each element's stiffness (k) can be derived. A matrix will be assembled from the element stifnesses and equations for forces and displacements can be found using the $F = k\delta$ correlation. These are then solved by applying known boundary conditions (e.g. forces, constraints and displacements) to the nodes and solving the matrix for unknown displacements and stresses.

3.4 Product development process

There are as many product development processes as there are product development projects. However, there are recommended theories and procedures intended to increase the possibility of a successful project. This project adheres to a funnel approach, as described in Chapter 2:

Methodology. The following section describes the methods used for concept generation and screening.

3.4.1 Morphological matrix

A morphological matrix can be a useful aid in generating a multitude of concepts and ideas. The method combines different solutions to sub-problems to create a complete product concept. Potential solutions for each sub-problem are listed in a table, where the rows represent the sub-problem and the columns the suggested solutions. Combinations of all potential solutions are derived and the concepts with potential are taken to further development. Obviously, this generates numerous concepts and, of course, many of them can be eliminated straight away since not all combinations are possible in reality. Nonetheless, this increases the number of concepts that might be worth considering and minimises the risk of miss out a competitive solution. (Johannesson, Persson, & Pettersson, 2004)

3.4.2 Elimination matrix

An elimination matrix is often used as the first structured elimination phase within a product development project. In this matrix the concepts generated are examined to verify if they solve the main problem, and if they have the potential to meet all requirements. Concepts which do not meet these criteria are discarded, whilst all other pass this screening gate. (Johannesson, Persson, & Pettersson, 2004)

3.4.3 Pugh matrix

A Pugh matrix, named after the Englishman Stuart Pugh, is a method to rank concepts in relation to each other. The method supports the evaluation of concepts and if the result indisputably shows that some concepts are inferior, these are eliminated. One of the concepts is chosen as a reference, preferably one that is well-known by all participants. All other concepts are compared with the reference concept, based on predetermined criteria, and are rated better (+), worse (-) or equal (0) to the reference. The individual scores of the concepts in relation to the reference are summed and a decision is taken whether to discard them or not. To validate the result from the first Pugh matrix it is almost always relevant to perform a second matrix, with another concept used as a reference, and with reviewed criteria. (Johannesson, Persson, & Pettersson, 2004) A regular Pugh matrix assumes that all criteria are of equal importance; hence it can be useful to revise the matrix with weighted criteria. This means that all criteria are given a value corresponding to their importance in comparison to the other criteria. The sum in a weighted Pugh consists of each score multiplied by corresponding weighting. (Ogot & Kremer, 2004)

3.5 Design for manufacturing and assembly

Design for manufacturing and assembly (DFMA, or sometimes DFM and DFA) is a method developed to be used in a new product development process. Its main focus is to eliminate redundant components by incorporating their functionality into other components and thus decreasing the manufacturing and assembly cost and time. The method is implemented early in the process, and consists of a number of questions asked, and answered by a yes or no. Answers sought for is if the function is needed, if it can be integrated into another part, if the position of the part is the most suitable or if it may be assembled differently. Depending on the answer the part may be eliminated, redesigned or incorporated into another component. Applying this method early in the process will lead to minimised late design changes during production ramp-up and reduce costs in the manufacturing and assembly. (Bayoumi, 2011)

3.6 Truck chassis design

Today, most truck manufacturers design their chassis' based around two main beams running longitudinally along the truck. To connect the main beams, and to stiffen the chassis, boxed cross-members are attached between the main beams. This layout produces a fairly narrow chassis, creating a lot of space on the sides of the main beams where tanks etc. can be mounted while remaining within the width limit of 2,550 mm.

For trucks, air suspension is essentially the industry standard. In an air suspension system, pressurised rubber bellows replace the coil springs commonly found on passenger car suspensions. The wheel axle is attached to a trailing arm mounted between the bellows and a set of front hangers or an additional set of bellows. Truck air suspension systems are usually more sophisticated than the trailer counterparts, and also offer lower ride height than what is available from trailer axle subcontractors.

3.6.1 Volvo truck chassis design

Volvo designs their chassis in accordance with the theory above. A standard truck chassis consists of two longitudinal U-beams facing each other at a distance of 850 mm, measuring outer end to outer end. Depending on the chassis application, Volvo uses two different heights of the main beams; either 266 mm or 300 mm. However, a flange width of 90 mm is used for both sizes. (Volvo Parts AB, 1995; Volvo Parts AB, 1999)

The main beams are connected by cross-members, also U-beams. Standard brackets attach the cross-members and the main beams, and all connections are either bolted or riveted. All holes are made in the metal sheets prior to bending the metal into beams. This computerised method makes the process fast and ensures that no unnecessary holes are introduced to the chassis. (Volvo Parts AB, 1995; Volvo Parts AB, 1999)

Volvo uses a variety of suspension systems, with different ride heights, load bearing capacity and functionality. The lowest ride height available today is 133 mm. Supporting struts and arms are used to mount the suspension to the chassis. Bellows are mounted underneath the beams with mounting brackets attached both to the inside and outside of the main beams. For suspension units on vehicles with narrower distance between wheel axles, there are configurations that have common centre mounting arms and brackets. (AB Volvo, 2011; Volvo Parts AB, 1999)

3.7 Dolly design

As previously mentioned, trailer manufacturers are commonly fairly small operations, with limited production volume and a relatively high degree of customisation of their products. This results in a high degree of manual labour during manufacturing, with chassis structures that are usually welded. The trailer chassis designs are usually what differentiate manufacturers' offerings from one another, seeing as most sub-systems are produced by subcontractors. However, since most manufacturers share the same subsystems, which are designed for roughly the same area-of-use, chassis designs are often fundamentally very similar.

The chassis has to cope with the dynamic loads applied by the mass of the cargo and vehicle accelerations. It also has to be stiff enough to ensure proper stability of the trailer. In practice, this means that essentially all trailers are made from different steel alloys. The steel beams or plates are welded together, forming some type of beam structure to which all other components are attached. In some cases, side supports for the drawbar are incorporated.

3.7.1 Dolly components

A dolly trailer is constructed from a variety of sub-systems. These are attached to a main chassis structure designed to cope with the static and dynamic loads applied during use. The sub-systems explained below are the basic mechanical components vital to a dolly trailer's primary intended function.

Fifth wheel

The fifth wheel (Figure 14) is where the kingpin of a towed semi-trailer attaches to the dolly; providing articulation for the vehicle around the vertical axis. The fifth wheel also supports the front of the semi-trailer horizontally, and can pivot around the transversal axis in order to accommodate changes of slope in the road such as bumps and hills.

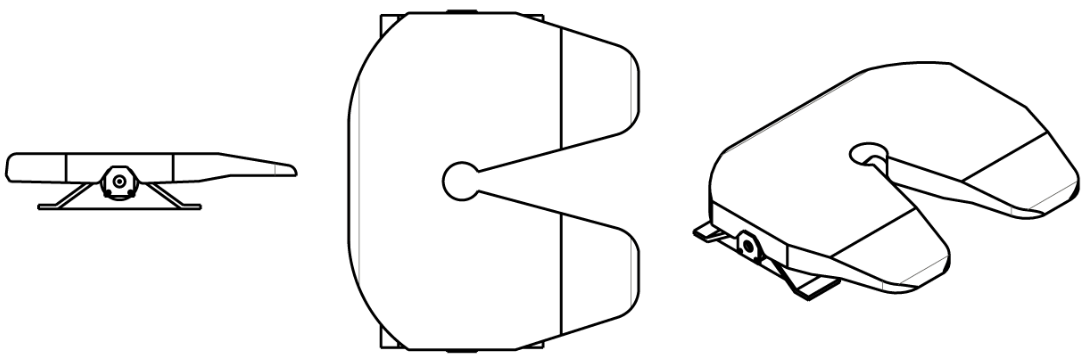

Figure 14 Fifth wheel, Jost JSK 36 DV 2.

Turntable

For safety reasons, the fifth wheel is installed on top of a turntable (Figure 15) in order to create redundancy in the articulation. This ensures that the trailer will always follow the towing vehicle smoothly, even if there is increased friction in the fifth wheel coupling. The turntable assembly encompasses a mounting plate attached to a large ball bearing.

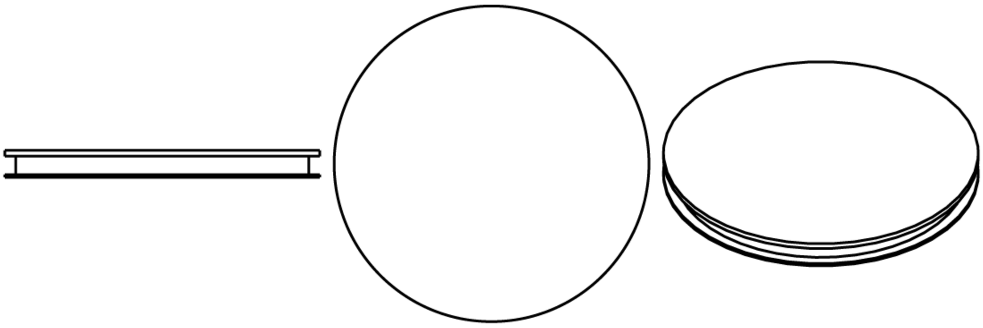

Figure 15 Turntable assembly, including a top plate.

Axles

Trailer axles are usually rigid, meaning that the opposing wheels are connected by a stiff transversal axle. Thus, opposing wheels do not move independently, but are affected by each other's vertical movement. However, the rigid midsection of the axle assembly does not rotate which means that the opposing wheels rotate independently from one another. The midsection is usually constructed from a hollow metal beam, with either a circular or square cross-section.

Suspension

Trailers also commonly use air suspension systems, although these are usually somewhat simpler in design than for their truck counterparts. The most common design is a trailing arm suspension with a set of front hangers, bellows, and a wheel axle mounted below or on top of the trailing arm.

Figure 16 Air suspension, SAF-Holland Z11-3020.

Braking system

There are two dominating solutions for braking systems on trailers; drum brakes and disc brakes. Traditionally, drum brakes have been the industry standard, but recently disc brakes have gained popularity as the available systems have become more sophisticated and offer higher performance. The largest inherent problem of drum brakes is that heat build-up during braking reduces brake performance and can cause loss of braking capability. Modern brake systems also have braking power distribution between trailers and truck via a Controller Area Network (CAN-bus).

Wheels & tyres

According to Olsson[3] the right rear wheel of the dolly and the right front wheel of the semi-trailer are the two wheels on the Duo[2] combination that are subjected to most wear. In order to decrease the wear on each wheel it is common to cross-change them; which means to diagonally switch places on the dolly's wheels. Large wheels do have smaller rolling resistance than smaller wheels; but evidently, smaller tyres lower the centre of gravity.

Pressurised air system

To power the brake system, and to provide pressure for the air suspension, trailers are fitted with pressure vessels containing pressurised air. The pressurised air system is connected to the truck's compressor and the pressure vessels on the trailer work as an air bank, providing a buffer for the compressor.

Landing gear

In order to support the drawbar when not mounted to a towing vehicle a so-called landing gear is used. The landing gear is mounted in front of the main chassis, usually on the drawbar assembly.

Drawbar assembly

The drawbar (Figure 17) is what connects the trailer to the towing vehicle in front. Its basic construction is a beam, usually rectangular, attached to the main chassis and extending forward in the longitudinal direction. Side supports intended to stiffen the drawbar against transversal bending may or may not be incorporated in the drawbar assembly. A drawbar eye is mounted to the furthermost point of the drawbar, allowing for the trailer to be coupled to the rear drawbar coupling of the towing vehicle.

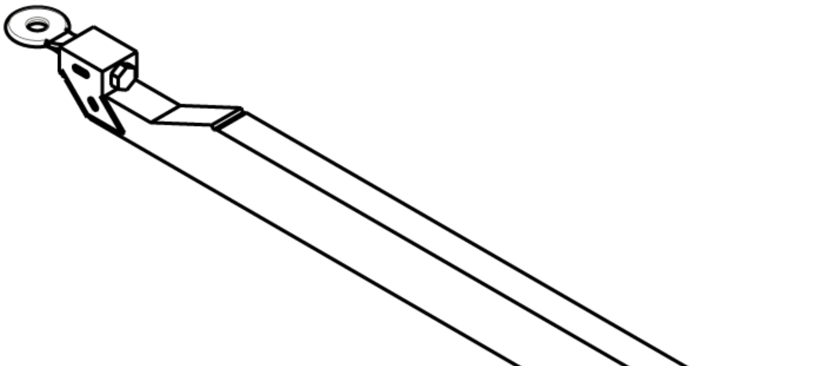

Figure 17 Drawbar assembly, without side supports. Drawbar eye: VBG 15-06, Drawbar: Parator.

Electronics and lighting

The electronics system is connected to the vehicle electronics system using one or more connectors depending on the complexity of the system. At a minimum, the electronics system must power the required lighting arrangement, as specified in the requirements specification. On modern vehicle combinations, A Computer Area

[3] Per Olsson (CEO of Parator Industri AB, interviewed by the authors 2011, January 06)

Network might be incorporated, allowing the towed trailers to communicate with a main computer on the truck or tractor. This is primarily used to actively control the brake force distribution between all axles and vehicles within the vehicle combination.

3.7.2 Basic theory on how to decrease the height of a dolly

Basically, there are three ways to lower a dolly. Perhaps the most obvious method is to change the chassis design, to one that facilitates a decreased height. Possible design changes are to reduce the height of the main chassis, i.e. decrease $h_{chassis}$ in Figure 18, and to reposition the turntable or the suspension. All these changes need precaution, since they may weaken the stability and structural integrity of the dolly.

In addition to design changes, it is possible to use the same chassis design, but still decrease the overall dolly height. This is accommodated by either the use of a suspension unit with a lower ride height ($h_{ride\ height}$) or wheels with smaller diameter ($Ø_{tyres}$). The size of the wheels determines the minimum theoretical height of the fifth wheel. This is due to the fact that the fifth wheel has to elevate the bottom of the semi-trailer enough to not interfere with the dolly wheels.

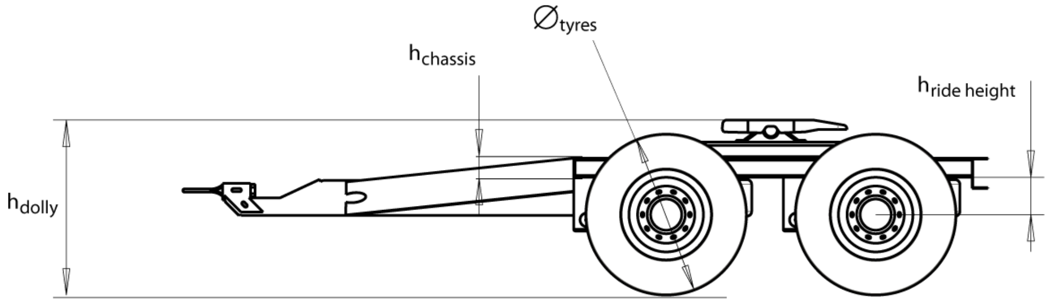

Figure 18 Explanation of dimensions

4 Development process

In this chapter the development process steps will be presented in chronological order. The focus will be on the outcomes of each phase, while the methods used are further described in Chapter 2: Methodology, and Chapter 3: Theory. This chapter is intended to act as a stepping stone leading up to Chapter 5: Results.

4.1 Pre-study

During the pre-study, knowledge about the dolly, its functionality, and interaction with other modules were studied. Furthermore, the pre-study lead to a requirement specification where the features of later developed concepts were first identified.

4.1.1 Study visits

In order to get a more hands-on understanding of the construction of different dollies and the processes involved in manufacturing, a series of study visits were conducted. Informal visits were made to truck parking lots and a truck rental company, in order to get an overview of many different manufacturers' approaches to dolly design. A more formal visit to Parator was set up in order to study their production facilities and to get detailed information regarding construction, requirements, operating conditions, industry trends etc. Through the study visit to Parator, contact information for further interviews was also obtained. Another study visit was also made in conjunction with the trip to Parator; this one to SSAB, a manufacturer of high-strength steel. A chassis construction with high-strength steel from SSAB had been tried for one of the trailers on a vehicle in another similar research project, the so-called ETT vehicle. The ETT research project focuses on heavy timber haulage, and information was sought regarding possibilities and design principles for the material.

4.1.2 Finite element analysis of the current solution

In order to evaluate the stiffness and strength of different chassis concepts and layouts, a reference model was needed. Based on 2D drawings of a standard production model dolly provided by Parator, a 3D representation was created using Pro/Engineer.

In order to reduce calculation times, and to reduce the complexity of the mesh, some simplifications were done to the dolly model to prepare it for FEA in Pro/Mechanica. For instance, all components which were not necessary for the analysis were removed; these included the wheels and axles, as well as the fifth wheel. Furthermore, attempts were made to further speed up computation times using mid-surface meshes instead of solid elements. However, such attempts were unsuccessful and satisfactory results were not achieved, so an all-solid element mesh was used.

Forces were applied to the drawbar and turntable based on the calculated D- and V-values. Three load cases were studied separately: two for D- and V-values of the drawbar, and one for the fifth wheel V-value. Displacement constraints where added to where the axles attach to the trailing arms for V-value calculations, and to the turntable for the calculation using the D-value. The result from the analysis using the V-value for the fifth wheel is shown in Figure 19.

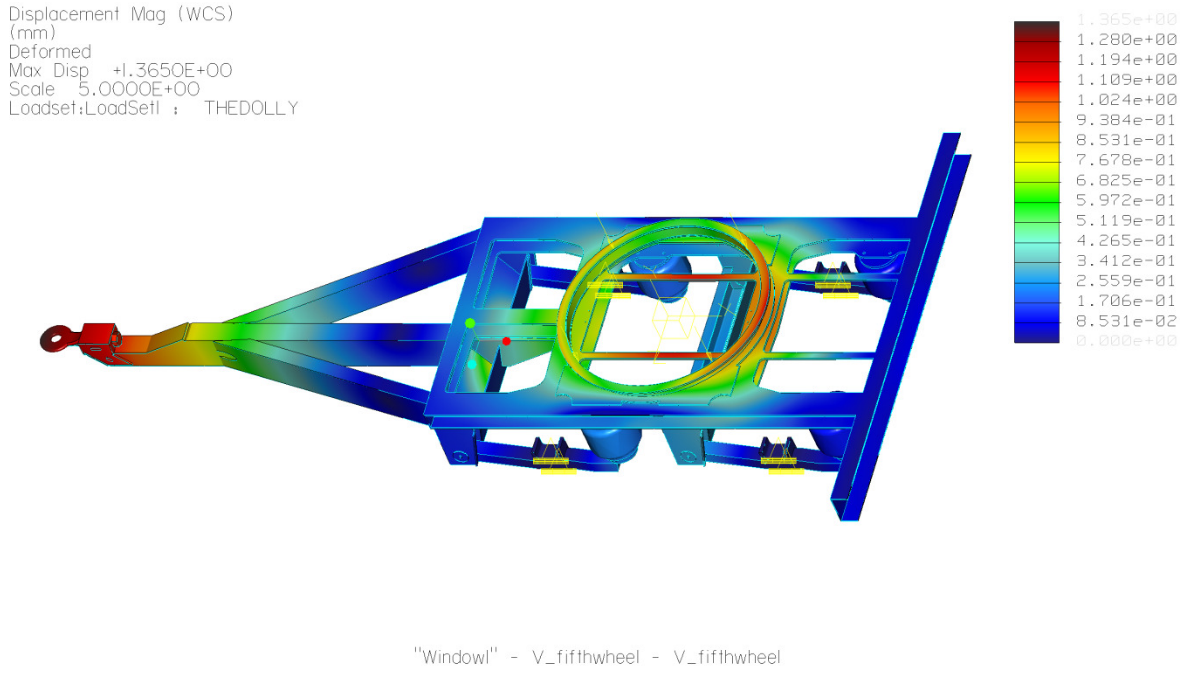

Figure 19 Displacements of current Parator concept

After running the analyses it became evident that it was extremely hard to produce a result where singularities were not present. Weeks were spent simplifying the model, modifying the mesh (although Pro/Mechanica does not offer very much control of meshing parameters), and redefining constraints. However, these attempts proved unsuccessful. This meant that it was very hard to interpret the stress calculations in regard to maximum stresses, and focus was altered to use the results from both stress and displacement calculations to act as more of a visual aid for chassis design iterations.

4.1.3 Reference beam calculations

With the use of basic beam theory, calculations were made for different types of beams. Obviously, the real load cases are more complex than these two-dimensional calculations can show, but finding the second moment of inertia for each beam gave an understanding of the mechanical properties of each beam type.

The first calculations made were for an I-beam, which is similar to the structure used in the current Parator design. These results help the dimensioning of beams of other types, since it is certain that the current dolly can withstand the present forces.

$$I_{x,reference} = \frac{1}{12} \cdot \left(w_f \cdot \left(\left(h_l + 2 \cdot t_f \right)^3 - {h_l}^3 \right) + h_l \cdot {t_l}^3 \right) = 10{,}909{,}440\ mm^4 \qquad (13)$$

$$I_{y,reference} = \frac{1}{12} \cdot (2 \cdot t_f \cdot {w_f}^3 + h_l \cdot t_l) = 6{,}751{,}000\ mm^4 \qquad (14)$$

$$A_{reference} = 2 \cdot w_f \cdot t_f + t_w \cdot h_w = 4{,}080\ mm^2 \qquad (15)$$

$t_f = flange\ thickness = 12\ mm$

$w_f = flange\ width = 150\ mm$
$t_w = waist\ thickness = 5\ mm$

$h_w = waist\ height = 96\ mm$

This can be compared to U-beams of two different heights used in a Volvo truck chassis, which will give the following area moments of inertia:

$$I_{y,Volvo266} = \frac{1}{3} \cdot (w^3 \cdot 2 \cdot t + (h_1 - 2 \cdot t) \cdot t^3) = 3{,}930{,}700\ mm^4 \qquad (16)$$

$$I_{x,Volvo266} = \frac{1}{12} \cdot \left(w \cdot ({h_1}^3 - (h_1 - 2 \cdot t)^3) + (h_1 - 2 \cdot t)^3 \cdot t\right) = 34{,}387{,}000\ mm^4 \qquad (17)$$

$$A = (h_1 - 2 \cdot t) \cdot t + 2 \cdot t \cdot w = 3{,}440\ mm^2 \qquad (18)$$

$$I_{y,Volvo300} = \frac{1}{3} \cdot (w^3 \cdot 2 \cdot t + (h_2 - 2 \cdot t) \cdot t^3) = 3{,}936{,}500\ mm^4 \qquad (19)$$

$$I_{x,Volvo300} = \frac{1}{12} \cdot \left(w \cdot ({h_2}^3 - (h_2 - 2 \cdot t)^3) + (h_2 - 2 \cdot t)^3 \cdot t\right) = 45{,}974{,}000\ \mathrm{mm}^4 \qquad (20)$$

$$A = (h_2 - 2 \cdot t) \cdot t + 2 \cdot t \cdot w = 3{,}712\ mm^2 \qquad (21)$$

$t = thickness = 8\ mm$
$h_1 = height = 266\ mm$
$h_2 = height = 300\ mm$
$w = width\ of\ flanges = 90\ mm$

As shown above, the Volvo beams have much larger second moments of inertia for bending in the x-direction, while the I-beams from Parator are superior when bending in the y-direction. In reality, this means that a Volvo U-beam is superior to withstand vertical forces, and vice versa when it comes to horizontal forces. The calculated areas are interesting in this case, since they are correlated to the mass of the beams, assumed that all beams have the same length. Hence, with equal lengths the Volvo beams will have a lower mass than the I-beam used by Parator.

4.1.4 Calculations of D- and V-values

According to theory, there are two possible ways to calculate the D- and V-values. The first method, based on the old standards, gives equations that are derived for centre axle trailers, and the second method is based on equations compiled from an ISO standard that is currently under development. Both these methods have been used in this study, since the first one is the current standard and the second one gives more representative values and will – according to all involved – become the future standard. Calculations have been made on the first configuration within the Duo^2 project, which is a tractor – semi-trailer – dolly – semi-trailer combination. The dimensions and loads are calculated for a dolly similar to the one specified in the project, i.e. with a 4.6 metre rigid drawbar and an 18 tonne bogie load. Standardised length (2.5 metres) and weight (3,000kg) of the dolly is also used.

$$(1) \rightarrow V_{drawbar} = 1.8 \cdot \frac{2.5^2}{4.6^2} \cdot 18 = \left\{x < L \rightarrow \frac{X^2}{L^2} = 1\right\} \\ = 1.8 \cdot 1 \cdot 18 = 32\ kN \tag{22}$$

$$(3) \rightarrow D_{drawbar} = g\frac{(26+24)\cdot(15+24)}{(26+24)+1(15+24)} = 220\ kN \tag{23}$$

$$(4) \rightarrow D_{fifth\,wheel} = g \cdot \frac{0.6\cdot(26+24+3)\cdot(24+15)}{(26+24+3)+(24+15)-15} \\ = 158\ kN \tag{24}$$

$$(5) \rightarrow V_{fifth\,wheel} = 15 \cdot g = 147\ kN \tag{25}$$

The future standard gives more accurate and lower values; this is due to the specially derived equations for each vehicle combination that takes more than one coupling into consideration, and the introduction of the dolly module.

$$(9) \rightarrow V_{drawbar} = max\left(\frac{54}{4.6}; 5\cdot\frac{18}{4.6}\right) = 5\cdot\frac{18}{4.6} = 20kN \tag{26}$$

$$(8) \rightarrow D_{drawbar} = \frac{13}{20}\cdot g \cdot \frac{(26+24)\cdot(18+24)}{26+24+18+24} = 146kN \tag{27}$$

$$(7) \rightarrow V_{fifth\,wheel} = 15 \cdot g = 147kN \tag{28}$$

$$(6) \rightarrow D_{fifth\,wheel} = \frac{1}{2}\cdot g \cdot \frac{(26+24+3)\cdot\left((15+24)+0.08\cdot(26+24+3)\right)}{26+24+3+15+24-15} = \\ 146\text{kN} \tag{29}$$

As the result from the calculations above shows, the outcome of the current standard generates larger loads. However, these equations are unable to take into consideration that there is more than one coupling in the combination, which the future standard can. Svensson[4] informs that the workgroup overseeing the ISO standard is hopeful

[4] Bolennarth Svensson (Business engineer, Coupling equipment, VBG Group interviewed by the authors 2011, March 15)

that the new standard will be in use sometime during 2012, and since this is an exploratory project for the future the values from equation (26) to (27) are more important to consider. Furthermore, it should be noticed that these values are intended for dynamical testing on the drawbar assembly alone; while in this project these loads are used as chosen static values for comparison between different concepts.

4.1.5 Interviews

In addition to the interviews conducted during the study visits, a number of phone interviews were carried out to determine further requirements and applicable legal directives and regulations. To gain as much information as possible, the interviews were held semi-structured; this means that some questions were determined beforehand, but follow-up questions were asked during the interviews.

During the interviews it became evident that the general consensus was that the dolly should be a passive module. Consequently, the idea of adding extra functionality, such as steerable front-axle or hydraulic drive, was discarded.

All interviewees were positive to smaller tyres to increase the loading volume, despite the increased rolling resistance in comparison with larger tyres. Additionally, Olsson[5], Jönsson[6] and Johansson[7] claims that due to cost and wear, the use of a single wheel configuration preferred to the twin-wheel configurations commonly found on trucks.

4.1.6 Current market situation

The market offerings for dollies are, in general, very diverse. Typically, a large number of smaller manufacturers offer customised, made-to-order dollies and trailers for a lot of different purposes and areas of use. Partly due to being fairly small, trailer manufacturers rely on suppliers for most sub-systems and components – making chassis design the main difference between competitors. However, the designs from most manufacturers are similar and are almost exclusively welded, partly since they are often made in relatively small workshops.

Sub-systems are often made by companies that specialise in one or a few of the components on a trailer, such as the axle assembly or turntable. The options available for sub-systems are quite few. Thus, many different trailer manufacturers will construct their chassis around the same components as their competitors. The axle assembly is a major component sourced from suppliers. Most axle designs are conceptually very similar when it comes to how the wheel axles are suspended, and according to Olsson choice of axle supplier is largely in accordance with customer preferences.

Krone, a relatively large German manufacturer of trailers, has recently introduced a ‘steerable dolly’. The purpose of adding active steering to a dolly is for a longer vehicle combination to be able to drive through a so-called “BO-Kraftkreis” – a defined turning circle with outside diameter 12.5 metres and inside diameter 5.3 metres. (Strassenverkehrs-Zulassungs-Ordnung, 2009) However, this regulation is not applicable in Sweden, and thus adds unnecessary manufacturing and component costs.

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[5] Per Olsson (CEO of Parator Industri AB, interviewed by the authors 2011, February 06)
[6] Ulf Jönsson (CEO of Börje Jönsson Åkeri AB, interviewed by the authors 2011, March 01)
[7] Alfred Johansson (Lead Engineer at Epsilon, interviewed by the authors 2011, January 06)

Benchmarking different manufacturer offerings is relatively hard, since detailed information is not readily available. Also, since trailer manufacturers tend to customise their products to a fairly large extent, it is challenging to determine any performance measures for the frame construction. However, data from subcontractors is more easily accessible, making it possible to weigh many different alternatives against each other for design decisions.

4.1.7 Axle assembly alternatives

As lowered height was seen as one of the major design challenges, different axle manufacturers where evaluated. As most offerings by the different companies are very similar in terms of design and load capacity, focus was set on the minimum ride height offered. As reference, the ALU 30 axle from BPW currently used by Parator has a ride height of 215 mm (BPW, 2011). The axle assembly with the lowest possible ride height produced by a subcontractor is the Z11-3020 axle from SAF-Holland's "Modul"-series (SAF-Holland, 2010). Other manufacturers produce models with almost as low ride height, but since the layout of other units are very similar, the Z11-3020 was chosen as the reference for designs where an axle assembly with low ride height was required.

4.1.8 Requirement specification

During the information gathering phase it was found that there are many stakeholders who have requirements on the dolly. Obviously, the Swedish Transport Agency and other government agencies have stated numerous of requirements that need to be fulfilled before it is legal to use a vehicle on the road network. These requirements are readily available and are measurable; and therefore easy to validate.

The manufacturers, haulage contractors (purchasers) and drivers (end users) all have requirements and demands on the dolly. These requirements were established throughout the project during discussions, interviews and study visits. Due to their origin these requirements may either be clearly stated or vaguely formulated, and therefore may be harder to verify. Hence, the requirement specification is divided into two parts, one part with the strict legal requirements and one part with requirements from all other stakeholders. Although, these two categories of requirements are related to each other and a requirement in the latter category may make some legal requirements applicable.

Legal requirement specification

The list of legal requirements on the dolly is extensive and consists of more than two hundred posts. With the knowledge from the pre-study in mind this section highlights some of the most important requirements for the project. A complete legal requirement specification may be seen in Appendix A.

- The axle spacing (d_{axles}, in Figure 20) of the bogie should be at least 1,300 mm to allow a bogie pressure of 18 tonnes.
- Since the dolly is intended for volume goods the requirements for low couplings are used. While the dolly is laden the height of the fifth wheel (h_{dolly}) cannot exceed 975 mm or fall short of 925 mm from the ground reference plane.
- The height of the fifth wheel (h_{dolly}), while it is uncoupled, from the ground reference plane should be lower than, or equal to, 1,000 mm.

- The height of the drawbar eye ($h_{coupling}$) from the ground reference plane should be in the range of plus/minus 25 mm from 380 mm.
- The total width of the dolly, including wheels, cannot exceed 2,550 mm.
- The dolly, including an attached semi-trailer, should be able to rotate 3.5 degrees towards the front, 4.5 degrees towards the back, 2 degrees towards the sides and the semi-trailer should be able to rotate up to 90 degrees, in the horizontal plane, from the dolly.
- Turntables are mandatory in Sweden, and must have at least ± 7 degrees rotation capability. This requirement is applied to ensure that the vehicle configuration may turn smoothly.
- The dolly must be able to withstand the calculated D- and V-values (Section 4.1.4) for both the drawbar eye and the fifth wheel.

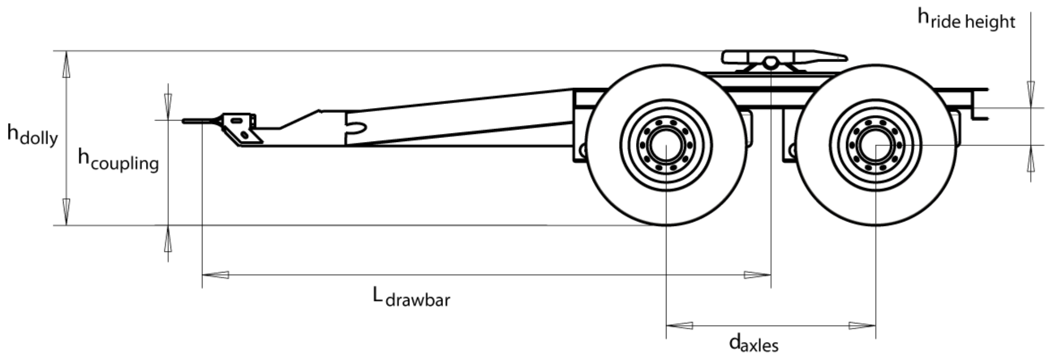

Figure 20 Explanation of dimensions in the requirements specification list

Other stakeholders' requirements

As previously mentioned, many stakeholders have requirements on the dolly. For instance, in most cases the end user is not the same as the purchaser – the purchaser is the haulage contractor while the end user is the truck driver. Evidently, these stakeholders state different requirements on the dolly. While price and maintenance cost are of importance for the purchaser, the ease of marshalling and driving characteristics are more important to the driver. Furthermore, both the trailer manufacturer and the manufacturer of subsystems have requirements on the dolly. In this section, some of the most important requirements from these stakeholders are listed. For a more comprehensive requirement specification list see Appendix A.

Many of these requirements are specified to make the dolly compatible with the mega-trailer that is already manufactured within the Duo^2 project. The list was continuously updated as the project progressed and new information was gathered through discussions and interviews.

- The nominal height of the fifth wheel coupling on the dolly should be 1000 mm.
- The mega-trailers in the Duo^2 have their kingpins mounted 1.6 metres in under the rear of the trailers. This requires the length of the drawbar ($L_{drawbar}$) to be 4.6 metres, measured from the drawbar eye to the centre of the bogie to accommodate turning space.

- The coupling to the trailer in front ($h_{coupling}$) should be 355 mm above the ground reference plane.
- The top of the drawbar cannot be more than 530 mm from the ground reference plane.
- The dolly should have two axles and four wheels, hence, a single wheel on each side of each axle.
- Depending on the solution chosen, the manufacturing of the designed dolly needs to conform to the manufacturing capabilities of either the Volvo Group or Parator.

4.1.9 Conclusions from the pre-study

Information gathering was not the sole purpose of the pre-study, it was also intended to pave the way for a successful development process. During the pre-study some important conclusions were drawn, which helped the decision-making later in the process. Such conclusions were:

- The dolly should be a passive module in the vehicle combination.
- Investigating the possibilities of making extremely low dollies is of high interest.
- Adapting Volvo components and design principles to a dolly construction is to be studied.
- The strength of the dolly should mainly be evaluated using D- and V-values from the future ISO standard.

4.2 Concept generation

Based on the information gathered, efforts were focused on generating a multitude of concepts for further evaluation and development. Both structured and unstructured methods were used during this phase in order to nurture both creative ideas and focused attempts at problem solving.

4.2.1 Brainstorming

The brainstorming concept generation method was used to produce a large quantity of different ideas without necessarily considering all limitations and regulations. This helped a lot in getting the thought process started and for identifying different problems and areas where improvements could be made. A list of all the generated ideas were compiled and discussed, and further brainstorming was carried out in an iterative manner. Of course, a lot of ideas that are generated in this way can be discarded straight away, but a large portion remained for further development.

4.2.2 Sketching

A large number of sketches were produced as a quick method of visualising different ideas and design concepts. These were used mainly for communication between parties involved, and to provoke discussion around the different solutions. Sketches came in handy while working out issues with different designs, but also as a fast method to generate alternatives for design improvements.

4.2.3 Morphological matrix

In order to find as many promising concepts as possible a morphological matrix was established (Table 1). The morphological matrix was focused on chassis design and basic layouts. For instance, packaging of many of the components and material selection was left out. These problems were considered issues for the detail design phase. Many of the sub-solutions in the morphological matrix were solutions that were generated during brainstorming sessions.

Table 1 Morphological matrix

		A	B	C	D	E	F	G
1.	**Horizontal plate design**	One top plate	One bottom plate	Two plates	No plates	Two plates. Top plate bent to lower height in middle.		
2.	**Beams**	Upright U-beams	Tilted U-beams (C)	I-beams	O-beams	Sandwich beam	T-beam	L-beam
3.	**Main connecting method**	Welding	Soldering	Bolting	Riveting	Gluing	Snap connect-ing	
4.	**Position of bellows and front hangers**	Top plate	Bottom plate	Beam bottom	Beam side	Inte-grated in beam	Cross-members	
5.	**Axle placement / layout**	Below main chassis	Through beams/ main chassis	Above main chassis	Curved axles			
6.	**Drawbar side supports**	Cont-inuous from beams	Bent profiles, attached to longitu-dinal chassis beams	No side support for drawbar	Fastened to front of the chassis	Inte-grated in plates	Pre-tensioned wires	
7.	**Turntable placement**	On top plate	On bottom plate	On cross-members	On longi-tudinal beams			

In theory it is possible to elicit 120,960 ($5 \times 7 \times 6 \times 6 \times 4 \times 6 \times 4$) concepts from the morphological matrix above. However, some of the alternatives either make no sense or are impossible to combine. Working in an iterative process, sub-solutions were combined into full concepts and then reviewed, evaluated, modified, and combined with other concepts to form new solutions. In total, nineteen "complete" concepts were derived from the morphological matrix and brainstorming sessions.

Table 2 is a morphological matrix with each category rearranged according to their ranking compared to the other solutions in the same category. Rankings were based upon discussion and how well the solutions will help the final concepts to meet the goals; i.e. lower the ride height, facilitate more standardised components and sound chassis design. The concepts are arranged from left to right in descending order according to ranking.

Table 2 Morphological matrix with ranking of each subcategory

		1.	2.	3.	4.	5.	6.	7.
1.	**Horizontal plate design**	D. No plates	A. One top plate	C. Two plates	E. Two plates. Top plate bent to lower height in middle.	B. One bottom plate		
2.	**Beams**	B. Tilted U-beam (C)	C. I-beam	A. Upright U-beam	G. L-beam	D. O-beam	E. Sandwich beam	F. T-beam
3.	**Main connecting method**	C. Bolting	D. Riveting	A. Welding	E. Gluing	B. Soldering	F. Snap connecting	G. Friction
4.	**Bellows and front hangers**	C. Beam bottom	B. Bottom plate	E. Integrated in beam	A. Top plate	D. Beam side	F. Cross beams	
5.	**Axle placement / layout**	A. Below main chassis	B. Through beams/ main chassis	D. Curved axles	C. Above main chassis			
6.	**Drawbar side supports**	B. Bent profiles, fastened longitudinal to chassis beams	C. Continuous from beams	F. Pre-tensioned wires	D. Fastened to front of the chassis	E. Integrated in plates	F. No side supports for drawbar	
7.	**Turntable placement**	A. On top plate	C and D. On cross beams and/or longitudinal beams	B. On bottom plate				

As can be seen in the rearranged morphological matrix, the ranking suggests an "ultimate solution" with no horizontal plates, but with the turntable placed on a top plate. This is obviously impossible and therefore a decision had to be made to use the concept ranked second best for either category one (Plate design) or for category seven (Turntable placement). However, review of the initial nineteen concepts showed that the top-plate solution was already represented, therefore it was decided to use the top ranked alternative for category one and the second best for category seven.

4.2.4 Description of concepts

Concept one

This concept is essentially derived from the dolly (Figure 1) currently manufactured by Parator. Two parallel horizontal plates are connected via horizontal plates, forming an I-beam construction. The majority of the chassis structure and components are connected by welding. Suspension bellows and front hangers are mounted to the bottom plate; with the axles located below the chassis main structure. Side supports for the drawbar are welded to the front of the chassis, while the turntable is located on the top plate.

Concept two

A single top plate and tilted longitudinal U-beams form the main chassis layout of this concept. Bellows and front hangers are attached to the bottom of the two longitudinal beams, with the wheel axles running below them. Bent U-beam profiles fitted inside the longitudinal beams act as side supports for the drawbar. The supports may be fastened by bolting them to the main beams. The turntable is placed on the top plate. An illustration of Concept 2 can be seen in Figure 21.

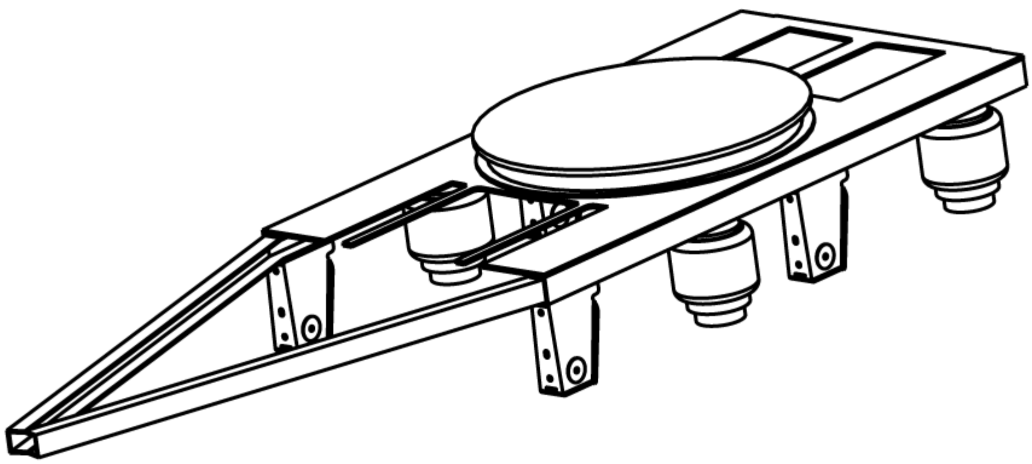

Figure 21 Concept 2

Concept three

Fairly similar to concept number two, the main chassis comprises a single top plate and tilted U-beams while bent U-beams form side supports for the drawbar. However, for this concept the bellows and front hangers are fastened directly to the top plate (Figure 22), while still having the axle running below the beams. As in concept two, the turntable is mounted directly on the top plate.

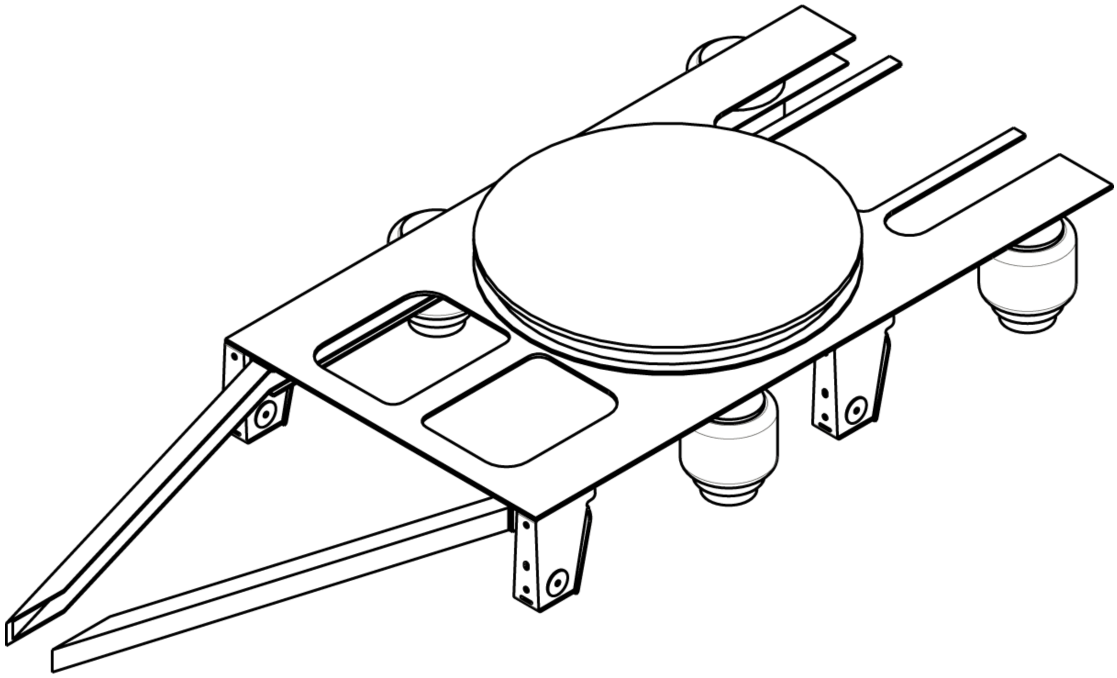

Figure 22 Concept 3

Concept four

For this concept (Figure 23), incorporating standing U-beams and a top plate, the bellows and front hangers are mounted to the top plate allowing for a very low mounting point of the fifth wheel. As opposed to the other concepts, the axles are passed through slots in the main chassis beams, allowing for the beams to be taller. The beams extend forward from the main chassis and form the side supports of the drawbar. The turntable is placed on top of the horizontal plate.

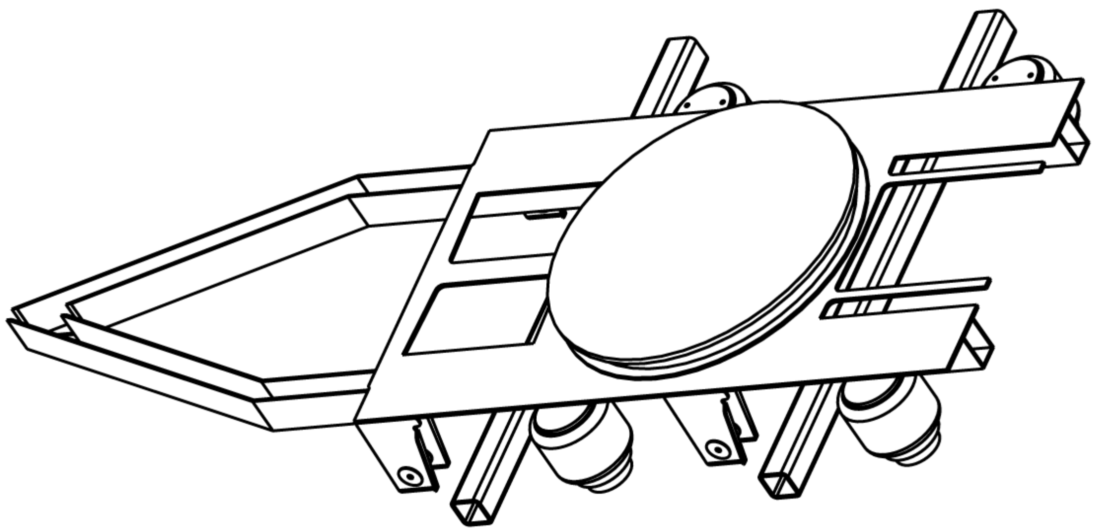

Figure 23 Concept 4

Concept five

This design is also based on the combination of a top plate and standing U-beams. The bellows and front hangers are attached to the top plate and the axle is running under the main chassis. The drawbar side supports are welded to the front of the chassis and the top plate is the base for the turntable. The concept is illustrated in Figure 24.

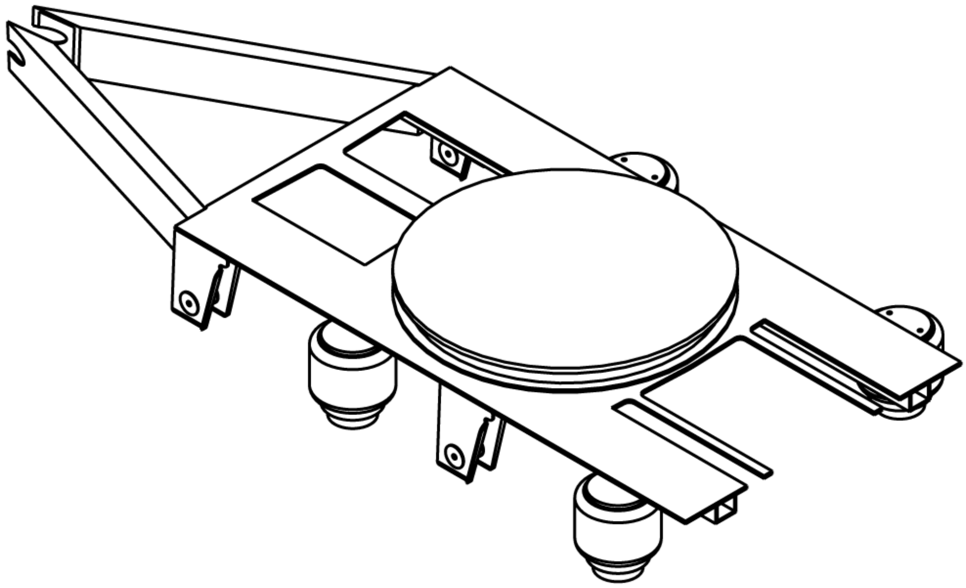

Figure 24 Concept 5

Concept six

Being fairly similar to concept one, with a main chassis constructed from I-beams, it differs in the use of a sole top plate (Figure 25), with welded on plates forming the bottom flanges. The bellows and front hangers are attached to the bottom of the I-beams, with the axle running below. The side supports for the drawbar are welded to the front of the main chassis, and the turntable sits on top of the main chassis.

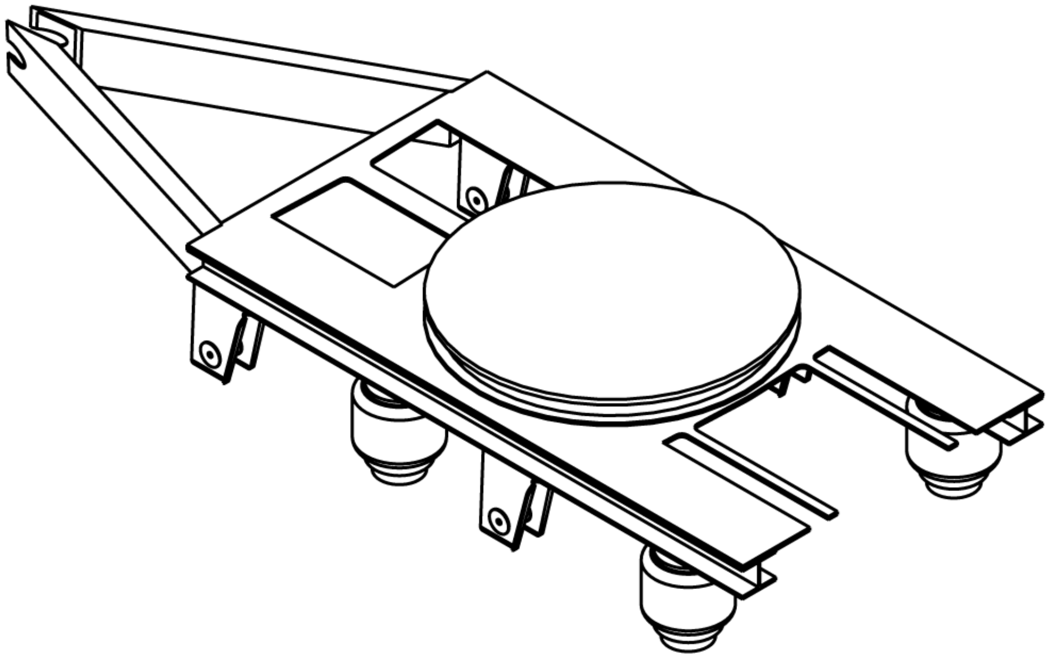

Figure 25 Concept 6

Concept seven

Having two horizontal plates, this concept (Figure 26) has similarities with the existing Parator concept. Front hangers and bellows are connected to the bottom plate, which in turn is connected to the top plate via O-beams. The drawbar's side supports are fixed to the front of the main chassis. Placing the turntable on the bottom plate – reaching up above the top plate – has enabled a lower design than the original concept.

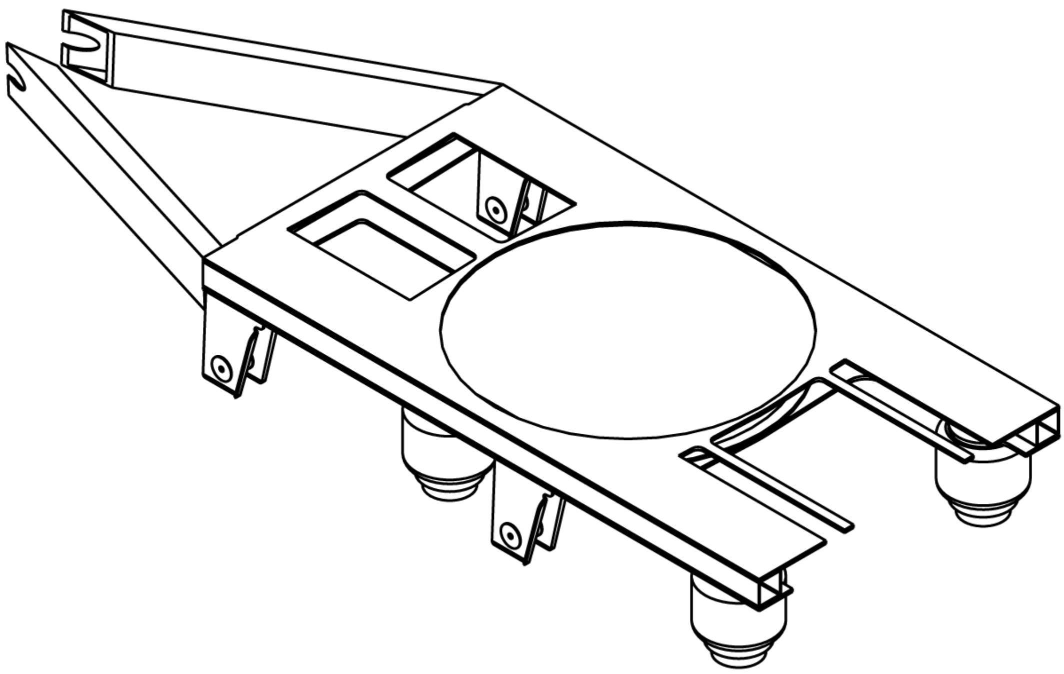

Figure 26 Concept 7

Concept eight

Two horizontal plates are used for this concept (Figure 27), with bellows and front hangers fixed to the bottom one. The plates are connected with tilted U-beams and side supports for the drawbar do also have U-beam profiles fastened with bolts inside the main chassis beams. As for concept seven, the turntable is placed on the bottom plate and is reaching up through a hole in the top plate.

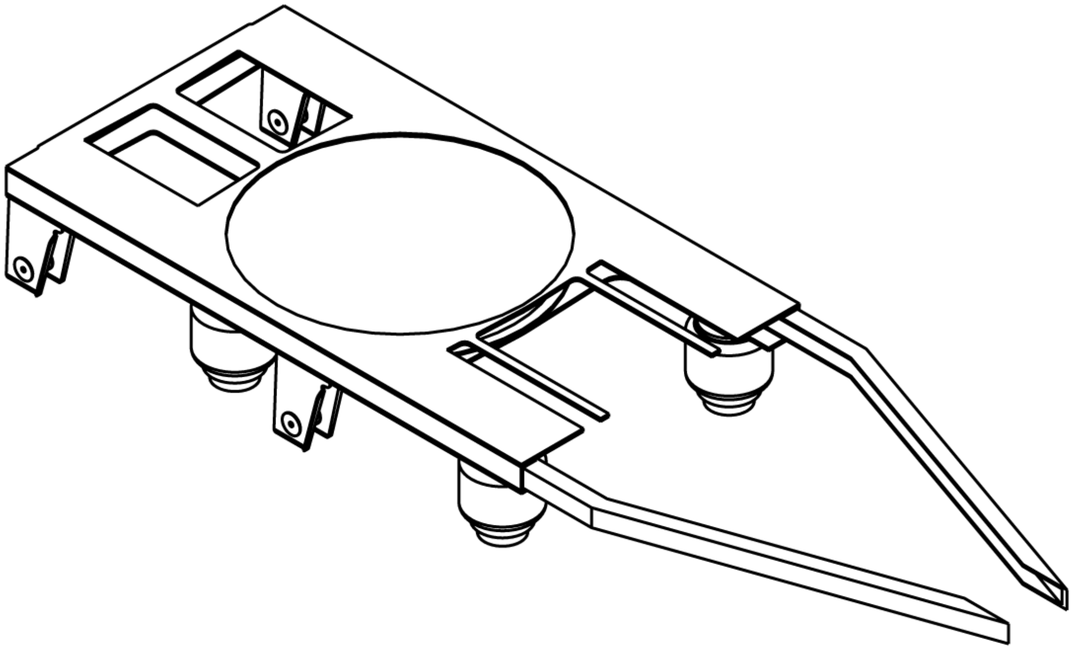

Figure 27 Concept 8

Concept nine

This design (Figure 28) features two horizontal plates, but has a smaller bottom plate than top plate. This solution helps to lower the ride height since the bellows and front hangers are attached to the top plate, with the wheel axles still running below the main chassis. Two bent beams are used as side supports for the drawbar and are connected to the main chassis' longitudinal beams. The turntable is placed on the top plate.

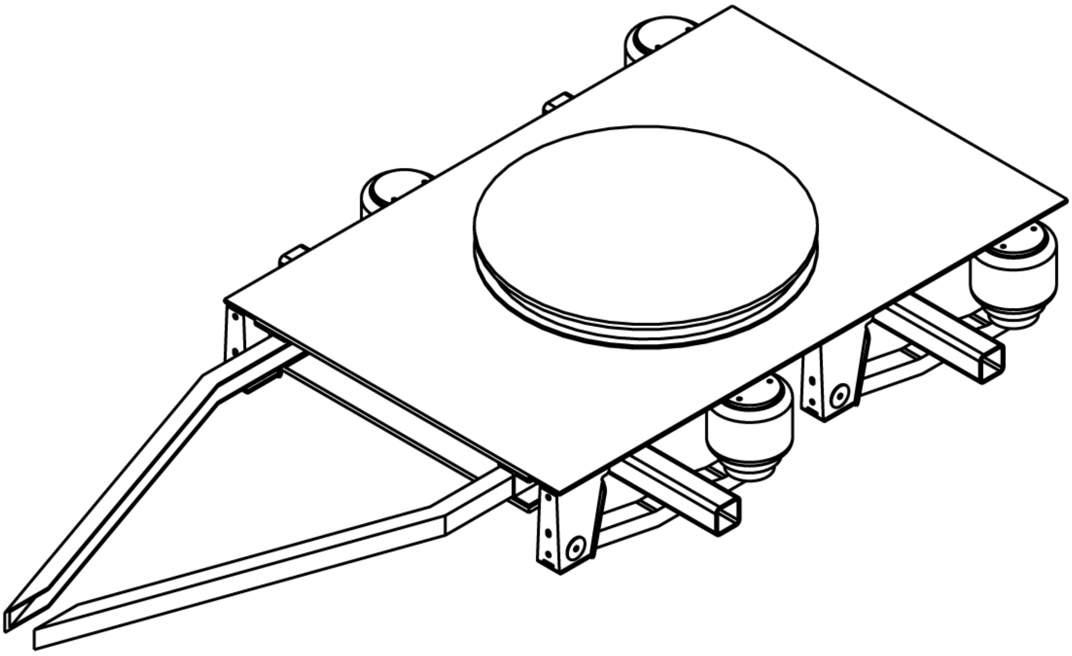

Figure 28 Concept 9

Concept ten

Incorporating no horizontal plates, this concept (Figure 29) is constructed using only beams – primarily U-beams. The chassis' main longitudinal beams extend forward from the main chassis and form the side supports for the drawbar. Bellows and front hangers are fastened underneath the longitudinal beams, while the turntable is standing on the transversal beams.

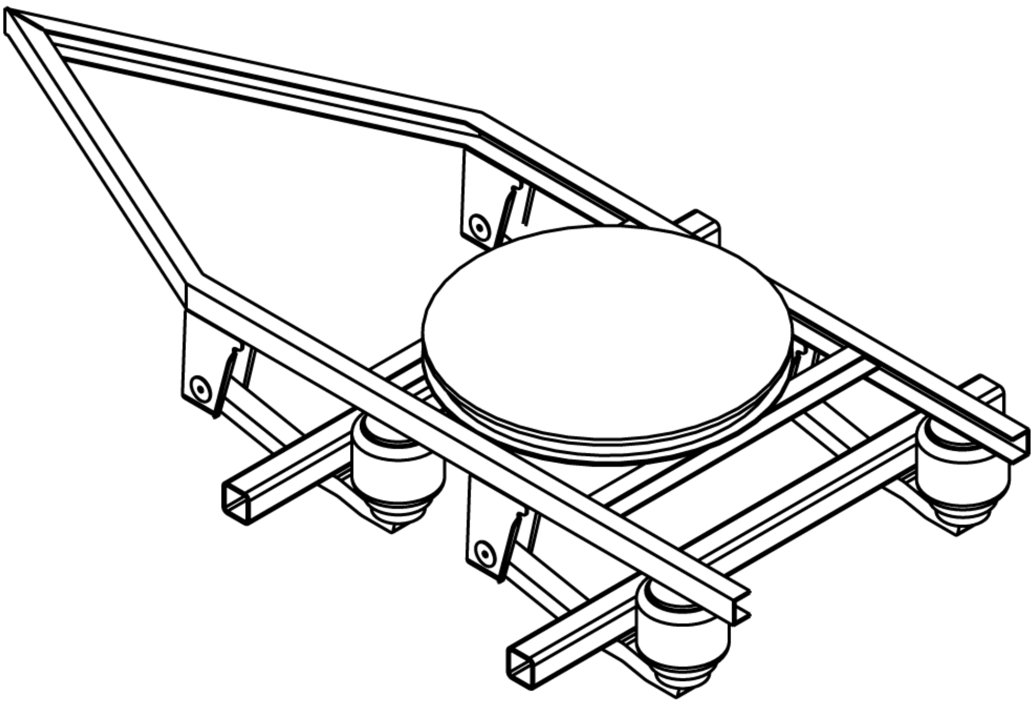

Figure 29 Concept 10

Concept eleven

For this concept (Figure 30), U-beams are welded to a single top plate forming the main structure of the chassis. The bellows and front hangers are attached to the bottom of the U-beams with the axles below the main chassis. The turntable is mounted on the top plate and pre-tensioned wires are used for side support of the drawbar.

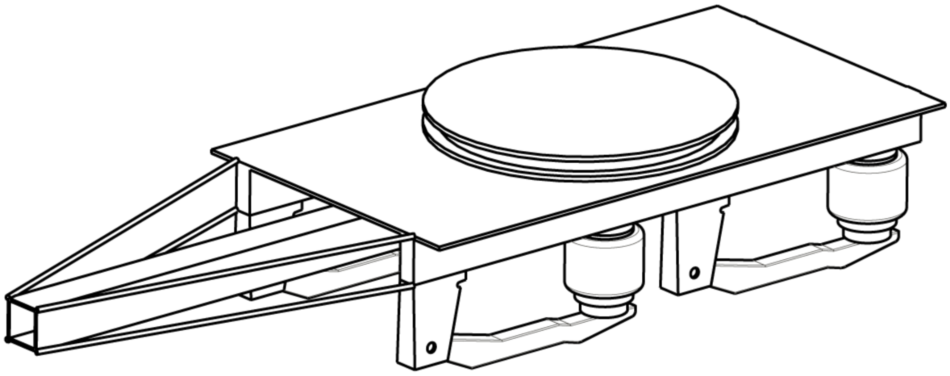

Figure 30 Concept 11

Concept twelve

This is a no-plate concept (Figure 31); with the main chassis instead bolted together solely from I-beams. The beam structure also forms the side supports of the drawbar and the turntable is mounted on top. The bellows and front hangers attach to the bottom of the beams with the axles mounted under the main structure.

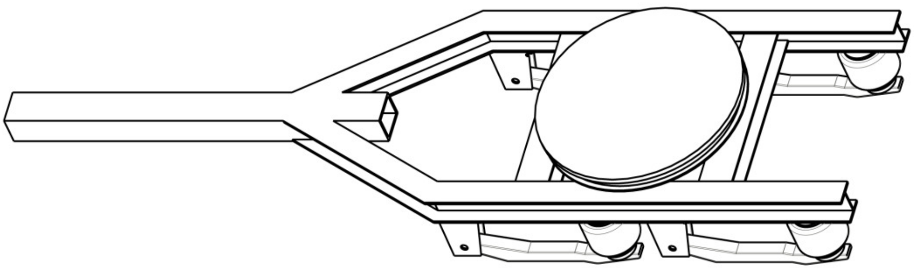

Figure 31 Concept 12

Concept thirteen

This concept (Figure 32) incorporates a top plate with U-beams welded to it. The U-beams are tilted 90 degrees and continue on to form the side supports of the drawbar. The front hangers and bellows attach to the bottom side of the beams, and the turntable is mounted to the top plate. The axles are located below the main chassis.

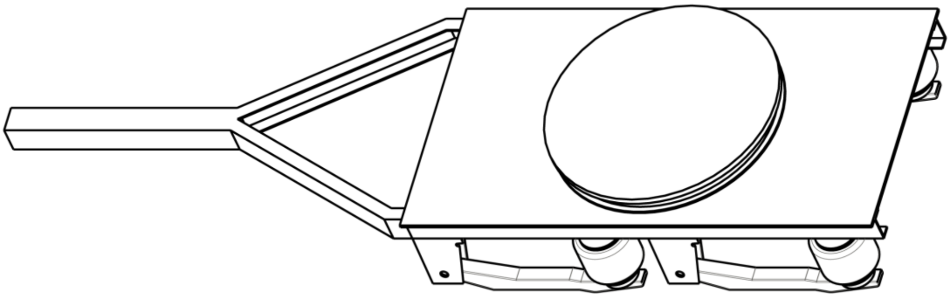

Figure 32 Concept 13

Concept fourteen

In this configuration (Figure 33), two plates are cut out and welded together with webbing in between forming I-beams. The top plate is bent, forming a recess in the middle to lower the height of the turntable which is attached on top. The plates also incorporate the side supports for the drawbar. The front hangers and bellows are attached to the bottom plate with the axles running below the main structure.

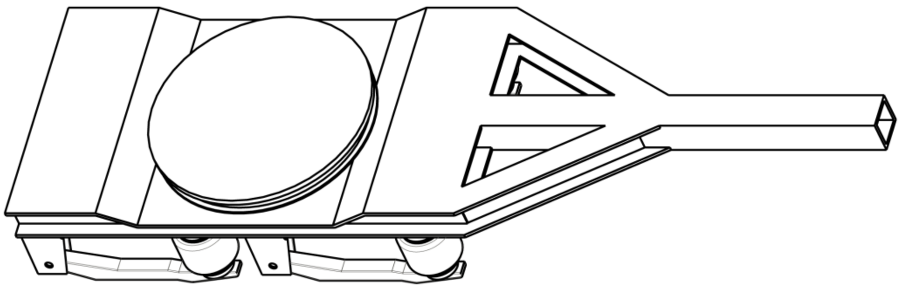

Figure 33 Concept 14

Concept fifteen

For this concept (Figure 34), a single plate forms the bottom of the main chassis, with U-beams welded on top of it. The turntable is then attached to the bottom plate, allowing for a relatively low mounting point of the fifth wheel. The axles are mounted below the main chassis, and bellows and front hangers attach to the bottom plate. The plate also acts as side support of the drawbar.

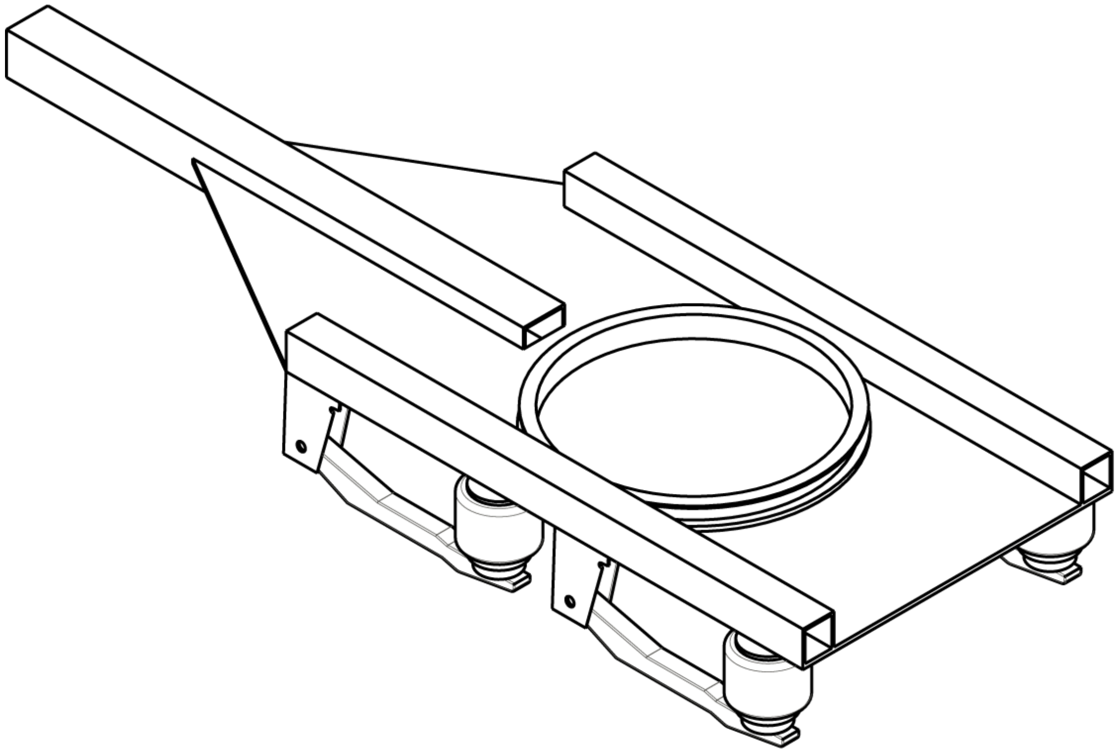

Figure 34 Concept 15

Concept sixteen

This is a two-plate design (Figure 35), with welded-on webbing connecting the plates forming an I-beam structure. The axles run below the chassis, with the front hangers and bellows welded to the bottom plate. The side supports are bolted to the longitudinal beams of the main chassis and the turntable is mounted on the top plate.

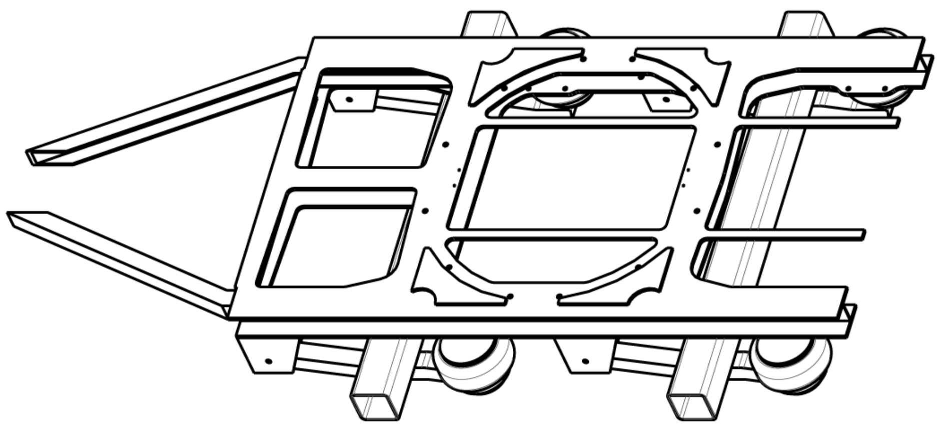

Figure 35 Concept 16

Concept seventeen

In this no-plate design (Figure 36), the main chassis is bolted together from U-beams. The longitudinal beams are bent, and continue on to form the side supports for the drawbar. The axles are mounted below the main chassis and the bellows and front hangers attach to the bottom of the longitudinal beams. The turntable is mounted on top of both the cross-members and longitudinal beams.

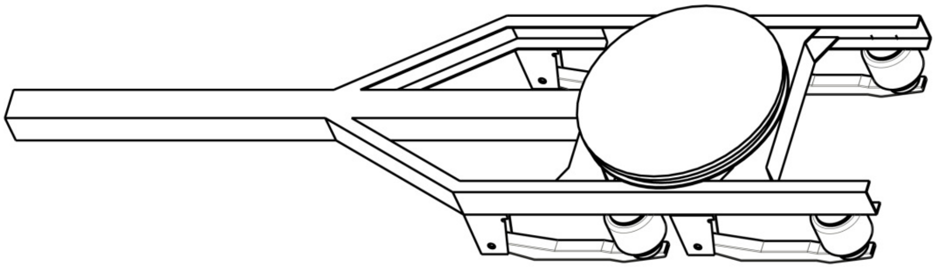

Figure 36 Concept 17

Concept eighteen

This concept (Figure 37) combines a top plate with L-beams attached underneath. To reduce vehicle height, the bellows and front hangers are attached to the top plate, and the axles are mounted through cut-outs in the L-beams. Side supports are made from bent sheet metal, and attach to the longitudinal beams while the turntable is attached to the top plate.

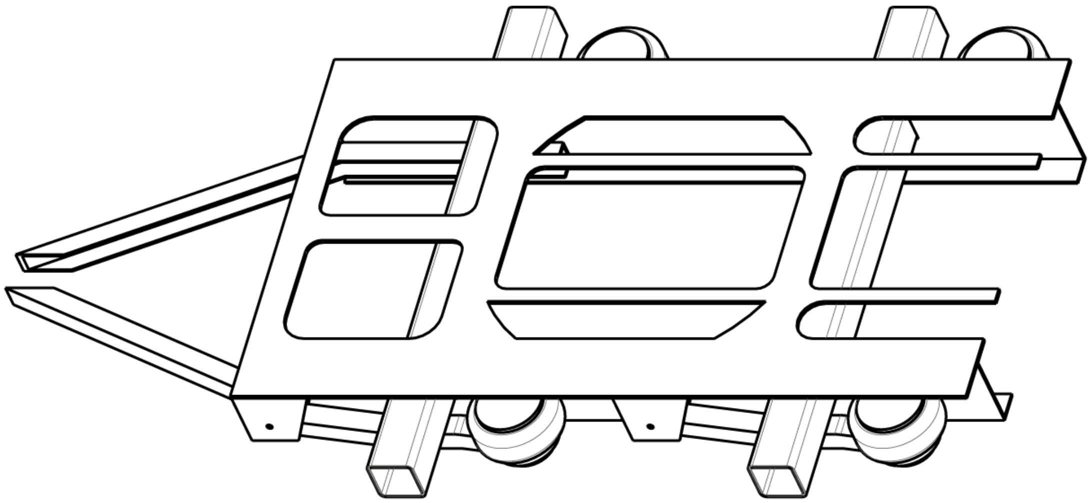

Figure 37 Concept 18

Concept nineteen

Two horizontal plates are connected with vertical plates forming the webbing of this I-beam design (Figure 38). However, while the bottom plate is horizontal, the top plate has a lowered mid-section. With the turntable mounted to the lower part of the top plate, this solution lowers the height of the fifth wheel coupling. Furthermore, the bellows and front hangers are mounted to the bottom plate, while the drawbar side supports are fixed longitudinally to the I-beams.

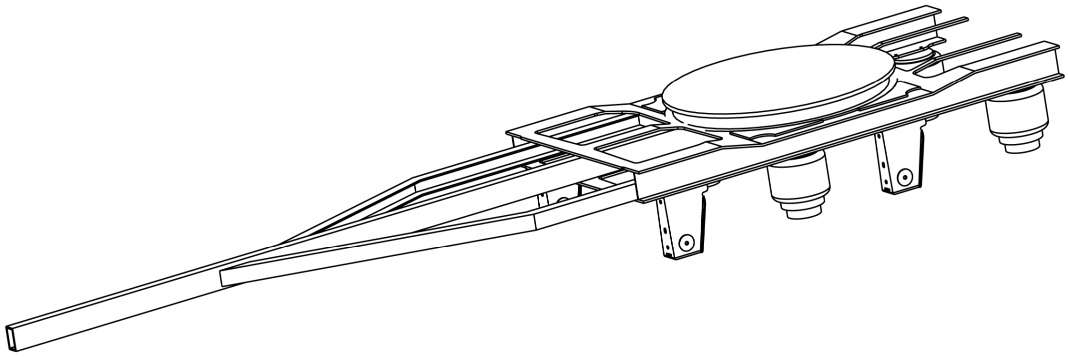

Figure 38 Concept 19

Concept twenty

Also a no-plate design, this concept (Figure 39) is based around two tilted longitudinal U-beams connected by transversal cross-members. The side supports for the drawbar are fastened to the longitudinal beams by bolting. Bellows and front hangers attach to the bottom of the beams and the turntable is placed on the transversal beams.

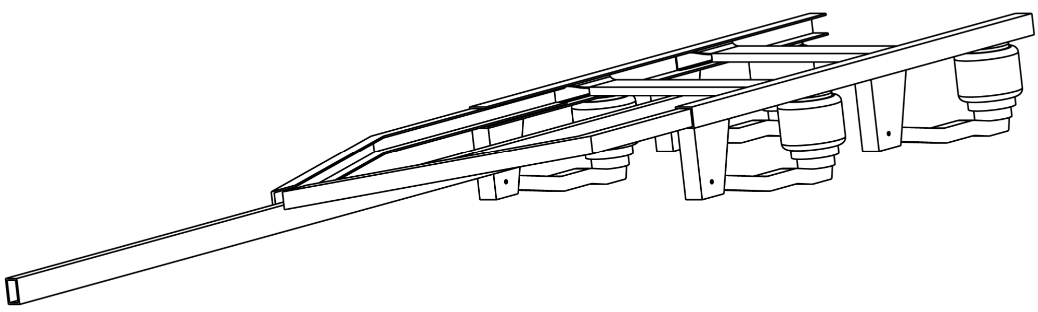

Figure 39 Concept 20

4.3 Concept evaluation and selection

With twenty concepts entering the concept evaluation phase it was crucial to decrease the number of concepts before starting the systematic analysis and evaluation process. Therefore, a few concepts were eliminated through an elimination matrix (Table 3), based on discussions and inputs from members in the Duo^2 project, the concepts were evaluated in terms of their ability to carry out the main function (be coupled to a vehicle in front and tow a semi-trailer), potential to meet the height requirement (1,000 mm from fifth wheel to ground reference plane) and manufacturability. These quite simple criteria were chosen to eliminate those concepts that are clearly inferior to other alternatives.

Table 3 Elimination matrix

Elimination matrix					
Created by:	Davidsson & Henriksson		**Created:**	2011-03-14	
			Modified:	2011-05-09	
Yes	Proceed				
No	Eliminate				
(?)	More information required		Search for more information		
(!)	Redefine requirement specification				
	A. Carries out main function				
		B. Height requirement			
			C. Manufacturability		
Concept				**Comments**	**Decision**
Concept 1	Yes	Yes	Yes		Proceed
Concept 2	Yes	?	Yes	See comment 1.	Proceed
Concept 3	Yes	Yes	No		Eliminate
Concept 4	Yes	Yes	Yes		Proceed
Concept 5	Yes	Yes	Yes		Proceed
Concept 6	Yes	Yes	Yes		Proceed
Concept 7	Yes	Yes	Yes		Proceed
Concept 8	Yes	Yes	No		Eliminate
Concept 9	Yes	Yes	Yes		Proceed
Concept 11	Yes	Yes	Yes		Proceed
Concept 12	Yes	Yes	Yes		Proceed
Concept 13	Yes	Yes	Yes		Proceed
Concept 14	Yes	Yes	Yes		Proceed
Concept 15	Yes	Yes	No		Eliminate
Concept 16	Yes	Yes	Yes		Proceed
Concept 17	Yes	Yes	Yes		Proceed
Concept 18	Yes	Yes	Yes		Proceed
Concept 19	Yes	Yes	Yes		Proceed
Concept 20	Yes	Yes	Yes		Proceed

1. Height requirement may not be fulfilled

4.3.1 Pugh

For an initial structured evaluation, the concepts were evaluated using two weighted Pugh matrices. In both matrices, the same criteria and weightings were used. The criteria chosen were such factors that during the concept generation phase were seen as design problems, or features that have great effect on the final solution:

- Height reduction possibility, weighted 3
- Weight, weighted 2
- Strength and ability to handle stress, weighted 3
- Manufacturability, weighted 4
- Assembly of the drawbar, weighted 3

The concepts were evaluated as better (+), equal (0) or worse (-) for each criterion in relation to a chosen reference. If a concept was ranked superior to the reference it got plus points equivalent to the weighting of that criterion, if ranked equal it got no points and if ranked worse it got a negative score equal to the weighting. The scores for each category were summarised and compiled for all concepts. Based on these results, concepts that were seen as uncompetitive could be eliminated.

In the first Pugh matrix (Appendix B) the existing concept from Parator was used as a reference. Twelve of the fifteen concepts scored better, one scored equal, and two scored worse than the reference. Among the concepts that scored higher points than the reference, concept four was the most superior. Six more concepts; five, twelve, thirteen, fourteen, seventeen and twenty, were significantly better than the reference, while four concepts scored only slightly better than the reference. Many concepts were ranked high in the height reduction possibility, mass, manufacturability and assembly of the drawbar criteria, whilst no concept outranked the reference in the strength and stress category. Not a surprising result, since the pre-study concluded that the existing dolly concept most likely is over-dimensioned.

A second Pugh matrix (Appendix B) was established to both verify the results from the first Pugh matrix, and to reach a decision in regards to elimination. In this matrix, concept twenty was used as reference, as it scored both well and similar to several other concepts in correlation to the first reference. A look at the second matrix reveals that concept thirteen scored one point higher than the reference, concepts fourteen and nineteen scored equal to, whilst all other scored worse than the reference.

Evaluation of the two Pugh matrices led to the elimination of eight concepts, i.e. eight concepts continued to the next phase for further development and assessment. Although scoring relatively poor in the matrices, concept one stayed in the process, as it is the original chassis design and thus a valuable comparison. Concept seven, nine, eleven and eighteen scored low in both matrices and were therefore discarded. Three concepts; number two, six, and twelve, were considered similar to, but with lower scores than, a few of the concepts that passed through this screening gate, and consequently did not pass this screening.

4.3.2 Expert discussions and combining of concepts

Eight concepts passed the Pugh matrices evaluation gate. At this point of the project a presentation was held for experts from Volvo and the Duo^2 project group. This proved valuable in the sense that input could be gained from uninfluenced individuals in the form of feedback and discussion regarding the progress so far, and the different concepts. Following the discussion, all concepts were reviewed again, and the conclusion was that the different concepts could be combined into new concepts; producing better designs while reducing the total number of concepts.

Concept fourteen and nineteen were combined into one concept as both concepts are virtually the same as concept one, except for the lowered mid-section of the top plate. Drawbar supports will be integrated into the main chassis structure. To accommodate a low drawbar position, the support section of the main chassis will be bent downwards.

Concept four, five and thirteen will be combined into a single solution and further developed in order to investigate possibilities of extremely low chassis design where the beams run through the chassis beams.

Concept 17 and 20 are very similar, however, concept 20 was deemed the more practically feasible concept and therefore concept 17 was excluded from further development.

After combining the concepts mentioned above, the four (including concept one) remaining concepts passed to a new design phase.

4.3.3 FEA and further design

In order to evaluate the different concepts on a structural level, and to investigate issues that might arise when introducing more subsystems, detailed CAD assemblies were completed for each remaining concept. The more accurate geometric representations were made to comply with manufacturer specifications of the different subsystems. Care was taken to ensure that the drawings would be representative of a "working" model, with no geometric interferences and space for systems to move around as intended. For comparison between the different concepts, and different design iterations of the concepts, strength and stiffness calculations were carried out using FEA.

4.4 Concept selection

When discussing and evaluating the three concepts for final selection it was a general consensus that the three different concepts all had potential and diverged so much from each other that it would be unwise to select one of them as an "overall best solution". As the merits of each concept were not directly in competition with each other, no concept was eliminated from further development. Instead, they were to be presented as possible design concepts. This was also motivated with respect to the purpose of the project initiation as an exploratory project. Consequently, the final concept selection ended here, with three concepts passing through to the detail design phase.

4.5 Detail design

In the detail design phase, the concepts were refined by incorporating all necessary sub-systems into the models and redesigning the chassis layouts using an iterative process utilising FEA computations. Investigations were done in regard to, for instance, beam thicknesses and cross-member layouts. A key priority in this phase was to make sure that the concepts met all requirements, such as height of the fifth wheel and the drawbar from ground reference plane, width of complete assembly and so on.

5 Results

This chapter presents the outcomes of the project, i.e. all three successful concepts are thoroughly described. Focus is on the mechanical design of the main chassis and solutions chosen. CAD models and finite element analyses of each dolly concept are also presented.

5.1 Concept 20

Concept 20 (Figure 40) is a concept that evolved through design studies of the manufacturing processes of Volvo truck chassis. Evidently, it has been proven during this project that similar manufacturing methods can be used for dollies as well. Drawings of the design are found in Appendix C.

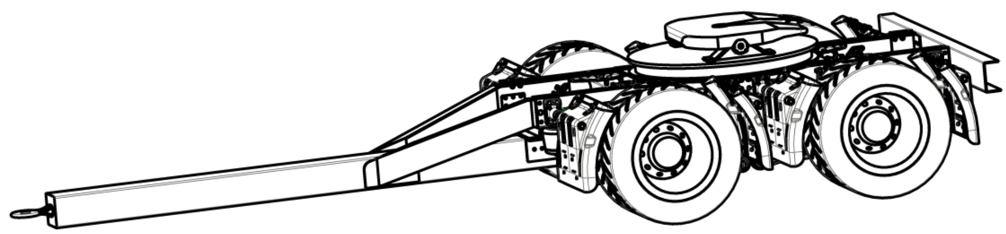

Figure 40 Concept 20

5.1.1 Main chassis

The main chassis consists of two longitudinal U-beams that are connected via three cross-members, with all connections bolted or riveted. All holes needed for fasteners are drilled before the profiles are bent to desired shapes. The U-beams are tilted, with the open channels facing each other, at a distance of 852 mm between the far ends.

The mounting flanges for the cross-members are standard components from Volvo, while the dimensions of the cross-members themselves are slightly modified, although. The turntable is centred on top of the longitudinal beams, with extra support from custom made support plates.

In order to fit the suspension, mudguards and other important modules, the longitudinal beams are 2,700 mm long; 200 mm longer than the Parator design. Furthermore, the beams are 185 mm tall, with 90 mm wide flanges. The height is derived from the dolly height in the requirement specification list, with the height of all other components subtracted.

To facilitate the attachment of the suspension, the flanges on the main beams have the same dimensions as on the higher truck chassis beams from Volvo. Moreover, a lighting rig is attached, using L-bar brackets, to the rear end of the main beams.

5.1.2 Suspension

A suspension system from Volvo, with a 133 mm ride height, connects the wheel axles with the main chassis. The suspension system consists of eight air bellows, two for each wheel; four shock absorbers, one for each wheel; two trailing arms holding the axles; and supporting struts, and fasteners. The main attachment consists of two rigid centre arms, connected to the two main beams, that are single-symmetric and supports the suspension for both wheel axles. The diagonal support struts are connected to cross-members on the main chassis. Air bellows are mounted to the bottom of the beams, with mounting brackets attached to both side of the beams.

5.1.3 Drawbar assembly

The drawbar is a 10 mm thick square (200 x 200 mm) beam attached with robust L-bars to two custom-made mounting beams. The foremost mounting beam is attached to the inside of the main beams, whilst the rear mounting beam, due to lack of available space inside, is attached underneath the main beams. For side supports, this concept encompasses bent U-beams, mounted inside the beams of the main chassis. Evidently, the side supports are bent in two directions. The coupling eye of the drawbar is screwed to the centre of the outer surface of the drawbar. This solution accommodates a coupling height of 355 mm, while the top of the drawbar is at a height of 455 mm above the ground reference plane.

5.1.4 Additional modules

Disc brakes, from a Volvo subcontractor, are mounted between the suspension and wheels and are communicating with the truck via the built-in controller area network. The wheel type is often specified by the user on basis of the intended use. Therefore, the design of this concept is done with the same wheels as specified to the current dolly in the Duo^2 project; i.e. Michelin XTA 2 Energy 445/45R19.5. In this design the lighting rig is identical to the rig used by Parator; loosely described as a U-beam with lights and retroreflectors from subcontractors.

The options for fifth wheels and turntables are few, and those available are very similar. Hence, the fifth wheel and turntable chosen were suggested by Parator. The fifth wheel is the 150 mm JSK 36 DV2 J from Jost and the turntable DK 90/16-1200 from BPW. On the turntable a twelve mm thick plate is mounted, working as a base for the fifth wheel. The height of the fifth wheel and turntable assembly combined is 252 mm.

Mudguards have been included in the design to verify the compatibility between them and other components in the system. In this case, as well, components from the standard assortment of Volvo have been used, since they are well proven. The mudguards are mounted on pipes that, in turn, are bolted to the outer side of the main beams. When towing a semi-trailer with the dolly it is legal to leave out the detachable top section of the mudguards, in order to save height. Nevertheless, one needs to carry them along on the journey.

5.1.5 Finite element analysis and computational evaluation

Figure 41 shows the result of one of the displacement magnitude computations. In the FEA model, no simplifications have been done to the chassis. However, due to complexity and for comparability reasons; the suspension is a simplified model of the BPW ALU 30 instead of the Volvo suspension. Forces were applied to the flanges of the turntable and the attachment points for the axles on the suspension trailing arms were held fixed. More displacement calculations can be found in Appendix D.

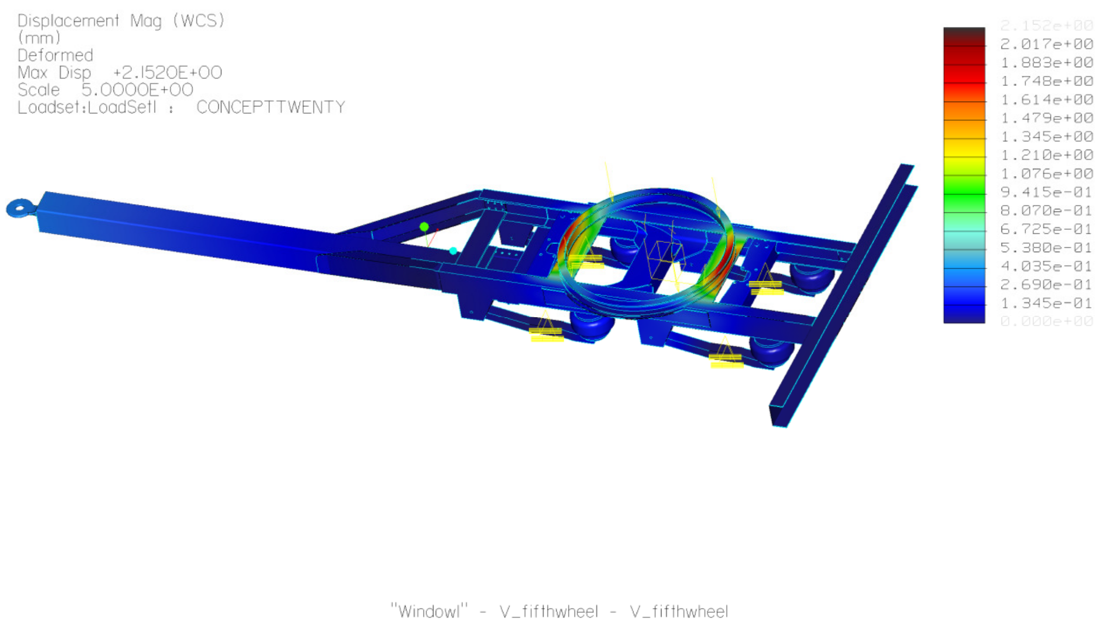

Figure 41 Displacement in the Concept 20, when applying the V-value to the turntable

5.2 Concept 4-5-13

The purpose of this design (Figure 42) is to present a concept investigating the absolute minimum height possible for a dolly. Such a low construction is made possible by mounting the front hangers and bellows directly to a top plate. To accommodate this layout, the axles are passed through slots in the main chassis beams. To get the chassis as low as possible, the SAF-Holland Z11-3020 axle assembly was used as it gives a ride height of only 170 mm. Appendix C presents drawings of the design.

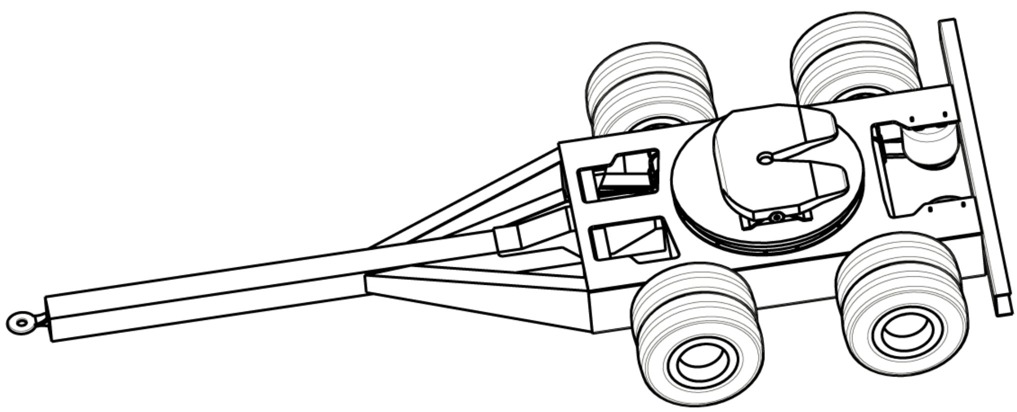

Figure 42 Concept 4-5-13

5.2.1 Main chassis

The main chassis encompasses a top plate and two longitudinal U-beams, tilted so that the open end faces the centre. Further reinforcement of the chassis is provided by cross-members connecting both sets of front hangers, as well as a few connecting the two main beams. The cross-members are designed to be manufactured from bent, rectangular sheet metal. The chassis components are connected by bolting or riveting. To accommodate the air suspension, the chassis main beams are fairly tall (400 mm). Inasmuch as the main beams are mounted on the outside of the suspension assembly, the main chassis is fairly enclosed, giving a boxed appearance.

5.2.2 Drawbar assembly

The Drawbar is bolted to the main chassis, which allows for it to be replaced with other drawbars of different lengths if needed. Side supports are made from sheet metal and are bolted to the drawbar and main chassis beams. The drawbar eye chosen is the 94/20/EG-compliant VBG 15-016000.

5.2.3 Wheels and tyres

In order to fulfil the legal requirements regarding clearance when the trailer pivots around the transversal axis, the height of this design is constrained by the wheel size chosen for the dolly. As trailer wheel and tyre sizes are fairly standardised, the wheel size was to be the smallest standard wheel available – 17.5 inches. The choice of tyres was based on data from manufacturers, selecting the smallest suitable tyres rated high enough to allow for an 18 tonne bogie load. A tyre size of 245/70 was chosen, as this gave the smallest overall diameter of 788 mm. Michelin (among others) supplies tyres of this size rated for the speeds and loads needed. However, these tyres have to be dual-mount – compromising rolling resistance and tyre wear for increased load capability.

5.2.4 Finite element analysis and computational evaluation

The results of an FEA iteration regarding displacement magnitude calculations can be seen in Figure 41. The axle attachment points have been constrained, and the fifth wheel V-value load has been applied, all other analyses can be seen in Appendix D.

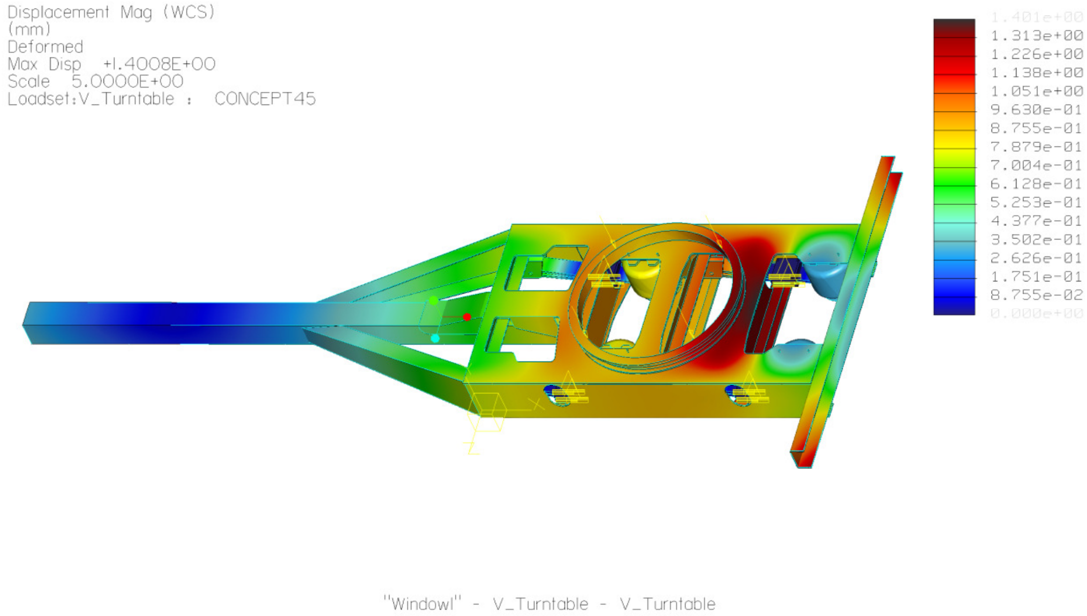

Figure 43 Displacement analysis of Concept 4-5-13

5.3 Concept 14-19

This concept (Figure 44) is to a large extent based on the Parator dolly. The idea is to adapt the original design to lower fifth wheel heights. Achieving the lower design is done by bending the top plate and creating a waist in the mid-section where the turntable is mounted. To reduce its height further, the SAF-Holland Z11-3020 axle assembly was used. Drawings of the concepts are to be found in Appendix C.

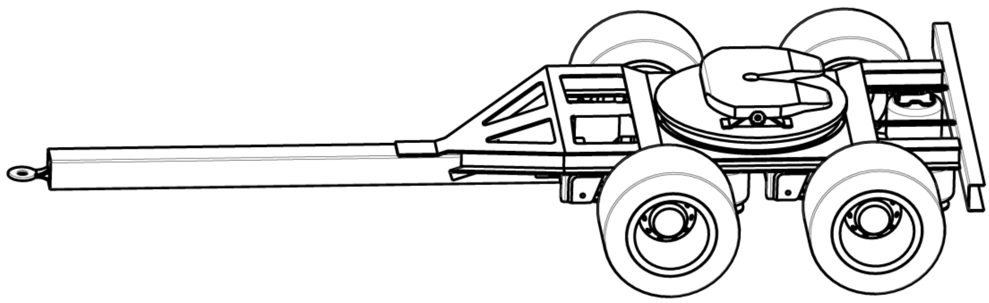

Figure 44 Concept 14-19

5.3.1 Main chassis

The chassis is a two-plate design, with a top and bottom plate forming the flanges of an I-beam construction. The top plate has been bent in order to accommodate the lower mid-section where the turntable is mounted. As the plate needs to be bent, it was decided to integrate the side supports for the drawbar into the plates. As can be seen in Figure 44 the plates extend diagonally downwards, and are bolted to the top and side of the drawbar. The I-beams are oriented so that there are two longitudinal beams running on each side and connected by transversal beams on each side of the turntable.

5.3.2 Drawbar assembly

The drawbar is bolted to the main chassis, allowing it to be replaced with other drawbars of different lengths if needed. As previously mentioned, the side supports are integrated into the top and bottom plates of the main chassis. Side supports are made from sheet metal and are bolted to the drawbar and main chassis beams. The drawbar eye chosen is the VBG 15-016000, as it is a proven design compliant with the 94/20/EG directives.

5.3.3 Wheels and tyres

The tyres used for this concept will be single-mount Michelin XTA 2 Energy 445/45R19.5, chosen for good fuel economy, low tyre wear, and commonality with previous dollies used in the Duo^2 project. Including rims, the overall diameter of the tyres is 896 mm and they have a width of 445 mm.

5.3.4 Finite element analysis and computational evaluation

The analysis in Figure 45 shows the FEA results of displacement magnitude computations. The load case and constraints are the same as for Concept 4-5-13.

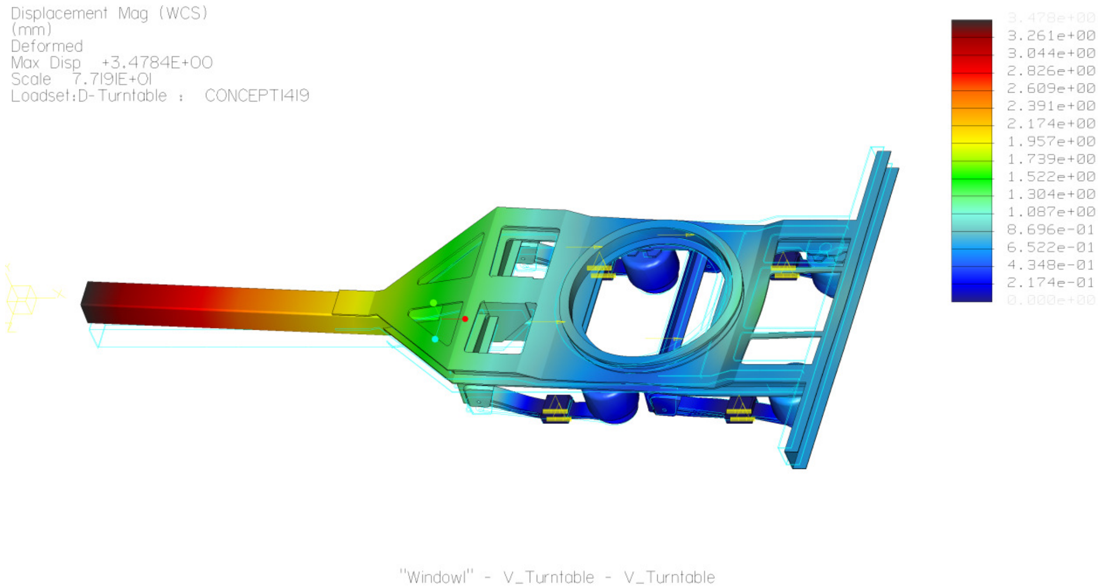

Figure 45 Displacement analysis of Concept 14-19

6 Discussion

This was an exploratory project; therefore, these concepts have not been designed with the intent of a market launch in the foreseeable future. Instead, the focus has been to investigate the potential implementations of different dolly concepts. Nevertheless, one may ask if not some of the dolly concepts show such potential that they may be realised into a production model? Reflections in this chapter will discuss the potential of the concepts and how the product development process worked as a framework for success.

6.1 Results

Chapter 5 Results presented detailed descriptions of three concepts. There are obvious differences between them; one is a completely new concept based upon truck chassis design, one is similar to the dollies manufactured by Parator, and the last concept presents an idea on how to design extremely low dollies.

The scope of the project was to investigate potential improvements and future possibilities with dollies. Within this scope, two different paths were established; the first was to explore if Volvo could use their skills to manufacture a successful dolly, and the second was to investigate how the existing dollies from Parator could be improved.

Within the time limit, the final concepts have been developed to a satisfactory extent. Naturally, it would have been preferred to have final designs completed with packaging of all components. However, this was considered unnecessary for this exploratory project and priority was therefore given to design and optimisation of the chassis. Additionally, packaging of included modules is much more time efficient if performed by a person who has experience from the included subsystems.

Finite element analyses in this project have been executed in Pro/Mechanica, the FEA application of PTC Pro/Engineer, which is not a dedicated FEA software package. The finite element analyses have been iterative and comparative of displacements rather than result oriented stress analyses. Desirably, the analyses should have been executed in a dedicated commercial engineering simulation software instead. Due to license reasons this was not possible, although it is believed necessary for further development of the concepts.

6.1.1 Concept 20

Concept 20 clearly indicates that it should be possible to design and manufacture a dolly using existing knowledge and manufacturing techniques found in-house at Volvo. Much of their components are transferable to a dolly with minor changes. The main beams in the presented concepts are, however, smaller than the ones used for truck chassis. This is something that was discussed within the project and ideas on how to design a dolly with standard heights from truck chassis beams were generated. Using a higher chassis would lead to quite large modifications of the beams, in order to fit the turntable and fifth wheel within the height requirement. Additionally, since it was proven possible to mount the suspension onto the lower beams and the finite element analysis and calculations proved their strength to be sufficient, the lower beams were chosen.

The whole drawbar assembly, including the bent profiles, needs to be further developed and verified through additional testing. Moreover, some of the L-beams and brackets used in the design could be changed to some in the standard assortment from Volvo.

Overall, the concept validates, in a satisfactory manner, the question posed; it is possible to manufacture a dolly using the same method as if manufacturing a truck chassis. The perspicacious mind, however, understands that there is some design work to complete before the concept is ready for a market introduction.

6.1.2 Concept 4-5-13

The design provides a chassis concept that shows how wheels are ultimately the restricting factor on the theoretical minimum height of a dolly. A decrease of overall height of the dolly is of course assumed to increase the cargo volume accordingly.

Some trade-offs have been made in order to achieve the low chassis height – such as the use of dual-mount wheels and tyres – and further investigation is needed to determine the full extent of these trade-offs, and their economical feasibility. Primarily, such an investigation should focus on how other modules in a vehicle combination could be made lower, as a result of the decreased dolly height, and how this affects the cargo space. It would also be interesting to study the effect of increased cargo space in relation to actual cargo volume, i.e. is the extra space being utilised to a satisfactory degree? These parameters should of course be evaluated based on the actual efficiency increases and cost savings, and how these compare to the expected tyre cost increases.

Further structural analysis could provide input regarding possible chassis design improvements, primarily cross-member design and layout. As the chassis is very tall compared to other designs, investigation of the possibility to use much thinner sheet metal, while still reaching strength and stiffness goals is considered highly interesting, and FEA analyses showed some promising results in that aspect.

Regarding manufacturability, the concept should provide fairly straightforward manufacturing processes, primarily bending and cutting sheet metal as well as water-jet cutting of the top plate. The design allows for a minimal amount of welding in favour of bolting or riveting, but the design of the connector layout needs further investigation.

6.1.3 Concept 14-19

This concept provides a viable solution for quick adoption of an existing concept into a production model, which could be beneficial if a design is to be tried out within the Duo^2 research project. The concept does meet the target height, with only slight changes to the original design. Integration of the side supports into the main chassis plates introduces additional bending operations, and larger plates. However, it does reduce complexity and welding, and bending is carried out on the top plate for the mid-section anyway.

The merits of this concept must also be weighed against its drawbacks. Since it is fairly close to an already proven design, it should offer reliability to a rather high degree. However, as a concept it has very little additional potential when it comes to lowering the height even further.

6.2 Methodology and process

The scope at initiation of the process was vague, which made the inlet to the development funnel wide. Consequently, this led to many possible ideas being investigated during the long pre-phase; it could be described as concurrent engineering without a clear goal in sight (or creative chaos). Even if it was time-consuming, a long and exploratory pre-study helped to create project delimitations and an extensive requirements specification. Nevertheless, the product development method followed structural and standard procedures derived from theory. The funnel approach, together with a Gantt chart helped to set the path and keep momentum to reach the fictive gates to downstream phases without delays. Given the fact of the dissimilarity between the three concepts, it is valid to discuss if it would have been an advantage to have separate evaluation processes for them. However, the uniform process was chosen to ease the evaluation of different concepts compared to the current Parator concept; and why develop concepts according to new standards that, evidently, are inferior to the current manufacturing standards?

Since much of the knowledge in the industry is based on experience it has been hard to validate much of the information and requirements gained in other ways than to trust the interviewees.

6.3 Aim and purpose fulfilment

This project has resulted in three concepts that all facilitate low dolly heights, one which gives a proposal on an extremely low dolly. There is still some development work to be done with the concepts, especially regarding packaging of modules and structural analysis, but all three concepts show potential for a future market introduction. Therefore we regard the aim to be achieved.

In a more overall perspective, the purpose was to increase the knowledge about dollies, and their potential, within Duo^2. Hopefully, this report gives an understanding of the possibilities and limitations regarding dolly design and manufacturing. Moreover, the extensive requirement specification list gives a compiled overview of all requirements on a dolly, and can also be used as a reference for other modules.

7 Conclusions

The intent of the study was to see what improvements could be made to a dolly trailer. After researching the subject and the systems involved, it became clear that the design improvement that would add the most value to the customer would be to increase the cargo space of a given vehicle combination. Hence, decreasing the height of the dolly – in turn creating more useful cargo space for a towed semi-trailer, became the main focus of the redesign. Ideas regarding other possible design changes were dismissed after it was clear that the dolly should preferably be a simple, passive component in the system.

As shown, there are multiple ways to reduce the overall height of the dolly. Without modifications to the chassis, height could be reduced by using a suspension unit with a low ride height or by using very small wheels and tyres. However, trade-offs exist when using these alternatives and the reduction in height is limited by what is available from subcontractors. Decreasing the height by redesigning the main chassis can offer possibilities for more dramatic reductions. Concept 4-5-13 presents a chassis design where the overall height has been reduced as much as possible. The most important conclusion to be drawn from this design is that it is the size of the tyres that ultimately constrains the minimum theoretical height of a trailer.

Investigations into the possibility of using Volvo truck parts to construct a dolly showed promising results. Applying the design principles of truck chassis design in combination with a Volvo air suspension unit produced a feasible design concept.

The study covers the development of possible dolly chassis designs for different manufacturing methods, and provides solutions for very low constructions. However, further calculations are needed for final dimensioning of beam geometries and connectors, as well as for dynamic evaluation of the chassis concepts.

7.1 Recommendations

As discussed in Chapter 6; the finite element analyses conducted in this project are considered unsatisfactory as stress calculations for final dimensioning. Hence, the chassis dimensions should be reviewed after further structural analysis using different FEA software.

Duo^2 aims to increase the efficiency in the haulage industry; one step on the way would be to practically investigate the effects of lower chassis designs and how they affect fuel consumption in relation to transported goods. Further studies are thus recommended on the effects of a low fifth wheel height on semi-trailer design, with respect to economy. The proposed low-height concept incorporates a non-standard layout with the axles running through the main beams. Further development, and a prototype vehicle, could be interesting in order to evaluate the design.

Another recommendation is to further investigate the potential of combining truck and trailer manufacturing. The project has shown feasibility for successfully applying truck chassis design principles and manufacturing to trailer chassis. Studies regarding adoption of available Volvo manufacturing equipment to produce trailers could be of high interest. A working prototype could be produced, either by Volvo or Parator, in order to study practical aspects of the design.

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Appendix A. Requirements specification list

REQUIREMENT SPECIFICATION

Carl Davidsson & Anders Henriksson

Requirement	**Value /**			**Source**	**Description / Comments**
1. Measurements					
1.1. Lengths					
1.1.1. Swept radius of trailer front in relation kingpin	≤	2040	mm	EC-9653 / SS-ISO 1726-1 / 2	Horizontal measurement. To any point of front of the semi-trailer.
1.1.2. Length from plane trailer front to kingpin	≤	1600	mm	From 1.1.2 and 1.3.1	Derived from Pythagorean theorem of the hypotenuse 1.1.2. and cathetus 1.3.1.
1.1.3 Length between wheel axles on dolly	≥	1300	mm	EC-9653	With 1300 mm spacing; 18t is allowed as bogie weight. Spacing under 1300 mm reduces allowed weight.
1.1.3.1. Length between wheel axles on dolly	<	1300	mm	EC-9653	With <1300mm and ≥ 1000mm spacing, 16t is allowed as bogie weight.
1.1.3.2. Length between wheel axles on dolly	<	1000	mm	EC-9653	With spacing <1000mm 11t is allowed as bogie weight.
1.1.3.3. Length between wheel axles on dolly	>	1800	mm	EC-9653	With >1800 mm spacing 20t is allowed as bogie weight.
1.2. Heights					
1.2.1. Normal / High couplings					
1.2.1.1 Height of fifth wheel while laden	≤	1300	mm	SS-ISO 1726:2005	From GRP, Ground Reference Plane
1.2.1.2. Height of fifth wheel while laden	≥	1150	mm	SS-ISO 1726:2005	From GRP, Ground Reference Plane
1.2.1.3. Height of fifth wheel, uncoupled	≤	1400	mm	SS-ISO 1726:2005	From GRP, Ground Reference Plane
1.2.2. Low couplings					
1.2.2.1. Height of fifth wheel while laden	≤	975	mm	SS-ISO 1726-2:2007	From GRP, Ground Reference Plane
1.2.2.2. Height of fifth wheel while laden	≥	925	mm	SS-ISO 1726-2:2007	From GRP, Ground Reference Plane
1.2.2.3. Height of fifth wheel uncoupled	≤	1000	mm	SS-ISO 1726-2:2008	From GRP, Ground Reference Plane
1.2.2.4. Height of drawbar eye coupling, laden		380±25	mm	SS-ISO 11407:2005	From GRP, Ground Reference Plane
1.2.3. Height of all vehicles	≤	4000	mm	EC-9653	
1.2.4. Drawbar diameter/height		250	mm	SS-ISO 11407:2005	At the long, "horizontal" part.
1.2.5. Height of all vehicles in Sweden	≤	4500	mm		
1.3. Widths					
1.3.1 Total width	≤	2550	mm	EC-9653	
1.4. Radiuses					

1.4.1. Rim radius		19,5 / 22,5	inches		Standard sizes in the industry, but no actual legal requirement.
1.4.3 Outer turning radius of truck		12500	mm	EC-9653	Maximum allowed, EU / Germany
1.4.4 Inner turning radius of truck		5300	mm	EC-9653	Minimum allowed, EU / Germany (not applied in Sweden)
1.4.5. Outer radius in Sweden		15000	mm		Please verify
2. Mechanical properties					
2.1. Axle loads					
2.1.1. Bogie load	≤	18	tonne	EC-9653	Legal requirements on 18 tonne bogie load (see 1.1.3)
2.1.2. Load equalisation between axles		Yes		VVFS 2003:22	A system for load equalisation between axles should be in use
2.2. Weight					
2.2.1. Total weight	≤	2500	kg		I.e. lower than existing one, if no value adding function is added. (2460kg)
2.2.2. Total weight		As low as possible			Limited loading capacity on truck…
2.3. Load carrying capacity					
2.3.1. Pressure					
2.4. Load cases					
2.5. Aerodynamics and rolling resistance					
2.5.1. Rolling resistance		To be reduced as much as possible			Rolling resistance is almost as "costly" to the fuel consumption as aerodynamic drag.
2.6.1. Aerodynamics		No increase of drag coefficient			
3. Lights and retroreflectors				VVFS 2003:22	"Vägverkets föreskrifter om bilar och släpvagnar som dras av bilar", VVFS 2003:22
3.1. Front positioning lamps					
3.1.1. Quantity		2	pcs		
3.1.2. Colour		White / Yellow			
3.1.3. Positioning					
3.1.3.1. Distance between lamps	≥	600	mm		Inner edges of the lamps. Horizontal measurement.
3.1.3.2. Distance from side of Dolly	≤	150	mm		From side of the dolly to closest point of the lamp. Horizontal measurement.
3.1.3.2 Vertical position of lamps		350-2100	mm		From GRP
3.2. Direction indicators					
3.2.1. Quantity		Even number			At least two on the back
3.2.2. Colour		Orange-			

		yellow			
3.2.3. Positioning					
3.2.3.1. Distance between lamps	≥	600	mm		Inner edge of lamps. Horizontal measurement.
3.2.3.2. Distance from side of Dolly	≤	400	mm		From side of the dolly to closest point of the lamp. Horizontal measurement.
3.2.3.3. Vertical position of lamps		350-1500	mm		From GRP. Min 500 mm for Category 5 in VVFS 2003:22, what is that?
3.2.4. Frequency		90±30	blinks per minutes		
3.2.5. Warning indicators					Should be connected to the warning indicator lights
3.3. Sidemarker light					
3.3.1 Quantity		Depending on the length of the dolly			Depends on the length of the dolly.
3.3.2. Colour		Orange-yellow			
3.3.3. Positioning					
3.3.3.1. Vertical position of lamps		350-1500	mm		From GRP. If design requires a lower value, it is legal.
3.3.3.2. Position from front and back	≤	2000	mm		Horizontal measurement. If L<6m, the front requirement does not need to be fulfilled.
3.3.3.3. Distance between lamps	≤	6000	mm		On each side.
3.4. Sidemarker retroreflectors					
3.4.1. Quantity		Depending on length of the dolly			Depending on length of the dolly
3.4.2. Colour		Orange-yellow			Should reflect orange-yellow light when exposed to light.
3.4.3. Positioning					
3.4.3.1. Vertical position of lamps		350-900	mm		From GRP. If design requires a lower value it is legal. If a higher value is required it can be up to 1200mm, or 1500mm if combined with sidemarker light.
3.4.3.2. Position from front and back	≤	2000	mm		Horizontal measurement. If L<6m, the front requirement does not need to be fulfilled.
3.4.3.3. Distance between lamps	≤	6000	mm		On each side.
3.5. Back positioning lamps					
3.5.1. Quantity	≥	2	pcs		

3.5.2. Colour		Red			
3.5.3. Positioning					
3.5.3.1. Distance between lamps	≥	600	mm		Inner edges of the lamps. Horizontal measurement.
3.5.3.2. Distance from side of Dolly	≤	400	mm		From side of the Dolly to closest point of the lamp. Horizontal measurement.
3.5.3.3 Vertical position of lamps		350-1500	mm		From GRP. The height limit can be increased to 2100 mm if the design requires it.
3.6. Stop lights					
3.6.1. Quantity	≥	2	pcs		At the rear of the vehicle. Activates when using regular breaking system.
3.6.2. Colour		Red			
3.6.3. Positioning					
3.6.3.1. Distance between lamps	≥	600	mm		
3.6.3.2. Distance from side of Dolly					
3.6.3.3. Vertical position of lamps		350-1500	mm		From GRP. The height limit can be increased to 2100 mm if the design requires it.
3.7. License plate light					
3.7.1. Quantity	≥	1	pcs		
3.7.2. Colour		White			The license plate should be readable at night
3.8. Front retroreflectors					
3.8.1. Quantity	≥	2	pcs		
3.8.2. Colour		White			When exposed to light it should reflect white light
3.8.3. Positioning					
3.8.3.1. Distance from side of Dolly	≤	400	mm		From side of the Dolly to closest point of the lamp. Horizontal measurement.
3.8.3.2. Distance between lamps	≥	600	mm		Inner edges of the lamps. Horizontal measurement.
3.8.3.3 Vertical position of lamps		350-900	mm		From GRP. The height limit can be increased to 1500 mm if the design requires it.
3.9. Rear retroreflectors					
3.9.1. Geometry		Triangular			
3.9.2. Quantity		2	pcs		
3.9.3. Colour		Red			When exposed for light it should reflect white light
3.9.4. Positioning					
3.9.4.1. Direction of one triangle peak		Upwards			Should point upwards.
3.9.4.2. Distance from side of Dolly	≤	400	mm		From side of the Dolly to closest point of the retroreflector. Horizontal measurement.
3.9.4.3. Distance between retroreflectors	≥	600	mm		From the inner edges. Horizontal measurement.

3.9.4.4. Vertical position of retroreflectors		350-900	mm		From GRP. The top limit can be increased to 1500 mm and the bottom limit can be eliminated if the design requires so.
4. Braking system					
4.1. Serviceable / Operational		Normal conditions		VVFS 2003:22	Including components shall be safe
4.1.1.Operational reserve		Large enough		VVFS 2003:22	To fulfil the requirements on brakes even if the system is warm or the brake pads are worn out
4.1.2. Manual control of braking force		Not legal			It should not be possible to manually modify the braking force.
4.1.3. Other systems using potential energy	≤	40	%		The working pressure of the braking system should not drop below 60 % of the calculated/estimated pressure.
4.2. Installation		Direct to wheels		VVFS 2003:22	Parking- and service brake. Braking components should be in direct contact whit the wheels or with components that are in direct connection with the wheels.
4.2.1. Pipes and tubes		Stable to chassis		VVFS 2003:22	There should be no risk of the of the operation of pipes and tubes being impaired by vibrations.
4.2.2. Fluid reservoir		Easy access		VVFS 2003:22	Easy to check the amount of braking liquid and to perform a top-up. The material should be resistant to corrosion and to battery acids.
4.2.2.1.Type-of-fluid sign		Yes			Should be in direct connection with the top-up inlet and tell what type of braking fluid that is used in the system.
4.3. Service brake					
4.3.1 Fitted		Yes		VVFS 2003:22	If the dolly weight is 750 kg or more; a service brake system should be fitted.
4.3.2. Calibration		Same on wheels on same axle			The wheels on one axle should be exposed to the same braking force if there is no significant difference in friction between wheel and road.
4.3.3. Installation					
4.3.3.1. Manoeuvrable		From tractor's braking			

		system			
4.3.3.2. Automatic brake		Connection loss			When either braking or mechanical connection is lost between tractor and dolly, the dolly's brake system should activate automatically.
4.3.3.3. No affect on the tractor's internal braking system					
4.3.3.4. Force regulator		Automatic			If the tractor has been fitted with automatic brake force regulators, this should also be installed on the dolly. If the trailer weight is over 3500kg; the brake force should be automatically compensated for wear.
4.3.4. Brake force		5.8	m/s2		From 60km/h to standstill if the dolly weight is below 3500 kg. (5 m/s^2 if weight is higher than 3500kg)
4.4. Parking brake					
4.4.1. Fitted		Yes		VVFS 2003:22	
4.4.2. Performance					Should hold the Dolly in sloping hills even if standing by itself. Mechanical system when applied
4.4.1.1.Operational angles		16%			With friction coefficient 0,6 and manoeuvre force 584 N.
4.4.1.2. Velocity resistance	≤	20	km/h		Without damage
4.4.3. Manoeuvrable		From right side			From right side of Dolly or at the drawbar. If a spring brake is used in the system there is no requirement to have a control.
5. Mudguards					
5.1. Front facing part					Must extend to a point at a plane intesecting the highest point of the tire at a 5° angle to the horizontal plane forward-downwards.
5.2. Rear facing part					Must extend down to a plane tangent to the wheel intersecting the GRP at a 14° angle
5.3. Width		Tire width			Must at least cover the width of the tire
5.4. Side height					Side height of the mudguard must be at least 10% of the width of the mudguard, this applies to the part extending rearwards from a vertical plane intersecting the wheel centre. The minimum

					height requirement is 30mm.
6. Legal requirements and standards					
6.1. ISO					
6.1.1. ISO 1102					Drawbar eye. Commercial road vehicles - 50 mm drawbar eyes - Interchangeability
6.1.2. ISO 11406					Commercial road vehicles - Mechanical coupling between towing vehicles with rear-mounted coupling and drawbar trailers - Interchangeability
6.1.3. ISO 11407					Commercial road vehicles - Mechanical coupling between towing vehicles, with coupling mounted forward and below, and centre-axle trailers - Interchangeability
6.1.4. ISO 15031-1 - ISO 15031-7					Road vehicles — Communication between vehicle and external equipment for emissions-related diagnostics
6.1.5. ISO 337:1981					Road vehicles -- 50 semi-trailer fifth wheel coupling pin -- Basic and mounting/interchangeability dimensions
6.1.6. ISO 4086					Road vehicles -- 90 semi-trailer fifth wheel kingpin -- Interchangeability
6.1.7. ISO 1726:2005					Road vehicles – Mechanical coupling between tractors and semi-trailers - Interchangeability
6.2. SIS					
6.2.1 SS 3585					Vägfordon - Tunga fordon - Bromsanpassning lastbil-släpvagn och dragbil-påhängsvagn
6.2.2. SS-ISO 1726-2:2007					Vägfordon - Mekaniska kopplingar mellan dragfordon och påhängsvagnar - Del 2: Utbytbarhet mellan dragfordon med låg...
6.2.3. SS-ISO 1726-3:2007					Vägfordon - Mekaniska kopplingar mellan dragfordon och påhängsvagnar - Del 3: Fordringar på

					påhängsvagnens kontaktyta...
6.2.4. SMS 801					Vehicles - Trailer drawbars - Connection for the drawbar eye
6.2.5. SMS 802					Vehicles - Trailer drawbars - Principal dimension
6.3. EC-regulations					
6.3.1 Council directive 96/53/EC					
6.3.2. 76/756/EEG					Lights and reflectors
6.3.3. ECE-reglemente 48					Lights and reflectors
6.3.5. ECE-reglemente 16					Braking system
6.3.6. 71/320/EEG					Braking system
6.4. Swedish law requirements					
6.4.1. VVFS 2003:22					Swedish Road Aadministration (Vägverkets) statutes, VVFS 2003:22
7. Environmental					
7.1. Volvo					
7.2. Society					
7.3. Fuel consumption					
7.3.1 Total fuel consumption for truck		Lower than existing one.			The intent of optimising construction is to have a positive impact on fuel consumption in relation to transported weight.
8. Economical					
8.1. Manufacturing cost					
8.1.1 Manufacturing cost		To be kept as low as possible.			
9. Functional					
9.1. Turning capability					
9.2. Degrees of freedom					
9.2.1. Normal / High coupling					
9.2.1.1. Rotation of the trailer towards the front		6	degrees	SS-ISO 1726:2005	
9.2.1.2. Rotation of the trailer towards the back		7	degrees	SS-ISO 1726:2005	
9.2.1.3. Rotation of the trailer towards the sides	±	3	degrees	SS-ISO 1726:2005	
9.2.1.4. Rotation of the trailer in horizontal plane	±	25-90	degrees	SS-ISO 1726:2005	When 8.2.2 is 7 degrees - In manoeuvring conditions with 8.2.2 varying 7-3 degrees
9.2.2. Low coupling					
9.2.2.1. Rotation of the trailer		3.5	degrees	SS-ISO 1726-2:2007	

towards the front					
9.2.2.2. Rotation of the trailer towards the back		4.5	degrees	SS-ISO 1726-2:2007	
9.2.2.3. Rotation of the trailer towards the sides	±	2	degrees	SS-ISO 1726-2:2007	
9.2.2.4. Rotation of the trailer in horizontal plane	±	25-90	degrees	SS-ISO 1726-2:2007	When 9.2.2.2. is 4.5 degrees - In manoeuvring conditions with 9.2.2.2 varying 4.5-3 degrees
9.2.3. Rotation of drawbar from coupling plane		6	degrees	SS-ISO 11407:2005	
9.3. Suspension					
9.3.1. Suspension devise		Satisfactory		VVFS 2003:22	Satisfying suspension between chassi and wheels.
9.3.2. Dampers		If 7.3.1. not enoguh		VVFS 2003:23	Should be implemented if suspension devise ability to reduce oscilliations is not satisfactory.
9.4. Durability					
9.4.1. Lifetime		At least the same as other trailers			
9.4.2.					
9.5. Maintenance					
9.6. Ease of use					
9.7. Turntable		Mandatory			In Sweden
10. Manufacturing constraints					
10.1. In-house					
10.2. Standardised components					
11. Ergonomic					
11.1. Safety					
11.1.1. Traffic safety		No negative impact regarding traffic safety			
11.1.2. Road user safety		No possibility for pedestrians to get under the Dolly			
11.2. Operation					
11.3 Ease of use					
11.3.1. Easy to reach vital components					
11.3.2. Intuitive design of interface					Cognitive design

layouts					
12. Appearance					
12.1 Conformance with other components					
13. Compatibility constraints					
13.1. Mechanical interfaces					
13.2. Electrical interfaces					
13.2.1 Loss of Voltage	≤	1	Volt		From the connection on the Dolly to the source of the power consumption
13.3. Hydraulic and pneumatic interfaces					

Appendix B. Pugh matrices

	Pugh matrix 1					
Created by:	Davidsson & Henriksson		**Created:** 2011-05-09			
Weighting:	1-5	**Score:**	Better(+), Equal (0) or Worse (-)			
		Reference	**Concept 1**	**Concept 2**	**Concept 4**	**Concept 5**
Criteria	**Weight**		**Score**	**Score**	**Score**	**Score**
Criterion 1	3	Concept Reference - Concept 1	0	-	+	+
Criterion 2	2		0	+	+	+
Criterion 3	3		0	-	-	-
Criterion 4	4		0	+	+	+
Criterion 5	3		0	+	+	0
		No. Of +	0	3	4	3
		No. Of + w weights	0	9	12	9
		No. Of -	0	2	1	1
		No. Of - w. Weights	0	6	3	3
SUM:	15	Sum:	0	1	3	2
SUM w. Weights:		Sum w. Weights:	0	3	9	6

		Reference	**Concept 6**	**Concept 7**	**Concept 9**	**Concept 11**
Criteria	**Weight**		**Score**	**Score**	**Score**	**Score**
Criterion 1	3	Concept Reference - Concept 1	0	+	+	0
Criterion 2	2		+	0	+	+
Criterion 3	3		-	0	-	-
Criterion 4	4		0	0	-	+
Criterion 5	3		0	0	+	-
		No. Of +	1	1	3	2
		No. Of + w weights	2	3	8	6
		No. Of -	1	0	2	2
		No. Of - w.	3	0	7	6

		Weights				
SUM:	15	Sum:	0	1	1	0
SUM w. Weights:		Sum w. Weights:	-1	3	1	0

		Reference	**Concept 12**	**Concept 13**	**Concept 14**	**Concept 16**
Criteria	**Weight**		**Score**	**Score**	**Score**	**Score**
Criterion 1	3	Concept Reference - Concept 1	-	0	+	0
Criterion 2	2		+	+	0	0
Criterion 3	3		0	-	0	0
Criterion 4	4		+	+	0	+
Criterion 5	3		+	+	+	+
		No. Of +	3	3	2	2
		No. Of + w weights	9	9	6	7
		No. Of -	1	1	0	0
		No. Of - w. Weights	3	3	0	0
SUM:	15	Sum:	2	2	2	2
SUM w. Weights:		Sum w. Weights:	6	6	6	7

		Reference	**Concept 18**	**Concept 19**	**Concept 20**
Criteria	**Weight**		**Score**	**Score**	**Score**
Criteria 1	3	Concept Reference - Concept 1	+	+	-
Criteria 2	2		0	0	+
Criteria 3	3		-	0	0
Criteria 4	4		-	-	+
Criteria 5	3		+	+	+
		No. Of +	2	2	3
		No. Of + w weights	6	6	9
		No. Of -	2	1	1
		No. Of - w. Weights	7	4	3
SUM:	15	Sum:	0	1	2
SUM w. Weights:		Sum w. Weights:	-1	2	6

Pugh matrix 2

Created by:	Davidsson & Henriksson		**Created:** 2011-05-10			
Weighting:	1-5	**Score:**	Better(+), Equal (0) or Worse (-)			
		Reference	**Concept 1**	**Concept 2**	**Concept 4**	**Concept 5**
Criteria	**Weight**		**Score**	**Score**	**Score**	**Score**
Criterion 1	3	Concept Reference - Concept 20	+	0	+	+
Criterion 2	2		-	-	-	-
Criterion 3	3		0	0	0	+
Criterion 4	4		-	-	-	-
Criterion 5	3		-	0	0	-
No. Of +			1	0	1	2
No. Of + w weights			3	0	3	6
No. Of -			3	2	2	3
No. Of - w. Weights			9	6	6	9
SUM:	15		-2	-2	-1	-1
SUM w. Weights:			-6	-6	-3	-3

		Reference	**Concept 6**	**Concept 7**	**Concept 9**	**Concept 11**
Criteria	**Weight**		**Score**	**Score**	**Score**	**Score**
Criterion 1	3	Concept Reference - Concept 20	0	+	+	0
Criterion 2	2		-	-	-	0
Criterion 3	3		+	+	-	+
Criterion 4	4		-	-	-	-
Criterion 5	3		-	-	0	-
No. Of +			1	2	1	1
No. Of + w weights			3	6	3	3
No. Of -			3	3	3	2
No. Of - w. Weights			9	9	9	7
SUM:	15		-2	-1	-2	-1
SUM w. Weights:			-6	-3	-6	-4

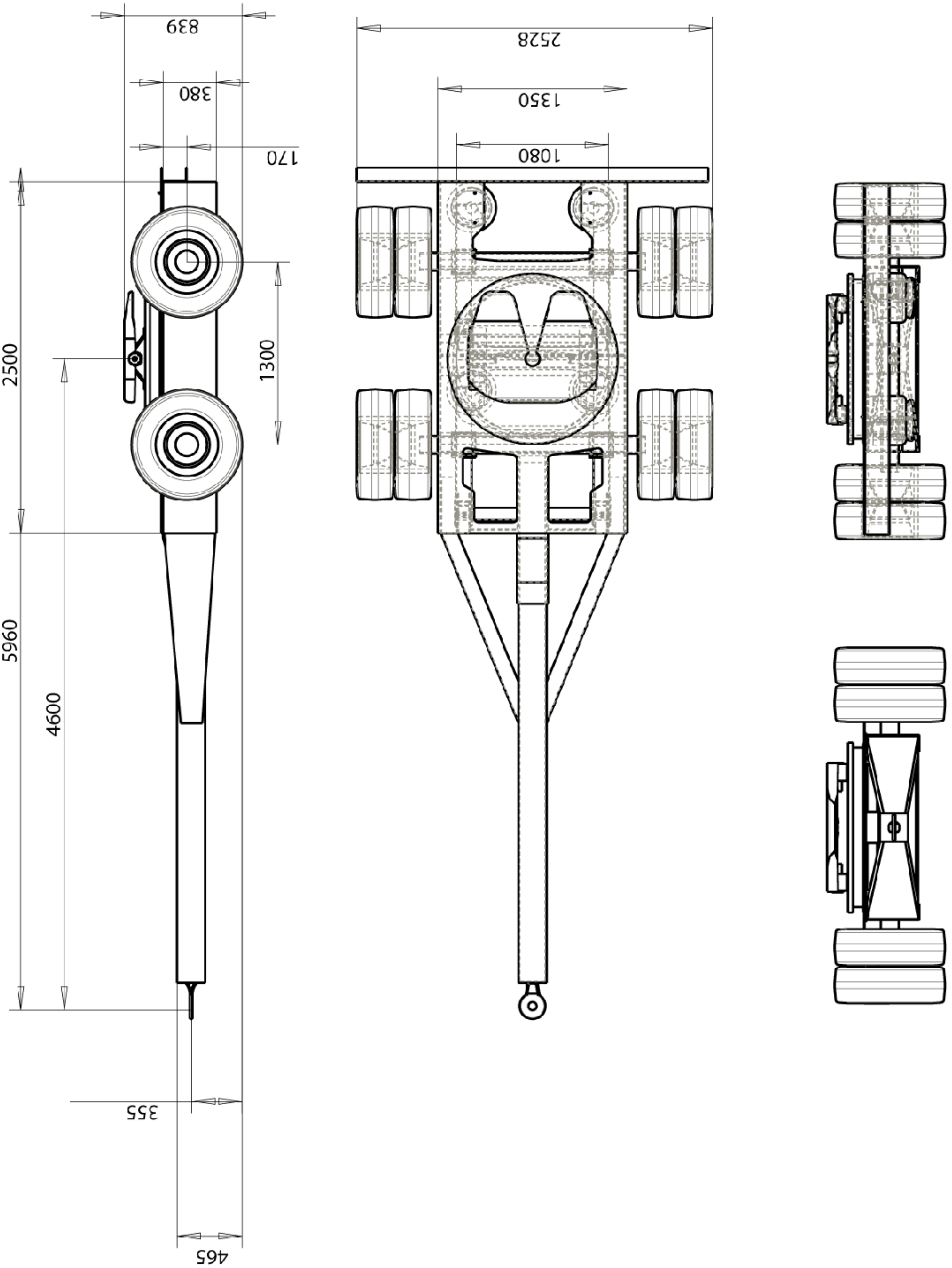
		Reference	Concept 12	Concept 13	Concept 14	Concept 16
Criteria	**Weight**		**Score**	**Score**	**Score**	**Score**
Criterion 1	3	Concept Reference - Concept 20	0	0	+	+
Criterion 2	2		0	-	-	-
Criterion 3	3		0	+	+	0
Criterion 4	4		-	0	-	-
Criterion 5	3		0	0	0	0
No. Of +			0	1	2	1
No. Of + w weights			0	3	6	3
No. Of -			1	1	2	2
No. Of - w. Weights			4	2	6	6
SUM:	15		-1	0	0	-1
SUM w. Weights:			-4	1	0	-3

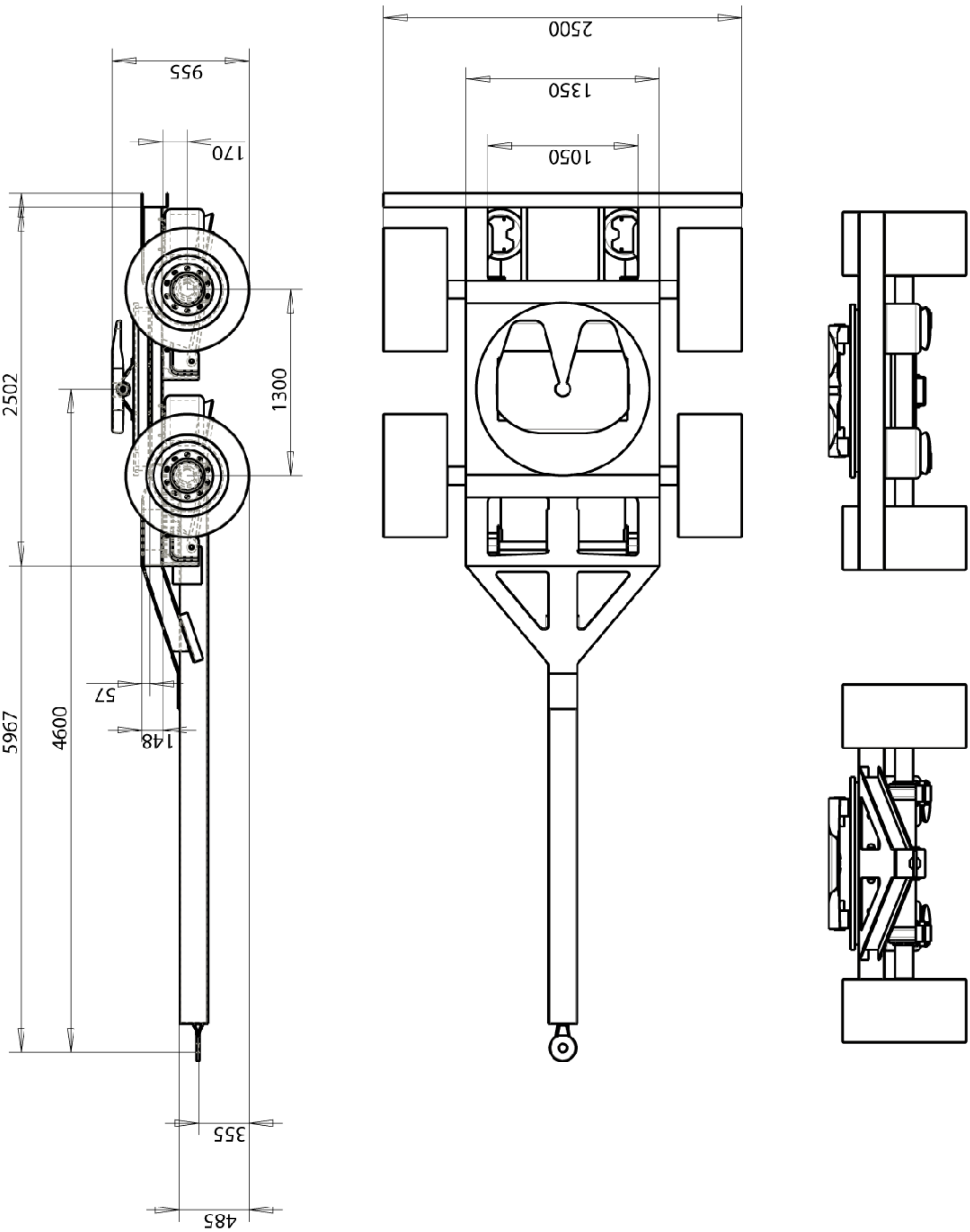
		Reference	Concept 17	Concept 18	Concept 19	Concept 20
Criteria	**Weight**		**Score**	**Score**	**Score**	**Score**
Criterion 1	3	Concept Reference - Concept 20	0	+	+	0
Criterion 2	2		0	0	-	0
Criterion 3	3		0	0	+	0
Criterion 4	4		0	-	-	0
Criterion 5	3		0	0	0	0
No. Of +			0	1	2	0
No. Of + w weights			0	3	6	0
No. Of -			0	1	2	0
No. Of - w. Weights			0	4	6	0
SUM:	15		0	0	0	0
SUM w. Weights:			0	-1	0	0

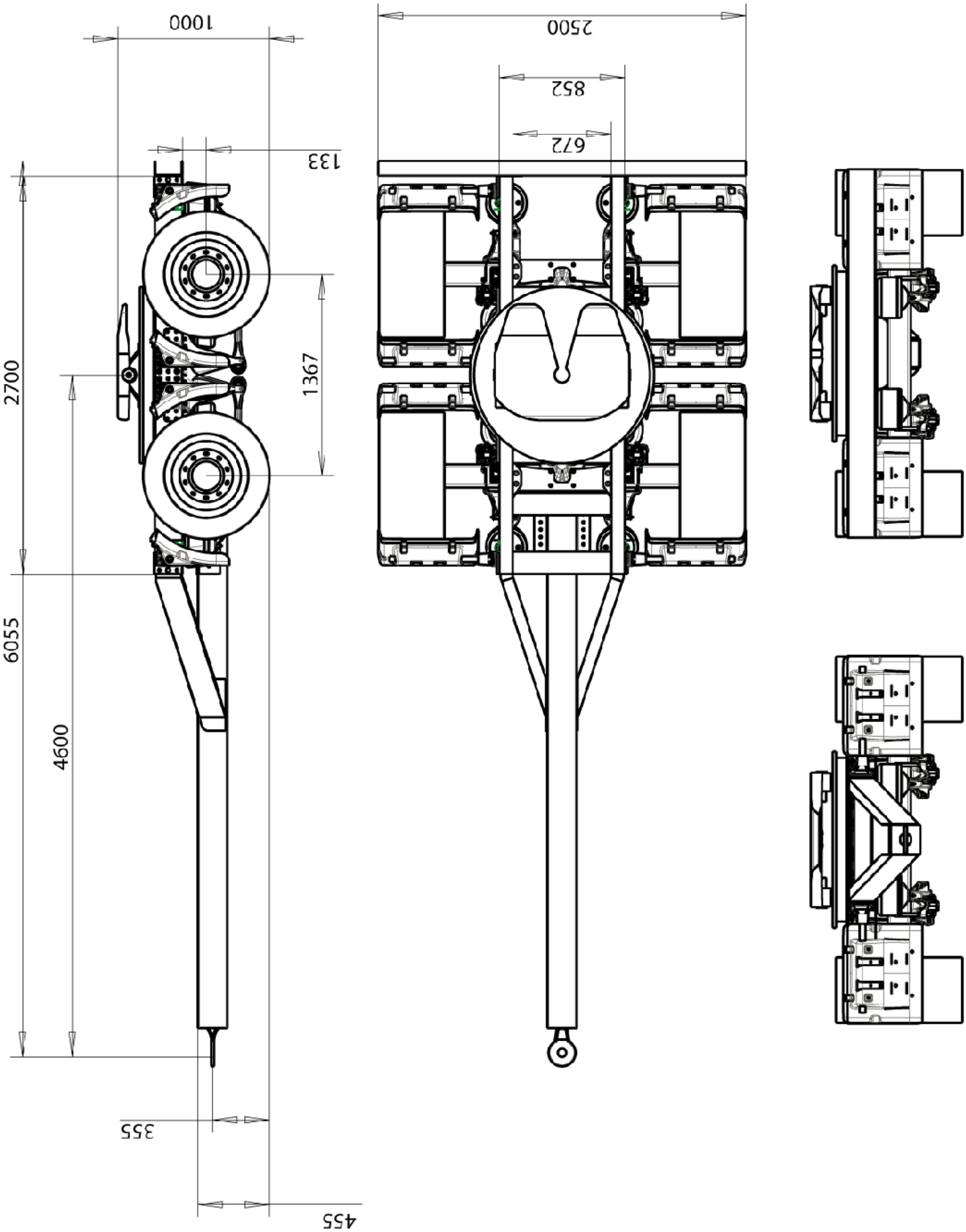
Criteria	Description	Verification / Validation
Criterion 1	Height reduction possibility	Calculations / Pro/E
Criterion 2	Weight	Volume * density / Pro/E
Criterion 3	Stress and strength	Pro/M, Excel
Criterion 4	Manufacturability	Reasoning
Criterion 5	Drawbar assembly	Reasoning

Concepts that were kept: 1, 4, 5, 13, 14, 15, 17, 19 and 20.

Appendix C. Drawings



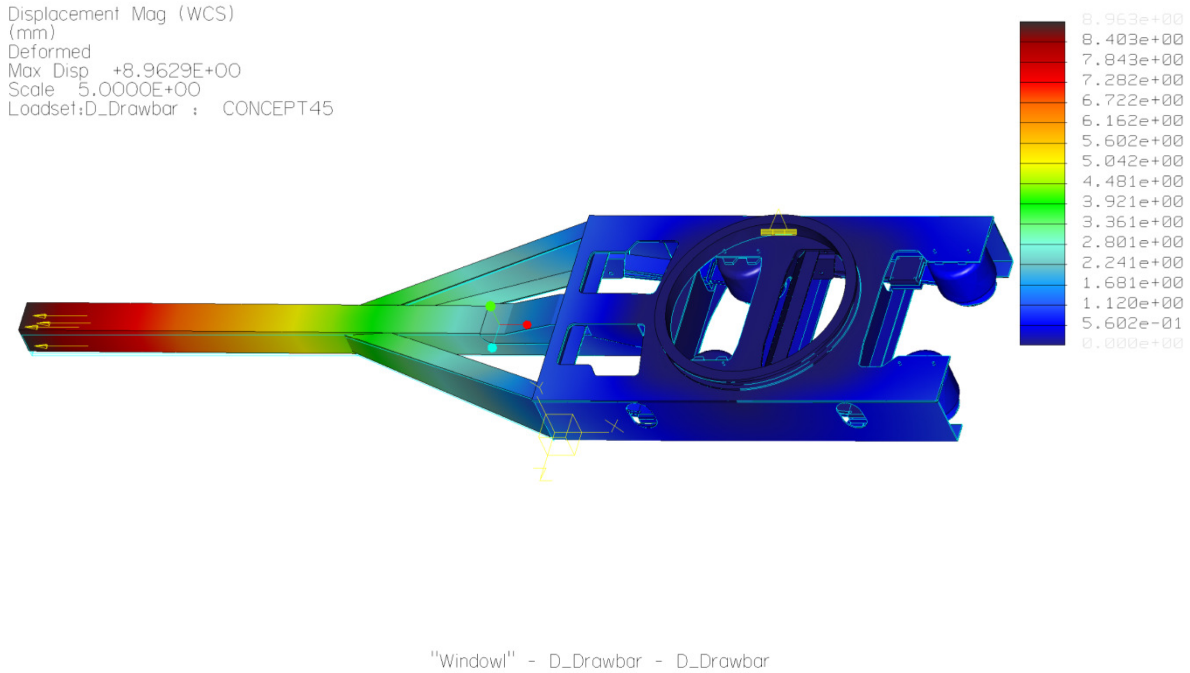

2500
1350
1050
955
170
2502
1300
5967
4600
57
148
355
485

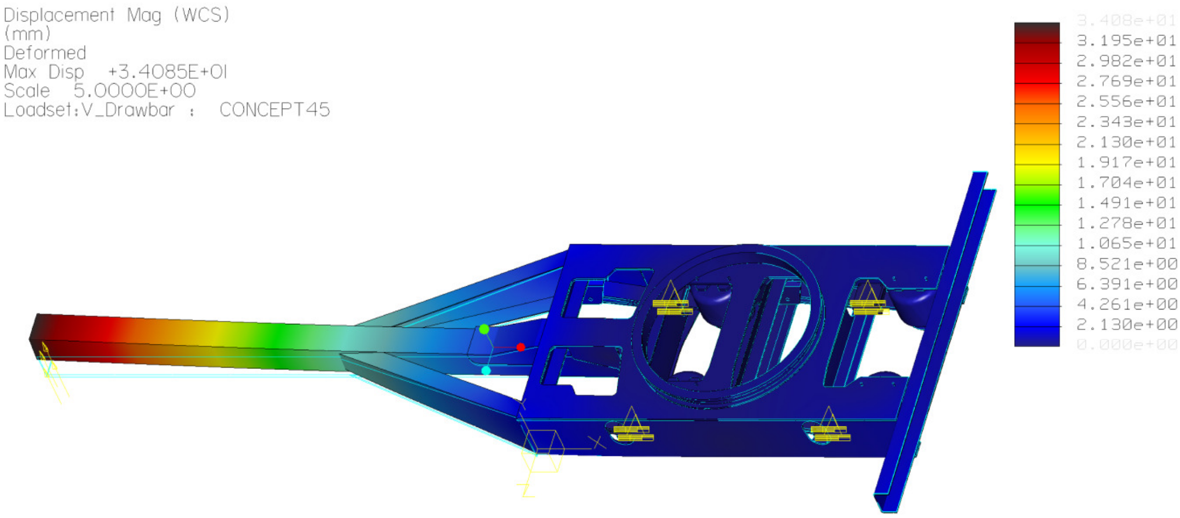

1000
2500
852
672
133
2700
1367
6055
4600
355
455

Appendix D. Finite element analysis

Displacement analyses of all three final concepts plus the design from Parator have been conducted in Pro/Mechanica. The results are presented in this Appendix.

Concept 4-5-13

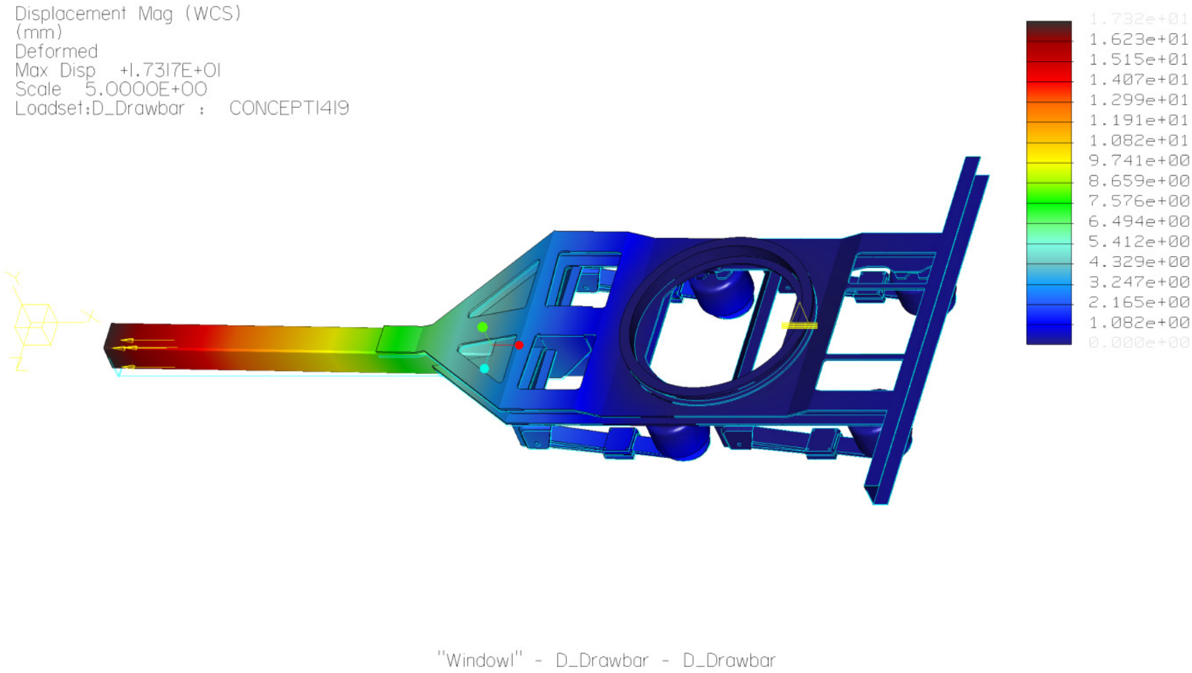


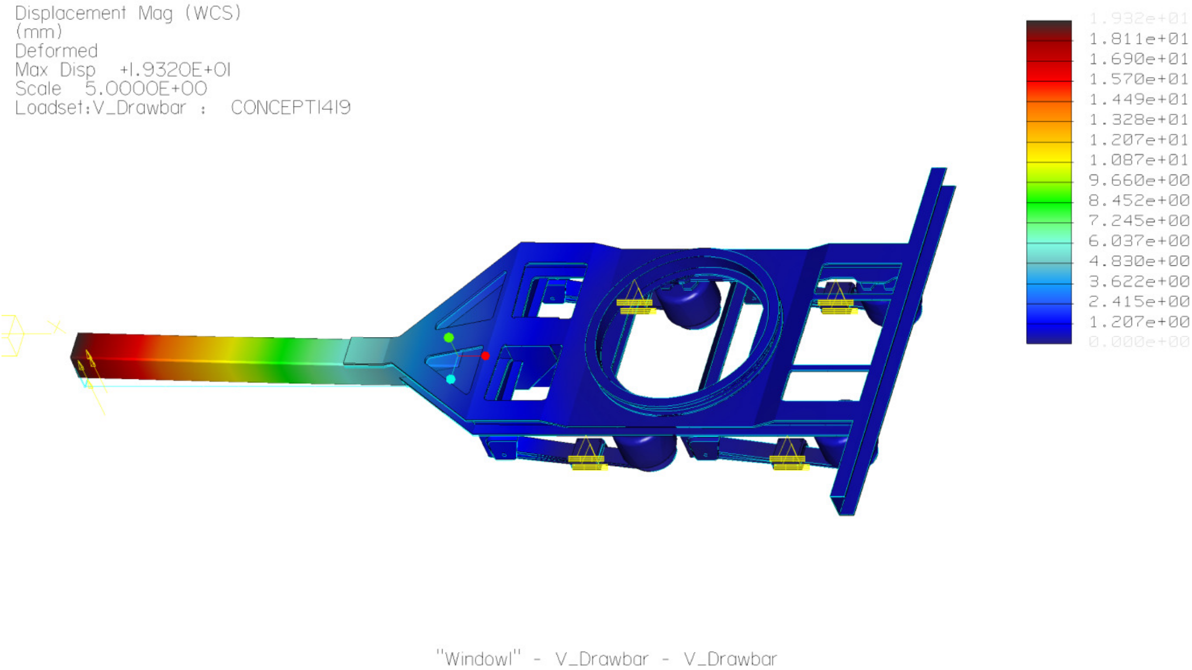


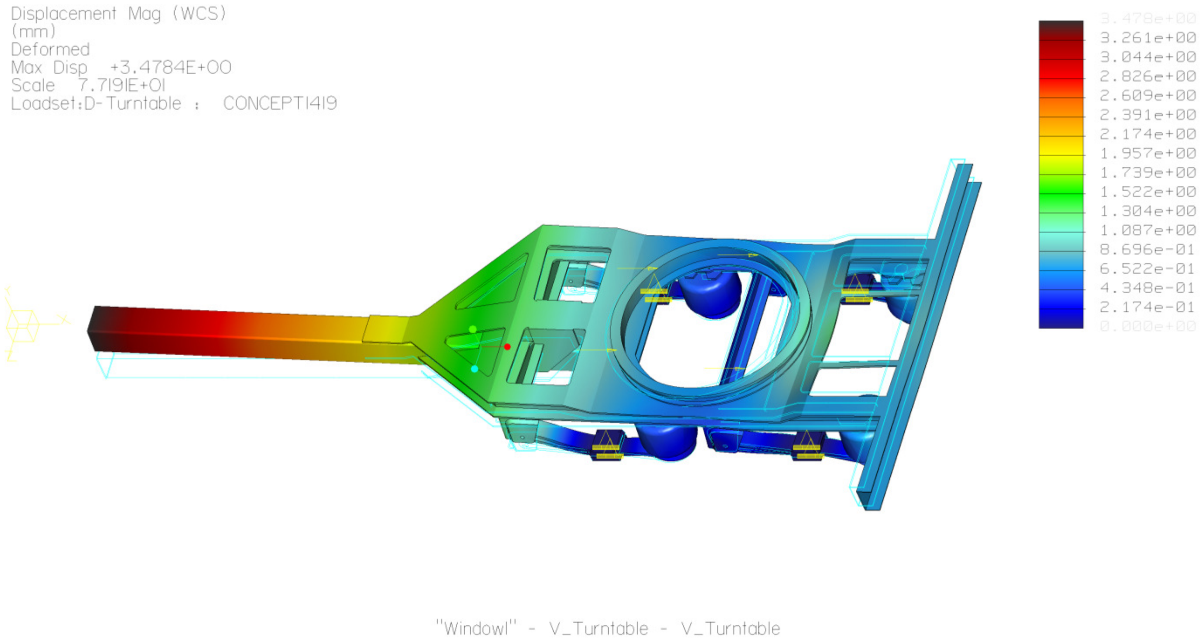
"Window1" - V_Drawbar - V_Drawbar

"Window1" - V_Turntable - V_Turntable

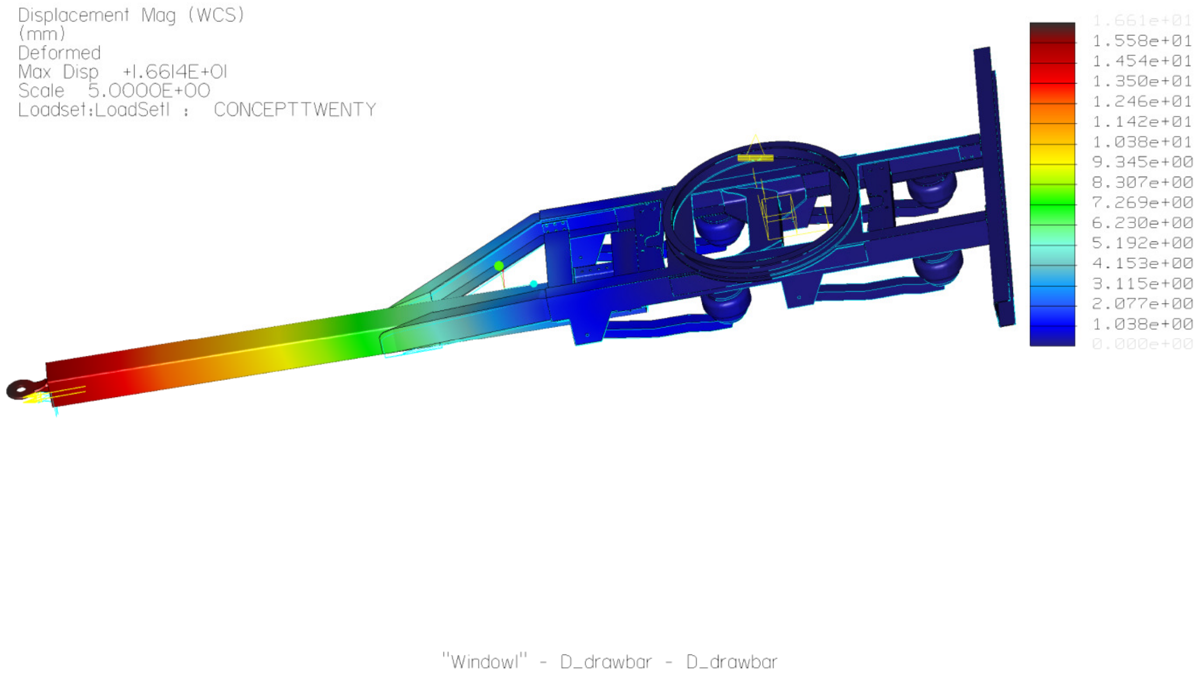
Concept 14-19






Displacement Mag (WCS)
(mm)
Deformed
Max Disp +3.4784E+00
Scale 7.7191E+01
Loadset:D-Turntable : CONCEPT1419
3.478e+00
3.261e+00
3.044e+00
2.826e+00
2.609e+00
2.391e+00
2.174e+00
1.957e+00
1.739e+00
1.522e+00
1.304e+00
1.087e+00
8.696e-01
6.522e-01
4.348e-01
2.174e-01
0.000e+00
"Window1" - V_Turntable - V_Turntable

Concept 20


Displacement Mag (WCS)
(mm)
Deformed
Max Disp +1.6614E+01
Scale 5.0000E+00
Loadset:LoadSet1 : CONCEPTTWENTY
1.661e+01
1.558e+01
1.454e+01
1.350e+01
1.246e+01
1.142e+01
1.038e+01
9.345e+00
8.307e+00
7.269e+00
6.230e+00
5.192e+00
4.153e+00
3.115e+00
2.077e+00
1.038e+00
0.000e+00
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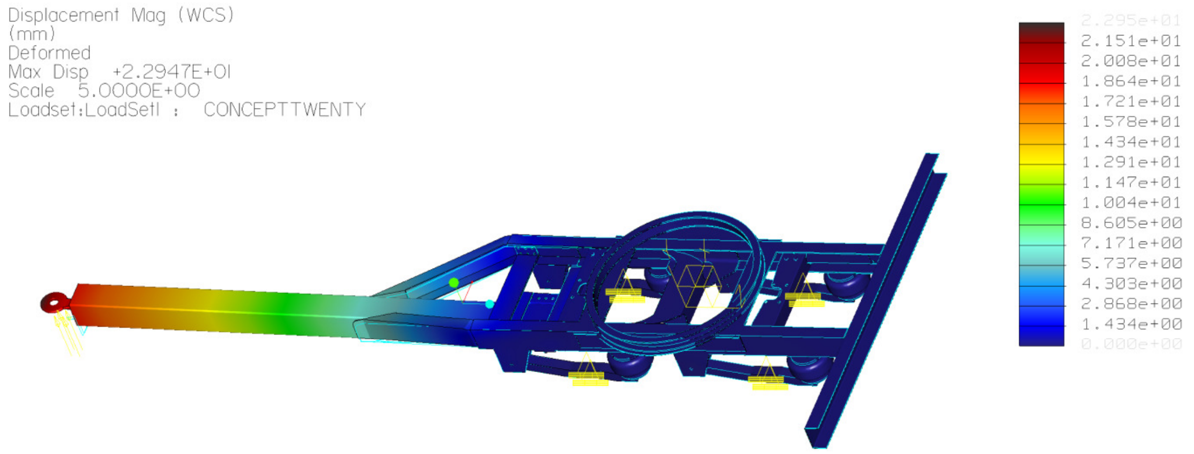
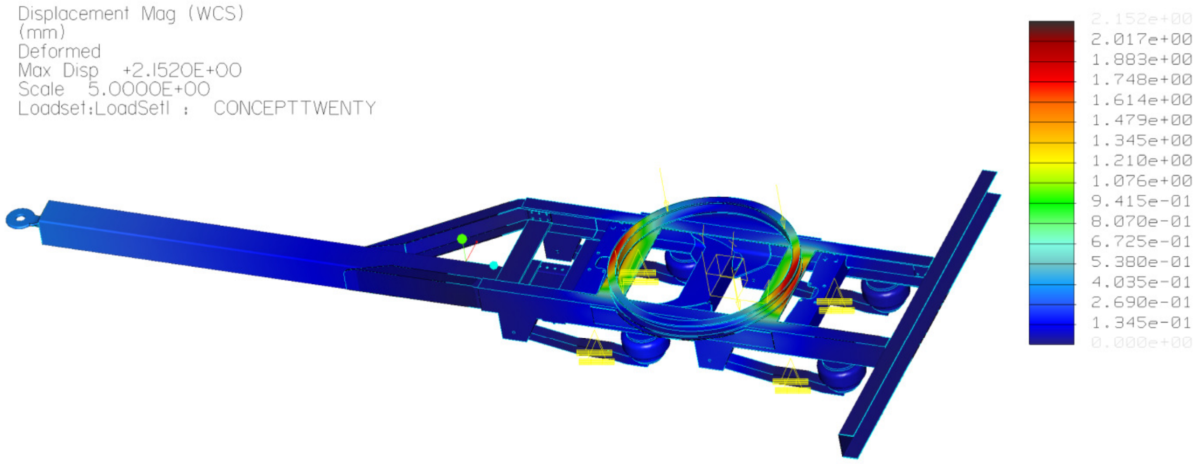


"Window1" - V_drawbar - V_drawbar



"Window1" - V_fifthwheel - V_fifthwheel