CHALMERS

Distributed hydraulic system in radar systems

A study of the possibilities for distributed hydraulics in Giraffe AMB

Master of Science Thesis in the Master Degree Programme of Product development

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Göteborg, Sweden, 2011

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SUMMARY
The master thesis has been conducted during spring 2011 with the aim to explore the possibilities of a distributed hydraulic system in Saab Electronic Defence Systems' ground-based radar system, Giraffe AMB. The system is today centralized driven by a single power unit and the main idea is instead to power each hydraulic function individually with a power module at each.

The thesis has resulted in two concept proposals, PowerPack and EHC (*electro-hydraulic cylinder*), with different levels of distribution. These are presented and evaluated against the aspects: cost, weight, space requirements, reliability, modularity, energy efficiency, installation, maintenance and service. Benefits and drawbacks have been identified that either favours or obstruct an adaptation.

Technical knowledge as well as the knowledge of product development process methodology gained from Chalmers University of Technology, especially *The Value Model* and *Axiomatic Design*, has acted as support for development.

The thesis shows potential for a distributed hydraulic system to be recommended in today's Giraffe AMB, though uncertainties exist. Costs, and possibly weight, are within acceptable range of the existing centralized system but a distributed system also utilizes many components which increases the risk of failure, i.e. lower the level of reliability. However, the concept of distribution brings many advantages to consider, e.g. reduced amount of piping, reduced amount of oil, easy installation, lower complexity and energy savings through function optimization. These are all contributions to increased reliability and accessibility of the radar system. Another drawback is furthermore the emergency operation.

In a fully distributed system, the only external interface for material or information transfer is electrical cables and mountings. This configuration is also proposed as a possible existing solution, i.e. concept EHC, a totally integrated solution.

Finally, it is recommended to further evaluate the concepts, especially EHC which has the potential to be a possible solution for next generation of Giraffe AMB. Another recommendation is to adapt a distributed hydraulic system to other possible applications, with fewer hydraulic functions.

Keywords: Distributed, Hydraulics, Radar system

Preface

This is a master thesis that has been carried out by two students at Chalmers University of Technology with a background from mechanical engineering. The project has been interesting and has covered a wide spectrum, thus the work has broadened the understanding and knowledge of both hydraulic systems and product development. Also, aspects such as economics, safety and to balance different requirements have given a more holistic knowledge and perspective.

We hope that the project has been useful for Saab EDS and that it can provide a basis for further discussion. In addition to Saab Electronic Defence Systems, and the employees that have been in contact with the thesis, we would like to send a special thanks to the following people that have provided support and useful advices.

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Lexicon

1. Hydraulic actuator – A hydraulic motor or cylinder that converts hydraulic power to mechanical work.

2. Reservoir – A tank where the hydraulic fluid is stored.

3. Distributed hydraulic system – Each hydraulic function has their own hydraulic power unit with no hydraulic connection to each other.

4. Ground-based radar system – A mobile radar system located in a 20ft container.

5. Hydraulic control system – Controls the movement in a hydraulic system.

6. Saab EDS – Saab Electronic Defence Systems

7. GAMB – Giraffe AMB is the existing ground-based radar system and the reference.

8. Valve – Valves regulates the fluid by opening, closing and partially prevent the fluid.

9. Electro-hydraulics – Hydraulic components with electronic included.

10. Green valve - Load-holding and lowering valve from Bosch Rexroth.

11. Electro-hydrostatic actuator – Self-contained hydraulic system on a servoactuator.

12. Power pack – A power pack comprises an electric motor, hydraulic pump, reservoir, valves, possible accumulator and different control devices in a compact unit.

13. Power unit – Electric motor and hydraulic pump.

14. CAN bus – Bus-based communication protocol.

15. Transducer – A sensor, converting one type of energy to another, e.g. pressure to electrical signal.

16. Stroke – The extension or retraction of the hydraulic cylinder rod.

17. Deplacement - The volume that is transferred by a pump during one full rotation.

18. Start torque – A motor’s specified initial torque.

19. Saddle torque – A torque developed at very low motor speeds (approximately 15% of rated nominal speed), creating a depression on the motor’s characteristic curve.

20. Breakdown torque – The highest torque available before the torque decreases due to machine acceleration.

Abbreviation list

C - Constraint

CN – Customer Need

CRS – Customer Requirement Specification

DP – Design Parameter

EDS – Electronic Defence Systems

EH - Electrohydraulics

EHA – Electro-hydrostatic Actuation

EHC – Electro-Hydraulic Cylinder

FR – Functional Requirement

GAMB – Giraffe Agile Multi Beam

QFD – Quality Function Deployment

SL – Support Leg

Formulary

Hydraulic cylinder

Pressure

$$p = \frac{F}{A \cdot \eta_{hm}} \quad \text{[eq. 1]}$$

Velocity

$$v = \frac{s}{t} \quad \text{[eq. 2]}$$

Flow rate

$$Q = \frac{v \cdot A}{\eta_v} \cdot 60000 \quad \text{[eq. 3]}$$

Effective area

$$A_1 = \frac{\pi}{4} \cdot D^2 \quad \text{[eq. 4]}$$

$$A_2 = \frac{\pi}{4} \cdot (D^2 - d^2) \quad \text{[eq. 5]}$$

Volume

$$V = A_1 \cdot s \quad \text{[eq. 6]}$$

Differential volume

$$V_d = V - ([A_1 - A_2] \cdot s) \quad \text{[eq. 7]}$$

Where,

p	*is the pressure*	*[Pa]*
F	*is the applied force*	*[N]*
D	*is the outer piston diameter*	*[m]*
d	*is the piston rod diameter*	*[m]*
A_1	*is the effective area in plus chamber*	[m^2]
A_2	*is the effective area in minus chamber*	[m^2]
v	*is the velocity of the stroke*	*[m/s]*
s	*is the stroke*	*[m]*
t	*is the required stroke time*	*[s]*
Q	*is the flow rate*	*[l/min]*
V	*is the cylinder volume*	[m^3]
V_d	*is the differential volume*	[m^3]
η_{hm}	*is the hydro-mechanical efficiency*	*[-]*
η_v	*is the volumetric efficiency*	*[-]*

$\eta_v = 1$

$\eta_{hm} \approx 0.95$

Hydraulic pump

Power

$$P = \frac{Q \cdot p}{600 \cdot \eta_t}$$ [eq. 8]

Deplacement

$$D = \frac{Q \cdot 1000}{n \cdot \eta_v}$$ [eq. 9]

Where,

P	*is the required drive power*		*[kW]*
D	*is the pump deplacement*	*[cm^3/rev]*	
n	*is the rotary speed of the drive motor*	*[rpm]*	
η_t	*is the total pump efficiency [-]*		
η_v	*is the volumetric efficiency*	*[-]*	

$\eta_t = \eta_v \cdot \eta_{hm} \approx 0.9$
$\eta_v \approx 0.95$

Electric motor

Power

$$P_{in} = P$$ [eq. 10]

Torque

$$M = \frac{D \cdot p \cdot 1.59}{\eta_{hm}}$$ [eq. 11]

Current

$$I_l = \frac{P_A}{\sqrt{3} \cdot U_p \cdot \cos\varphi}$$ [eq. 12]

Where,

P_{in}	*is the input power*	*[kW]*
M	*is the torque*	*[Nm]*
I_l	*is the line current*	*[A]*
P_a	*is the active power*	*[W]*
U_p	*is the principal voltage*	*[V]*
Cosφ	*is the power factor*	*[-] (0.7 – 0.95)*

(Högskolan Dalarna, 2007)

1 Introduction

The introduction aims to provide a basis of what the study comprises, i.e. its background, purpose, goals and limitations.

1.1 Background

In today's ground-based radar systems there are hydraulic functions to, e.g. raise the mast and operate the supporting legs. This is done using a central electrically driven hydraulic system from which all physical information flows are originated to. A hydraulic control system gets signal inputs from different toggles and sensors and based on their signals control which functions and flows that are to be used. The hydraulics is mainly used during deployment which takes about 10 minutes to perform and the speed of each function is, in the hydraulic context, relatively low.

1.2 Purpose

The purpose with this master thesis is to map and investigate the opportunities to develop a new distributed hydraulic system. The system focus shall be on a more flexible system than today's system. The idea is to make it more flexible by splitting the system into different hydraulic modules. The purpose of this is to make changes or reconstruction of different components easier without any need of redesigning the entire system. It would also make it easier to perform maintenance and service. With a new standardized and modular system it is possible to reduce the amount of cables and pipes which will reduce the risk for leakage.

1.3 Goal

The goal is to develop one or several concepts of a distributed hydraulic system, consisting of standardized hydraulic modules. These concepts shall be evaluated against different aspects such as cost, weight, space requirements and other performance goals. Furthermore, the goal is to provide an evaluation of the serviceability, maintainability, reliability and safety together with analyses on space requirements, principal controls and power supply. The concepts shall form a foundation for an evaluation of the new concept/concepts compared to the old solution.

1.3.1 Method of development

The thesis has used the support of two product development practices, i.e. "Axiomatic design" and "The value model". These models originate from the literature "Produktutveckling" (Johannesson et. al., 2005) and "The value model" (Lindstedt & Burenius, 2006) respectively. They have supported the thesis with tools and methods to effectively and in a structured manner carry out the product development process. In addition, information searches, supplier contact, a risk analysis and dimensioning calculations have supplemented the models. The work have been thoroughly planned and executed following a structured Gantt scheme.

1.3.2 Character of end result

This project shall result in one or a few different concepts which shall be illustrated with a CAD model in ProEngineer. The drawings shall help to illustrate the design and ideas in a complete system. The new concept(s) shall be compared with the old solution with assistance of price estimations and concept data.

The result shall be presented in a report that describes all concepts, how different values are estimated and the method that has been used. The report shall include the following main aspects:

- Requirement specification
- Functional specification
- Estimated initial costs
- Primary risk analysis
- Level of modularity/distribution
- Concept illustrations
- Evaluation of the serviceability, maintainability, reliability and safety
- Configuration description
- Suitability analysis

1.4 Delimitations

The concept(s) shall take the following delimitations into consideration:

- A detailed architecture of cabling, pipes and wires shall not be developed.
- The project shall not result in a physical model/prototype.
- Cost and weight of concepts are not required to be exact, estimations are accepted.
- No hardware will be physically developed, only virtual models and visualisations.
- No software will be developed.
- The structure of the concept's layouts and design shall not be constrained to the current Giraffe AMB. Interfaces, connections, size-limitations are still open for exploration.
- The concept(s) shall not touch upon the visualization of fault messages and other signal logic on the control panel and system as a whole.
- No automatic control engineering calculations will be performed.
- No finished control system shall be designed.
- The concept(s) shall not include the design of the control panel.
- The concept(s) shall primarily be based on existing mast, though design and functions may be modified.
- The concept(s), and their design, shall to as great extent as possible be based on standard components, though customized solutions are accepted but not preferred.

- No detailed evaluation of couplings, seals, pipes, hoses, filters and oil shall be carried out.
- No in-depth analysis of exact valve properties will be included, only selection of types.
- No in-depth analysis of exact sensor properties will be included, only selection of types.
- No detailed drawings/models shall be designed, only conceptual visualizations.
- No calculations regarding heat emission/cooling requirements of the hydraulic power unit shall be carried out.
- No calculations of pressure shocks/variations and its effect on component dimensions/performance will be made. The aspect will only be considered when selecting components.
- Mechanical modifications shall not be evaluated with calculations due to limited time resources. It is also not in the scope of the main goal of the study which is to evaluate a distributed hydraulic system.

1.5 Outline of report

The outline of the report is based on the development process used in this project. It starts by describing the background information and basic hydraulic theory needed to form a theoretical basis and to obtain an understanding of the area and its prerequisites together with market trends. The method is then described which presents how the results have been obtained, how the development process was carried out and what tools that were used. A presentation of the results gained from the study is then presented. It describes the alternative ideas and solutions, arguments for elimination and descriptions together with evaluations of the final concept(s). The report ends with a discussion of the drawn conclusions and the suggested recommendations in order to verify the fulfilment of the goals.

Note: Figures without reference has been made by the authors of this thesis.

2 Theoretical framework

This chapter is a theoretical chapter that includes descriptions of hydraulic components in general and how a hydraulic system works. Furthermore, it deals with trends and technologies within the business. The existing system which also is the reference is described here.

2.1 Basic theory

The basic theory aims at providing the basic technical descriptions of hydraulic components that the current Giraffe AMB comprises or in some other way are relevant to the results of this study.

2.1.1 Hydraulic system

There are three different ways of transmitting power, electrical, mechanical or with fluid. Hydraulic power use fluid to transmit power and motion, compared to the other methods hydraulic systems can transfer power more economically. It is also very useful for long distances. One of the major advantages with hydraulic systems is the easiness to control the system with high accuracy. It is easy to start, stop and change speed. With hydraulics is it possible to multiply forces simply and with high efficiency. A hydraulic system can provide a constant torque or force regardless of changes in speed. They are often simpler and easier to maintain. Some drawbacks with hydraulic systems are handling with oils, leakage, lines can burst with risk for injuries and there is a risk of fire when leakage occurs (Doddannavar & Barnard, 2005, pp. 175-176).

All hydraulic systems are quite similar with some differences regarding components and configuration. There are six different components that are essential in hydraulic systems:

- Reservoir – the reservoir holds the liquid.
- Pump – the pump forces the liquid through the system.
- Power source – Often an electric motor that drives the pump.
- Valves – The valves controls the direction, pressure and flow rate.
- Actuator – The actuator converts fluid energy to mechanical power, it can be a cylinder that provides linear motion or a motor that provides rotary motion.
- Piping – Pipes and hoses carries the liquid from one location to another.

Those components together form a foundation in a hydraulic system, by mixing and adding components many different functions can be achieved (Doddannavar & Barnard, 2005, pp. 175-176). A generalized basic hydraulic circuit is illustrated below in figure 1.

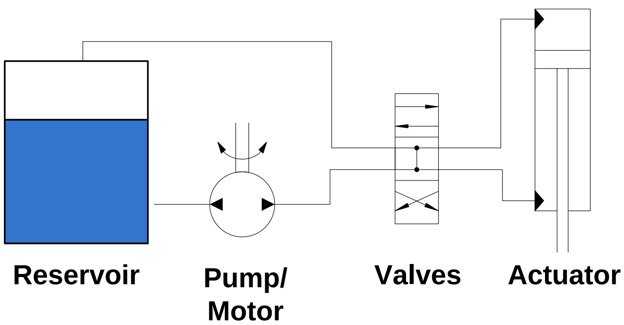

Figure 1. A generalization of how a hydraulic system can be conducted, with the main components included.

2.1.2 Hydraulic cylinder

Hydraulic cylinders, also known as linear actuators, are the component in a hydraulic system that converts the hydraulic power from a pressurized hydraulic fluid into linear mechanical power.

A hydraulic cylinder basically consists of a piston inside a cylindrical housing (barrel) and a rod which extends outside the barrel. The barrel is closed on each end by a cylinder bottom and head cap. To transfer the hydraulic fluid, there are inlets and outlets positioned on the barrel. Furthermore, the piston separates the inside of the cylinder in two chambers, a cap end chamber (bottom) and a rod end chamber (piston rod side). Other parts that are included in the hydraulic cylinder are cylinder bottom connections, seals and cushions.

A hydraulic cylinder is powered by a hydraulic pump, see section 2.1.3, and the linear force applied by the piston is dependent of its effective area and the pressure inside the barrel but also of an efficiency factor. *Note: the area of the piston is smaller when applying hydraulic fluid from the opposite direction due to the rod area.*

Hydraulic cylinders are classified as:

- Single acting cylinders
  A single acting cylinder is only pressurized at one end while the opposite end is vented to the atmosphere or tank (Doddannavar & Barnard, 2005, p. 84), see figure 2.

Figure 2. Single acting cylinder

- Double acting cylinders
  Double acting cylinders are designed so that pressure can be applied in either inlet or outlet port, providing linear power in both directions, see figure 3. These units are the most commonly used cylinders in hydraulic applications. Furthermore, since the exposed areas in the cylinder are unequal during extract and retract operation there is a difference in operation speed and force (Doddannavar & Barnard, 2005, p. 85).

Figure 3. Double acting cylinder

2.1.2.1 Cylinder types

There are also two main different types of cylinders, i.e. tie-rod and welded body cylinders.

- Tie-rod cylinders
  Tie-rod cylinders have square or rectangular end caps secured to each end of the barrel by using rods that pass through holes in the end caps. They have good serviceability and reparability since they can be completely disassembled. The majority of industrial, heavy-duty application cylinders use tie-rod structure (HydraulicsPneumatics, 2011).

- Welded body cylinders
  Welded cylinders use end flanges that are welded to the barrel with an end cap attached to each flange. This type of structure is lighter and more compact than the standard tie-rod configuration and has a wide application range. Welded body hydraulic cylinders dominate the mobile hydraulic equipment market, e.g. construction and material handling equipment but are also commonly used in heavy industry applications such as cranes and large off-road vehicles (HydraulicsPneumatics, 2011).

There are a number of advantages with welded body cylinders compared to tie rod. (HydraulicsPneumatics, 2011)

- Welded cylinders have a narrower body and often a shorter overall length which enables them to better fit into tight application limitations.
- Welded cylinders do not suffer from failure due to tie rod stretch at high pressures and long strokes.
- The welded design allows for customization. Special features can easily be added to the cylinder body, e.g. special ports, custom mounts, valve manifolds, etc.

2.1.2.2 Cylinder variants

Apart from standard cylinders many other variants exist and some examples, relevant to the application, are described here.

Telescopic cylinders
If there are restrictions in space, a telescopic cylinder can be used, see figure 4. This is built up of several stages of pistons and cylinders arranged inside each other and where the last stage contains the final piston rod. These solutions can be either single or double acting and the principle of motion is the same as for the above mentioned cylinders. It is mainly used in mobile applications and the collapsed length can be as little as 15 times its extended length, though the cost is several times that of a standard cylinder of equivalent performance (HydraulicsPneumatics, 2011).

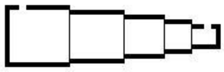

Figure 4. Telescopic cylinder

Servocylinder
Servocylinders are "smart machine elements" that integrate the hydraulic cylinder, various electronics or transducers and different valves, see figure 5. It provides instant feedback signals to help control mechanical position or other parameters in a mechanism, performing complex motions. Also valves are included in the integrated control, thus providing compact distributed controls directly on the cylinder for faster responsiveness (Agostani, Marco; Atos, Electronic department).

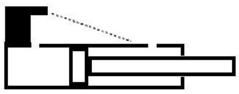

Figure 5. Servocylinder

2.1.2.3 Cylinder mountings

There are various types of standard cylinder mountings on the market which permits flexibility in the attaching of cylinders. Therefore, the mechanical linkages in hydraulic applications are limited only to the fluid power designer (Doddannavar & Barnard, 2005, p. 90). Important to think about though when selecting mounting is that no transversal forces may be built in since it will result in a faster wear of seals and bush rings (Haugnes, 1987, p. 65).

2.1.3 Hydraulic pump

Hydraulic pumps are one of the most vital components in a hydraulic system and it is important to choose a pump that suits the application and its needs. The purpose of pumps in a hydraulic system is to provide a flow of hydraulic fluid to the actuators. The pump converts mechanical energy into hydraulic energy that pressurizes the actuators. Hydraulic power is thus determined by pressure and flow. A pump can be constructed in a way where either flow or pressure is fixed and the other parameter can vary with the load. If the flow is constant the pressure will increase with increased load on the pump (Doddannavar & Barnard, 2005, pp. 37-38).

The capacity of a pump is determined by how much fluid that is delivered from each rotation of the pump axis. This is also known as the pumps deplacement. Pumps are usually classified into two categories, non-positive deplacement pumps and positive deplacement pumps. Non-positive deplacement pumps can also be called hydro-dynamic pumps. Positive deplacement pumps are also known as hydrostatic pumps (Doddannavar & Barnard, 2005, pp. 37-38).

Positive deplacement pumps are the only ones that are used in hydraulic applications. This type release a fixed amount of fluid per revolution, thus the flow is proportional of deplacement and rotor speed. These pumps can overcome high pressure resulting from mechanical loads and resistance to flow by friction. The advantages towards non-positive deplacement pumps are the capability to generate high pressure, size, high volumetric efficiency, almost the same efficiency over pressure range and wider operating range (Doddannavar & Barnard, 2005, p. 40).

The most common pumps in hydraulic systems are internal gear pumps, external gear pumps, radial piston pumps and axial piston pumps. Those pumps are described shortly beneath.

2.1.3.1 Gear pumps

Gear pumps are simple, compact and inexpensive pumps with fixed deplacement and few moving parts. Depending on component structure the gear pump can either be classified as external or internal.

- External gear pumps
  The basic principle in external gear pumps are simple, there are two gears in mesh inside a pump case, see figure 6. Both gears are mounted on one shaft each and one of the shafts is coupled to a prime mover called drive shaft. The first gear drives the second gear. Fluid is then transported from the inlet to the pressurized side within the space between teeth and case, and then it is pushed out in the hydraulic hose (Doddannavar & Barnard, 2005, p. 41).

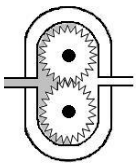

Figure 6. External gear pump

- Internal gear pumps
  Internal gear pumps have one internal gear (idler) and one large exterior gear (rotor), see figure 7. Liquid enters the suction port between the rotor and the idler and then travels between the teeth. This kind of pumps are very all-round, thus they can handle a wide range of viscosity and temperature. Also, due to few moving parts they are easy to maintain (Doddannavar & Barnard, 2005, pp. 45-46).

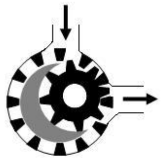

Figure 7. Internal gear pump

2.1.3.2 Piston Pumps

Piston pumps works under high pressure and has very high efficiency. A piston pump uses a reciprocating piston that can take in fluid when it retracts and discharge it when it extends. There are two different types of piston pumps, axial and radial piston pumps. Both are also available as fixed and variable deplacement pumps (Doddannavar & Barnard, 2005, p. 53).

- Radial piston pumps
  Radial piston pumps consist of a rotating cylinder where equally spaced radial pistons are placed along the centre line, see figure 8. All the pistons are pushed against the inner surface of a stationary ring mounted on the cylinder by springs. During the first half of each revolution the piston draws in fluid and during the second half it drives fluid out. With greater ring eccentricity the stroke length gets longer and more fluid could be transferred. Also, size, number of pistons and stroke length determines the pumps deplacement. It is possible to vary the deplacement by moving the reaction ring to increase/decrease piston travel (HydraulicsPneumatics, 2011).

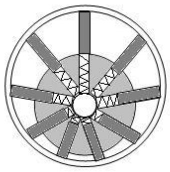

Figure 8. Radial piston pump

- Axial piston pumps
  There are two types of axial piston pumps, bent-axis piston pumps and swash plate piston pumps. The principle is the same but they are constructed and designed with different components. In general axial piston pumps consist of a rotating cylinder with equally spaced radial pistons placed around the centre line, see figure 9. Pistons are pushed against a stationary swash plate at one end of the cylinder by springs, the swash plats plate sits at an angle to the cylinder. To increase the amount of fluid transferred it is possible to increase the angle relatively to the cylinder which will increase the pistons stroke (HydraulicsPneumatics, 2011).

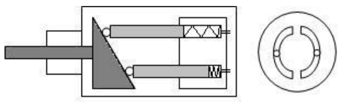

Figure 9. Axial piston pump

2.1.4 Electric motor

Electric motors are used to provide pumps with mechanical energy in a hydraulic system, for a distributed hydraulic system will the number of electric motors be equal to the number of pumps in the system. The electric motor transforms electrical energy to mechanical energy. An electric motor operates through an interaction between magnetic flux and electric current. Force is developed because of a charge moving in a magnetic field producing a force which is orthogonal to the motion of the charge and to the magnetic field (Beaty & Kirtley, 1998, p. 2).

Electric motors come in many different shapes and sizes dependent of the requirements of the specific application. There are generally two different classifications regarding electric motors, AC or DC motors. Each category has a couple of sub categories. The technology within microprocessor-controlled power converters for both AC and DC drives has reached a level of development which enables almost any application to be handled by both AC and DC drives. The reference uses an AC motor to power the main pump and a DC motor to the backup pump. In general are DC motors more complicated and requires a lot of maintenance which makes them more expensive in a lifetime. The AC motor is simple, sturdy and does not require much maintenance. This makes them less expensive over a lifetime. This is just general rules and they may vary for different applications, each motor has to be carefully considered with mission goals, power available and costs in mind (ABB, 2001).

2.1.5 Control valves

Control is one of the most important aspects of hydraulic systems and for any one of these systems to function as required, proper selection of control components is essential. Primarily, fluid power is controlled by control devices called valves (Doddannavar & Barnard, 2005, p. 93).

A valve is used mainly for adjusting or manipulation of the flow rate and basically consists of an orifice whose flow area can be varied. The valve together with an actuator that is used for the external motion in response to a positioning signal is called control valve. There are mainly three types of control valves (Doddannavar & Barnard, 2005, p. 94).

- Direction control valves
- Pressure control valves
- Flow control valves

2.1.5.1 Directional control valves

Directional control valves are used to control the direction of flow in a hydraulic circuit, routing the fluid to the preferred actuator. Primarily, they are designated by the number of possible positions, port connections or ways in which they are actuated or energized. There are various mechanisms for actuating or shifting this type of valve and includes hand lever, foot pedal, push button, mechanical, hydraulic pilot, air pilot, solenoid and spring (Doddannavar & Barnard, 2005, p. 94).

Directional control valves are usually designed to be stackable, one valve for each hydraulic cylinder, and there is one fluid input supplying all the valves. These valves are chosen by flow capacity and performance. Some are designed to be proportional, concerning flow rate and position, while other may be on-off only (HydraulicsPneumatics, 2011).

Spool-type directional control valve

A spool-type directional control valve usually consists of a spool inside a cast iron / steel housing. The spool can slide to different positions inside the housing, to intersecting grooves. Channels in the housing route the fluid in different flow paths based on the position of the spool. The spool may be operated through mechanical actuation, manual operation, pneumatic operation, hydraulic or pilot control and electrical operation, though the most common way to actuate the spool valve is to use a solenoid (Doddannavar & Barnard, 2005, p. 101).

Check valve

Check valves are the simplest type of directional control valves. They are one-directional valves which permit free flow in one direction and prevent any flow in the opposite direction, e.g. allowing an accumulator to charge and maintain its pressure when the machine is turned off (Doddannavar & Barnard, 2005, p. 99).

Pilot controlled check valves are a second type of check valve that are one-directional, permitting free flow in one direction but also permits flow in the normally blocked direction if a pilot pressure is applied at the pilot pressure port of the valve, i.e. it is able to be opened, for both directions, by a foreign pressure signal. Pilot check valves are often used in hydraulic systems where it is desirable to stop the check action of the valve, e.g. locking hydraulic cylinder in position (Doddannavar & Barnard, 2005, p. 100).

2.1.5.2 Pressure control valves

Pressure control valves protects the system against overpressure conditions which may occur from gradual build up due to decreasing fluid demand or an unexpected surge due to opening or closing of the valves (Doddannavar & Barnard, 2005, p. 94).

There are two basic principal types of pressure control valves; direct-acting pressure control valves and pilot-operated pressure control valves. The operating principles of all the pressure control valves originate from these two types (Doddannavar & Barnard, 2005, p. 105).

Pressure-relief valve

The most widely used type of pressure control valve is the pressure relief valve. It can be found in practically every hydraulic system. It has the function to limit pressure to a specified maximum value. This is done by diverting the pump flow back to the tank (Doddannavar & Barnard, 2005, p. 106).

Pressure-reducing valve

Pressure-reducing valves are used to limit pressure in one or two legs in a hydraulic circuit. By reducing the supply pressure of the hydraulic fluid less force is generated, as can be needed for various circuits. A pressure-reducing valve is actuated by the downstream pressure and a start closing as the pressure reaches the valve setting (Doddannavar & Barnard, 2005, pp. 108-109).

2.1.5.3 Flow control valves

Flow control valves are devices that control, adjust and manipulate the fluid flow rate in a hydraulic system. The valve consists of a flow passage or a port whose flow area can be varied. Its role in a hydraulic circuit is essential and its position is critical for optimum system performance. They regulate the supplied volume of oil to different parts of the system. Non-compensated flow control valves are used where precise speed is not required whereas pressure-compensated flow control valves are used in order to produce a constant flow rate. Furthermore, flow control valves are classified as fixed, adjustable, throttling and pressure compensated (Doddannavar & Barnard, 2005, p. 114).

Solenoid valve
Solenoid valves are an electromechanical valve, typically with two or more ports, that is controlled by an electric current through a solenoid coil. Hydraulic solenoid valves control the flow of hydraulic fluid (Price Wheeler Corp, 2010).

Load-holding valve
These valves are pressure control valves which prevent a pulling or pushing load from accelerating uncontrollably during movements in load direction but also from proceeding with higher speed than intended, i.e. determined by the inflowing oil on the pump's side. Consequently, the load-holding valve prevents a collapse or eventual rupture of the oil column. Its main application is within lifting-, pivoting-, turning- or other comparable constructions where double acting cylinders or motors are utilized (Hawe Hydraulik SE, 2002).

Ball valve
A ball valve a variant of a flow control valve and is made up of a ball with a hole straight through. The ball is rotated inside a machined seat. As the ball rotates in its seat the size of the accessible passage varies, generating different flow rates (Doddannavar & Barnard, 2005, p. 117).

2.1.5.4 Manifolds

Leaky fittings could be a problem for hydraulic circuits, especially when the number of connections increases. In this sense, manifolds play a very important role since their integration in hydraulic circuits considerably helps to reduce the number of external connections required. It can be described as an interface for modular stacking of valves and other components with integrated channels (Doddannavar & Barnard, 2005, p. 131).

2.1.6 Accumulator

An accumulator is a device in a hydraulic system which is used to store energy in the form of pressurized fluid. To accumulate the energy, incompressible fluid is stored in a reservoir under pressure by an external source. The source can be gravity, mechanical springs or compressed gas. The accumulator is designed to quickly release stored fluid power when required. This ability makes them useful for improving the hydraulic efficiency in some applications by providing the system with fluid when pressure or flow is higher than normal. Thereby, pumps and motors can be designed for lower requirements. An accumulator can also be used to absorb shocks in the system, smooth out pulsations, supplementing pump flow, maintaining pressure and fluid dispensing (HydraulicsPneumatics, 2011).

There are mainly three different types of accumulators, weight-loaded, spring-loaded and gas-loaded accumulators (Doddannavar & Barnard, 2005, pp. 146-147). Gas loaded accumulators or hydro-pneumatic accumulators as they also are referred to, are the most common type and has been found more useful in practical situations compared to the other types. This accumulator use Boyle's law of gases, where the pressure of a gas varies inversely with its volume for a constant temperature process. The potential energy is decided of the compressibility of the gas and the gas forces the oil out in the system when it expands.

The sequence of releasing oil can be controlled and modified to fit the application (Doddannavar & Barnard, 2005, p. 148). Below is a figure (fig. 10) that illustrates different states of an operating gas loaded accumulator. The static condition is simply its normal state prior to use. The pre-charged state is when the accumulator is charged with its set amount of gas, ready to be utilized, and the fully charged state is when the accumulator has been loaded with hydraulic oil resulting in the liquid compressing the gas, hence pressurizing the accumulator.

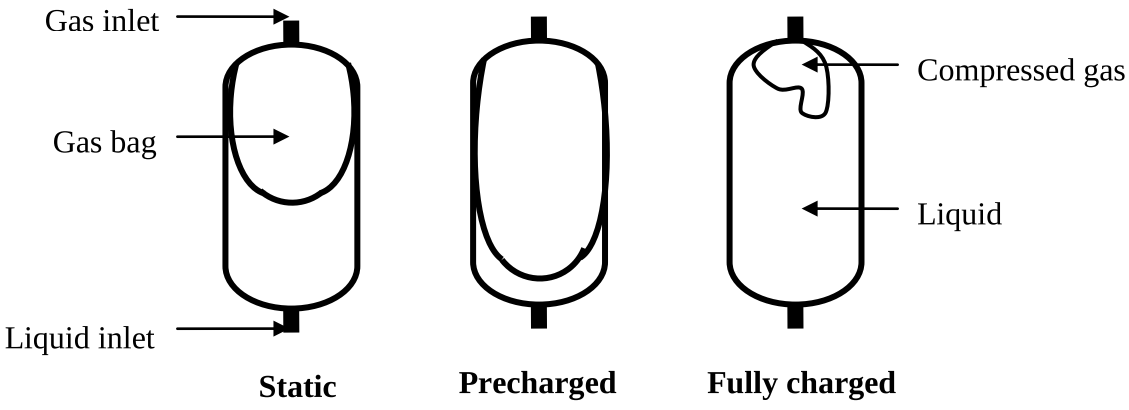

Figure 10. Description of different accumulator states

2.1.7 Remaining system components

The hydraulic system also comprises components such as reservoir, sensors, pipes, hoses, control system and mechanical structures, though these are not considered to require detailed technical descriptions and thus are excluded from the theoretical section.

2.1.8 External effects

To withstand environmental and physical wear effectively, the design of the system must consider aspects such as material properties together with sealing in order to prevent wear, leakage, corrosion or effects from dirt or moisture etc. Also, with all components of the system considered to be elastic, these will flex and change dimensions due to changes in fluid pressure, temperature and strain (HydraulicsPneumatics, 2011) (Ahlgren, 2011). It is important to have these changes in mind due to their high relevance, especially in this application where the environmental conditions are rough and strongly varying.

Furthermore, one must also consider system shock pressures. If a hydraulic system includes speed control or energy-absorbing devices, pressure spikes could occur that are two to three times above normal system pressure. Therefore, to determine the loading and then mount accordingly to sustain the port seal reliability is important (HydraulicsPneumatics, 2011).

2.2 Market trends and technologies

The hydraulic industry can be said to be quite conservative due to its relatively mature technology, thus the general trends within the industry today have a hard time to reach any major breakthroughs. New technologies emerge, though the industry is rather precautious in adopting them, thus still keeping costs at relatively high levels. The trends that can be seen today are mainly towards more electronics integrated into components together with more advanced controls, e.g. integrated sensors and controls, digital control and new software to ease implementation and service through “plug-and-work” principles, bus based communication interfaces etc.

Another trend is towards more components adapted for specific applications but also modular systems for more flexibility. A growing trend is moreover to make hydraulic solutions more energy efficient and focus is a lot on reducing energy by new configurations of operation and through more effective components. Furthermore, wireless control of hydraulic systems is getting more popular with the emerging electro hydraulics (Andersson, 2009).

2.2.1 Integration

An unambiguous trend within hydraulics is integration of components directly on or in the cylinder and stretches as far as integration of entire hydraulic systems on the actuator. The underlying reasons for this are the need for compact solutions but also to minimize energy losses and cost. Also, integration of electronics is gaining speed which enables these integrated solutions to emerge. Concepts like “Power by wire” (Moog Inc, 2010), electro hydraulic cylinder, servo cylinders and integrated valves on cylinder are some examples.

2.2.1.1 EHA – Electro Hydrostatic Actuator

The emerging industry trends demands more compact, accurate actuation whereas electro hydrostatic actuation (EHA) provides these benefits where high force requirements dictate the use of hydraulic power. The technology has so far mostly been focused on the aircraft industry where the technology has matured and has successfully helped reduce weight, increase the reliability and eliminate the need of piping thus reducing leakage. EHA has been proven in the industry for flight controls for many years and the expertise gained through practical experience has now also been applied to industrial applications to provide innovative results. As example of industries where it has been implemented, subsea oil exploration and wind turbine pitch control can be mentioned (Moog Inc, 2010).

2.2.1.2 VMC – Valve Meets Cylinder

Cylinder mounted valves is an idea that has not yet been fully adopted, although several interesting concepts exists on the market. To mount the valves directly on the cylinder is supposed to reduce the flow losses but also cost by eliminating a certain amount of piping. Also, dynamic stability would be improved and energy reductions obtained (Andersson, Energieffektiva hydrauliklösningar hjälper maskinkonstruktörer att klara TIER 4 - Budskapet på Bosch Rexroth Mobile 2009, 2009). This is an interesting trend, in accordance with other concepts where components are put directly on the cylinder, which would favour an integrated solution for distributed hydraulic systems.

2.2.1.3 “Power pack”

In line with the integration trend, the power unit in mobile hydraulics has become more modular and integrated in order to obtain a compact solution where all components are assembled in a system package. These solutions are flexible, permitting a large variety of different configurations adapted for specific applications and installations. They are often called “compact power modules” or “power packs” (Fluid Scandinavia, 2009). These are further described in section 4.1.2.

2.2.1.4 EHC

The so called “*electro-hydraulic cylinder*” is a product developed to follow the trend of integration thus providing a compact and flexible solution. It is developed by Kent Börjesson Teknik AB and is one of few similar solutions on the market. The patent has recently been applied for and awaits approval (Börjesson, 2009-2011).

The idea with the EHC is to gather all components in one unit to be able to easily change and serve the units, providing a distributed system with drive at each function (Börjesson, 2011).

2.2.2 Electro-hydraulics

To integrate electronic controls and bus-based communication and to refine these technologies is a growing trend within the hydraulic industry, resulting in more advanced controls of hydraulic components and faster and more flexible communication systems, i.e. higher performance and efficiency. The bus-based electro-hydraulic components are still rather costly due to the slow market penetration and the industry’s conservativeness, especially for mobile hydraulics where the development has proceeded slower than expected, though the potential of more effective systems and more advanced controls seems very promising.

2.2.2.1 CAN bus control

A trend within hydraulics is that more and more applications are using bus-based communication with, e.g. CAN communication protocols. Though, this has been underway for many years and the development has been quite slow. This has resulted in that components with CAN compliance still are rather expensive since the technology has not yet been fully adopted in the industry. However, the technology is very advantageous for most hydraulic systems and would provide a large number of benefits if applied, e.g. plug-and-work functionality, easier installation and diagnostics, faster communication and lower implementation costs. It also allows for more advanced technologies or components to be used more flexible which could improve a hydraulic system and its controls further.

The *Controller Area Network* (CAN) has today established itself as the standard bus system for mobile applications, though it was originally developed by Bosch for use in the automotive industry (Moller, 2005). CAN-bus is defined as an ISO standard computer network protocol under ISO11898, designed for microcontrollers and devices to communicate with each other without a host computer. CAN have gained a widespread popularity for embedded controls in areas like, e.g. industrial automation, mobile machines, military and other harsh environment network applications (EE Herald, 2006).

2.2.2.2 Electro-hydraulic components

This trend has been ongoing for many years but never been commonly adapted and one reason for this has been the problem to agree with a common industry standard regarding both software and hardware. Many suppliers have over the years used software that is only compatible with their own hardware, the difficulties to mix components from different suppliers has prevented the development. Now have many of the suppliers changed opinion and there is a strong trend against common industry standards (Smith & Batavia, 2008).

Atos is one supplier that works a lot with electro-hydraulics with components developed in areas like proportional valves, deplacement control for variable pumps and servo cylinders. It is important with mechanical robust electronics to be able to handle vibrations and tough environment. The new electro-hydraulics helps to ease installation, simplify parameter setting and improve diagnostics of valves. The electro-hydraulics is compact and can give information about position, speed and force at the actuators. Motion cycles and hydraulic parameters could be setup from computer software and controlled with different interfaces like CANbus and Profibus. Distributed computer force makes it possible for proportional valves to receive signals from position- and pressure sensors which lead to increased flexibility and performance when automating machinery (Balzarini, Fabio; Atos Technology dept., 2007).

Bosch Rexroth also has a wide spectrum of electro-hydraulic components and with such plug-and-play solutions comes a lot of advantages. The supplier takes over dimensioning, customization, calibrating and deliver a complete solution ready to install (Dr. Köckeman & Bosch Rexroth AG, 2005).

2.2.3 Energy efficiency

Another trend is the aspect of energy consumption where hydraulics is leaning towards more efficient and smarter solutions. A distributed hydraulic system is in a sense also a step in the direction of more energy efficient systems since each function is optimized to its individual load and energy is used accordingly instead of the unnecessary power consumptions in a centralized system where power is determined by the highest momentary load. Apart from this there are examples of areas where energy efficiency is in focus, e.g. the “green valves” for saving energy when lowering booms or masts and the use of variable speed electric motors and fixed deplacement pumps to optimize the flow and energy consumption during operation.

2.2.3.1 “Green valve”

The “Green valves” is a solution from Bosch Rexroth newly released on the market. It is a load-holding and lowering valve that makes mobile equipment more energy efficient and easier to control (Bosch Rexroth Group, 2010). The idea is to use the force of gravity to lower booms or masts instead of engine power. This type of valve decreases the power requirements for that functionality drastically and improves stability and control, according to the company press release. The valve barely requires any oil flow which means more flow available for other simultaneous movements. Furthermore, the integrated control eliminates the need of damping devices, e.g. orifices, thereby saving some costs and installation space (Bosch Rexroth Group, 2010).

2.2.3.2 Variable Frequency Drive of electric motors

A trend within hydraulics is frequency control of electric motors to vary the flow from the pump. The idea is not new but over the last years a couple of companies have introduced own solutions with complete integrated control electronics. The technology is often referred to as *variable frequency drive* (VFD) and brings many advantages, e.g. reliability, flexibility of control and significant energy savings. It is the most effective energy savers in pump applications (Turkel, Salomon S.; EC&M, 1999). The pumps rotation will always be adjusted to deliver the correct amount of oil needed in the system. The rotational speed of the motor are changed with frequency that varies and thereby provide control. According to Kawasaki and Bosch Rexroth is it possible to save up to 70% of the energy compared to conventional hydraulic systems (Ilsøy, 2009).

Bosch Rexroth and PMC Servi provide solutions with everything included in one product, pump, frequency-controlled motor/servomotor and controller to regulate flow, direction and pressure. The control unit can either be attached directly on the unit or in a control cabinet. The control unit can be connected to the control system and controlled with Ethernet, Profibus or CAN bus (Ilsøy, 2009).

2.3 Existing reference

The current hydraulic system is used to perform the following main functions:

- Lift and level Giraffe AMB shelter
- Raise mast
- Position support leg cylinders
- Lock mast for transport

The system consists of a large range of components. It is centralized driven which means that it is powered by a central power unit feeding all functions of the radar system. It includes hydraulic cylinders for the above mentioned functions, 14 cylinders in total. The cylinders are driven by a hydraulic unit which includes:

- Hydraulic pump
- Electric motor
- Reservoir
- Filters
- Directional control valves
- Flow control valves
- Pressure control valves
- Emergency unit
    - Electric motor
    - Hydraulic pump

To adjust speed and flow for different forces an axial piston pump with variable deplacement is used together with control valves. This makes it possible to vary speed and pressure with constant speed on the electric motor. The motor rotates with a constant speed of 1450rpm during operation. To be able to manage the components a hydraulic control system is used which includes hardware and software for the hydraulic control, inclinometers and a hydraulic control panel. To connect all the components together and to transport the hydraulic fluid, pipes and hoses are used. Moreover, to verify the positions for the cylinders a lot of sensors are used in various positions on the radar system measuring for example position, pressure and rotation angle in order to operate the system in pre-defined sequences. These sequences are configured so that only one function acts at the same time.

If the motor, pump or electric source breaks in deployment mode it is possible to use the backup system to get back in transportation mode. The backup system consists of a smaller gear pump and a 28V DC motor connected to the existing system. The electric motor is powered by the electrical system on the truck.

The system is today used in rough and largely varying environmental conditions which put requirements on the hydraulic components. A summary of the main requirements and prerequisites for developing a new distributed system is given in table 1. For further more detailed requirements see full customer requirement specification in appendix I.

Table 1. Summary of indata from reference Giraffe AMB

Reference indata

	Giraffe AMB	Hydraulic system		
Weight (kg)	9700	1441		
	Shelter	**Leg compartment**		
Dimensions (mm)	2438 x 2438 x 6058	660 x 1806 x 308		
	Support leg cyl.	**Mast cyl.**	**Parking cyl.**	**Mast lock cyl.**
Stroke (mm)	850	1457	393	80
Max force (kN)	150	95	20	3
Cycle time (s)	305	120	30	-
Stroke speed (mm/s)	8-12.8[(1)]	44[(1)]	11.8[(1)]	-
	General			
Tank size (liter)	122.5			
Max flow rate (l/min)	42			
Motor power (kW)	5.5			
Power supply (-)	3 x 230/400 V AC			
Emergency power supply (-)	28/24 V DC			
Temperature requirements (°C)	-45 to +75			

[(1)] Time measurements

3 Method of development

The chapter addresses methods and tools that have supported the development work of concept suggestions. It includes descriptions of these methods and how the study has been carried out. Firstly, the preliminary development is described, mainly including the areas of information gathering, market mapping and risk analysis. A description of the concept development work is then given where axiomatic design and the value model have played a central part. The further development then follows where dimensioning and calculations are highlighted. The chapter then ends with describing the evaluation process of produced concept suggestions.

3.1 Preliminary development

With the preliminary development, the aim was to obtain a knowledge base about hydraulics and to find what is new and emerging in the industry. A thorough information gathering process was conducted together with a market mapping where a lot of supplier contacts and interviews provided information but also industry magazines etc. to identify trends. The system was then evaluated and functions identified using product development tools provided by *The Value Model* (Lindstedt & Burenius, 2006) and *Produktutveckling* (Johannesson et. al., 2005). This mapping formed the base for the development work. Also, a requirement specification was produced where requirements and desires were identified. To help translate these requirements into design parameters and to support the further development, a *Quality Function Deployment* (QFD) was also conducted. Furthermore, a risk analysis using *Failure Mode and Effect Analysis* (FMEA) and *Variation Mode and Effect Analysis* (VMEA) was carried out to help identify risks to operators and sensitive areas of the hydraulic system.

3.1.1 Information gathering

In order to gain the knowledge needed to carry out the project, a thorough search for information was conducted. Prior to selecting and dimensioning components enough knowledge had to be obtained, thus searches on the internet, patent databases, industry magazines, conversations with industry people and semi-structured interviews where tools that supported this stage of the project.

Also, a study of industry trends was conducted, using the above mentioned tools, in order to get ideas and new solutions of how a distributed hydraulic system could be configured. This work provided a foundation for idea generation and concept development where emerging technologies were further evaluated.

To also fully understand today's hydraulic system of the Giraffe AMB, studies were carried out of existing product documentation provided by Saab EDS but also through observations at site. This was essential for the study in order to be able to provide a foundation for comparison and to have something to start from.

3.1.2 Functional mapping

As said above, an essential part of the study was to gain knowledge of the existing Giraffe AMB hydraulic system but also the ability to create customer value. According to The Value Model, customer value is defined as the relationship between perceived benefits that the customer gains and the total expenditure over time. Functions are furthermore a good way of describing the benefits provided by the product from a customer's point of view. The functions could then be divided into four categories, i.e. main, additional, support and undesired functions (Lindstedt & Burenius, 2006, p. 540). The aim is then to obtain measurable function values that describe the performance of the product. Tools such as Idef0 process mapping (fig. 11) and system architecture trees supported the work of identifying main, additional, support and undesired functions and also to obtain knowledge of the system. These tools provided a thorough base for understanding and further development using axiomatic design, see section 3.2. The result of the functional mapping is found in appendix II.

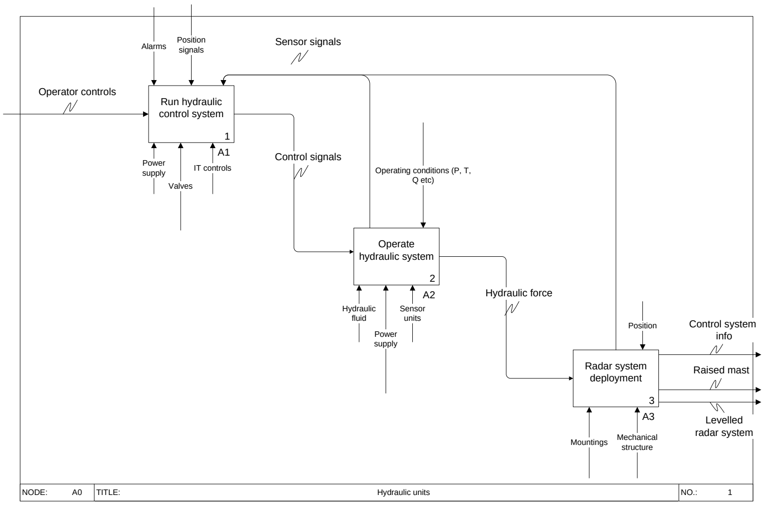

Figure 11. Illustration of a Idef0 process description

3.1.3 Customer requirement specification

In addition to information gathering and functional mapping, the product needs a customer requirement specification in order to have preset project borders. The customer requirement specification provides a structured documentation of requirements that makes it easier to create customer value, i.e. to identify what the customer expects of the product is highly important in order to create value (Lindstedt & Burenius, 2006).

Since this study aims at comparing two principally different hydraulic systems; a centralized and a distributed, some kind of linkage to set out from was needed. Therefore, many of the performance requirements of existing Giraffe AMB were transferred to the new specification. The aim for this was to use the same technical framework when developing the concepts, though with some areas where the boundaries where somewhat vague in order not to limit the development and open up for new ideas, e.g. space requirements, cost, weight, design etc. These aspects are important when comparing the systems but should not limit the development. The customer requirement specification can be found in appendix I.

3.1.4 Quality function deployment

The QFD method is a tool to translate customer and user requirements into technical requirements and specifications, i.e. measureable design goals to critical design parameters. In addition to the translation of requirements into quantified design specifications the QFD could also comprise a market benchmarking, e.g. competitor analysis (Johannesson et. al., 2005, p. 250).

The process consists of four steps, although all steps are not always followed.

- Market benchmarking, i.e. to establish goals based on customer needs, requirements and expectations.
- Competitor analysis, i.e. how the competitors meet the customer needs and requirements.
- Identification of priorities in development efforts in order to improve market acceptance.
- Translation of customer requirements into quantified technical specifications for design and manufacturing.

(Johannesson et. al., 2005, p. 251)

The QFD method structures this information in a matrix, often called "the house of quality", such matrix can be found in appendix II and in figure 12.

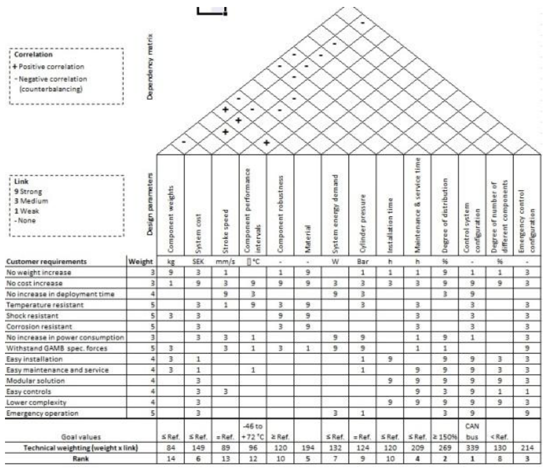

Figure 12. The "House of quality" matrix to translate customer requirements into design parameters

In the centre matrix elements, the correlation between customer needs and design parameters is evaluated through rating, i.e. how strong the correlation between the two is for each element. The "roof" contains markings of dependency between design parameters, e.g. negative/counteracting or positive correlation. The right section, as well as the lower section, contains the benchmarking, a comparative analysis against both customer needs and design parameters respectively (Johannesson et. al., 2005, p. 251) (Lowe, 2011).

Altogether these ratings and the benchmarking ends up in a weighted sum for each design parameter which provides further guidelines of what design parameters and requirements that are important to focus on in order to meet the market needs.

It is important to note that the QFD work shall not be carried out too formalistic but provide a foundation for discussion and documentation. It will act as support in the development work in order to reach consensus of the importance of requirements and parameters and how these shall be interpreted (Johannesson et. al., 2005, p. 253).

In this study, the section with benchmarking is not relevant since the comparison is between today's centralized system and a distributed system, thus it is excluded. The study does not take into account a competitor analysis.

3.1.5 Mapping of market components and system solutions

The component market mapping was a vital part of the project with the purpose to scan the market for components and hydraulic solutions suitable for a distributed hydraulic system. The task was carried out with help of Internet research, patent databases, industry magazines and interviews. Together with the research of market trends, new interesting components, e.g. integrated solutions and electro-hydraulics, could be identified from various suppliers and then evaluated. Further telephone interviews and supplier visits supported this phase of verifying advantages and disadvantages. Also, these visits and conversations provided info on other relevant solutions that the suppliers offered. In summary, the market mapping resulted in an overview of available products for distributed hydraulics.

3.1.6 Risk analysis

The risk analysis was essential to identify hazards and provide guidelines to minimize the risks when designing the hydraulic system. The risk assessment covers both operator safety and system related hazards. Two different tools has been used, FMEA and VMEA, both carried out for a general hydraulic system and not for specific concepts.

3.1.6.1 FMEA

FMEA is a hazard identification technique, used to define, assess and provide guidelines to minimize the risk of errors' occurrence. During this project the method has been used to identify hazards regarding operator safety and system related issues due to its capabilities to study each individual failure. The FMEA analysis is a very important tool in the product development process to early minimize the hazards in a new product. It's a systematic method that notifies in advance about possible misdeeds and consequently helps to prevent dangers (Kececioglu, 1991). It is furthermore very flexible, thus it can be adapted to almost any sort of situation, granted that it displays the following aspects:

- Identification of known or possible failure modes
- Recognition of the cause-effect chain of events leading to that specific outcome
- Suggests a possible corrective action for the occurrence of a failure, and evaluates its consequences

(Johansson, 2006).

Moreover, the FMEA for operator safety consists of a classification phase where a risk class, high medium or low, is calculated for each risk based on the classification of the two different criteria *Severity* (S) and *Probability (P)*. The classification has in this study been based on qualitative assumptions due to lack of statistical input. In order to obtain a risk class, a risk matrix based on the two criteria and a predefined risk index has been used, see figure 13 below.

Table 2. List of risk index with respective risk level and required action

Risk index	Actions required	Risk level
1-10	Risk can be accepted	Low (L)
11-19	Must be reduced	Medium (M)
20-25	Requires priority actions	High (H)

Severity \ Probability	1	2-3	4-6	7-8	9-10
1	1(L)	2(L)	4(L)	7(L)	11(M)
2-3	3(L)	5(L)	8(L)	12(M)	16(M)
4-6	6(L)	9(L)	13(M)	17(M)	20(H)
7-8	10(L)	14(M)	18(M)	21(H)	23(H)
9-10	15(M)	19(M)	22(H)	24(H)	25(H)

Figure 13. Risk matrix to classify risks as high, medium or low according to a risk index.

The result from the risk classification has then formed a priority list of risks as a basis for further development with respect to operator safety.

Also, the classification method using a risk priority number (RPN) has been used. Operator safety has used both classification methods in order to cover a wider spectrum and to evaluate the difference of the results. Regarding system reliability, only the RPN classification has been used. The RPN classification is based on the multiplication of *severity* (S), *probability* (P) and *detectability* (D). The risks are then summarized in a priority list.

$$RPN = S \cdot P \cdot D \qquad \text{eq 3.1}$$

The FMEA process allows for each single individual failure to be studied independent on others, let aside the ones directly causing, or affecting, the issue at hand. This way, the main failure modes which will eventually provoke, or significantly contribute to, an accident can be accurately studied (Shahriari, Mohammad; Chalmers University of Technology, 2010).

ALARP

When the hazards are identified and assessed they are ordered in a ranked list, as stated above, and could then be categorized within three different categories, i.e. accepted risks, *As Low As Reasonable Possible* (ALARP) and priority risks. Focus should mainly be on priority risks through redesign and other measures. For the ALARP-risks the focus is on minimizing these as low as reasonable possible (Shahriari, Mohammad; Chalmers University of Technology, 2010). This division was used for operator safety on the risk level classification method.

3.1.6.2 VMEA

In the competitive market of today, it is essential to deal with unwanted variations in order to ensure and improve the quality and reliability. A VMEA analysis has been conducted to deal with unwanted system related variations, as a complement to the FMEA. The aim with this is to estimate variations in the product that could be a risk, the result shall then help to avoid variations and design the system in a robust way. The different variations that occur affect product/process characteristics in many different ways, resulting in unwanted outcomes. Some characteristics suffer more than other, due to their increased sensitivity to variation and should therefore be identified early in the development process (Shahriari, Mohammad; Chalmers University of Technology, 2010).

VMEA helps to more effectively analyze the impact of various changes in product characteristics and allows for proactive prevention of these risks. VMEA is a relatively newly developed tool but has come to be of great interest due to its simplicity and usability. It is a tool most often based on statistical values to find critical and sensitive areas in the terms of effects of unwanted variation, though this study will be based on qualitative classification rather than quantitative using statistics due to lack of input material (Six-Sigma, 2007).

The goal with VMEA is to find the most critical and sensitive factors affecting the product/process and to manage them early in development (Six-Sigma, 2007).

Approach:

1. Initially the general product characteristics (KPC) are broken down into sub-components (sub-KPC) .Then identification of noise factors (NF) that could affect each Sub-KPC.
2. Estimation of how much each Sub-KPC affects KPC and how each NF affects respective Sub-KPC
3. Estimation of how much each NF varies.
4. The result is compiled and analyzed (Six-Sigma, 2007)

To create a thorough VMEA and to maximize the information from different areas and levels in the organization, it is often useful to create an Ishikawa diagram to find the root causes, see figure 14. To cover all necessary areas in the organization, the concept of the seven M's (Management, Man, Measurement, Material, Millue, Method, and Machine) can be applied, though the characteristics selected can be customized to fit the product/process and provide a more appropriate terminology and association (Six-Sigma, 2007). The Ishikawa diagram can be found in appendix III.

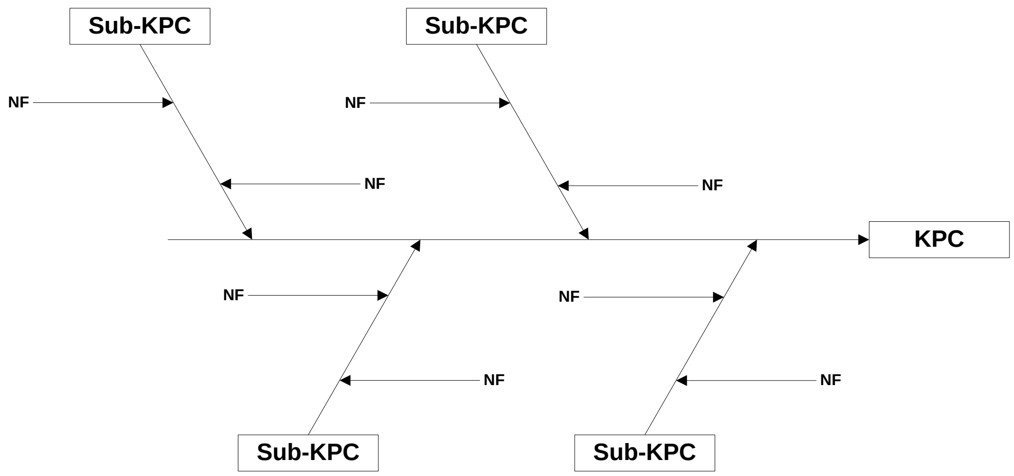

Figure 14. Ishikawa diagram of key product characteristic

Furthermore, when performing the ranking of the different factors, certain specific criteria's should be taken under consideration.

VRPN (Variation Risk Priority Number) is calculated with the following equation:

$$VRPN = S_1 \cdot S_2 \cdot V \qquad \text{eq. 3.2}$$

where,
S_1 is the sensitivity factor of KPC to the influence of Sub-KPC.
S_2 is the sensitivity of the Sub-KPC to the influence of the NF.
V is the size of variation of the NF.
Note: KPC = Key Product Characteristic

The factors that get the highest calculated VRPN value are referred to as the most sensitive and should therefore be thoroughly analyzed. These factors may expose the organization to harm and cause severe consequences if not being handled as early as possible (Shahriari, Mohammad; Chalmers University of Technology, 2010).

For the analysis of the different factors in the VMEA, certain criteria have been considered to develop a comprehensive method for understanding and weighting the parameters, see table 3-5. These parameters have been categorized in intervals, depending on sensitivity and affect of each other.

Table 3. Criteria for assessing the transfer of variation from sub-KPC to KPC (Shahriari, 2010)

Criteria [a]	Weight
KPC Sensitivity to Sub-KPC: Very low	1-2
KPC Sensitivity to Sub-KPC: Low	3-4
KPC Sensitivity to Sub-KPC: Moderate	5-6
KPC Sensitivity to Sub-KPC: High	7-8
KPC Sensitivity to Sub-KPC: Very high	9-10

Table 4. Criteria for assessing the sensitivity of Sub-KPC to noise factors (Shahriari, 2010)

Criteria [b]	Weight
Sensitivity of Sub-KPC to Noise Factor: Very low	1-2
Sensitivity of Sub-KPC to Noise Factor: Low	3-4
Sensitivity of Sub-KPC to Noise Factor: Moderate	5-6
Sensitivity of Sub-KPC to Noise Factor: High	7-8
Sensitivity of Sub-KPC to Noise Factor: Very high	9-10

Table 5. Criteria for assessing the variability of noise factors (Shahriari, 2010)

Criteria [c]	Weight
Size of variation in Noise Factor: Very low	1-2
Size of variation in Noise Factor: Low	3-4
Size of variation in Noise Factor: Moderate	5-6
Size of variation in Noise Factor: High	7-8
Size of variation in Noise Factor: Very high	9-10

3.2 Axiomatic design process

In the study, the product development practice Axiomatic design has been used as a structured support method, though not all phases of the method have been carried out since it only has acted as a way of thinking and a framework for development.

The design synthesis of axiomatic design is an interaction process where you "zig-zag" between what you want to achieve and how you will achieve it. The process uses the two domains "*Functional*" and "*Physical*" where the goal (WHAT) is specified in the functional domain as "*Functional requirements*" (FR) and the solutions (HOW) fulfilling the goal is specified in the physical domain as "*Design parameters*" (DP). The design process is then based on the interaction between these domains on each hierarchical product level, also called FR–DP mapping. This process is presented in figure 15 below where the arrows illustrate the iterations.

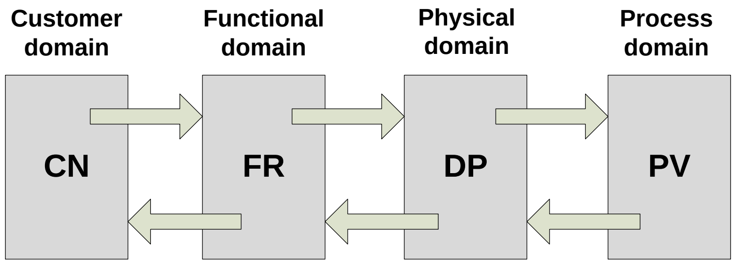

Figure 15. Mapping ("zig-zagging") between domains according to axiomatic design methodology

The interaction between the functional domain and the physical domain is done in a hierarchical process, starting at a general product- or system level. First the highest level FR is defined and a corresponding DP is selected among generated alternatives. The concept generation strategy is then to:

- Derive as many sub-solution alternatives as possible for each sub-function on current hierarchical level.
- Combine sub-solution alternatives into total solution alternatives on current hierarchical level.
- Choose the best total solution on each hierarchical level.
- Proceed with the next hierarchical level and start the process over.

Functional requirements shall not be decomposed to the next hierarchical level until a corresponding design parameter exists.

For the complete product development process, there are two additional domains called the "*Customer domain*" and the "*Process domain*" (Johannesson et. al., 2005, p. 165). In this study only the customer domain is in focus. The customer domain is where *customer needs* (CN) are identified and formulated and similar to the interaction mentioned above there is a interaction between the customer domain and the functional domain where the customer needs are translated into design criteria/functional requirements and *constraints* (FR and C). A QFD (see section 3.1.4) can in this case be useful where the design criteria of the QFD correspond to the axiomatic FR and C (Johannesson et. al., 2005, p. 165).

Since the hydraulic system already exists, though in a centralized version, many of the functional requirements was transferred to this product's requirement specification in order to more easily compare the systems in the study. Although, a QFD was, as described, compiled to better follow the methodology and get a structured way of working together with a deeper knowledge of the system requirements and their relations to different design parameters. The QFD and the results from the functional mapping provided the basis for the functional structure in the functional domain.

Furthermore, since the mast hydraulics and the support leg hydraulics are used for different purposes and have different functions, the most reasonable was to divide those two functions and describe a hierarchical structure for each, both located in appendix II. The design process in this case was based on two product hierarchy levels and this is described in figure 16-17. Furthermore, the development process is described in the next section. An illustration is given in figure 18. Figure 19 furthermore shows the elimination process, according to Johannesson (2005), which were applied for selection of each design parameter.

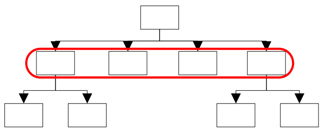

Figure 16. Product hierarchy - Level 1

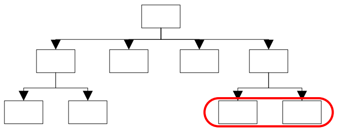

Figure 17. Product hierarchy - Level 2

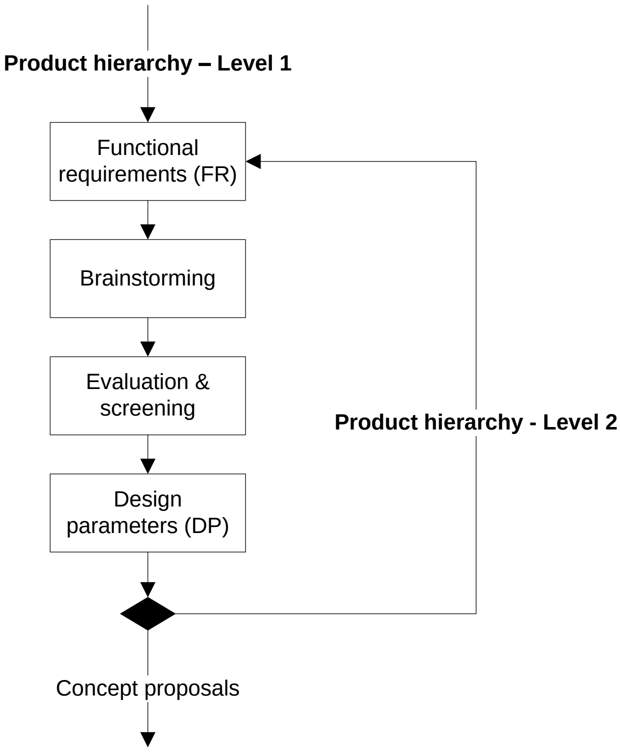

Figure 18. Development process description

3.2.1.1 Product hierarchy level one

Firstly, a decomposition of the level one functional requirements (FR) were compiled with the aid of the functional mapping and the QFD.

Brainstorming
With all functions in place, brainstorming session ideas together with the market mapping results founded the basis of an idea list for the first level in the product hierarchical structure, compliant with the axiomatic design methodology. This list used the structure of a morphological matrix, though concepts were not generated through it but rather provided an organized collection of all ideas sorted by function or other relevant categories.

Screening 1 – Pre-evaluation matrix
Next step was to eliminate the ideas not suitable, or in some way not realizable, for the application at hand together with the ideas that for obvious reasons did not meet the specified requirements. For this task a pre-evaluation matrix was used where all ideas were evaluated against certain general criteria, e.g. in line with the ones mentioned above, and graded on a plus-minus scale based on discussions and general facts. An idea with a negative sign was then directly eliminated. The results can be found in appendix V.

Screening 2 –Non-weighted Pugh matrix
For those functions connected to ideas relevant for further evaluation and elimination, a second screening was carried out. A non-weighted Pugh matrix (Lindstedt & Burenius, 2006) provided the tool for this evaluation where a qualitative classification based on subjective evaluations provided the scoring of each alternative. The results are found in appendix V.

Screening 3 – Weighted Kesselring matrix
In those cases where the screening results were indistinct or decisions could only be taken on unsubstantial grounds, a criteria weight matrix (Kesselring) was used. As for the previous screening tool, the classification was also here based on subjective evaluations since quantitative criteria assessment (Johannesson et. al., 2005, p. 140) was hard to achieve due to the nature of the requirement specification and the possibilities to gain accurate data for each idea. The result from this weighted evaluation can be found in appendix V.

3.2.1.2 Product hierarchy level two

The identical process as for level one was applied to the next level in the axiomatic product hierarchy, see FR and DP schemes in appendix II.

3.2.1.3 Concept selection

Through the design mapping according to axiomatic theory, together with an integrated elimination process, two principally different concept proposals were elaborated with configurations of a distributed hydraulic system for mast hydraulics, support leg hydraulics and support function hydraulics. Standard components were evaluated against each other and their suitability as a whole. With the methodology, a total solution could be obtained. The outcome was one concept with total distribution, i.e. one power unit for each cylinder, and one semi-distributed concept where each power unit drives two to three cylinders. Both distributions were chosen to compare this difference in distribution and also due to the suitability for each concept's components and subsystems. A description of each concept, called *PowerPack* and *EHC*, is given in section 4.3.

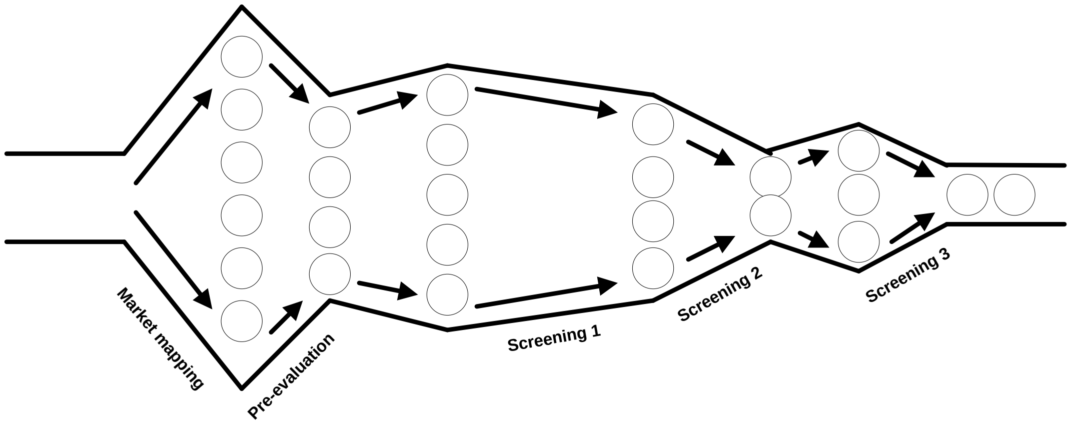

Figure 19. General evaluation process from product development methodology

3.2.2 Axiomatic analysis process

To support design decisions on an unbiased and rational basis the axiomatic methodology uses defined and commonly accepted principles, or axioms, that indicates what is generic "good" properties and provides a basis for comparison between solutions.

Axiom 1 – Axiom of independency
Functional requirements (FR) shall be formulated, and if possible be retained, independent of each other during the design process.

Axiom 2 – Axiom of information
Minimize the content of information in a design solution.

These two axioms together with further theorems and corollaries provide the foundation of the analysis process where functional coupling and information complexity are evaluated through the so called design equation (Johannesson et. al., 2005, pp. 159-162) (see eq. 3.3).

[FR] = [A] {DP}   eq. 3.3

The analysis process has in this study been excluded since hydraulic systems are mature technical systems that mainly consists of the same components and the development in this thesis is more about selecting appropriate components, thus to evaluate functional coupling is not relevant in this case. The axiomatic design process has though acted as a structured support to concept development with its mapping between the functional domain and the physical domain, evaluating each function separately. Finally, an evaluation of the total compliance was done. The methodology of axiomatic design has been very useful in the development and has provided an effective working practice.

3.3 Further development of selected concepts

The axiomatic design process resulted, as said, in two main concepts for further development. Subsequent to selection of conceptual hydraulic configurations, selection of specific components was initiated. The components were dimensioned through calculations to find a solution as close as possible to an optimal configuration.

The development of concepts included price estimation, hydraulic configuration, weight analysis, description of functions and illustrations. A large part of the further development process was to find and estimate prices and data of different components. The prices come from different suppliers, catalogues and estimations from industry experts. Some has also been estimated with the help from previous reference offers. A lot of the decisions regarding the final concepts have been taken with recommendations from industry experts in mind.

To illustrate the ideas, 3D CAD models have been created in Pro Engineer. The aim of the illustration is to show the size and look of the system in its intended environment and also to evaluate possible component positions.

3.3.1 Method of calculation

To obtain data on hydraulic components from suppliers, and to more accurately compare a centralized system with a distributed, dimensioning calculations were carried out. This was especially important for the hydraulic pump and the electric motor since these components are mainly the ones that deliver the expected performance. The process and methods used is described in this section.

3.3.1.1 Time measurements

Since the original time requirements are based on a total time for, e.g. raising the mast and leveling the radar system, more detailed time segments were needed. This is due to that the cylinders have varying speed during different phases of their execution together with time for tuning the position and assuring smooth motion. In order to use a comparable time requirement for dimensioning of components, time measurements of the different phases were carried out. The phases of the two functions are as follows:

Level radar system
- Position support leg cylinder
- Unloaded stroke
- Loaded stroke

Raise mast
- Smooth acceleration
- Normal operation
- Smooth deceleration

These time phases have, through measurements by physical observation using a stop-watch, been evaluated and the result is described in section 4.2.

3.3.1.2 Dimensioning of components

The calculations, in order to be able to dimension the hydraulic components, originates from the technical input in the customer requirement specification document, time measurements, diagram deduction and assumptions, e.g. using the same properties of the hydraulic cylinders as in the Giraffe AMB. The parameters that were used as input is the following:

- **Stroke speed** (m/s)
  From time measurements, diagrams and total time from the specification provided by Saab EDS.
- **Max force** (N)
  From diagram deduction performed on material provided by Saab EDS and using earlier mechanical studies of today's Giraffe AMB and from specifications.
- **Force during normal operation** (N)
  From diagram deductions performed on material provided by Saab EDS (mast) and assumptions of a radar system leveled on a horizontal ground and its weight evenly distributed on all four legs (support legs).
- **Counterweight force during unloaded stroke** (N)
  From earlier specifications provided by Saab EDS.
- **Cylinder dimensions** (mm)
  From original specifications provided by Saab EDS.
- **Efficiency factors**
  From assumptions within commonly used industry intervals.

Also, input from conversations with people from the industry has contributed to the dimensioning. Using hydraulic formulas (see formulary) properties such as flow rate, pressure, power and torque could be calculated, thus outlining the basis for selection of components.

Since focus was mainly on keeping existing hydraulic cylinders and their dimensions, the power unit components was dimensioned with the existing pressures in mind. Also, to get a more fair comparison, the dimensioning was based on the same cycle time requirements, i.e. the same cylinder stroke speed was applied to the distributed system when dimensioning the components. This provided the input, thus approximated flow rates and pressures could be obtained.

To dimension the hydraulic gear pump the fixed deplacement had to be set. This parameter is dependent of the desired flow rate and the electrical motor rotational speed which is set to be varying in both concept proposals, see section 4.3. Since the motor speed and thus the flow rate is set to be varying, dependent of load, the selection of deplacement can vary. The flow rate and deplacement are in this case the parameters that control the dimensioning, thus the rotational speed is the parameter that will be dependent of these two.

The hydraulic pumps though use a specified value of the lowest allowed rotational speed which varies with supplier. Variations between approximately 500 – 1000 rpm are common. This has to be considered when tuning the flow rate and deplacement, i.e. as too high deplacement would require a too low rotational speed. Furthermore, the pump needs to cope with the pressures and thus be specified accordingly.

The normally specified working rotational speed of 4-pole electric motors, which is appropriate for this application due to, e.g. its higher torque, is most often between 1400-1500 rpm. To obtain a hint of what deplacement to set, this working speed was used together with the desired flow rate and the result was a calculated deplacement to set out from. Since suppliers offer different standard components with different deplacements, the ones within close range to the calculated value could be chosen and the rotational speeds of each evaluated. The focus when selecting was then to get the rotational speed interval as small as possible and that this parameter did not get too high or too low.

The electric motor was then evaluated against minimum rotational speed, calculated torque and the required input power, obtained from hydraulic calculations. The entire dimensioning sequence is illustrated in figure 20 below.

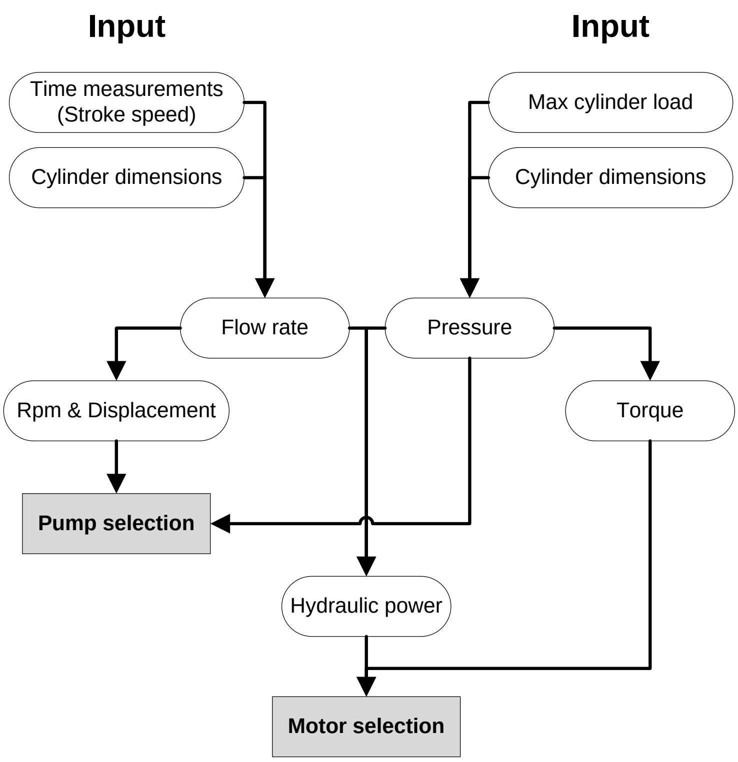

Figure 20. Method of calculation; Input is stroke speed, cylinder load and cylinder dimensions

Furthermore, estimations of reservoir size has also been conducted by estimating the volume of hydraulic oil needed through simple addition and with the knowledge gained from interviews as support.

In cases where the idea of an accumulator has been applied, dimensioning calculations using the free online software "*Accumulator simulation program*" (ASP) by HYDAC Inc. This software processes the following parameters:

- Pre-charging pressure (Pa)
- Highest working pressure (Pa)
- Lowest working pressure (Pa)
- Working volume (l)
- Lowest operating temperature limit (°C)
- Highest operating temperature limit (°C)
- Cycle time (s)
  Note: Assumed cycle time.
- Process (Adiabatic/Isothermal)
  Note: Adiabatic is assumed since the process is relatively fast.

The output is diagrams on accumulator size (volume) and its variations due to temperature changes. This was considered since the hydraulic system operates in rough environments with large temperature differences.

3.4 Evaluation and verification of concepts

The evaluation and verification phase of the study consists of three main areas, i.e. from dimensioning calculations collect information such as price, dimensions and weight of components and verify the concepts compliance against the customer requirement specification. Also, the thesis has evaluated the concepts on the aspects of modularity, reliability, maintenance and service. Finally, evaluations of the concepts from a dimension and positioning point of view by using 3D CAD models have been conducted. CAD models have been compiled for visualization purposes.

3.4.1 Summary of concept properties

The calculations have formed the foundation for selecting components and based on these data, component properties such as cost, weight and dimensions have been collected through supplier contact and catalogue searches. All data have then been summarized in a table to provide a structured basis for evaluation. The summary document can be found in appendix VI.

3.4.2 Concept verification against CRS

To ensure or evaluate whether all customer requirements are met, the concepts have been verified against the CRS document. This has been done by producing a functional specification of the concepts, synchronized with the customer requirement specification layout, and each requirement has then been evaluated. This document can be found in appendix VIII.

3.4.3 Geometry evaluation

To evaluate the positioning issue, CAD models have been used to as large extent as possible. Where models of any component have been missing an approximated model has been drawn in order to illustrate the space demands. The models have then been used to identify possible placements of power units etc. Also, they have provided visualization material in order to illustrate the concepts. Images of the concepts can be found in section 4.5 and the evaluation of positions is found in section 4.4.8.

4 Result of study

The chapter aims to present the relevant results of this thesis. It firstly provides insight to alternative ideas that were evaluated, followed by the results from calculations and time studies of which the component selection was based on and where focus has been on the hydraulic pump and the electric motor. The proposed solutions for a distributed hydraulic system are then described, i.e. proposals of potential and realistic configurations of hydraulic components into a distributed system. The distributed hydraulic system is finally evaluated against various criteria, e.g. reliability, economics, weight, space requirements and maintenance, and the result of the risk analysis is also presented. The chapter ends with visualizations through CAD models to illustrate the distribution and the configuration of hydraulic units, also the required space of the components.

4.1 Concept idea foundations

This section describes the two main foundations that the elaborated concepts are built on, i.e. power packs and electro-hydraulic cylinders. It provides descriptions of the technologies, their components as well as their possibilities and suitability for a distributed system.

4.1.1 EHC

The most optimal solution of a distributed hydraulic system would be a module where everything is integrated in one unit, utilized on each function and only connected through an electric wire. A product that is somewhat in line with this way of thinking is the *electro-hydraulic cylinder*, see section 2.2.1.4, provided by Kent Börjesson Teknik AB. It is a totally integrated solution, much like the EHA, and can be adapted to different applications.

An EHC is simply a complete hydraulic system in one unit. The basic component is the cylinder on which the entire system is built. On the outside of the cylinder an external quadratic pipe is attached. This pipe acts as the reservoir together with the outer cylinder wall. On the top of the cylinder a special back plate is placed where the electric motor, hydraulic pump, a coupling between the pump and motor axis, two check valves, two pressure reducing valves and one solenoid valve are positioned. The only necessary connections to the surroundings are cables to power the electric motor and physical attachments to keep the electro-hydraulic cylinder in position

The electro-hydraulic cylinder is a very simple hydraulic system with few components, few connections and the flow is regulated by the varying speed of the electric motor. The flow direction in the circuit is decided by the pump.

The hydraulic gear pump in the unit works in the same way as a hydraulic motor, which means it can rotate in both directions. When the cylinder is moving outwards the hydraulic pump is rotating in one direction and the hydraulic oil is transported to the plus chamber from both the reservoir and minus chamber. When the cylinder retracts the pump changes direction and transports oil from the plus chamber to the minus chamber. Redundant oil goes back to the reservoir. To lock the cylinder under pressure a solenoid valve is used, which in this case means that the solenoid valve closes when the hydraulic oil in the plus chamber is under pressure. (Börjesson, 2011).

This electro-hydraulic cylinder is a product developed to follow the trend of integration thus providing a compact and flexible solution that is one of few similar solutions on the market. The major advantages with an electro-hydraulic system are the simple installation, few components, everything included in one unit and no need for pipes or hoses to external components. Because of the compactness of the system and the simplicity in installation it is possible to easily replace the electro-hydraulic cylinder. It is also possible to take one electro-hydraulic cylinder from the system and place it in another application or use the unit in another function (Börjesson, 2011).

The electro-hydraulic cylinder is a closed system which in this case means that there are no needs for hydraulic pipes or hoses. In a conventional hydraulic system pipes and hoses are used to connect all the system components which lead to a much higher risk for leakage and a more complex installation (Börjesson, 2011).
A drawback with this solution could be that the components are positioned in sensitive areas, directly out on the cylinder, though modifications could possibly be made to solve this issue further on. Also, there are limitations in emergency operation, i.e. if the electric motor or the pump fails. Though, it provides the possibility to use an AC/DC converter to power the motor in case of main power failure.

4.1.2 Power pack

A power pack comprises an electric motor, hydraulic pump, reservoir, valves, possible accumulator and different control devices in a compact, self-containing, package. The interfaces are standardized and it uses modular plates that are compact in design to minimize the size of the power pack. It has a variety of component combinations and mounting positions and the power pack is configured based on what the application requires (HYDAC, 2011). An illustration is given in figure 21 that shows the modularity of a power pack.

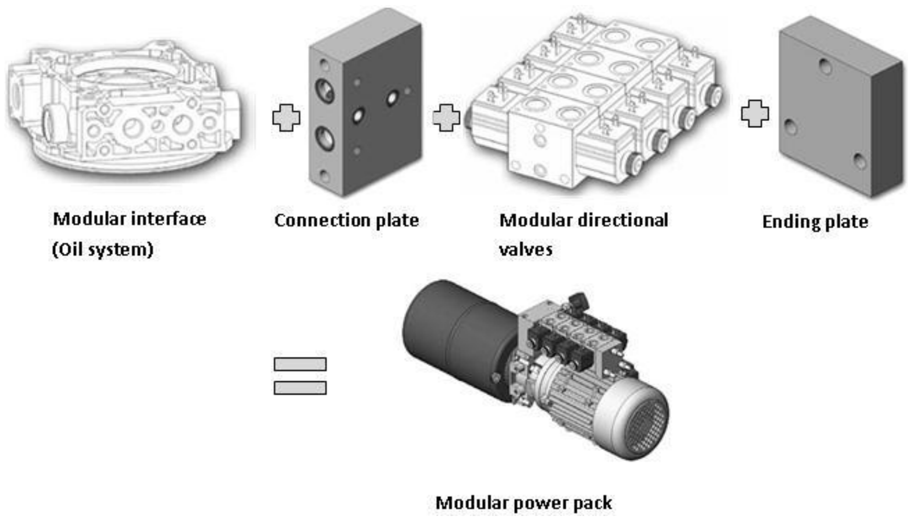

Figure 21. Illustration of power pack modularity

This is a realizable option to power one or several functions and could be a possibility for a distributed system. Although, to utilize such a power unit for minor functions such as parking cylinders and mast lock cylinders individually would be geometrically demanding and increase the total weight.

4.2 Alternative ideas and technologies

To summarize other potentially good ideas, evaluated through this study, a list has been compiled below. These texts describe the underlying thoughts of the ideas followed by evaluations of whether it could be suitable for a distributed hydraulic system or not.

4.2.1 Telescopic cylinder

The idea of using telescopic cylinders is of geometric reasons where this kind of cylinder requires less space but provides a long stroke. The primary target was to utilize this in the mast hydraulics to eliminate the large number of cylinders used for that particular function. Though, this type has not enough stiffness to cope with transversal loads and you would lose the stability of the mast if using only a telescopic cylinder to raise it. This is since it then would be sensitive to side loads and would have to carry all load by itself (Stacke Hydraulik, 2011). A combination of standard cylinders and a telescopic was also considered where only the upper mast cylinders were replaced by a telescopic. This would though mean that a larger flow is needed since the fully extended telescopic cylinder contains more fluid, assuming for mechanical strength reasons that the dimensions of the last section correlates to the existing cylinder dimensions. To then keep the same time objective would require quite a large rise in flow rate with a larger power unit as result which is not preferred.

4.2.2 Extension tube as reservoir

The existing support leg configuration today withholds an extension tube above the hydraulic cylinder with the purpose of gaining stiffness and stability to the structure. It is today only a hollow tube with an inner volume of about 10 liters. An idea is to use this tube as a reservoir in order to utilize the existing space more effectively. This would only require some modifications to the existing cylinder configuration and improve the possibilities to fit the remaining components of the power unit into existing support legs compartment. The restrictions would though be the positioning of the hydraulic pump since it is preferably placed beneath the reservoir to avoid air in the system. This means that it would have to be positioned at the bottom of the compartment or alternately directly integrated on the cylinder.

4.2.3 “Green valve”

The green valve, described in section 2.2.3.1, was considered as an idea for the mast hydraulics with the aim of reducing size, weight and cost of the power unit. However, since the current mast structure is designed to keep the upper section in a weight equilibrium position when raised, only gravity is not enough to lower the mast and especially not in windy conditions. Furthermore, the size and weight of the power unit would not get reduced since it is the raising sequence that is the dimensioning factor. Although, an upside would be that the overall energy consumption could be reduced thus making the total radar system more energy efficient. For this application though, it is not suitable and does not comply the aim of the study.

The green valve has also been considered as a device for emergency operation of the mast, lowering it if main power or any component should fail. Though to operate the valve some oil flow is still needed, thus requiring some kind of extra device nonetheless.

4.2.4 Electric linear actuator as positioning and locking device

Since the radar system today uses hydraulic cylinders for as many as 14 functions it is hard to see that a distributed system could provide that many advantages with respect to cost, weight and space requirements (Börjesson, 2011) (Karlsson, 2011). Also to combine two functions, such as support leg cylinder and parking cylinder, gives a dependency that is undesirable. An idea is then to deviate from hydraulics for the support functions, e.g. positioning and locking of support legs and mast respectively.

Instead of using hydraulic cylinders a linear electric actuator could be utilized since the forces are quite within range for these devices and you eliminate the dependency of functions and could focus on a single function when dimensioning. Also, extra piping and tubing is eliminated. However, potential problems such as cost, weight, and space requirements might arise together with the aspect that the emergency operation needs to be modified. A linear electric actuator requires a separate motor that could be space demanding and they tend to cost and weigh more than a hydraulic cylinder of the same size, at least for the positioning application. However, in a wider perspective, this does not necessarily mean a drawback of the total system.

4.2.5 Electro-Hydrostatic Actuation (EHA)

Electro-Hydrostatic Actuation is often referred to as ”power by wire” and are self contained actuation systems, combining design elements from electric and electro-hydraulic actuation, i.e. a unit withholding electric and hydraulic components as a compact package, controlled by a common controller and software system. The described unit typically includes a servomotor, hydraulic pump, integrated valves and feedback sensors, accumulator and a servoactuator which altogether transforms an electrical input command signal from an electric source into motion (Moog Inc, 2010).

When comparing EHA with electric or hydraulic actuation, EHA is an advantageous option for traditional hydraulic applications where high force requirements exist together with the need for specific advantages of electric technology such as energy savings, environmental cleanliness or cost of hydraulic piping. Furthermore, EHA is an option for traditionally electric applications that have high forces and require redundant and/or advanced failsafe systems (Moog Inc, 2010).

EHA could be described as a compact alternative of electro-hydraulic systems which, in general, provides the possibilities of a decentralized hydraulic system. The trend, as described in section 2.2.1, demands more compact and accurate actuators and, according to Moog, EHA is the way to go for many applications. The technique has mostly been used in the aircraft industry where the technology has matured and successfully helped to reduce weigh, increase reliability and eliminate hydraulic piping. (Moog Inc, 2010). The technique is new but it has a lot of potential and could be very useful in a future distributed hydraulic system. Though, the technique is today expensive, especially for heavier applications. Also, since the technique is in such an early stage for industrial applications, the solutions are not that standardized. An idea that is somewhat similar to EHA is though the so called “electro-hydraulic cylinder”, see section 4.1.1.

4.2.6 Servocylinder

The idea of using a servocylinder originates in the efforts of making each power unit as small as possible by improving the motion control and steering of the actuators. Today the cylinders uses sensors and an inclinometer to level the shelter, though when this is done the system takes a relatively long time to tune itself into position after actuating the shelter, i.e. the shelter is first actuated a bit and then tuned one leg at the time into a horizontal position. The idea is then to make this tuning smoother by having continuous feedback also when actuating the shelter. In this way, time could possibly be saved and thus less flow would be required since the actuators can utilize this saved time in the combined lifting/levelling operation, i.e. operate in a slower pace but with continuous levelling.

To confirm this, a more thorough research would be needed that does not fit into the scope of this project though according to Håkan Karlsson, engineer at PMC Hydraulics and part of the development team of the Giraffe AMB, a servocylinder would probably not save enough time to obtain a smaller size of the power unit. This is due to that it today already operates with feedback, i.e. ground pressure communicates with the inclinometer and the difference in control would probably not be that large (Karlsson, 2011). A servocylinder is also more costly and the possible benefits might not weight up these extra costs.

4.2.7 CAN bus

Integration of CAN bus as a communication interface would require a microcontroller and CAN-compliant control components such as valves, sensors and switches connected to the bus-line. In figure 22, the general configuration of a CAN bus-based system is illustrated.

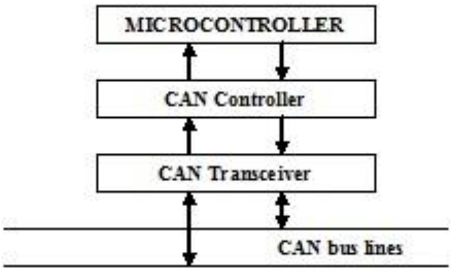

Figure 22. Illustration of a CAN bus structure

From a total system perspective, it is simple to add stations such as hydraulic control to an existing CAN network without any major hardware or software modifications to present stations as long as the new stations are purely receivers. This allows for a modular concept and also permits the reception of multiple data and the synchronization of distributed processes (Nangia, Agrawal, & Gupta, 2006).

Many industries have adopted the CAN bus standard, thus gained a lot in reliability and flexibility. For some applications, the cost and speed to deploy or reconfigure a communication network is vital. A CAN bus can be installed, then equipments can be added thanks to the plug-in functionality of CAN with its Higher Layer Protocols (EE Herald, 2006).

By using CAN bus protocol, a hydraulic system would be both less complex and costly to install and provide a fast communication. Together with electro-hydraulic components, e.g. valves, a very flexible and easy hydraulic system could be obtained that performs faster and more reliable. Also, CAN bus would open up new possibilities for operator control and diagnostics through, e.g. easily integrated wireless communication. The amount of cabling would also get reduced. Examples of existing system solutions with CAN bus interface, including microcontroller, valves, sensors etc, is, e.g. the PLUS+1 series from Sauer-Danfoss (Sauer-Danfoss, 2011) and BODAS series from Bosch Rexroth (Bosch Rexroth, 2011).

Further features and advantages

- CAN provide sophisticated error detecting mechanisms and re-transmission of faulty massages. It has also the ability to self-diagnose & repair data errors.
- CAN bus systems have high immunity to electromagnetic interferences.
  (EE Herald, 2006).
- Via the various configurable inputs and outputs it is possible to connect all types of sensors and actuators directly to the control unit and components such as proportional valves can be controlled directly.
- In case of failure, the system provides quick and easy diagnostics.
- The technology has implemented, internationally agreed, standards.
  (Moller, 2005)
- CAN is suitable for small networks.
  (CiA, 2011)
- CAN is able to operate in extremely harsh environments.
- CAN have the additional possibility of remote (wireless) maintained diagnostics which makes it capable of significantly contribute to an increased vehicle availability and productivity.
  (EE Herald, 2006).

The disadvantages of CAN bus in a hydraulic system is the cost of compliant hydraulic components which still is relatively high due to the slow adaptation of the technology in these kinds of hydraulic applications, i.e. there are few standardized hydraulic components with CAN compliance. Although, bus-based hydraulic control is getting more and more established in the industry thus it might get less costly in the near future, assuming further industry implementation of the technology.

Since the CAN interface technology needs to be further adopted by the hydraulic industry applications, it is perhaps more of a future issue. A timeline is though difficult to set since the technology has been a hot topic in mobile hydraulics for many years but not reached any major breakthrough. To weigh in the reduced cost for installation and control system development would on the other hand be an aspect that could make an investment of a CAN bus compliant hydraulic system more beneficial. This evaluation though spans outside the time resources of this study.

4.2.8 Manual operation

To operate the system shall be easy and not expose the operator to any risks. Today the operation is controlled by a control panel positioned away from the support legs. There are also switches on each support leg compartment in order to position and lower the legs manually. Furthermore, the directional control valves can also be manually controlled by using levers. To control the support legs too near the actuators could expose an operator, or others, of risks so to solve this in another way could be beneficial. Also, to position a power unit in a position outside a reachable range requires some electrical controls.

The manual control of a distributed hydraulic system could easily be done using the same control panel as today, though since each function has its own power unit, the wiring and control configuration would differ. The most convenient would be to use centralized controls and not change that much of the existing panel.

To distribute the manual directional valve controls, e.g. levers, however would be inconvenient and not user friendly. Instead, other control components such as electrical switches or regulators could be used, positioned away from the actuator. Also, using CAN bus more easily opens up possibilities for further control alternatives such as wireless control.

Since the flow rate of the distributed system is best controlled by varying the speed of the electric motor by frequency, the manual steering could be done using proportional, variable control devices. An example could be to use electronically controlled wheels or similar and thus providing a larger variation of manually controlling the speed and motion of the cylinders.

4.2.8.1 Remote control

An alternative idea to operating the hydraulic system from a control panel located near the actuators could be to integrate remote control instead. It would be possible with most communication interfaces though perhaps especially appropriate with bus interface. The operator would then manually control the system by using a remote control device and would be able to position him/herself in a safe distance from the actuators and with a better overview of the entire system. This solution would not require much modification of the control system and especially not with CAN bus but it would raise the total system cost.

4.2.9 Emergency operation

In case of power loss or component failure an emergency operation system is necessary to get the hydraulics in transport mode. The system shall only be used to go from transmission mode to transport mode if something breaks. In the reference system this problem is solved with an extra electric motor and pump, powered by the electric system of the truck. Moreover, the time requirements are lower for the backup system, approximately 30min.

Several different ideas of how this problem could be solved in a distributed hydraulic system are presented in this section. All these solutions have not been fully evaluated due to limited project time resources. Many ideas though have potential to be realizable.

4.2.9.1 Extra power unit

This is the same solution that is used in Giraffe AMB where one extra electric motor and pump, which is powered with an alternative source, is added to the system. For a distributed system this would mean an extra motor and pump for each hydraulic function. The truck’s 24V system could be used to power those extra power units if the main power fails.

The major advantage with this solution is the access to a complete extra power unit. No matter of what the problem is an extra system is available and ready to drive the hydraulic system. The major drawback with this idea in a distributed system is the need of a large number of components since an extra electric motor and pump is needed for each function. This would mean increasing cost, weight and space.

4.2.9.2 Accumulator

With an accumulator is it possible to get the system back in transport mode without power supply. The accumulator could, after operation, be preloaded with enough oil and with necessary pressure to get the cylinder back in fully retracted position. One accumulator can be used at each hydraulic function and can also serve as complement to the power units to reduce the power requirements when grouping.

After each operation the power unit will continue to work to preload the accumulator with a specific pressure. This shall be made both when grouping and preparing for transport mode. Though for an accumulator to meet the requirements of the application's functions, the dimensions would be quite large, especially to cope with large temperature variations.

The volume of an accumulator highly depends on the temperature variations. Since the system will operate in extreme temperature conditions a very large accumulator would be needed, see calculations in section 4.2.2. Also, if power fails prior to pre-charging the accumulator, it will not be able to carry out its function.

The accumulator can also be used to compensate for pressure drops in the system and to keep the cylinders in position over time. It it possible to compensate for position changes when the radar system is grouped without starting the power unit. Although, size is also here a limiting factor.

Another option is to use an accumulator together with lowering valves for mast operation. The idea is to use valves to lower legs and mast to as great extent as possible and then use an accumulator when required. This alternative has not been further evaluated though since such detailed studies of all subcomponents do not fit into the project scope. It also requires more input data to accurately decide the operating characteristics of such accumulator. However, with the calculations presented in section 4.3.2 in mind, the volume tends to be rather extensive which does not favour this solution.

4.2.9.3 Portable pump unit

Another idea regarding emergency operation is to use a portable pump unit with motor. Such package would be similar to the extra power unit but portable. The idea is to use quick couplings and simply plug it in with hydraulic hoses in cases where emergency operation is needed. In the case of power supply failure is it necessary to either use several units. The support legs cannot be operated together without several units and would need to be lowered a short distance at a time which is time consuming. This does however not refer to an electric motor failure since the probability of all motors to break at the same time is assumed to be very low. If one electric motor fails there are still functioning units left to operate.

One risk in this case is the connection of hoses in a pressurized system which can be dangerous. To use these, above mentioned, specialized quick couplings would though solve the problem. These are couplings made for this kind of task and are standardized products provided by, e.g. Parker Hydraulics. Another risk is dirt and other contaminants which could get into the system when interchanging hoses, thus resulting in operational problems.

4.2.9.4 Hand pump with electric motor

To disinvolve the hydraulic system from a power supply dependency one could use a hand pump in case of emergency. The idea is to use the same principle as many trailers use to operate their support legs. A hydraulic pump is connected to a handle and the leg can be operated by hand. Although, a fully manual emergency operation would require large efforts and lots of time from the operator but would also involve risks of operating close to mast movements.

As a further alternative there are standard rotary hand pumps that can be included in the hydraulic circuit and then driven by a portable electric motor. It has been highlighted as a possible solution during conversations with industry people though no standard rotary hand pumps that fits the application has been found, thus no recommendation can be made.

In the “electro-hydraulic cylinder” it would be possible to connect such device directly to the electric motor to operate it. A downside with this could be that the portable device is not strong enough to cope with the torque, though transmissions could be used.

Furthermore, a regular hand pump could also be used to provide the extra required power when lowering the mast and legs, as mentioned in section 4.1.10.4, with valves that operates where gravity do its part.

4.2.9.5 AC/DC Converter

The idea with an AC/DC converter is to use the DC power supply in the truck and convert it to power the AC motors at each power pack. This would make it easy to change power input to the motor if the main power is lost. Although, this backup system only helps if there is a power loss, not if any component fails but it would require almost no space which is a big advantage.

4.2.10 Distribution

There are many ways and levels of hydraulic distribution possible in the Giraffe AMB, i.e. the hydraulic units can be utilized in different ways and operate different numbers of hydraulic actuators. Each function could be driven by its own power unit or one power unit can share several functions. To use one power unit for each function, including parking cylinders and mast lock cylinders, would be the most optimal alternative through a distribution point of view, though it would require 14 units. It might be a disadvantage concerning price, weight and space requirements but not necessarily. To include the support functions, i.e. the parking cylinders and the mast lock cylinders, is then another realistic alternative. Some ideas on how the power modules could be distributed are illustrated in figure 23.

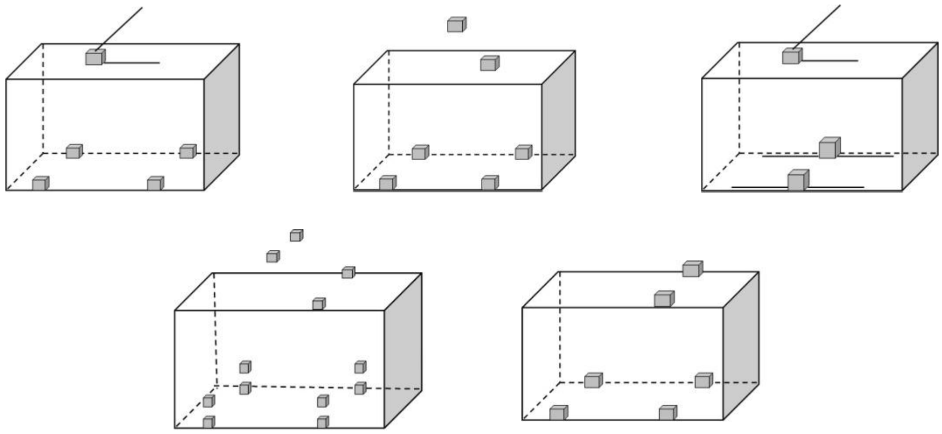

Figure 23. Examples of different distribution alternatives, a square represents a power unit.

In the mast case, it would not be beneficial to use two power units for each pair of cylinders since each would require the same high flow rate and almost the same maximum force. This would then require relatively large power units and since the two pairs of cylinders do not operate simultaneously it would be very unnecessary to utilize two units, thus a single unit powering all four cylinder plus the mast lock cylinders would be a more appropriate solution. Also, to put a power unit on the mast, to utilize for the upper mast cylinders, would change the total centre of mass of the upper section and thus requiring a redesign. Furthermore, since that power unit would be exposed to the movements of the mast, the risk of air present in the system would be higher due to the assumed intense movements of the oil.

However, to utilize two power units, one at each side, and power the left and right cylinders separately would reduce the flow requirement to half since the operation is in sequence, i.e. only one cylinder would be powered by one power unit at a time. This would reduce the size of the power module and also increase the level of distribution. Each power unit would though need to power a mast lock cylinder each and would require accurate controls by the control system to synchronize the strokes.

The support leg modules in the figures above include the parking cylinders but there are also the alternatives where several support legs share the same power unit. Although, this alternative would somewhat deviate from the whole idea of a distributed hydraulic system but could act as a compromise.

However, since each support leg does not require the same large amount of flow and power as a shared power unit, smaller units can be used, i.e. a power unit for each support leg is possible and would be the better alternative than the above when striving for a distributed hydraulic system to use in comparison with today’s system.

Furthermore, as proposed above in section 4.2.4, to exclude the support functions from the hydraulic modules and power these functions with electric linear actuators instead would further increase the level of distribution, compared to the solution with four support leg units. It would then free these units from dependency, i.e. the power units would only drive and control one function and a less complex system could then be obtained.

4.3 Dimensioning & component selection material

This section presents the results of the dimensioning calculations for selecting electric motor and hydraulic gear pump. Firstly, the results from the time measurements are presented. These results originate from different measurements of the time to lower and pull up the support leg cylinders. Mast cylinder time requirements were obtained through diagrams and requirements provided by Saab EDS.

The time study was carried out only as a support for dimensioning and in order to split the total time requirements into smaller phases for each cylinder and its deployment sequence. Table 6 shows the times measured for the unloaded stroke, i.e. the stroke prior to applying ground pressure, assuming a horizontal ground and position of the radar system. The time is measured on operating one, two and all four legs both up and down. Table 7 shows the time for all four legs to lift the shelter 207 mm, thus obtaining a stroke speed in loaded condition with an already levelled shelter. Table 8 finally shows the results of how long time it takes to extract and retract the parking cylinders.

The reason to the low number of measurements was due to time and resource limitations of the first planned study, hence to use a larger number of measure points would be preferred. Although, the measurements gave some hint of what times to expect and since the aim of the study is to obtain an approximate comparison the results can be used as guidelines. Also, diagrams and an approximated figure of the flow rate was given as an information basis, e.g. 5-6 l/min to each support leg during loaded condition and about 10 l/min during unloaded stroke. Since the results from the time study indicated a number close to this, it was assumed to be good enough and further measurements was not necessary. The result was chosen to provide input in the dimensioning and to use a number with higher accuracy, i.e. based on more sample points, would not result in any major changes in the end. Furthermore, the time and availability resources was, as said, rather limited due to the fact that the study needed input to proceed and in order to keep the set planning it was necessary to move on with an approximated figure.

It is also important to note that the load in this case was from the shelter only and not the entire load, including truck, which affects the stroke speed. This was due to that the available truck had a weight outside permitted limits. The measurement although gave a comparable reference.

Instead, with respect to calculated power requirements, the power input was limited to 1.1 kW (standard motor specifications) for each leg and together with the required pressure a stroke speed and flow rate could be calculated. This was then used to obtain the speed of a maximum loaded stroke. Assuming a linear correlation between load and stroke speed, see diagram from the time measurements in appendix VI, the velocity of lifting the shelter and truck could then be approximated. Another assumption here was that the total weight of the shelter and truck was equally distributed on all four cylinders when operating in a horizontal position.

Furthermore, the limitation of power input was done due to the fact that the stroke speed during max load today takes longer time than required. The power input otherwise would have to be very large. Therefore, to then deploy the system in a slower pace during max load is accepted. Also, as the Giraffe AMB uses approximately 5.5 kW on all four legs a division results in 1.325 kW on each leg. The selection then comes to the standardized power of motors which are 1.1 kW or 1.5 kW. The goal is to use as small components as possible and as little energy as necessary, thus the 1.1 kW power input was selected with additional support of hydraulic calculations.

Table 6. Time measurements on support leg without load

Support leg without load (850mm)	Down			Up		
	1 leg	2 legs	4 legs	1 leg	2 legs	4 legs
Measurement 1 (s)	66			39,5		
Measurement 2 (s)	65			39,5		
Measurement 3 (s) (using manual lever)	66			33,2		
Measurement 4 (s)		66			58	
Measurement 5 (s)			86			55
Speed (m/s)	**0,012879**	**0,012879**	**0,009884**	**0,021519**	**0,014655**	**0,015455**
Area (m2)	0,012271	0,012271	0,012271	0,00591	0,00591	0,00591
Flow rate (l/min)	**9,48**	**9,48**	**7,28**	**7,63**	**5,20**	**5,48**

Table 7. Time measurements on support leg with load (shelter only)

Support leg with load (207mm)	Down	
	4 legs	
Measurement 1 (s)	25,9	*Note: Load = Only shelter (approx. 22,5 kN)*
Speed (m/s)	**0,007992**	
Full stroke (s)	106,3527	
Area (m2)	0,012271	
Flow rate (l/min)	**5,88**	

Table 8. Time measurements on parking cylinders; Extraction & retraction

Parking cylinder	Down			Up		
	1 leg	2 legs	4 legs	1 leg	2 legs	4 legs
Measurement 1 (s)	33			29		
Speed (m/s)	**0,011818**			**0,013448**		
Area (m2)	0,001257			0,001257		
Flow rate (l/min)	**0,89**			**1,01**		

These dimensioning stroke speeds together with the power input results in sequence times which are added and evaluated against the total time requirement. This total time requirement for the support legs altogether is set to 335 seconds, including the deployment phases: lowering support legs, unloaded stroke, loaded stroke and leveling.

During operation with both truck and shelter the total time for a full stroke of one leg cylinder is approximately 105 seconds, though the unloaded stroke is done individually and thus this partial time must be doubled. This assumes that there are two operators that control the sequence, one on each pair of legs. This calculation is also applied to the time for extracting the parking cylinder. The total time is then calculated as:

$$t_{total,SL} = 2 \cdot t_{parking\ cyl.} + 2 \cdot t_{unloaded} + t_{loaded} + t_{levelling} \quad \text{eq. 4.1}$$

$$t_{total,SL} = (2 \cdot 33) + (2 \cdot 24) + 81 + t_{levelling} = 195 + \ t_{levelling}$$

Figures are taken from the calculations in appendix VI. The time left for leveling the shelter is then 140 (335 – 129) seconds which is a highly realizable time.

The mast cylinders set out from the total time requirement of 120 seconds for raising the mast and the same requirement for lowering the mast. This time was divided into 45 seconds for the lower mast and 55 seconds for the upper mast, including time for acceleration, deceleration and sequence control by the control system. The pump capacity of today's Giraffe AMB is 42 l/min and since there are only two mast cylinders in operation at the same time the flow rate to each can be set to 21 l/min. This was the dimensioning flow rate in the calculation process, resulting in a time requirement of about 33 seconds for a full stroke.

The operation sequence of the mast cylinders does not vary as much as the support leg cylinders, thus no time measurements were required. Furthermore, the time that the system was aiming for decided the flow rate which in turn decided the required power input of the electric motor. The calculations in appendix VI imply that a 3 kW or a 4 kW electric motor is needed to be able to cope with the maximum load and flow rate of two cylinders but still have an acceptable cycle time, i.e. the normal operation requires a lot less power though the maximum load must be considered. Also, in the maximum load case the cycle time must be set to a higher value since the motor otherwise would be extensively large. In case of operating the mast cylinders with two power units, i.e. the left and right cylinders individually, would be possible with a 1.5 kW electric motor.

By using existing cycle times as the reference, no addition of times is needed in this case and the requirement will be met. It is also important to note that the calculations were carried out assuming full stroke with constant flow rate which is not the case, though the relevant issue here is the dimensioning maximum stroke speed and flow rate. For further results, see calculations in appendix VI.

With the required flow rates and the pressure, input power could be obtained. As said above, the electric motor power was limited to 1.1 kW for the support legs and 1.5 kW or 3-4 kW for the mast cylinders, depending on configuration. This resulted in longer cycle times for these cases.

When maximum load is applied to the support legs, with limited power input, the loaded stroke time will increase to 93 seconds instead of the earlier 81 seconds. In the mast case with 3 kW, the time increases to approximately 64 seconds for the lower cylinders and 97 seconds for the upper cylinders, compared to the 33 seconds for normal operation. The same apply for two 1.5 kW motors. With 4 kW these times are 48.5 and 73 seconds respectively. These increases in cycle times are summarized in table 9 below.

Table 9. Cycle time increase with set power at max loads together with total cycle time, levelling excluded

	Normal	SL – Max load	Mast - Max load	Increase	$t_{operation}$
1,1 kW (SL)	81 s	93 s		+ 12 s	207 s
3 kW (Mast)	33 s + 33 s		64s + 97s = 161 s	+ 95 s	215 s
4 kW (Mast)	33 s + 33 s		48.5s + 73s = 121.5 s	+ 55.5 s	175.5 s

4.3.1 Motor & pump selection

The required flow, pressure, hydraulic power, torque and an evaluation of the deplacement and rotational speed provided the basis for selection of electric motor and hydraulic pump. The different deplacements were here evaluated against rotational speed, see appendix VI.

In the mast cylinder case the deplacements that were evaluated varied between 18 – 32 cm^3/rev and also the deplacement 9.9 cm^3/rev. An "optimal" deplacement, based on required flow rate and nominal motor speed, was calculated. This resulted in a deplacement of 30.5 – 31 cm^3/rev for the larger variants of electric motors while the result was around 15-16 cm^3/rev for the 1.5 kW unit. This was also dependent on specified nominal speed of different motors. Although, the last mentioned deplacement resulted in a torque that was outside the limits and the existing power modules with that motor size could only provide pumps with 9.9 cm^3/rev deplacement, thus that was selected for evaluation.

The different deplacements were analyzed against the operation phases: working load and max load with set power. Also max load and operation with accumulator was evaluated though outside of the main scope. The deplacements were also analyzed against the power inputs: 1.5, 2.2, 3 and 4 kW.

By setting the required flow rate and a fixed deplacement, the rotational speed required could be calculated for the working load phase. Furthermore, the set power and the pressure provided a required flow rate for the maximum load where the rotational speed then could be obtained according to previous example. The calculations can be studied in detail in appendix VI, though an example is presented in table 10 below.

Table 10. Example of calculated selection material for motor and pump

4kW; D = 28 cm^3/rev				
	Working load		Max load (Set power (P))	
	Lower cylinders	Upper cylinders	Lower cylinder	Upper cylinder
F (N)	15500	21500	60000	90000
p (bar)	19,736	27,375	76,397	114,595
n (rpm)	1563,909774	1503,759398	1062,913534	708,6090226
Q (l/min)	41,60	40,00	28,27	18,85
D (cm3/rev)	28,000	28,000	28,000	28,000
P (kW)	1,520	2,028	4,000	4,000
M (Nm)	9,249	12,829	35,802	53,703
t (s)	33,01	34,33	48,57	72,85

The example shows that with a 4 kW electric motor and a pump deplacement of 28 cm^3/rev, the rotational speed will vary from about 700 rpm and up. This is then evaluated against specified minimum rpm of motor and pump so that it does not exceed the supplier's limits.

Also, the torque is calculated and evaluated against electric motor specifications. The electric motor characteristics are such that it has a torque that varies with rotational speed. The power of the motor decides its rated torque, though its limits are higher. The different measures are called starting torque, saddle torque and breakdown torque and are specified by the motor supplier as, e.g. these are gained from a specified factor multiplied with the specified rated torque. These torques occur at different speeds, thus creating a torque curve and focus when selecting electric motor is then to stay below this curve. One should also consider that the motor can only cope with torques close to its characteristic curve for a shorter period of time, e.g. 30 seconds.

This was evaluated and examples of such curves are presented in figures 24-26.

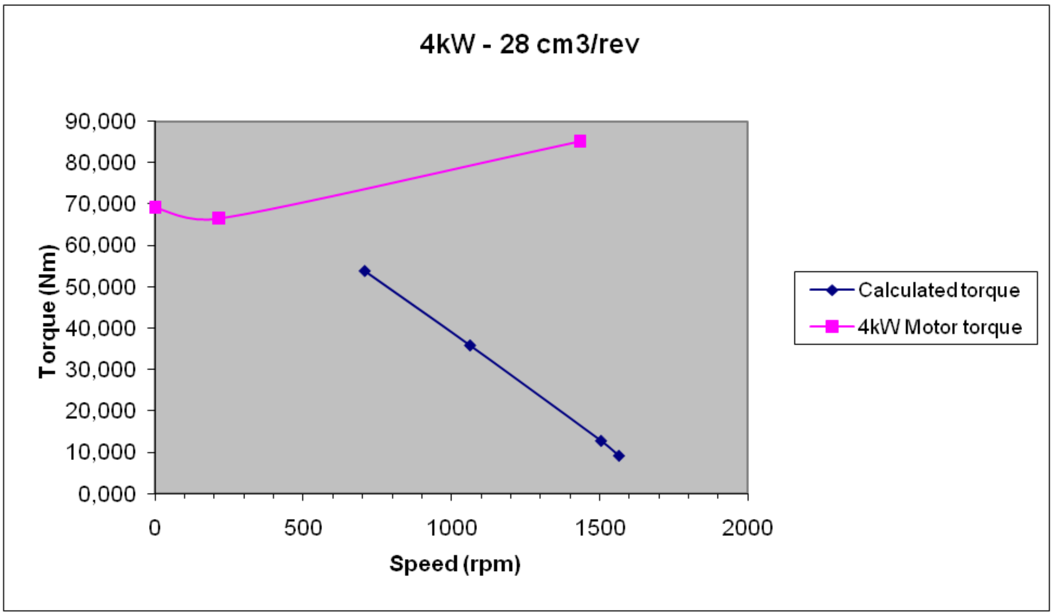

Figure 24. Example of torque curve with a 4 kW motor and a 28 cm3/rev deplacement pump, calculated torque is the required torque at different rpm and the upper line illustrates the motor characteristics.

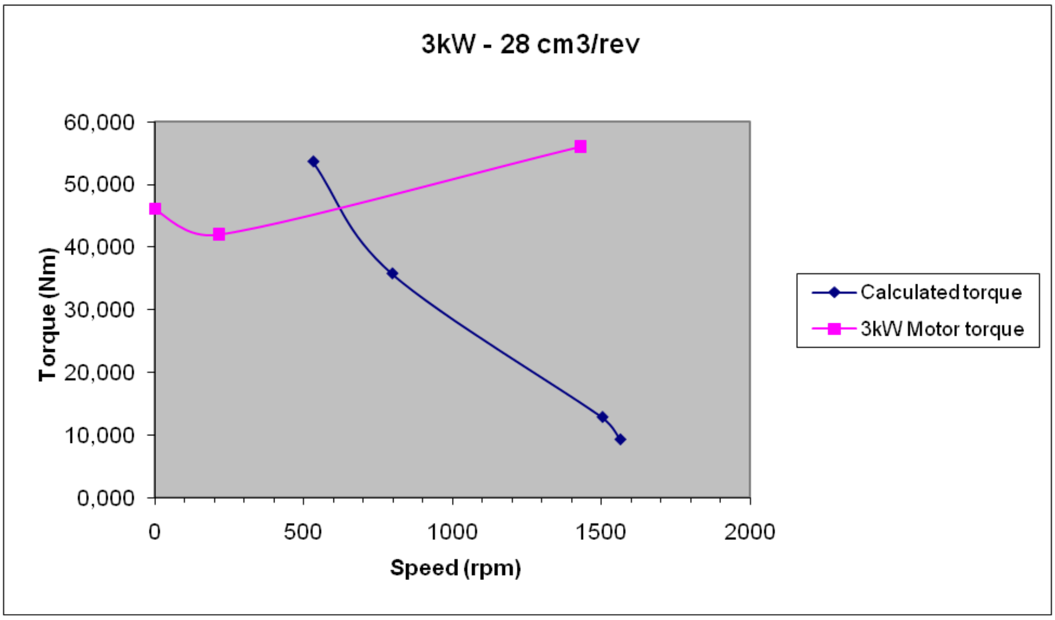

Figure 25. Example of a not acceptable torque curve with a 3 kW motor and a 28 cm3/rev deplacement pump

As the example shows, the torque with a 4 kW motor and a deplacement of 28 cm^3/rev is ok while a 3 kW motor will not cope with the torque. Additional diagrams are found in appendix VI.

The same procedure was carried out for the support legs and an example of motor torque curve is also presented below with the rated torque inserted.

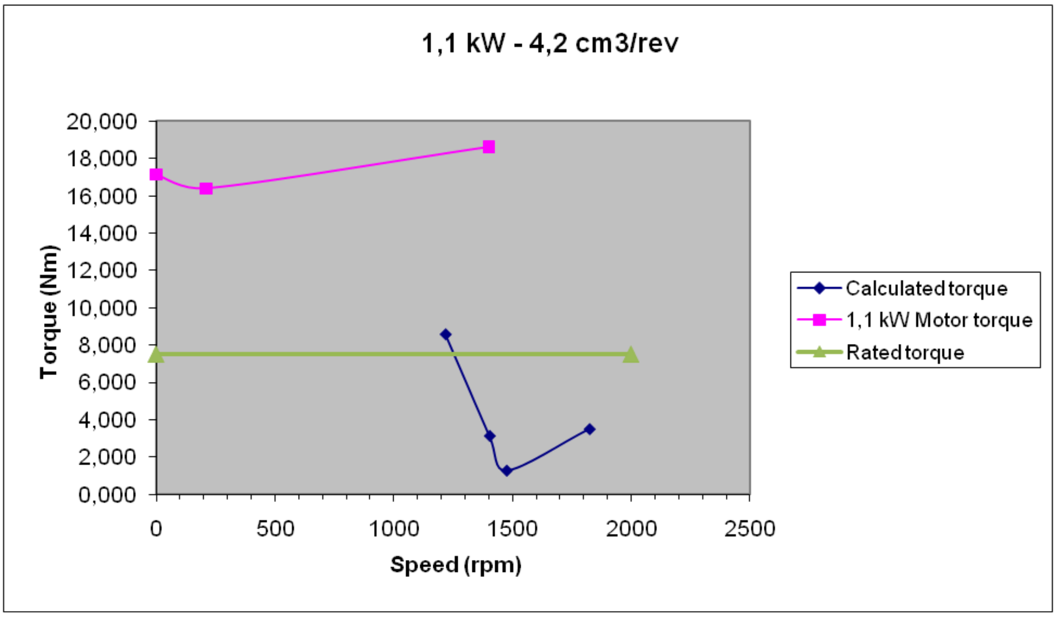

Figure 26. Example of a torque curve with a 1.1 kW motor and 4.2 cm3/rev deplacement pump, including rated torque of the motor

The deplacements that were evaluated for the support leg hydraulic pumps were within 3.2 – 4.8 cm^3/rev and with a power input of 1.1 or 1.5 kW. A summary of possible electric motors and hydraulic pumps are given in appendix VI, after the calculations.

From evaluation, the recommended selections are a 1.1 kW motor with a 3.75 cm^3/rev or 4.2 cm^3/rev hydraulic gear pump for the support leg unit and either a 3 or a 4 kW motor with a 20 - 22.5 cm^3/rev or 28 cm^3/rev hydraulic gear pump respectively for the single mast unit. Double mast units are recommended to use a 1.5 kW motor and a 9.9 cm^3/rev pump. More data can be found in appendix VI.

4.3.2 Accumulator

Accumulators have already from the beginning been interesting components. The idea was to use them to reduce the power requirements of the functions, i.e. to cover the momentary peaks so that the power units can be minimized. It was also an idea for backup operation. At first it seemed like a good alternative with lots of potential, though after some consulting from Håkan Karlsson at PMC Hydraulics it was further evaluated. According to Karlsson, unreasonably large accumulators are necessary to be able to handle the variations in operating temperature with the required forces.

To calculate how much the temperature affects the sizing of the accumulator the software Hydac ASP v.4.31 was used. The first test was to simulate an operation where the accumulator is used to reduce the requirements for the power packs. The simulated case covered the worst case scenario, with max wind in negative GAMB direction, i.e. from behind, based on results of a Saab EDS structural analysis report (Lindahl, 2009)

Figure 27 below presents an example of simulation input. The simulation is based on the decision that the accumulator is activated when the load rises above 50 kN.

- The maximum force was read from charts and the piston area originates from the existing cylinders. These values where then used to calculate the maximum and minimum pressure according to equation 1 in the formulary.
- Maximum and minimum operating temperature comes from the requirements specification, see appendix I.
- The differential volume is the necessary volume of oil that is needed to raise the mast when the loads are over 50kN. When the loads are below 50kN the power pack is used to raise the mast.

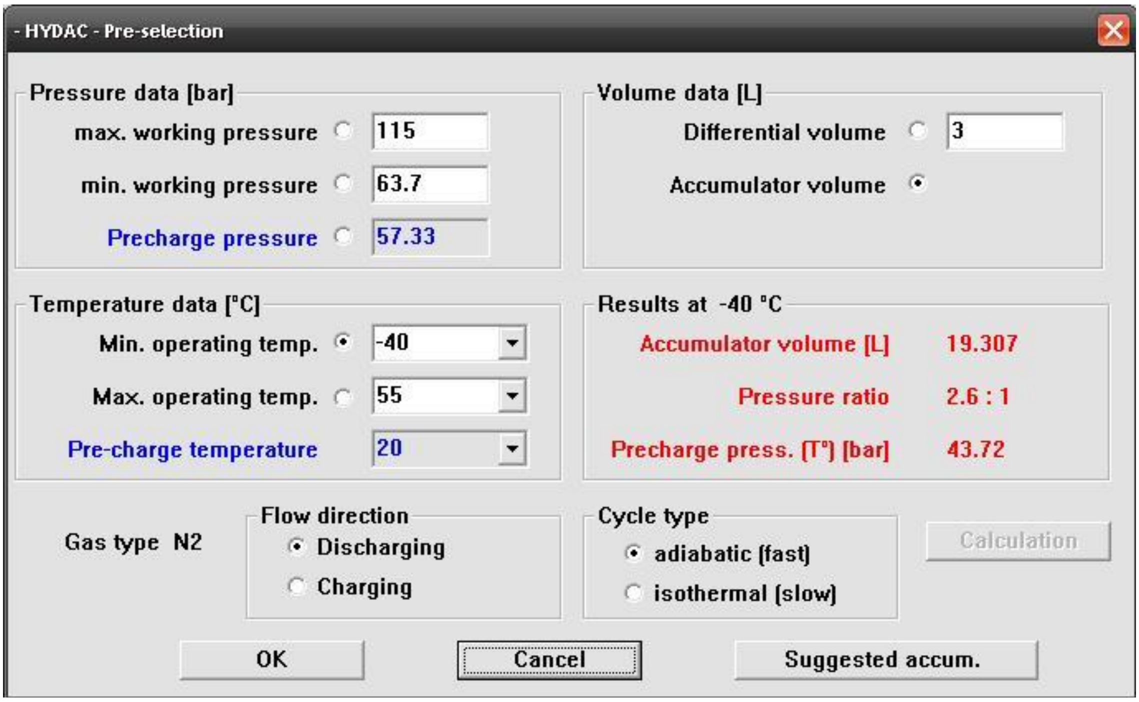

Figure 27. Example of accumulator simulation where required accumulator volume is calculated.

The simulation shows that an accumulator volume of 19.3 litres is necessary. To investigate the influence of the temperature an operation cycle is simulated. From the same charts as the forces originates from comes also the operation time. The operation time is the time where the accumulator operates instead of the power pack. This value was estimated to 30 seconds.

Figure 28 shows the differences in volume with a specific pressure for both maximum and minimum temperature. The chart shows that large variations in volume occur because of variations in temperature. As also can be seen is that the difference in volume, impacted by temperature, in this case is around four litres.

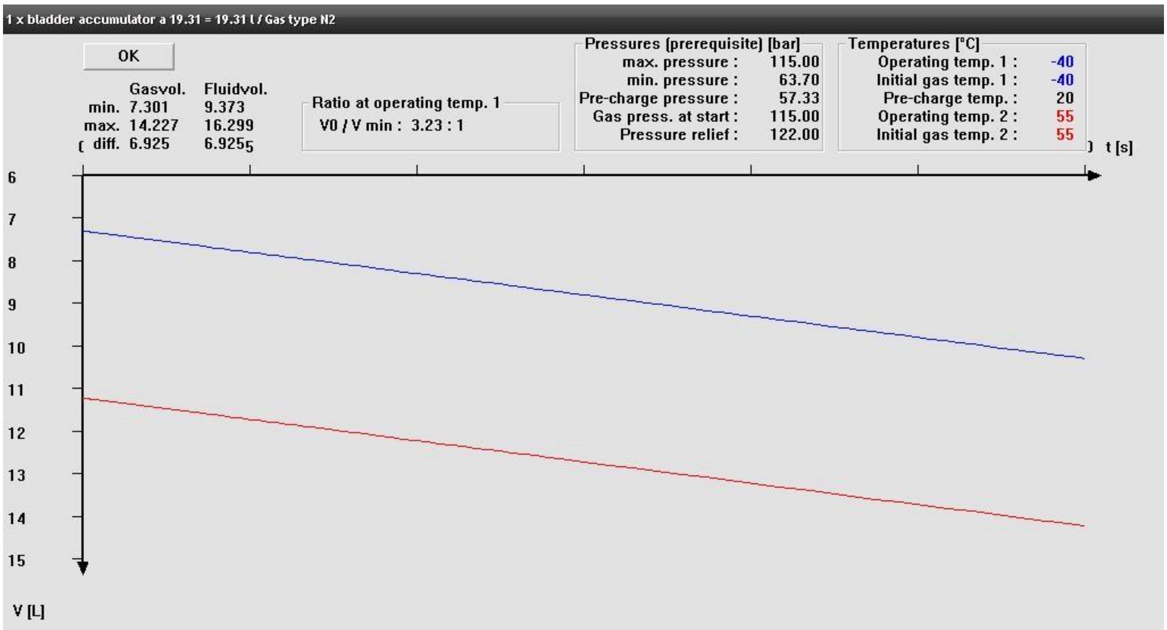

Figure 28. Result of temperature impact of accumulator volume from simulation

The test was also made with a constant temperature of 20 °C which gives an accumulator volume of 13.4 litres. This shows that if the accumulator would be designed for indoor use the size would be reduced by almost six litres at the same values of pressure and volume, thus even without the temperature influence rather large volumes would be necessary, see figure 29.

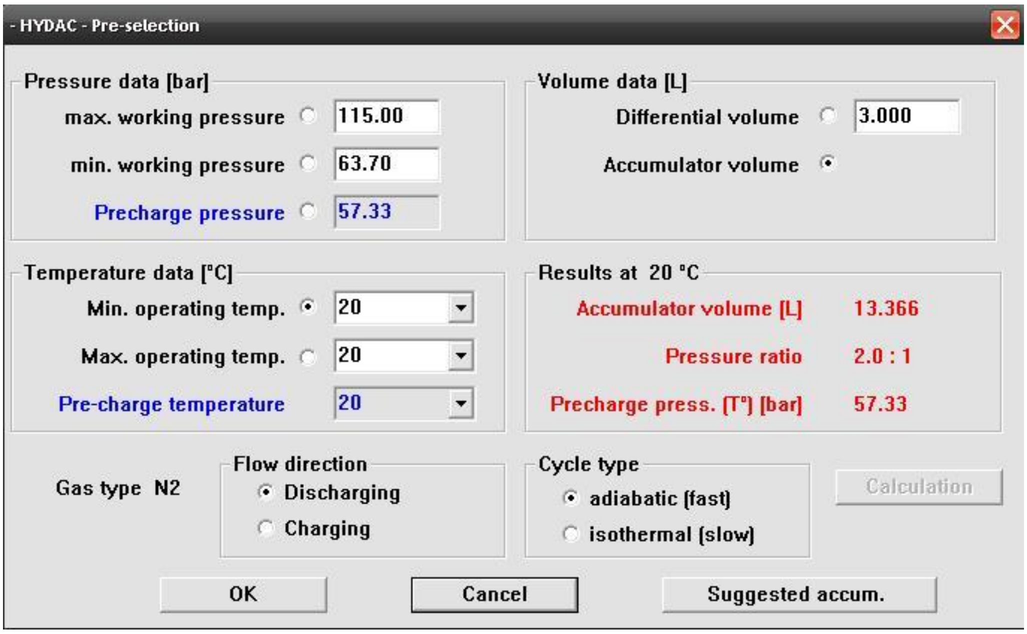

Figure 29. Result of accumulator volume simulation with constant temperature.

In the case of using accumulators for the support leg operation, the available space is relatively limited. With the simulations and expert recommendations in mind the decision was taken to not develop the idea further.

4.4 Proposed solutions

The section presents the two different concept proposals called *PowerPack* and *EHC* which are realizable examples of distributed hydraulic systems, though in different levels of distribution. These are firstly thoroughly described and then evaluated. Advantages as well as potential drawbacks of each are furthermore raised to provide a solid base for understanding their potential, possibilities and difficulties.

4.4.1 Concept PowerPack

With the first concept the main idea is to provide a solution that are flexible, compact and increases the availability of the hydraulics. The aim was to basically use the existing structures as much as possible but split up the power unit into distributed modules that drives a smaller number of functions, i.e. the hydraulic power units will be positioned closer to the actuators than in the reference. It is a concept with the goal of suiting the existing Giraffe AMB. Below in figure 30 a generalization of the hydraulic configuration is illustrated with a basic hydraulic circuit.

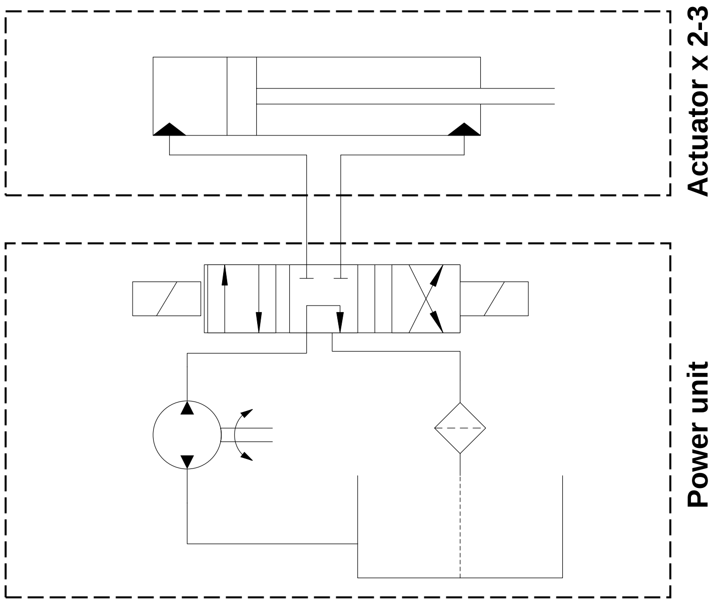

Figure 30. Generalization of the PowerPack configuration with a separate modular unit divided from the actuator.

To actualize this, power packs are used which are small hydraulic units including all necessary components but in a compact module that can be positioned in conjunction with the actuators, see section 4.5. This concept consists of four power packs placed at each support leg, driving both the parking cylinder and the support leg cylinder; hence it includes two directional valves. The mast however uses two slightly bigger versions of the hydraulic power pack. The mast power packs will drive two mast cylinders, one power unit for each side, and also one mast lock cylinder. Furthermore, the existing reference cylinders are used. An option is here to utilize a bigger single unit that powers all mast cylinders, though this solution is only a proposal and is not evaluated against cost and weight.

Each power pack works in a similar way as today's system, though components do differ some. In every unit a hydraulic gear pump, electric motor, valves and reservoir is

included together with a temperature sensor and a pressure transducer. Although, a frequency converter is added, as a standalone unit not included in the power pack offer, which controls the speed of the AC motor to adjust the flow rate.
To control the system the same configuration as in the existing system is used but the concept has the possibility of using a CAN bus interface though the costs will then increase. The support leg will be equipped with a pressure transducer that indicates ground pressure. The cylinders also have position sensors that prevent manoeuvring in transport mode. Regarding the mast operation rotary sensors shall be installed in the joint for both upper and lower mast, those sensors shall indicate position. Both upper and lower mast cylinders shall have position sensors that indicate faulty movements.

Furthermore, the mast transport lock cylinder shall have position sensors that indicate locking position and fully extracted position. Operation of mast requires a clearance from position sensors at lock cylinders prior to operation. In summary, all sensors and transducers are transferred from the reference solution since no redesign is made. Finally, if CAN bus interface shall be implemented, the sensors need to be CAN compliant.

The backup system of a distributed hydraulic system is a troubling issue. An extra pump and motor for each power pack would increase the number of components, the weight and the space requirements greatly, thus an alternative is needed. A backup system is required but there are though few or no optimal standard solutions that fit this application, hence the configuration needs detailed development work that does not fit into the scope of this study. There are some alternatives to solving this issue, presented in section 4.1.10.

Concept PowerPack uses a portable pump unit, as a main alternative, that could be plugged in through fast tube couplings and electric connections. These can be configured in many different ways and in this case a 1.5 kW power unit, the same as for the mast cylinders, is preferred to be used for both support legs and mast. The portable power unit can then be placed and fastened on, e.g. a folding table from the shelter wall next to the leg compartment, and finally connected to the control system and the cylinder. It shall be driven by the power DC supply in the truck.

Since the control system already is configured for similar power units it should be rather easy to operate the emergency unit. The unit could furthermore be stored in the previous power unit compartment.

The concept is a realizable solution though there are both positive aspects as well as drawbacks. Below are a short summary of advantages and disadvantages of concept 1.

Advantages

- Higher degree of distribution..
- All power packs are optimized to its function.
- Lower energy consumption during operation.
- Decreased amount of piping.

Disadvantages

- Hydraulic hoses are still necessary to some extent.
- More complex backup system for emergency operation, no extra pump.
- Many components.
- More space demanding.
- Design modifications needed.

To be able to estimate price, weight and performance some components have been recommended. The following components could be used in this concept but there are also many other possible components with similar properties available.

Table 11. List of proposed components/power modules

Quantity	Component	Supplier
4-6	Power module (SL) – CA / KE series	Hydac / Bosch Rexroth
1 / 2	Power module (mast) – x / KE	Bosch Rexroth
1 / 1 / 4	KE unit / EH pump (EHP) / Hand pump (PMC12)	Bosch Rexroth

On next page a summary of the concept's configuration is presented.

Figure 31. General illustration of a modular power pack

Function/Characteristic	Concept "PowerPack"	
General		
Hydraulic circuit	Open - Open center	
Hydraulic module distribution	6 units	
Hydraulic control system		
Function: Control components	Existing	Option: CANbus
Operation controls		
Function: Operate system	Panel	Option: Remote control
Function: Operate manually	Levers	
Function: Emergency operation (SL)	Portable pump unit	Option: El. hand pump
Function: Emergency operation (mast)	Portable pump unit	Option: El. hand pump
Power unit	CA / KE series	Option: Single components (mast)
Function: Pressurize hydraulic fluid	Power pack	Option: EH Pump
Function: Pump hydraulic fluid	Pump only	
Pump type	External gear	
Deplacement (SL)	Fixed - 3.75 - 4.2 cm^3/rev	(Recommendation)
Deplacement (mast)	Fixed - 20 - 22.5 cm^3/rev	(Recommendation)
Function: Convert electrical power (SL)	3 x 230/400 V AC motor - 1.1 kW	
Function: Convert electrical power (mast)	3 x 230/400 V AC motor - 1.5 kW	Option: 4 kW; Bosch Rexroth ZL
Function: Powering pump device	Varying torque & speed	(Standalone freq. converter)
Hydraulic actuator		
Cylinder principle	Double acting	
Cylinder type	Welded	
Function: Actuate mast	Standard	
Function: Actuate radar system	Standard	
Lock & Positioning device		
Function: Lock mast	Hydraulic cylinder	
Function: Position support legs	Hydraulic cylinder	

Reservoir

Store hydraulic fluid (SL module)	Open reservoir - approx. 6-7 l	Option: Use extension cylinder
Store hydraulic fluid (mast module)	Open reservoir - approx. 13 l	

Valves

Function: Hold load	Load-holding valve	Option: EH valve
Function: Direct fluid	Proportional directional valves	Option: EH valve
Function: Control flow	Flow control valve	Option: EH valve
Function: Releve pressure	Pressure relief valve	Option: EH valve

Pipes & Hoses

Transport fluid	Hoses

Sensors

Measure oil temperature	Electronic temperature sensor	
Measure pressure	Pressure transducer	
Measure oil level	TBD	Option: Visually on reservoir
Measure position	Position transducer	

4.4.2 Concept EHC

With the second concept, distribution is in total focus. Each hydraulic function has its own power unit included directly on the actuator. Figure 32 provides a generalized illustration of the hydraulic circuit with the main components, though more valves and sensors is included in the actual hydraulic circuit.

This is a very simple, flexible and compact solution. The concept consists of electro-hydraulic cylinders (EHC) that replace all existing cylinders. An option could be to replace the parking cylinders and mast lock cylinders with electric linear actuators that uses a 3-phase 230/400 V AC power supply. Electric linear actuators could be used due to limit the space requirements. The cost of the linear actuators is similar to the respective electro-hydraulic cylinder though they are more compact which makes them suitable for this application. A major downside is however their weight and the backup alternatives if components fail.

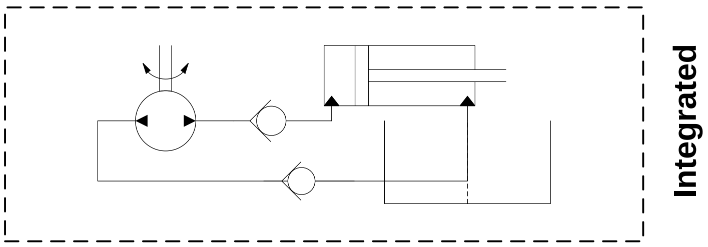

Figure 32. Generalization of the integrated EHC hydraulic circuit with basic components.

The EHC is independent from a hydraulic perspective and is only connected to other functions through the control system. An electro-hydraulic cylinder contains all the necessary parts in a hydraulic system and the system is like a normal hydraulic cylinder in appearance only that it is quadratic and has a motor and pump attached on the top. The reservoir encloses the cylinder body as a shell, thus giving the quadratic shape.

The motion shall be controlled with a variable frequency drive that changes the speed of the electric motor. The control system have the possibility of using either the existing control interface or a CAN bus interface where each unit easily can be connected to the control system. To be able to determine the speed of the electric motor the control system shall receive position and pressure signals in the same way as today. This input shall also help to position all the cylinders simultaneously together with the information from the inclinometer. The electro-hydraulic cylinders shall thus be equipped with the same sensors as the reference and first concept. There is no reason to change this when all the necessary information will be provided to control the system.

Regarding sensors for position, pressure, temperature etc the configuration in this concept is the same as for previous proposal and the reference, see section 4.3.1.

Electro-hydraulic cylinders are very simple hydraulic systems with few components, few connections and they can be configured to be compliant with a variable frequency drive, thus flow can be regulated by the varying speed of the electric motor (as in concept PowerPack).

To lock the cylinder under pressure a solenoid valve is used, which in this case means that the solenoid valve closes when the hydraulic oil in the plus chamber is under pressure (Börjesson, 2011).

The weight of one EHC is approximately 50% higher than one regular standard cylinder, according to Kent Börjesson Teknik AB. This assumption has been applied to the reference cylinders for comparison, with an assumed value of the extension cylinders excluded, since no other exact data can be provided at the moment. The increasing weight is because of an extra cylinder reservoir, larger back-piece and the hydraulic unit on the cylinder. This will result in a total weight somewhere around 1655 kg which is about 215 kg more than the reference weight.

In case of machine failure it is necessary to have a backup system. The backup system in this concept consists of both an AC/DC converter and a portable drive unit. The converter is used so that the system can be powered if the main power supply fails. The additional portable drive unit, or a kind of “drilling machine”, can be connected directly to the electric motor axis to power the system if the motor breaks. This axis is present at the back of the electric motor, i.e. it is on the opposite side to the main drive shaft. This is though not possible for the mast cylinders since it would not be geometrically compliant and also very unsafe for the operator to lower the mast in that way. Furthermore, it would be possible to use a hand pump connected either directly on the cylinder or with fast couplings. Below are some advantages and disadvantages presented for the described solution.

Advantages

- High degree of distribution.
- No hydraulic pipes or hoses, this decreases the risk for leakage drastically.
- Lower energy consumption during operation.
- Easier to replace functions.
- Simple installation.
- Compact solution.

Disadvantages

- Design modifications needed.
- More complex backup system for emergency operation, no extra pump.
- Higher weight.

To be able to estimate price, weight and performance some components have been recommended. The following components could be used in this solution:

Table 12. List of proposed components/power modules

Quantity	Component	Supplier
4	Electro hydraulic cylinder - Support leg	Kent Börjesson Teknik AB
4	Electro hydraulic cylinder - Mast	Kent Börjesson Teknik AB
4	Electro hydraulic cylinder - Parking	Kent Börjesson Teknik AB
2	Electro hydraulic cylinder – Mast lock	Kent Börjesson Teknik AB
(2)	Electric linear actuator - Parking	Mekanex AB
(2)	Electric linear actuator - Mast lock	Mekanex AB
1	Emergency unit	-

On next page a summary of the concept’s configuration is presented.

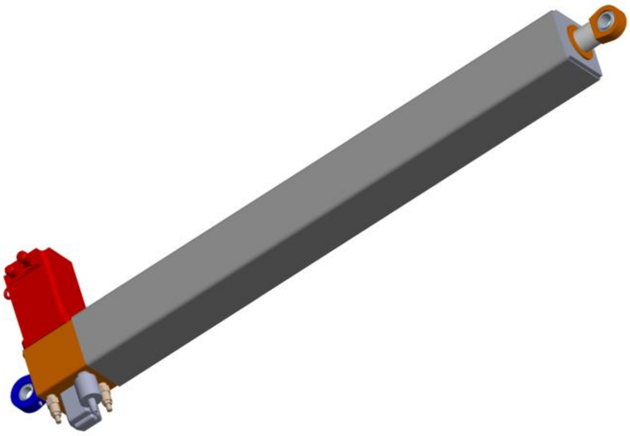

Figure 33. Illustration of an electro-hydraulic cylinder from Kent Börjesson Teknik AB

Function/Characteristic	Concept "EHC"	
General		
Hydraulic circuit	Open - Open center	
Hydraulic module distribution	14 units	
Hydraulic control system		
Function: Control components	Existing	
Operation controls		
Function: Operate system	Panel	
Function: Operate manually	Electr. switch/regulator	
Function: Emergency operation (mast)	Electric AC/DC converter	
	Portable drive unit on motor shaft	Option: Hand pump w. fast couplings
Function: Emergency operation (SL)	Electric AC/DC converter	(Few other alternatives)
	Portable drive unit on motor shaft	Option: Hand pump w. fast couplings
Power unit		
Function: Pressurize hydraulic fluid	"Electro-Hydraulic Cylinder"	
Function: Pump hydraulic fluid	Pump only	
Pump type	Bi-directional gear pump	(Hydraulic gear motor)
Deplacement (SL)	Fixed	
Deplacement (mast)	Fixed	
Function: Convert electrical power (SL)	3 x 230/400 V AC motor - 3 kW*	*(Specified by supplier, assumption)
Function: Convert electrical power (mast)	3 x 230/400 V AC motor - 7.5 kW*	*(Specified by supplier, assumption)
Function: Powering pump device	Varying torque & speed	(Standalone freq. converter)
Hydraulic actuator		
Cylinder principle	Double acting	
Cylinder type	Welded	
Function: Actuate mast	"Electro-Hydraulic Cylinder"	
Function: Actuate radar system	"Electro-Hydraulic Cylinder"	
Lock & Positioning device		
Function: Lock mast	"Electro-Hydraulic Cylinder" - 350W	Option: Linear actuator
Function: Position support legs	"Electro-Hydraulic Cylinder" - 350W	Option: Linear actuator

Reservoir

Store hydraulic fluid (SL module)	Open reservoir - approx. 6 l/cyl.	(Cover around cylinder body)
Store hydraulic fluid (mast module)	Open reservoir - approx. 5 l/cyl.	
Store hydraulic fluid (lock module)	Open reservoir - approx. 0.3 l/cyl.	
Store hydraulic fluid (position module)	Open reservoir - approx. 2 l/cyl.	

Valves

Function: Hold load	Solenoid valve	(Magnetic lock)
Function: Direct fluid	None	
Function: Control flow	None	
Function: Releve pressure	Pressure relief valve	

Pipes & Hoses

Transport fluid	None

Sensors

Measure oil temperature	Electronic temperature sensor	
Measure pressure	Pressure transducer	
Measure oil level	TBD	Option: Visually on cylinder
Measure position	Position transducer	

4.5 Verification of capability study

This section aims at evaluating a distributed hydraulic system and the two concepts, PowerPack and EHC, as the result of this study. It includes the conclusions from the risk assessment and the studies of the aspects modularity, reliability, maintenance/service, energy efficiency, costs, weight and positioning. Finally the fulfilment of requirements is verified.

4.5.1 Risk analysis

The results gained from the risk analysis provide a sound basis for what priorities that should be made when designing the system. The study has focused on both operator safety risks and system reliability risks for a general hydraulic system applied to the Giraffe AMB and the result is presented in this section.

4.5.1.1 Operator safety

From the FMEA one can conclude that the most critical risks that need to be considered are mainly maintenance and service related where injuries could occur if the proper equipment or safety gear is not available. Also proper maintenance protocols needs to be present and followed thoroughly to avoid these kinds of risks. Furthermore, many medium size risks, according to the FMEA RPN-list, are related to working or operating close to the actuators. These are also risks that must be considered when further developing the hydraulic system and is closely linked to the control system and how the system is operated. An example could be to operate the hydraulics by using a remote operator panel which moves the operator out from the risk zone and at the same time provides a wider overview of the operation. Moreover, proper signs and markings are necessary to avoid injuries and thorough training is a prerequisite.

Working close to sharp edges and hot equipment is also aspects that needs consideration, thus the design should strive for smooth and rounded edges and corners and hot equipment, which is assumed to be relatively non-existing due to the intermittent operating cycles, should be enclosed, protected or marked with warning signs.

More thorough results are presented in appendix III. The risks are numbered in order to keep traceability.

4.5.1.2 System reliability

From the FMEA performed on system reliability one can conclude that components that can withstand environmental effects play a vital role in obtaining a robust and reliable system. Temperature variations are especially important since the hydraulic system is sensitive to these changes. To strive for components and a hydraulic oil that can operate in a large temperature span is necessary, otherwise some modifications and surface treatments are needed. Also, components needs to be enclosed or protected and not be placed in a sensitive and exposed position, thus enclosure of external components on the EHC must be considered.

Furthermore, coupling and cable breakage due to mechanical and environmental wear are important to consider since these are the links between the system components. They are often put in exposed positions or wrongly mounted, creating tensions and unwanted loads on sensitive areas, which contributes to a breakage. The best would be to eliminate hoses as much as possible which also is one of the distributed system's main advantages. Together with compact power modules, including manifolds and close interfaces, the amount of hoses, pipes and couplings can be minimized. In cases where these are necessary it is important to mount correctly and to avoid exposed positions. Also, to position these components in places with intense movements are not to recommend. This is though assumed to be avoided with the existing structures. The only uncertain variable is the position of the power pack.

One must also consider built in system mechanisms when designing the hydraulic system. These phenomena are naturally occurring but can be minimized or almost avoided by using quality components and dimension the system based on these disturbances. Since this application does not operate in intense working cycles, many of these issues do not have the same effect though they need to be considered nonetheless.

More thorough results are presented in appendix III. The risks are numbered in order to keep traceability.

The VMEA preformed on system reliability shows approximately the same results where variations in environmental effects and variations in measuring and maintaining the system influence the total reliability. One can see from the ranking of sub-KPC's that milieu, maintenance, mechanisms and measurements issues are the main aspects to focus on when it comes to system reliability.

Table 13. Ranking of Sub-KPC from risk assessment using the VMEA method

	Sub-KPC	%	ΣVRPN
Ranked Sub-KPC's	Milleu	28,8	**158099**
	Maintenance	28	**153664**
	Mechanicms	14,2	**78278**
	Measurements	14,2	**78048**
	Machine	11,8	**65044**
	Man	2,99	**16444**
		Σ	**549576**

These results are presented in appendix III, where also more detailed results can be found.

4.5.2 Modularity

While the reference model utilizes one power unit to drive 14 hydraulic functions the level of distribution, in this case calculated as the number of drives divided by the number of hydraulic functions, is as low as possible for this specific application (7%). The concept proposals however utilizes several drive units to power these functions, thus the level of distribution is higher which also the aim of the study was.

Furthermore, the centralized hydraulic system of the reference solution has a large amount of dependencies among the different functions and is in general a very complex system to control. A distributed hydraulic system however only has dependencies among the drive units through the control system in order to carry out the main functions properly but the component structures are much simpler, e.g. each power unit is only dependent of the conditions of one or a few functions and the physical dependencies are fewer with eliminated piping etc.

4.5.2.1 Concept PowerPack

This concept can be said to be a compromise of a fully centralized hydraulic system and a fully distributed hydraulic system, i.e. a semi-distributed hydraulic system. It utilizes six power units to drive all hydraulic functions, distributed on each support leg and two up at the mast. The level of distribution then increases to about 43%, hence the modularity can be said to increase. Also, a lot of the physical dependencies are eliminated. The support leg power unit is still dependent of both the leg and parking cylinder and each mast power unit is dependent of two mast cylinders together with one mast lock cylinder. However, to use these power pack solutions for each hydraulic cylinder would not be reasonable from a weight and space requirement perspective.

The power units in this case are modular all-in-one solutions and each unit is optimized to a few dedicated functions, although the actuator and the power module are divided and not integrated which would further increase modularity. Furthermore, the solutions allows for less piping and shorter installation time.

The conclusion here is that the concept has a higher modularity than the reference based on these mentioned reasons together with the fact that the interfaces of the drive units are standardized and modular, though in the sense of distribution it is not optimized but a realizable compromise.

4.5.2.2 Concept EHC

This concept proposal can be said to be fully distributed in the sense of measuring the distribution level as above. It utilizes 14 drive modules, integrated on each cylinder, to power 14 hydraulic functions, thus the level of distribution is 100%. It is perhaps the most interesting concept to compare the reference with since they are the two extremes of centralized and distributed hydraulic systems respectively.

The modularity of this concept is clearly higher due to the all-in-one package out on each function, i.e. it is one single unit with only the electrical connections as external interface. Each unit is independent of one another, apart from the communication needed for proper simultaneous operation. It is a simple solution that eases installation, maintenance and the possibilities to replace functions, i.e. it is one unit to install and maintain instead of many separate components.

4.5.3 Reliability

From a reliability perspective distributed hydraulic systems, compared to the reference, have both advantages and disadvantages. As seen in the risk analysis one of the criteria that affect the reliability is pipes and hoses. The reference has approximately 27.5 meter of hoses and 65 meter of pipes installed, i.e. 92.5 meter feed lines in total (approx. from part list and CAD drawing), see figure 33. This number can be heavily reduced, especially with the EHC module that have no external pipes or hoses at all.

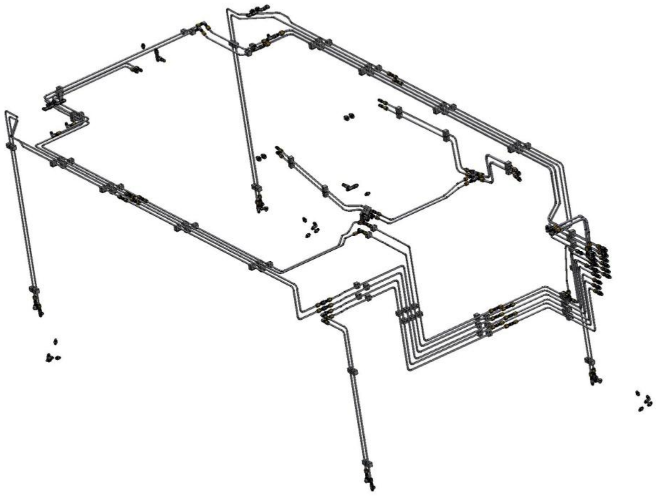

Figure 34. Giraffe AMB's extensive piping that can be eliminated.

One of the disadvantages with a distributed hydraulic system is the weaker emergency operation system. The reference uses a complete extra backup system with pump and motor powered by the truck. Both concepts can be delivered with a hand pump installed. It is also possible to have an external pump unit with fast couplings in an emergency situation. The drawback with this is that every unit is controlled and powered independent of the other hydraulic units. In case of power supply failure this requires more manpower than the reference and the operators will be the control system. This increases the risk for human errors. An AC/DC converter that switches power supply could be an alternative to this but has not been evaluated in detail.

With a distributed hydraulic system comes an increasing amount of components. Each hydraulic function has its own hydraulic unit with pump, motor, reservoir, piping and valves. Considering the increased number of components there is an increasing risk of failure with many parts and the collaboration between them.

An advantage with distribution through a reliability perspective is the availability of the system. Many components will be more available and easier to reach in case of failure. This especially applies for pipes and valves. It will contribute to fast and easy maintenance and service and through that increase the availability of the radar system. With efficient maintenance and service, the radar system can return to operation mode faster.

4.5.3.1 Concept PowerPack

The power pack concept will have approximately the same amount of hoses but no pipes in the shelter. Each power pack could be connected through hoses in conjunction with the hydraulic function. This would mean that only around 30 % of all feed lines in the reference architecture will be necessary. Reduced piping means reduced couplings which together leads to decreasing risk for leakage and failure.

Concept PowerPack has a reduction of feed lines of approximately 70 %..

4.5.3.2 Concept EHC

Concept EHC will reduce these circuits with 100 % which in turn can provide a measure of the decreased risk of leakage since these factors are in relation to each other.

4.5.4 Maintainability & Serviceability

Both concepts allows for better accessibility and flexibility in the sense of replacing units due to failure. This is because of their increased modularity and decreased physical dependencies but also due to the distribution of the power units. One can also easily recognize where a failure occurs. Furthermore, if CAN bus is utilized the technology allows for easy and detailed diagnostics of failures which makes the service less complex.

4.5.4.1 Concept PowerPack

To perform maintenance depends on the position of different components and their accessibility to the operator. Concept PowerPack requires the power unit to be placed in positions that are relatively troublesome to reach if no redesign is made or if the power units are not allowed to be positioned outside the leg compartment. The case of redesign has not been evaluated enough though; hence it is possible that maintenance in this sense could be easier.

The decreased amount of feed lines also implies eased maintenance since less time and efforts are needed on these sensitive components.

4.5.4.2 Concept EHC

The concept proposal EHC however has almost everything integrated and the components that are most sensitive in this case is, e.g. the electric motor and sensors which are easily accessible directly on the cylinder.

The eliminated feed lines imply even easier maintenance than concept PowerPack though the amount of electrical wiring could instead pose a risk. This is however assumed to not be a larger issue than today since the electrical wiring already exists to some extent out to each cylinder.

4.5.5 Energy efficiency

Since each unit is less dependent and optimized for its dedicated functions, the energy efficiency increases. Also, since the electric motor is controlled by frequency, providing only the power needed at the specific time, the energy use will decrease greatly. Today the power is almost fixed on the electric motor, only small variations occur, hence the power provided is often more than required which results in wasted energy.

If measuring energy savings from the maximum power that the system uses during its operation, the concepts will use less energy. Today the electric motor is specified to 5.5 kW and the corresponding active power from the diesel power supply is 7.2 kW which is constantly delivered.

4.5.5.1 Concept PowerPack

Concept PowerPack only uses up to 5.5 kW from the power supply simultaneously during maximum loads on all four support leg cylinders together, which rarely or never occurs, and this corresponds to an energy saving of about 24 %. It is though important to have in mind that the energy savings during normal operation and less loading are even larger. The energy savings during extraction are illustrated in table 14 below. A full summary is found in appendix VI.

4.5.5.2 Concept EHC

Concept EHC has a specified maximum power of 7.5 kW which is more than the reference, though this amount of power is not really necessary according to the calculations. The specified power of the electric motors in this case are only rough estimations by the supplier based on insufficient data, thus a comparison with this concept would not provide a fair result. The same specifications as concept PowerPack will apply here.

4.5.5.3 Summary

The energy savings are both calculated for the largest, simultaneously operating, electric motor capacity and for the largest dimensioned power requirement during different operation phases. These data are shown below.

Table 14. Summary of energy savings when operating with a frequency controlled motor

Support leg cylinders	**Stroke 850 (Normal op.)**	**Stroke 850 (Max load)**	**Stroke 850 (Shelter only)**	**Stroke 850 (Max load) Set power**
Mast cyilnders	**Stroke 1457 Mean load**	**Stroke 1457 Max load**	**Stroke 1457 Mean load**	**Stroke 1457 Max (set power)**
Power cons. savings (%) (By largest, simultaneously operated, motor capacity)	**20,00**	**x**	**20,00**	**20,00**
Power cons. savings (%) (By largest P during normal op.)				
Unloaded SL stroke	**55,67**	**55,67**	**55,67**	**x**
Loaded SL stroke	**67,72**	**11,97**	**86,13**	**23,61**
Upper mast stroke	**63,38**	**-53,31**	**63,38**	**30,56**
Lower mast stroke	**73,61**	**-2,20**	**73,61**	**30,56**

As can be read from table 14 the potential energy savings are very beneficial. The only case where more energy is needed is when the mast cylinders are operating under maximum load. This is avoided since the power input is fixed, thus saving energy though operation time is increased. Although, it is important to note that the hydraulic system is not utilized that intensively, i.e. power is not used for longer periods, but in the big picture energy is saved nonetheless and the radar system can be operational longer.

4.5.6 Economical study

The economical study comprises cost estimations of components and these are no exact figures. However, they do give a hint of what to expect. The result shows that for concept EHC, the cost is lower with a margin interval of around 27-43 % compared to the reference. This is based on the two extremes of the sum of the obtained prices which especially varies for the frequency control (1000-14000 SEK/motor to control). The same applies for concept PowerPack which has a margin of 12-25 % where also the price of the power pack is a varying factor.

Many of the prices obtained are rough estimations and shall thus not be taken as exact figures. To obtain more accurate figures would require detailed dimensioning and specifying of a large number of components which does not fit into the thesis scope and the time limits. Since the prices may differ a lot depending on such specification it is also difficult to obtain estimated prices from suppliers.

Furthermore, since the estimated prices refers to components of mainly standard design this margin shall account for surface treatment, special products, frequency drives, some extra cost margin for emergency units and also a fault margin for installation, setup and estimation errors. Also, development and modification costs need to be included in this margin.

A further analysis of the price for CAN compliant components has not been possible due to slow response from suppliers. A hint however of what price to expect is, with a valve as an example, an increase of about 2-3000 SEK/valve (Karlsson, 2011). This is a rather large increase that would affect the cost quite greatly. The evaluation of saved development and setup cost due to CAN bus adaptation is difficult to carry out at this level though it is a factor to consider.

4.5.6.1 Concept PowerPack

With the above statements in mind it can be said that it is uncertain whether concept PowerPack will meet a cost level below or equal to the reference. Though, since the cost for customized and treated cylinders, which are one of the largest costs, is already included in the cost of concept PowerPack it is only customizing the power units that the margin shall cover. To evaluate whether the margin will be enough is however difficult to determine with the obtained input.

4.5.6.2 Concept EHC

Moreover, concept EHC has also the potential of staying below the reference cost even with all its extra customization costs. The cylinders in this case need some surface treatment etc to manage the environmental conditions and components need to be of a specific tolerant type. However, the indicated margin interval has the possibility to cover these costs or at least be within range.

A further issue is to switch the EHC for the parking and mast lock functions and use linear actuators instead. This result in a slightly lower cost and a margin of about 28-44 % compared to the reference. It is though important to note that the linear actuators brings about 100 kg of extra weight. For further results see appendix VII.

4.5.6.3 Summary

In summary, it is difficult to say more than that both concepts seems relatively reasonable from an economical perspective, although concept EHC is probably the best alternative in this sense. Below in table 15 is a summary of cost margins as a result of the economical study.

Table 15. Cost margin of concepts compared to reference cost.

Concept	EHC	PowerPack	Reference
Margin interval (%)	27 – 43 %	12 – 25 %	x SEK
With linear actuators	28 – 44 %	-	-

4.5.7 Weight study

The weight study comprises estimations of component weights to provide a total weight that is compared to the reference.

4.5.7.1 Concept PowerPack

The result shows that concept PowerPack instead shows results of a similar weight as the reference, around 1440 kg, which is based on the difference in weight between the power packs and the existing power unit. Since the concept utilizes most of the existing components such as cylinders etc, it only comes down to these two. Together with less piping, the several power packs and units for backup operation weighs almost the same as the existing power unit.

4.5.7.2 Concept EHC

Concept EHC would weigh about 1655 kg, with mechanical structure excluded, which is about 215 kg more than the reference weight (1440.5 kg). This could correspond to nearly two EHC mast cylinders so if the Giraffe AMB would have had fewer hydraulic functions/cylinders, the weight requirement could have been met. The weight is though based on rough estimations by the supplier and should not be taken as an exact value. Furthermore, and as said above, to switch to linear actuators as parking and mast lock cylinders would bring a weight increase of about 100 kg.

Below, in table 16, are the weights summarized.

Table 16. Weight of concepts compared to reference weight

Concept	EHC	PowerPack	Reference
Weight (kg)	1655	1338	1440.5
With linear actuators	1760	1460	-

For further results see appendix VII.

4.5.8 Positioning study

The conclusions to be drawn from the positioning study are that it is difficult to adapt a distributed solution without any modifications.

4.5.8.1 Concept PowerPack

In the case of concept PowerPack it is not possible to fit such power module in the support leg compartment, thus redesign of this compartment is needed. The compartment then needs to be extended in width to position a power unit on the side. This extension could also be optimized to create a small power unit compartment beside each support leg compartment. Another solution would be to use a separate reservoir at the top of the compartment and thus minimize the extension requirement. This would though still need modifications and the whole idea of modularity would be gone, resulting in lower accessibility with spread out components.

Regarding the mast power units, these would fit on the side of the lower mast sections as can be seen in section 4.5, figure 38.

4.5.8.2 Concept EHC

The concept EHC however have the possibilities to fit into existing leg compartments, though with some modifications to the link arm mountings and the extension cylinder. Due to the increased width and depth of the cylinders, where the reservoir is surrounding the cylinder, some extension in compartment depth may become necessary.

As for the lower mast section, these cylinders will fit to the existing mounting space though it will interfere some with the surroundings, e.g. extending sensors and valves will interfere with the shelter roof, which needs minor modification. This will especially occur when folding the mast.

The upper mast cylinders will interfere with the upper mast section when folded, thus some redesign of that is necessary. Furthermore, due to the increased dimensions of the EHC, the mountings on the mast need to be extended some. The extending motor of the cylinder will be pointing upwards and will not interfere geometrically. Illustrations of the positions and interferences are given in section 4.5.

4.5.8.3 Summary

Any exact measures of the concept modules are difficult to provide. The power packs vary in size by supplier and configuration and the EHC is still only an estimation, thus to set a specified geometry would be very uncertain at this time. It can be said that the power packs are approximately of the same size and varies around the below approximated values.

- Mast power module – 340 x 740 x 250 mm
- Support leg power module – 280 x 215 x 725 mm

(values are approximated from Bosch Rexroth – KE series data sheet RE18306-01)

Furthermore, the power unit section of the EHC will vary around the measures 170 x 150 x 490 mm. (approximated from provided conceptual CAD model)

The result of this is that it is difficult to integrate either of the concepts into existing geometry, thus redesign is necessary which make the proposals more suitable for next generation of GAMB.

4.5.9 Requirement fulfilment

The concepts have been evaluated against the customer requirement specification to verify the fulfilment of requirements and desires. From this, a functional specification has been set up with evaluation of each requirement, see appendix VIII.

The only requirement/desire that is confirmed to not be fully fulfilled is the weight for concept EHC. There are also some question marks regarding concept EHC and load/stiffness requirements. Since the solution at this stage consist of a proposed example by the supplier based on insufficient data it cannot be accurately determined whether the requirements are fulfilled or not. Although, the units are very adaptable for the application and the fulfilment should therefore not be any problem. Also, the time requirement for emergency operation has not been possible to evaluate due to the nature of the proposed solution of this function. It is though possible to configure these solutions as well to fit the application, thus there are no major difficulties at achieving the requirement.

Furthermore, the desire regarding a bus-based control system can be fulfilled if Saab EDS choose to go for that direction. The possibilities are there, but at a higher cost, so it is up to Saab EDS to decide whether it is necessary or not.

Apart from these issues, all relevant requirements are estimated to be met. There are though some requirements where fulfilment has not been possible due to lack of time and physical products for testing. There are also some requirements and desires that are outside the scope of the thesis and were mainly put in the specification to give a more holistic view of the tough conditions that the product need to cope with, see functional specification in appendix VIII.

Moreover, the design parameters gained from the QFD have been evaluated. The QFD provided a ranked list of important issues which is shown in table 17 below.

Table 17. Top 6 ranked design parameters with their respective goal values, gained from the QFD

Top 6	Goal values
1. Degree of distribution	≥ 30 %
2. Control system configuration	CAN bus
3. Material	*
4. Component weight	≤ Ref.
5. Emergency control configuration	*
6. System cost	≤ Ref.

The concepts have been compared to this top six ranked list to verify the goal values.

- It can be concluded that CAN bus is possible, though it is corresponding to higher costs. The control system plays a vital role but since the configuration is very similar to the existing, except from that the main control is of the motor speed, it should not be any difficulties to obtain a system as good as today's. To verify this deeper although lies outside the project scope.
- The degree of distribution, as measured in this study, is met. This is quite natural since the study aims for a distributed system.
- The emergency operation is important to consider and is an issue for a distributed system.
- The costs of the concepts have the potential of ending within an acceptable range of the reference cost.
- Finally, the component weights of concept EHC will not be met which is the main drawback of this system. It is up to Saab EDS to decide the importance of this aspect as a whole.

4.6 Visualisation of proposed solutions

To illustrate the principal layout and configuration of the concepts, visualizing approximated 3D CAD models are presented. The aim is to provide a further explanation and description of the concept proposals and their components' positions as a part of the whole radar system. See figures below.

4.6.1 Concept EHC

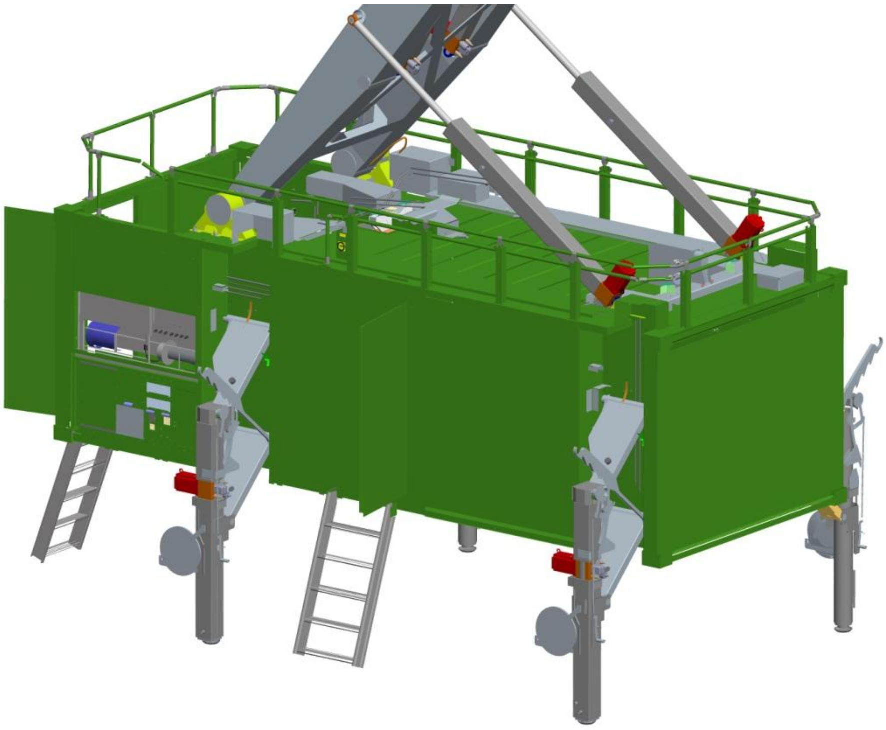

Figure 35. Overview of positions for electro-hydraulic cylinders in concept EHC

Figure 36. Mast EHC positions

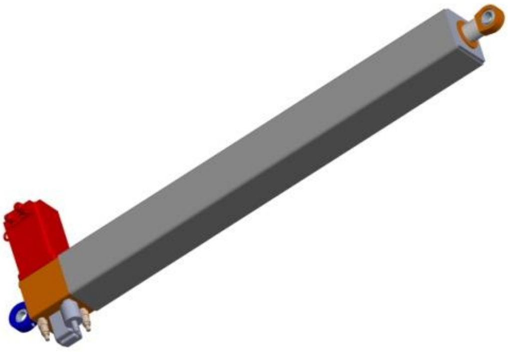

Figure 37. Standalone illustration of electro-hydraulic cylinder

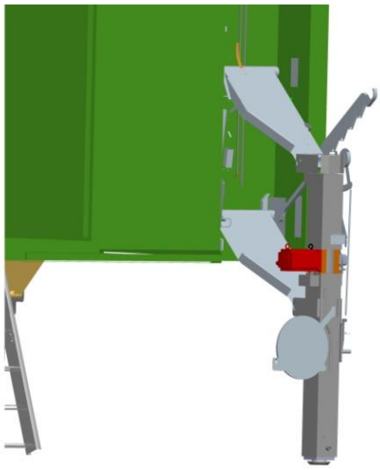

Figure 38. Close up of support leg EHC

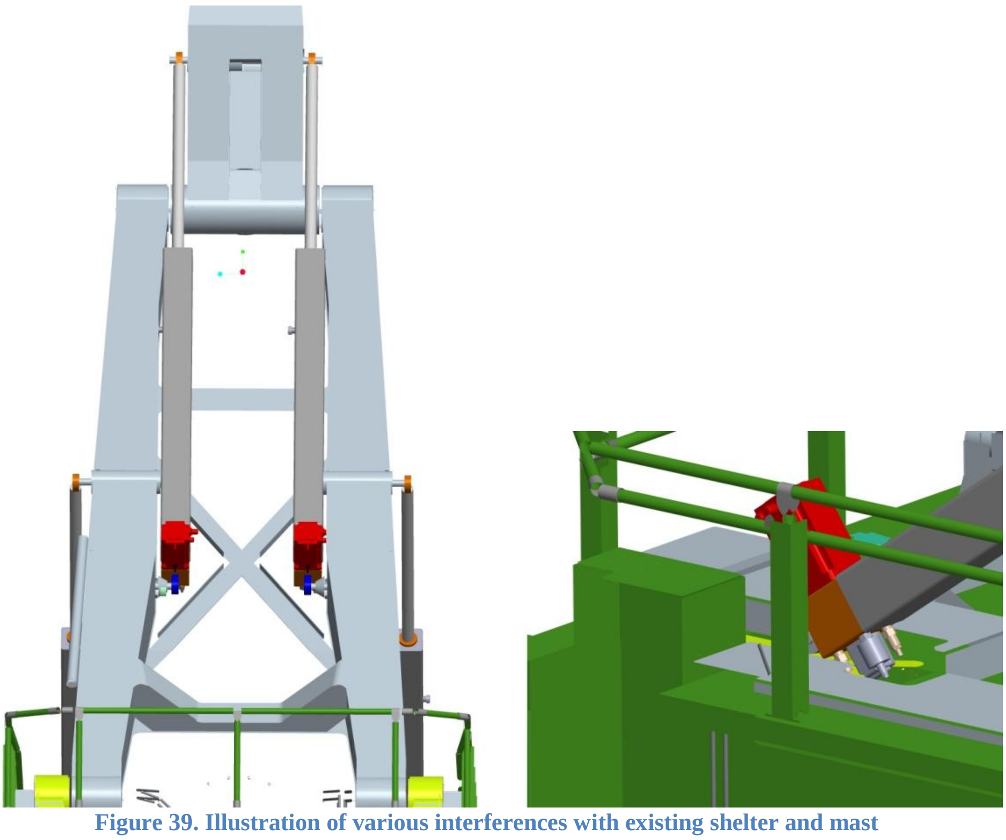

Figure 39. Illustration of various interferences with existing shelter and mast

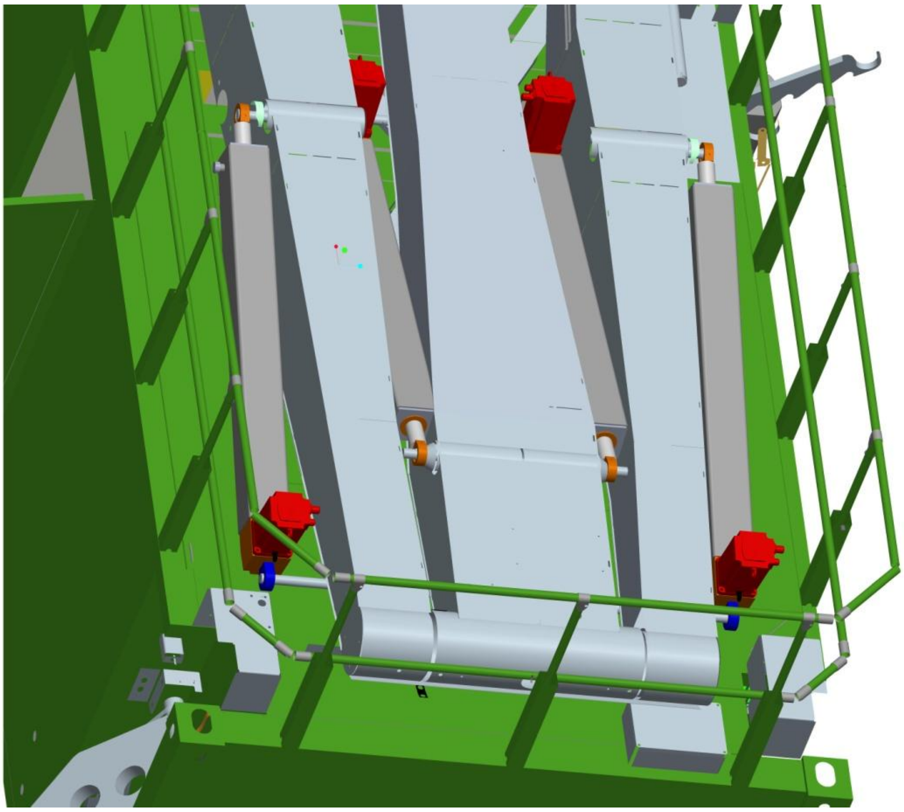

Figure 40. EHC with folded mast. Outer cylinders interfere with roof and inner cylinders interfere with the wide section of the upper mast section.

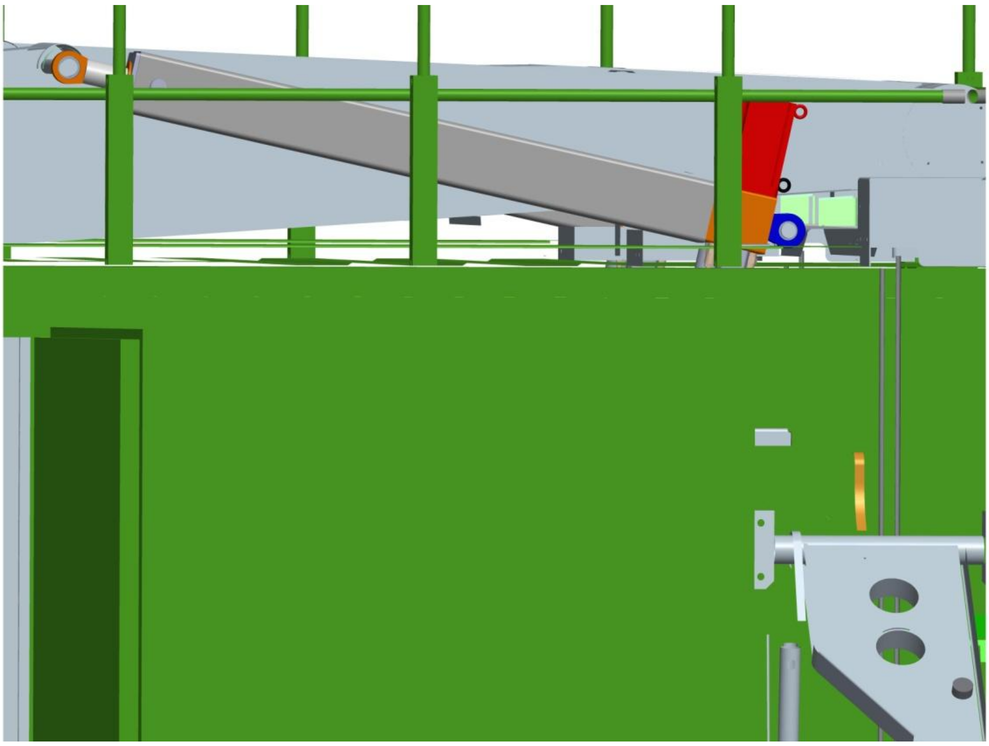

Figure 41. Close-up on lower mast cylinders with interfering pump and valves on the roof.

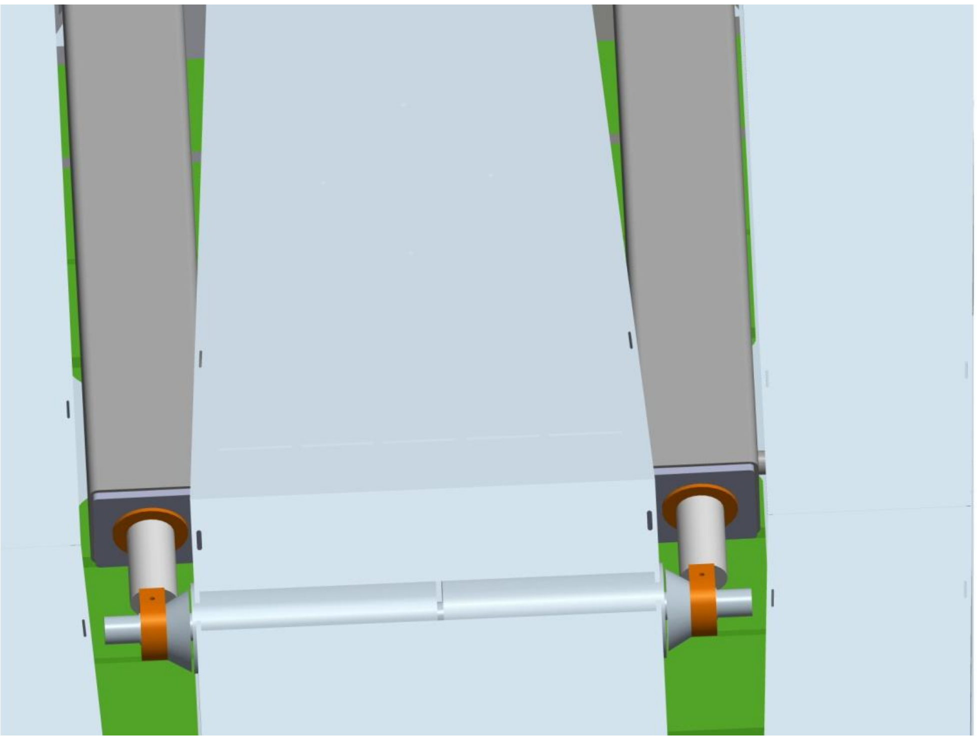

Figure 42. Close-up of upper mast cylinders that interfere with the upper mast section when folded.

4.6.2 Concept PowerPack

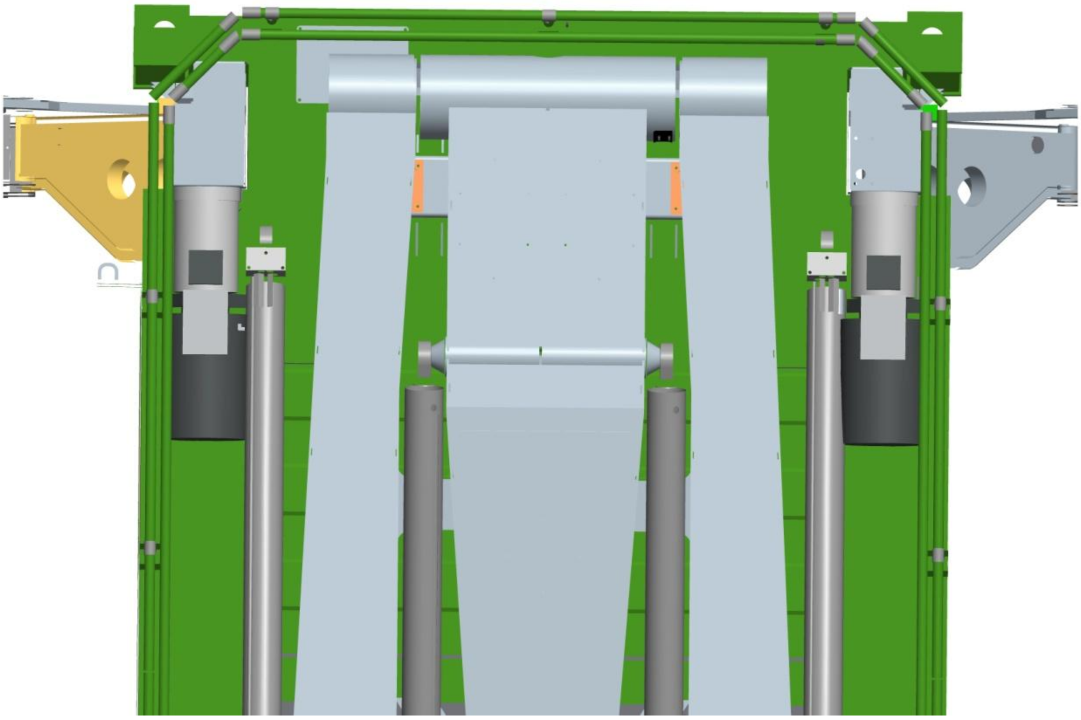

Figure 43. Mast power units, positioned on roof sides. No major interferences.

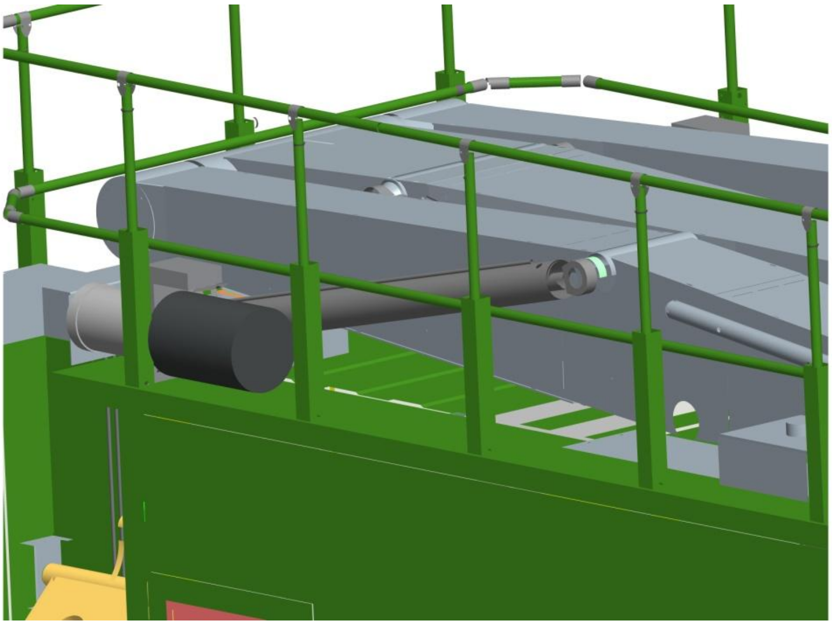

Figure 44. Mast power unit from another angle, example of position.

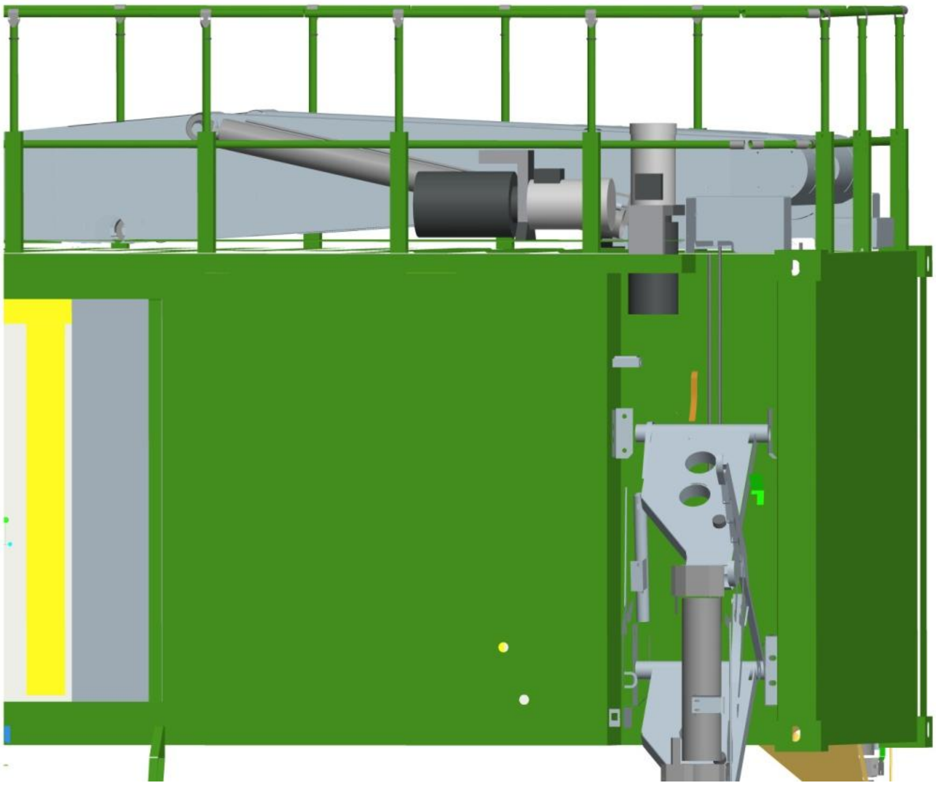

Figure 45. Example of support leg power unit position, above support leg; Shelter front. Compartment needs modification.

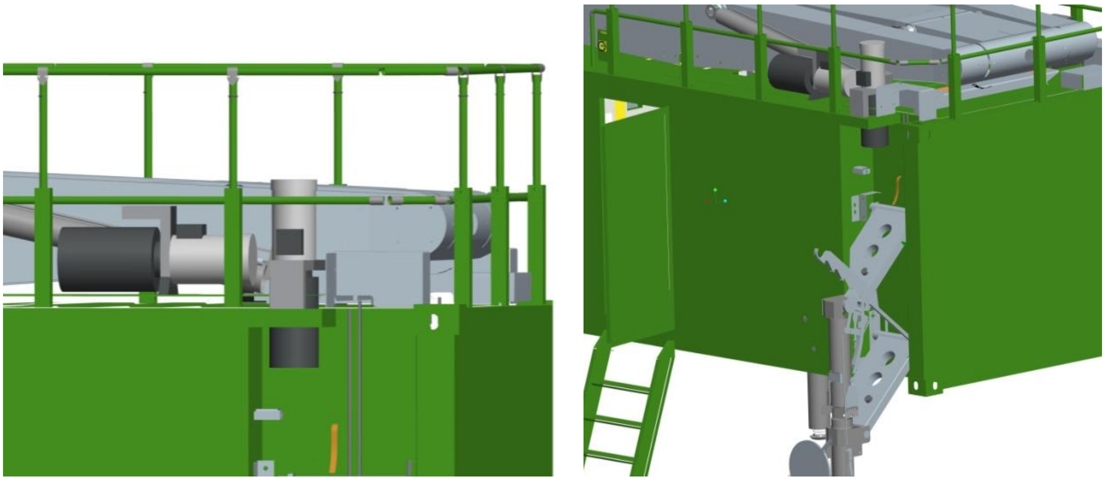

Figure 46. Various views of shelter front power packs, proposed positions.

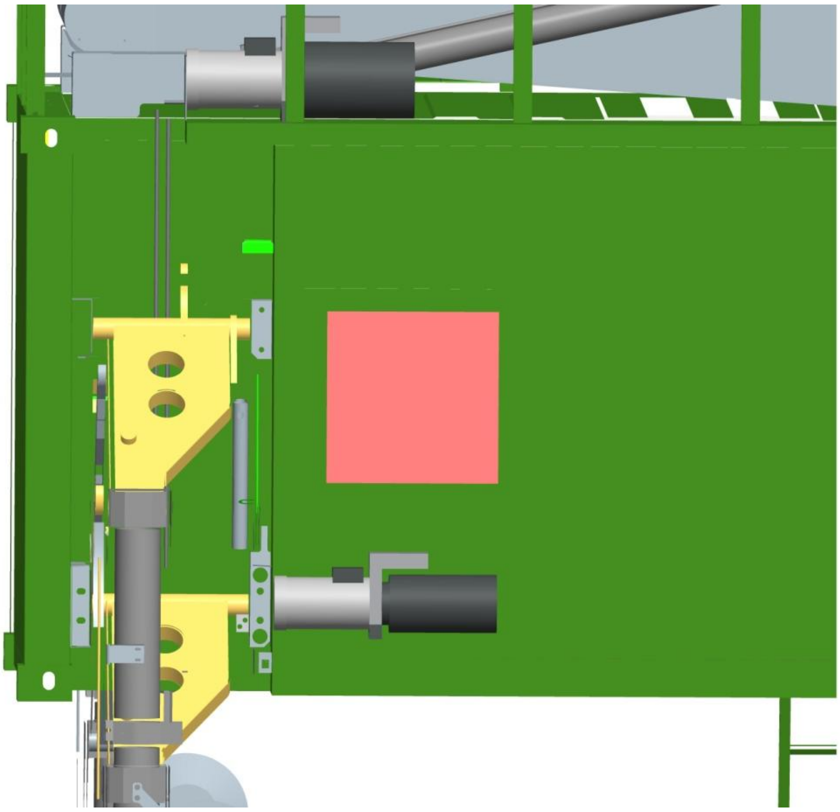

Figure 47. Alternative positioning of support leg power pack; Shelter rear end; Positioning horizontal/vertical outside leg compartment due to interference of mast joint.

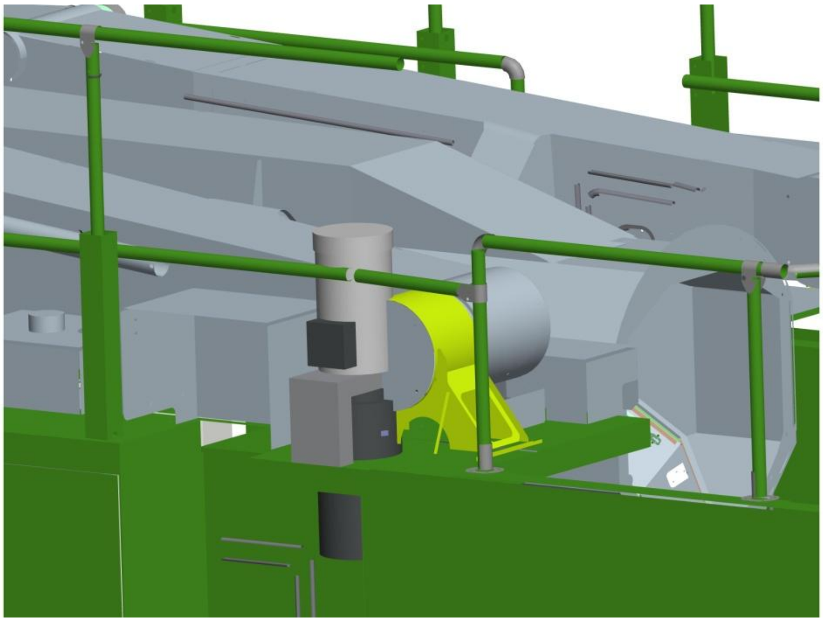

Figure 48. Close-up of an example with rear support leg power pack positioned as in the front; Interference with mast joint. Not a possible positioning in existing GAMB.

5 Discussion of results

The aim of this study has been to explore the possibilities of using a distributed hydraulic system, as an alternative to a centralized hydraulic system, in the existing and also future Giraffe AMB radar system. The goal was also to propose a few concepts of how a distributed hydraulic system could be configured and compare these to the existing reference, i.e. the hydraulic system of the Giraffe AMB.

5.1 The result

The conclusions that can be drawn from this thesis study is that a distributed hydraulic system is technically realizable and would result in a lot of benefits but also some drawbacks that makes the decision of adapting a distributed hydraulic system quite difficult. The main issue is the weight where a fully distributed system, in the Giraffe AMB and with EHC, utilizes a larger number of high weight components due to the fact that there are 14 functions to power individually. Each function though utilizes smaller components, thus fewer functions could make a distributed hydraulic system reasonable from a weight perspective. If, e.g. two mast EHCs would be eliminated, the weight would decrease below the reference value.

In the end the comparison of cost, weight and space requirements are some of the main decisive parameters. A distributed system in the Giraffe AMB implies rather similar levels of costs and space requirements. Due to the larger amount of hardware the cost and space requirements are generally higher although the lower complexity and the smaller components mean that the proposed solutions possibly could fit into existing compartments. Also, since no piping is needed, the cost for installing together with the cost and weight of the material itself can be eliminated, thus making the total cost lower.

As for concept Power pack the cost may increase, this is though uncertain and needs further and more detailed evaluation. The weight will be similar to the reference and the power module itself would, with slight modifications and extension of the leg compartment, fit into the same and on the shelter roof. It is though difficult to adapt such solutions directly to the existing Giraffe AMB as the concept aimed for. It can also be concluded that the power packs found on the market are, as standard, not fully adapted to extreme conditions. However, there are possibilities to combine components that meet the requirements but this will raise the cost further.

Concept EHC has a larger weight but will probably not exceed the reference cost. This is due to the less complex and integrated system but also the eliminated pipes and hoses since the EHC only utilizes electrical cables as external transfer interface. Although, the specified cost for these solutions are approximations made by the supplier and does not include any specialized surface treatment etc. The cylinder also implies customized support leg mountings which will raise the total cost. The margin of this is however between 27-43 % and is assumed to be within a reasonable limit, resulting in similar total costs as today with extra surface treatment, special components etc.

As said, the EHC concept needs some modifications of the mountings, especially the support leg mountings which may need some redesign. The upper mast needs some modification as well as the roof. Despite of this redesign, the solution will for the most part fit into the compartment and on the mast, though with a slightly deeper leg compartment if electro-hydraulic cylinders are used as parking cylinders. There is also the alternative possibility to connect a hose from the leg cylinder and let that power unit drive the parking cylinder, otherwise linear actuators could be used. These though mean higher cost and weight.

In summary, it can be concluded that both concepts have the possibility to fit into existing geometry, though with more or less redesign and modifications. The mechanical principle and the structure of the support legs can be reused, thus a distributed hydraulic system can rather easily be adapted. However, since concept EHC requires some redesign, the mechanical properties may change which needs further evaluation. It can therefore be recommended that this concept is suitable for the next Giraffe AMB generation only.

Other benefits of a distributed hydraulic system are the level of modularity and less physical dependencies, the increased reliability with, e.g. less piping, and the energy savings that can be obtained through frequency control of the electric motors. It is also likely that the service and maintenance will be easier to perform when the system components, especially valves and piping, are less complex configured and heavily reduced. It is also easy to identify where problems occur. The drawback though from that perspective is the increasing amount of components that needs service and maintenance.

Another drawback, and a troublesome issue, of a distributed hydraulic system in the Giraffe AMB is the emergency operation. Since it would be very unnecessary, expensive and weight demanding to use one extra power unit for each function to utilize when main power supply or components fails. Another alternative is needed. However, to solve that requires more complex solutions that are more demanding to the operators. Due to the separation of functions and their dependencies to the power unit, it also implies that the emergency operation of the support legs during power loss needs to be done one leg at the time which is time consuming. Although, concept EHC will be able to avoid this by utilizing an AC/DC converter in order to switch power supply. This can be done since its only external interface is electrical cables, though it will not solve the issue of component failure.

Concept PowerPack however cannot solve the issue with power supply failure as easy which is a drawback that perhaps does not provide grounds for adaptation. It though needs further evaluation to ensure such statement and the concept could still be relevant for other applications of Saab EDS's product portfolio.

There are different, more or less complex, alternative solutions described in the report, though all implies some drawbacks. The proposed solution for emergency operation is believed to be the most appropriate one but a combination of different solutions may be needed, especially for mast operation since it would require two portable units to obtain a synchronized operation.

5.2 The development method

The methods used have mainly acted as support for structuring the development work and provide a basis for discussion and gaining knowledge. The axiomatic design process was not strictly followed and the coupling analysis was excluded. It was the structured process of generating concepts together with its principles and framework that provided a good way of thinking when developing proposals. Its way of using a hierarchical functional domain and find solutions to each functional requirement individually fitted this type of development very well since it involves many standard components and since the project was about finding a common hydraulic system but distributed, i.e. the focus was not on finding a new revolutionary solution but rather to find proposals where common hydraulic components and existing solutions were configured to fit a distributed hydraulic system.

Furthermore, the support of different tools and methods, e.g. Idef0, risk analysis, QFD, elimination matrices etc., have helped greatly to clarify possible issues in the development work as well as contributed to provide structure and width to the study.

Overall, the methods and tools used have been chosen with respect to relevance and to exclude the coupling analysis in the axiomatic design process was based on this decision. Instead, elimination matrices were used to generate each design parameter or component. Although, a coupling analysis of the concepts could, with further afterthought, also have been an appropriate alternative to identify specific dependencies in the system. The result was though satisfying anyhow.

5.3 Sensitivity factors

This project has been a study on concept level for a future distributed hydraulic system which means that many numbers and prices are not an exact science. Some variables that might affect the end price and data will be presented below.

The data in many cases are estimations together with expertise information from people within the industry. Another factor that contributes to the variation is the system's time of use. This system may, if adapted, first become realized in a couple of years into the future. During this period is it likely that the prices will change and these variations could affect the decisions of introducing the system or not. Though, when it comes to general component prices is it not likely that this will change that much over time in the coming years. Hydraulics is a quite mature technique with slow changes regarding the systems.

A thing that might get more standardized in the coming years is CAN bus components, the technique has been around for many years but never become commonly adapted. It is likely that the price will decrease for such components which are of great interest when it is time to upgrade the system.

Another factor is the variations from estimations and prices from different suppliers. The prices are in some cases, e.g. EHC and power packs, estimations and not a final offer. This result in an extra insecurity and the final price will probably differ from the estimated price, though the estimated prices are although a hint of what to expect. For the electro-hydraulic system the price is estimated by the supplier based on standard components with no special modifications. A development cost and a cost for production will also be added here and this cost is difficult to estimate but the cost study shows that there is a reasonable margin to cover these aspects without raising the cost to an unacceptable level.

Also, to obtain prices has not been as successful as expected due to slow response from suppliers and the fact that each idea or solution, that were under evaluation, needed to be almost fully specified in order to obtain an acceptable value. The prices would otherwise vary and to receive an estimated price was troublesome. This was especially difficult for the price inquiry of power packs which needed extensive info. This was time consuming to provide, thus reducing the accessible supplier lead time.

Another factor might also have been the unwillingness and time resources of supplier sales support to prioritize a master thesis work. However, separate standard components could more easily be obtained from supplier price lists and sales support. As far as the result is concerned, rough estimations from industry people and approximately specified offers although give a hint of what to expect.

Furthermore, the price will also be affected of installation costs. With a new distributed system the piping will be heavily or completely reduced which will save time and money. Though, instead there are some extra components and units that have to be installed individually which probably will consume time and effort. In the end is it likely that the cost and installation time will be reduced but it is difficult to put an exact number on it.

The times of operation are in many cases estimated and combined with measurements. These time estimations affect the calculations when dimensioning components which in turn will affect the selection of components. Thus the price would also be affected. All these small variation factors could in the end result in large variations of the price.

Another issue to be considered are the robustness of the EHC. Since these are rather new solutions no extensive environmental testing, other than proven operation in naval environment, have been conducted. This is a sensitivity factor that needs to be evaluated further to ensure requirement fulfilment. Though, according to the supplier, the solutions should endure such requirements.

Also, the power packs are not specified for such rough conditions that the requirements demand. These classifications do not have the wide range that is required, e.g. temperature. No standardized solutions for extreme environments have been found, although these modular solutions can be configured with special components. This will raise the price of such module and is important to consider. However, it is mainly the hydraulic oil that is the most sensitive component to such environment. The mechanical components are easier to adapt to the requirements.

6 Conclusions of study

To summarize, the result of the study is that the Giraffe AMB has too many functions for a distributed hydraulic system to be fully suitable for adaptation, though it is possible to realize such solution. It is up to Saab EDS to consider what aspects that are of most importance and from that decide if a realization is beneficial or not. However, other applications within Saab EDS product portfolio, with fewer hydraulic functions, may fit an adaptation to a distributed system since the idea of distribution implies many benefits. In this case, weight is the main factor that limits the further utilization of such an idea.

The result shows that concept PowerPack shows potential but may not be appropriate to consider in the existing GAMB due to its space requirements and the required redesign of the shelter. Though it is a possible solution for next generation of GAMB platforms and could also suit other applications. The same apply for concept EHC which also have the potential to be adapted in next generation of GAMB platforms and the concept also takes the idea of distribution even further with total integration.

Furthermore, together with a CAN bus interface a distributed hydraulic system could become a very flexible and reliable system but the costs of that technology is higher. Although, the cost might in a larger perspective not be a limiting factor.

Table 18 and 19 below presents a summary of the benefits and drawbacks of a distributed system and should be considered as a base of discussion.

Table 18. Benefits and drawbacks of concept "PowerPack"

	Advantages	Disadvantages
Concept "PowerPack"	Higher reliability Less piping Faster installation Higher accessibility Easy maintenance & service Fits on existing shelter Energy savings up to 50-70%	More components Higher cost Requires more space Modifications of leg compartment needed More complex emergency operation

Table 19. Benefits and drawbacks of concept "EHC"

	Advantages	Disadvantages
Concept "EHC"	Higher reliability No piping Faster installation Higher accessibility Easy maintenance & service Fits on existing shelter Energy savings up to 50-70%	More components Higher weight Design modifications needed More complex emergency operation

7 Recommendations for further development

This chapter provides recommendations to further develop a distributed hydraulic system in the existing or next generation of Giraffe AMB as well as other applications in Saab EDS' product portfolio.

- The first recommendation is to evaluate what aspects that is of most importance when configuring the hydraulic system and revise the benefits and drawbacks provided by this report as basis of discussion.
- Both concepts show potential. It is therefore recommended to keep further contact with the supplier and evaluate cost and weight more in detail based on further specified modules.
- It is preferred to analyze the electro-hydraulic cylinders against environmental requirements together with supplier to ensure requirement fulfillment.
- It is recommended to consider possible redesign alternatives to decrease the number of hydraulic functions which would increase the possibilities of adapting a distributed system and thus gaining its many benefits.
- To further evaluate emergency operation alternatives and carry out more detailed studies of such solution is preferred.
- If further efforts are made on adapting a distributed hydraulic system, considerations regarding cylinder mounting modifications are needed and structural analyses required.
- It is recommended to seek alternative applications where fewer hydraulic functions are used. There are potential of using a distributed hydraulic system in such application which then would bring many benefits.
- Finally, the main recommendation for the development of the next generation Giraffe AMB is to consider concept EHC as an alternative.

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Appendix

Appendix I - Customer Requirement Specification (CRS)

Category	No.	Requirement	Data	D/R	Validation	Verification
1. Characteristics						
1.1 Performance						
1.1.1 General						
	1.1.1.1	The hydraulic system shall not affect the possibility of loading the entire radar system onto a truck.		R	Saab EDS	Functional specification, CAD-models
1.1.2 Weight						
	1.1.2.1	Hydraulic system (total weight incl. mechanical structures of support legs)	1889 kg	D	Saab EDS	Component specifications (weight)
1.1.3 Operational range						
	1.1.3.1	The system shall manage to operate i.e. lift the radar cabin to horisontal position and reverse, on all ground slopes ≤ 7° without truck.	≤ 7°	R	Saab EDS	Cylinder specification (length of stroke)
	1.1.3.2	The system shall manage to operate i.e. lift the radar cabin to horisontal position and reverse, on all ground slopes ≤ 5° with truck.	≤ 5°	R	Saab EDS	Cylinder specification (length of stroke)
1.1.4 Accuracy						
	1.1.4.1	The system shall automatically ensure that the resulting horisontal position of the radar cabin is within ± 0.3° i.e. that the radar system is levelled.	± 0.3°	R	Saab EDS	Hydraulic cylinder supplier verification
1.1.5 Positional locking						
	1.1.5.1	No piston movement or slipping is allowed for the support leg and mast cylinders in any of their static positions.		R	Saab EDS	Hydraulic cylinder supplier verification
	1.1.5.2	The positional locking must withstand the cylinder maximum operating and non-operating loads.		R	Saab EDS	Supplier verification & Mechanical calculations
1.1.6 Power loss						
	1.1.6.1	During power loss, all cylinders shall keep their positions.		R	Saab EDS	Supplier verification
	1.1.6.2	All cylinders must keep their non-operating load taking performance.		R	Saab EDS	Hydraulic cylinder supplier verification

Category		No.	Requirement	Data	D/R	Validation	Verification
	1.1.7 Cylinder maximum loads						
	Support leg cylinders						
		1.1.7.1	Case 1: Maximum axial loads, non-operating mode (no electrical power), individual cylinder.	150kN	R	Saab EDS	Supplier verification & Mechanical calculations
		1.1.7.2	Case 1: Maximum transversal loads, non-operating mode (no electrical power), individual cylinder.	20kN	R	Saab EDS	Supplier verification & Mechanical calculations
		1.1.7.3	Case 2: Maximum axial loads, non-operating mode (no electrical power), individual cylinder.	100kN	R	Saab EDS	Supplier verification & Mechanical calculations
		1.1.7.4	Case 2: Maximum transversal loads, non-operating mode (no electrical power), individual cylinder.	30kN	R	Saab EDS	Supplier verification & Mechanical calculations
	Mast cylinder(s)						
		1.1.7.6	Maximum axial loads, operating mode, individual cylinder.	95kN	R	Saab EDS	Supplier verification & Mechanical calculations
		1.1.7.7	Maximum axial loads, non-operating mode (no electrical power), individual cylinder.	95kN	R	Saab EDS	Supplier verification & Mechanical calculations
	Mast transport lock						
		1.1.7.8	Maximum load, individual cylinder.	3kN	R	Saab EDS	Supplier verification & Mechanical calculations
	1.1.8 Cylinder stiffness						
		1.1.8.1	For redesigning of mechanical structures/ interfaces, the stiffness of the entire system shall not be negatively affected.		R	Saab EDS	Supplier verification & Mechanical calculations
	1.1.9 Buckling						
		1.1.9.1	The support leg cylinder and piston shall be dimensioned to prevent buckling at their most extended position. Safety factor 2.0 is included. Boundary conditions according to Euler 1.	300 kN (150*SF kN)	R	Saab EDS	Supplier verification & Mechanical calculations
		1.1.9.2	The mast cylinders and pistons shall be dimensioned to prevent buckling at their most extended position. Safety factor 2.0 is included. Boundary conditions according to Euler 2.	110 kN (55*SF kN)	R	Saab EDS	Supplier verification & Mechanical calculations

Category		No.	Requirement	Data	D/R	Validation	Verification
	1.1.10 Power usage						
		1.1.10.1	Power usage shall be minimized		D	Saab EDS	Supplier specifications & testing
		1.1.10.2	The power consumption of the system shall on avarage be	≤ 7 kW	D	Saab EDS	Supplier specifications & testing
1.2 Operation time							
				Temp.	Section	Factor	
			The required times in section 1.2.1-1.2.2 are valid within the ambient temp. range 0°C to +55°C. At ambient temp. below 0°C the times are allowed to be extended with the following factors.	-20°C -40°C	Both 1.2.1 1.2.2	x2 x2 x4	
	1.2.1 General						
		1.2.1.1	The total time for deployment of the entire radar system shall be maximum 10 minutes with main power supply.	10 min	R	Saab EDS	Supplier specification (flow rate) & approximation
	1.2.2 Emergency operation						
		1.2.2.1	The time required from operational conditions to transport position shall be less than 30 minutes without main power supply.	30min	R	Saab EDS	Supplier specification (flow rate) & approximation

Category	No.	Requirement	Data	D/R	Validation	Verification
2. Interfaces						
2.1 Mechanical interfaces						
	2.1.0.1	The interfaces of the hydraulic system including support leg cylinders, mast cylinder(s), mast transport lock and hydraulic control unit shall consist of standard components.		D	Saab EDS	Component specification
2.2 Electrical interface						
2.2.1.Power supply						
	2.2.1.1	The power supply driving the hydraulic pump shall comply with the nominal voltage 3x230/400V AC.	3x230/400V AC	R	Saab EDS	Supplied power specifications
	2.2.1.2	The hydraulic control system shall comply with the nominal voltage 28V DC.	28V DC	D	Saab EDS	Supplied power specifications
	2.2.1.3	The system shall have an emergency external power supply/other solutions for lowering the mast and positioning of the support legs for transport if main power loss occurs.		R	Saab EDS	Functional specification
2.2.2 Control signals to/from hydraulic control system						
	2.2.2.1	The hydraulic system shall be controlled by a bus-based control system.		D	Saab EDS	Functional specification
	2.2.2.2	The hydraulic control system shall recieve information for: • overload condition for each support leg • mast up/down • safety switch when someone enters the roof • hydraulic faults • level alarms • oil pressure/level/temp in hydraulic unit • ground pressure in support leg cylinders • pressure in mast cylinder(s) • emergency stop • black out • locked/open rear transport lock • locked/open front transport lock • position of mast cylinder(s) • parking of support legs • rotation of mast • antenna parking status • hydraulic pump control • emergency pump control • support leg switch of manual operation		R	Saab EDS	Control system architecture

Category	No.	Requirement	Data	D/R	Validation	Verification
3. Reliability						
3.1 Life time						
	3.1.0.1	The hydraulic system is expected to be in use for at least 20 years and with an operating profile according to section 3.2.	20 years	D	Saab EDS	Approximations based on supplier specifications
	3.1.0.2	The system shall be able to handle storage for 6 years with storage environment according to section 5.	6 years	D	Saab EDS	Approximations based on supplier specifications
3.2 Operating profile						
	3.2.0.1	The hydraulic system shall have the possibility to be operated manually.		D	Saab EDS	Functional specification
	3.2.0.2	The equipment shall withstand an operating profile during a period of 20 years with 10 000 operations. (one setup & one take down)	10 000 operations	D	Saab EDS	Approximations based on supplier specifications
	3.2.0.3	The equipment shall withstand to be used in deployed operational position during a period of three months continuously.	3 months	D	Saab EDS	Approximations based on supplier specifications

Category	No.	Requirement	Data	D/R	Validation	Verification
4. Maintainability						
4.1 General						
	4.1.0.1	The hydraulic system and control system shall be designed for simple maintenance and repair.		D	Saab EDS	Functional specification, CAD models & service operator verification
	4.1.0.2	The hydraulic system and control system shall have a modular design with replaceable units for quick change in field operation.		D	Saab EDS	Functional specification, CAD models & service operator verification
	4.1.0.3	Preventive maintenance shall be of limited range.		D	Service & Maintenance operators	Supplier specifications
4.2 Interchangeability						
	4.2.0.1	Any unit shall be interchangeable without any trimming or alignment.		D	Service & maintenance operators	Standard components used

Category	No.	Requirement	Data	D/R	Validation	Verification

5. Environmental requirements

5.1 Climatic environment

Category	No.	Requirement	Data	D/R	Validation	Verification
5.1.1 General						
	5.1.1.1	The system shall be designed for coastal climate and industrial pollution.		R	Saab EDS	Saab EDS post treatment, assumptions & supplier specification
5.1.2 High temp. during operation						
	5.1.2.1	The hydraulic system shall be able to operate in a maximum ambient temperature of +55°C	+55°C	R	Saab EDS	Supplier specification
5.1.3 High temp. during storage						
	5.1.3.1	The hydraulic system shall be able to be stored in a maximum ambient temperature of +71°C	+71°C	R	Saab EDS	Supplier specification
5.1.4 Low temp. during operation						
	5.1.4.1	The hydraulic system shall be able to operate in an ambient temperature of -40°C	-40°C	R	Saab EDS	Supplier specification
5.1.5 Low temp. during storage						
	5.1.5.1	The hydraulic system shall be able to be stored in an ambient temperature of -46°C	-46°C	R	Saab EDS	Supplier specification
5.1.6 Solar radiation						
	5.1.6.1	The hydraulic cylinders and other exposed components shall be designed for maximum intensity of 1120 W/m2.	1120 W/m2	D	Saab EDS	Saab EDS post treatment & Supplier specification
5.1.7 Humidity (function & storage)						
	5.1.7.1	The hydraulic system shall withstand severe condensing humidity resulting from non-controlled temperature and humidity in tropical areas.		R	Saab EDS	Saab EDS post treatment & Supplier specification
5.1.8 Fungus						
	5.1.8.1	The hydraulic system shall not be affected by fungus growth i.e. no damage nor performance degradation.		R	Saab EDS	Saab EDS post treatment & Supplier specification
5.1.9 Rain						
	5.1.9.1	The hydraulic cylinders and other exposed components shall be designed for max intensity of 100 mm/h of rain.	100 mm/h	D	Saab EDS	Assumptions & Supplier specification

Category		No.	Requirement	Data	D/R	Validation	Verification
	5.1.10 Sand & Dust						
		5.1.10.1	The hydraulic cylinders and other exposed components shall be designed to withstand air containing sand and dust.		D	Saab EDS	Functional specification
		5.1.10.2	The hydraulic cylinders and other exposed components shall be designed to prevent clogging or build up of sand and dust.		D	Saab EDS	Functional specification & Supplier specification
	5.1.11 Low pressure						
		5.1.11.1	Minimum operational pressure shall be 65kPa (3500m above sea level) at maximum ambient temp. +20°C.	65 kPa	D	Saab EDS	Supplier specification
			Minimum operational pressure shall be 75kPa (2500m above sea level) at maximum ambient temp. +35°C.	75 kPa	D	Saab EDS	Supplier specification
			Minimum non-operational pressure shall be 19kPa (12000m above sea level).	19 kPa	D	Saab EDS	Supplier specification
	5.1.12 Snow						
		5.1.12.1	The hydraulic cylinders and other exposed components shall during transport, storage and operation withstand snowfall corresponding to an intensity of 50mm/h in melted form.	50 mm/h (melted)	D	Saab EDS	Assumptions & Supplier specification
	5.1.13 Hail						
		5.1.13.1	The hydraulic cylinders and other exposed components shall withstand hailstorms with hails of diameter of 10mm with full performance afterwards.	10 mm	D	Saab EDS	Assumptions & Supplier specification
	5.1.14 Ice during storage & transportation						
		5.1.14.1	The hydraulic cylinders and other exposed components shall be designed to withstand 13 mm ice thickness.	13 mm	D	Saab EDS	Assumptions & supplier specifications

Category	No.	Requirement	Data	D/R	Validation	Verification
6. Design rules and requirements						
6.1 General						
	6.1.0.1	The hydraulic units shall have a modular design/configuration.		D	Saab EDS	Functional specification & CAD models
	6.1.0.2	The support leg hydraulic units with its components shall not, in parked position, extend from the shelter walls.		R	Saab EDS	Functional specification & CAD models
	6.1.0.3	The mast cylinder hydraulic unit(s) shall not extend from the roof and not interfere with the mast's space requirements.		R	Saab EDS	Functional specification & CAD models
6.2 Enclosure protection						
	6.2.0.1	Sensitive components shall be enclosed for protection.		D	Saab EDS	Functional specification & CAD models
6.3 Connections						
	6.3.0.1	All connections for pipes, hoses and cables shall be easily accessible for mounting and dismounting.		R	Saab EDS production, service operators	Functional specification & design (CAD models)
	6.3.0.2	Connections shall be of standard connection types.		R	Saab EDS	Component specification
	6.3.0.3	All connections shall be secured against accidental loosening. Solded lugs are not permitted.		R	Saab EDS	Connection supplier verification
6.4 Dimensioning						
	6.4.0.1	The hydraulic system shall fit into existing dimensions of the shelter (HxWxL).	2438 x 2438 x 6058 mm	R	Saab EDS	Functional specification, Drawings, Component specifications
	6.4.0.2	The support legs shall not geometrically/physically, during deployment, interfere with the truck.		R	Saab EDS	Functional specification, Drawings, Component specifications
	6.4.0.3	The bottom of the shelter shall be able to be lifted 2100 mm above ground by the support legs.	2100 mm	R	Saab EDS	Functional specification, Drawings, Component specifications

Category	No.	Requirement	Data	D/R	Validation	Verification
6.5 Materials & surface treatment						
	6.5.0.1	The metallic materials used in equipment shall be corrosion resistant or treated to be corrosion resistant.		R	Saab EDS	Saab EDS post treatment & Supplier specification
	6.5.0.2	Non-metallic materials like plastics, rubber etc. shall be moisture, UV, flammable and fungus resistant during its intended lifetime.		R	Saab EDS	Saab EDS post treatment & Supplier specification
	6.5.0.3	All materials shall be chosen considering extreme temperatures and all other environmental conditions specified in section 5.		R	Saab EDS	Supplier component & material specification
6.6 Mechanical components						
	6.6.0.1	All components shall be carefully chosen considering performance, environmental resistance, easy service and handling.		R	Saab EDS & Project team	Supplier specification & Functional specification
	6.6.0.2	For choice of mechanical components ISO-standard shall be used.		R	Saab EDS	Verify against ISO
6.7 Cables & protection of circuits						
	6.7.0.1	The apparatus and circuits shall be arranged to facilitate their operation and maintenance, and at the same time be arranged to ensure the necessary degree of safety.		R	Saab EDS	Functional specification, CAD models & Risk assessment
6.8 Moisture						
	6.8.0.1	The equipment shall be designed to achieve necessary ventilation. Special attention shall be paid to avoid water condensation inside structures. If necessary, there shall be holes for draining of moisture.		R	Saab EDS	Functional specification & design (CAD models)
6.9 Cleanness						
	6.9.0.1	The mechanical design shall be carried out in consideration of easy cleaning of the equipment. All components shall have a material or surface treatment resistant to deterioration.		R	Saab EDS, maintenance operators	Functional specification & design (CAD models)

Category	No.	Requirement	Data	D/R	Validation	Verification

7. Product safety requirements

7.1 General

	7.1.0.1	The design of the hydraulic system shall be performed with necessary safety, to avoid damage to person, property, system and environment at prescribed use and handling.		R	Saab EDS	Risk assessment
	7.1.0.2	A Risk analysis shall be made on the system.		R	Saab EDS	Risk assessment

Appendix II – Functional mapping

1 Main functions

1.1	Support legs	Level	Radar system (GAMB)
1.2	Mast cylinder	Raise	Mast

2 Additional functions

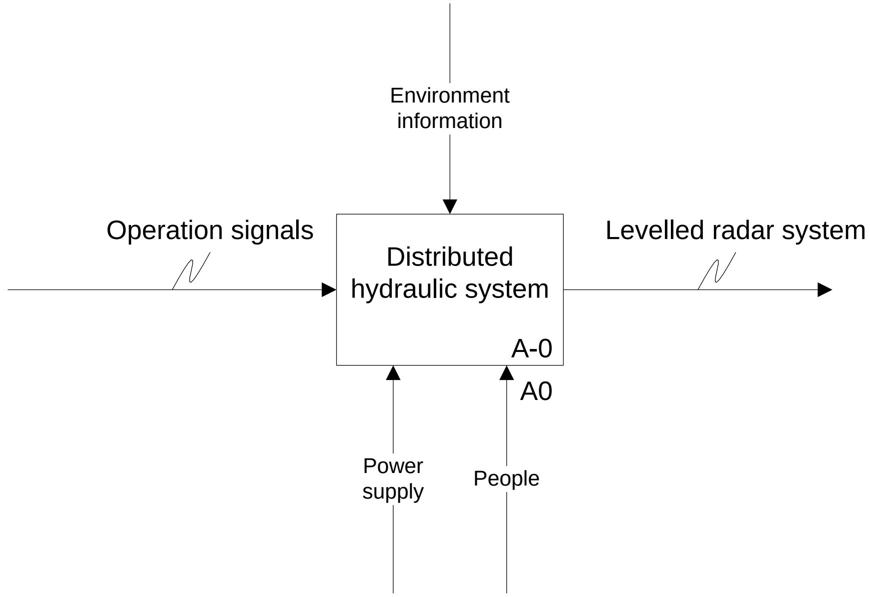
2.1	Hydraulic actuator	Position	Support legs
2.2	Locking system	Lock	Mast
2.3	Hydraulic control system	Control	Hydraulic system
2.4	Manual control interface	Control	Hydraulic system
2.5	Hydraulic pump	Pressurize	Hydraulic fluid
2.6	Directional control valves	Direct	Hydraulic fluid
2.7	Pressure control valves	Control	Pressure
2.8	Flow control valves	Control	Flow rate
2.9	Load-holding valves	Hold	Load
2.10	GAMB power supply	Power	Distributed hydraulic units
2.11	Hydraulic fluid	Pressurize	Actuators

3 Support functions

3.1	Filters	Clean	Hydraulic fluid
3.2	Reservoir	Store	Hydraulic fluid
3.3	Cooling system	Cool	Hydraulic fluid
3.4	Sensors	Provide	Information
3.5	Pipes	Transport	Hydraulic fluid
3.6	Hoses	Transport	Hydraulic fluid
3.7	Connections	Secure	Pipes & Hoses
3.8	Mechanical interface	Support	Support legs
3.9	Mountings	Support	Actuators
3.10	Mountings	Support	Hydraulic control system
3.11	Emergency power supply	Power	Distributed hydraulic units

4 Undesired functions

4.1	Hydraulic system	Consume	Power
4.2	Hydraulic system	Weight	GAMB
4.3	Hydraulic units	Require	Space
4.4	Hydraulic fluid	Generate	Heat
4.5	Hydraulic fluid	Pressurize	Hydraulic system
4.6	Hydraulic system	Leak	Hydraulic fluid
4.7	Pipes & hoses	Transport	Hydraulic fluid



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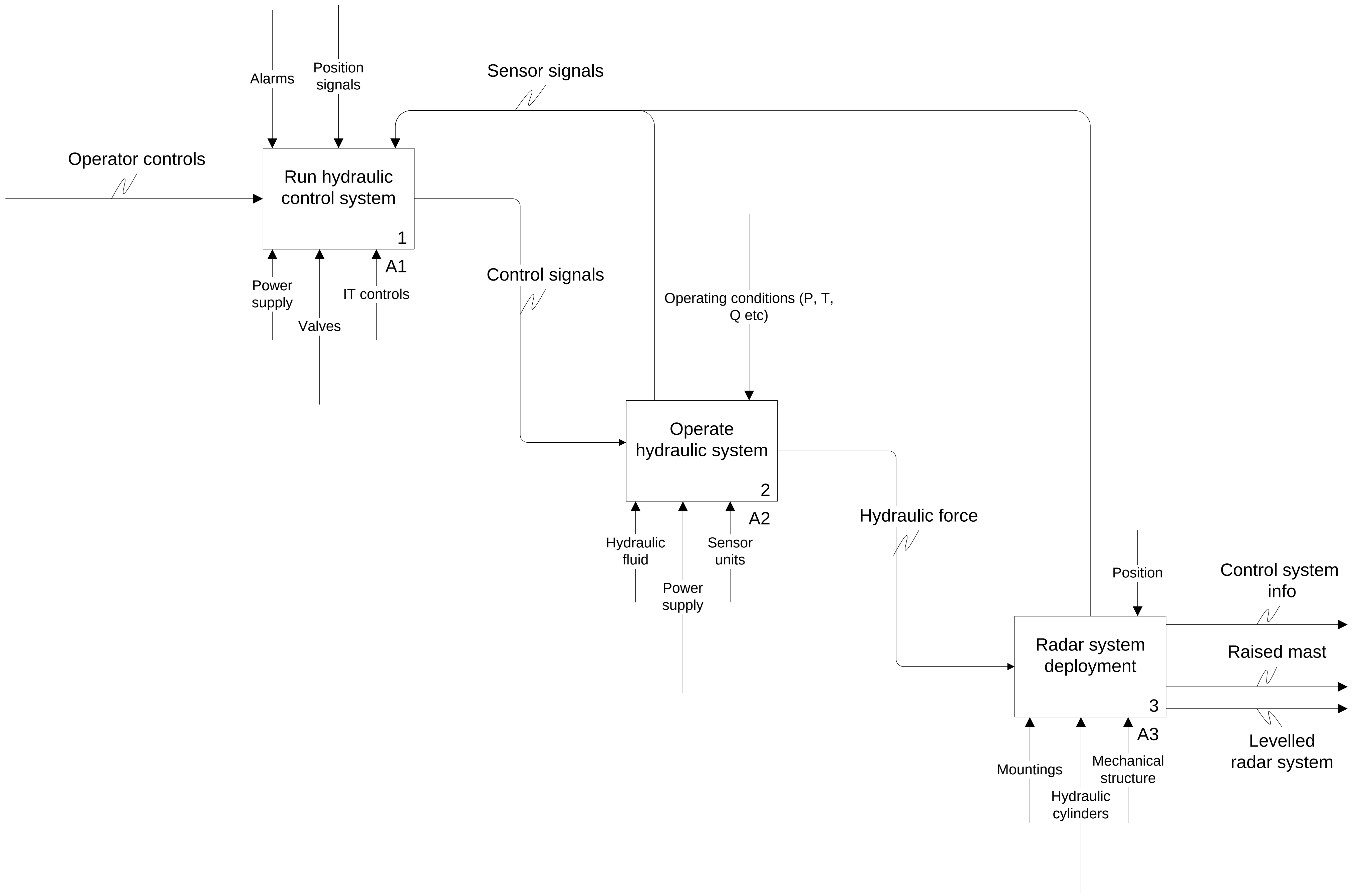

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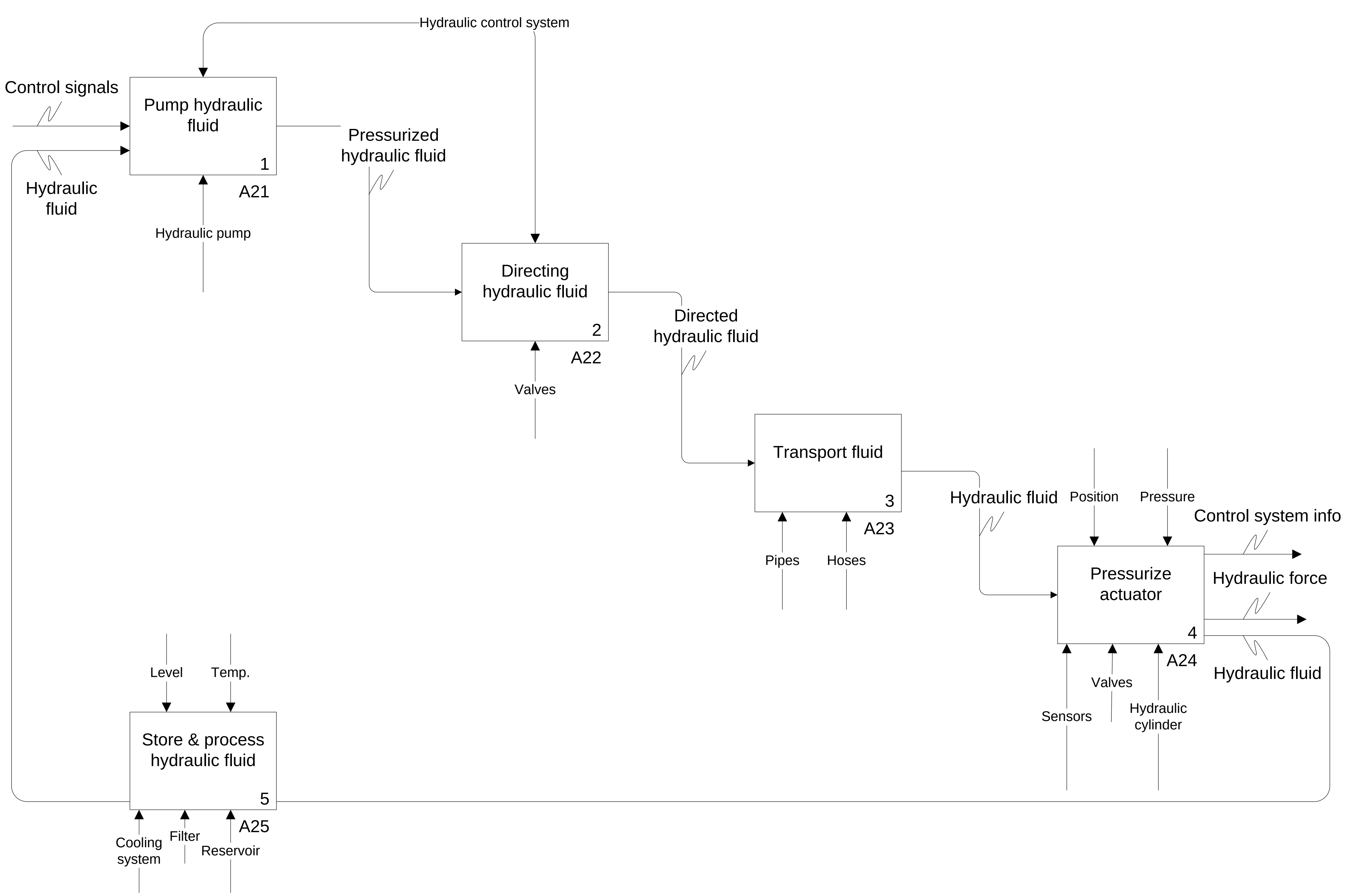

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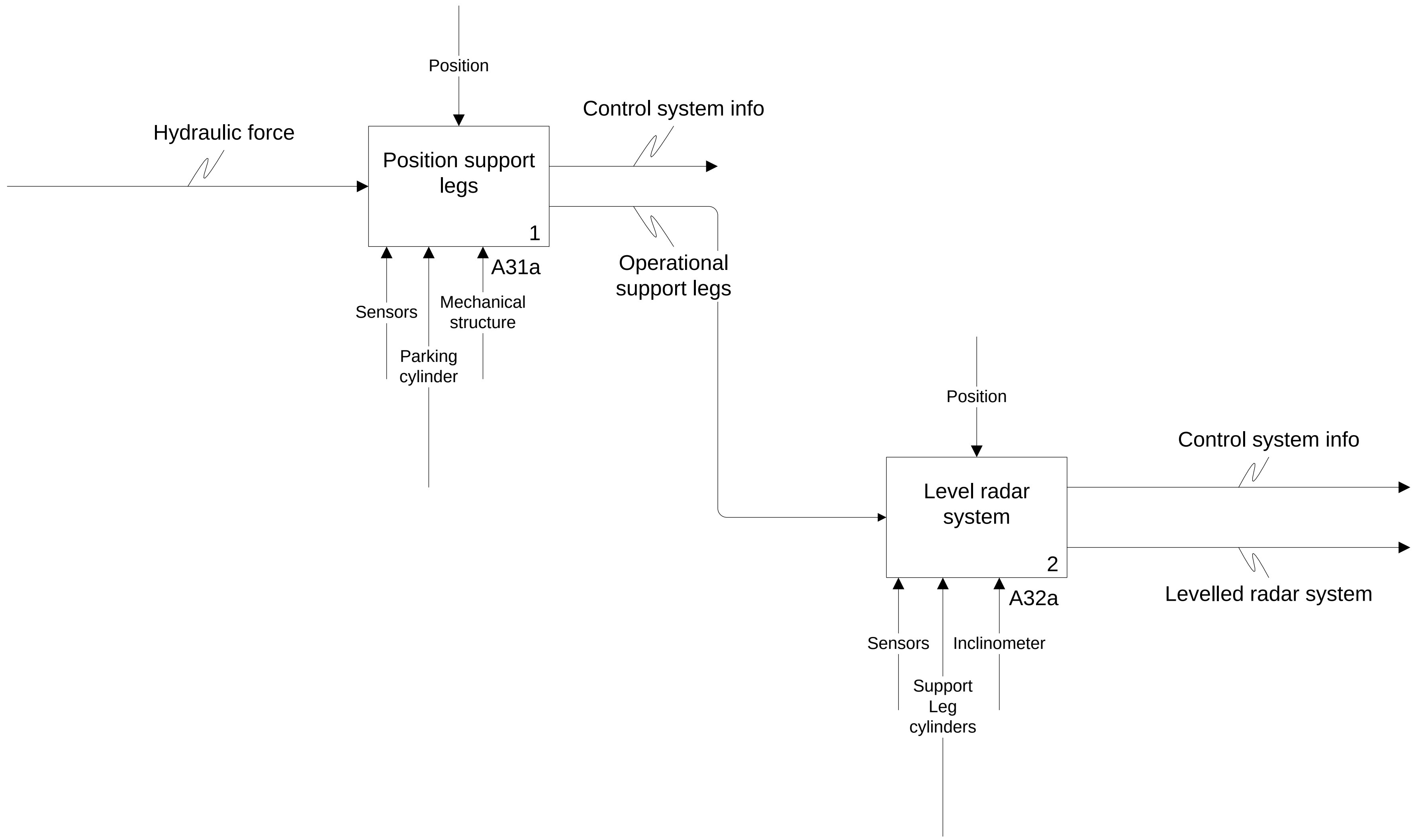

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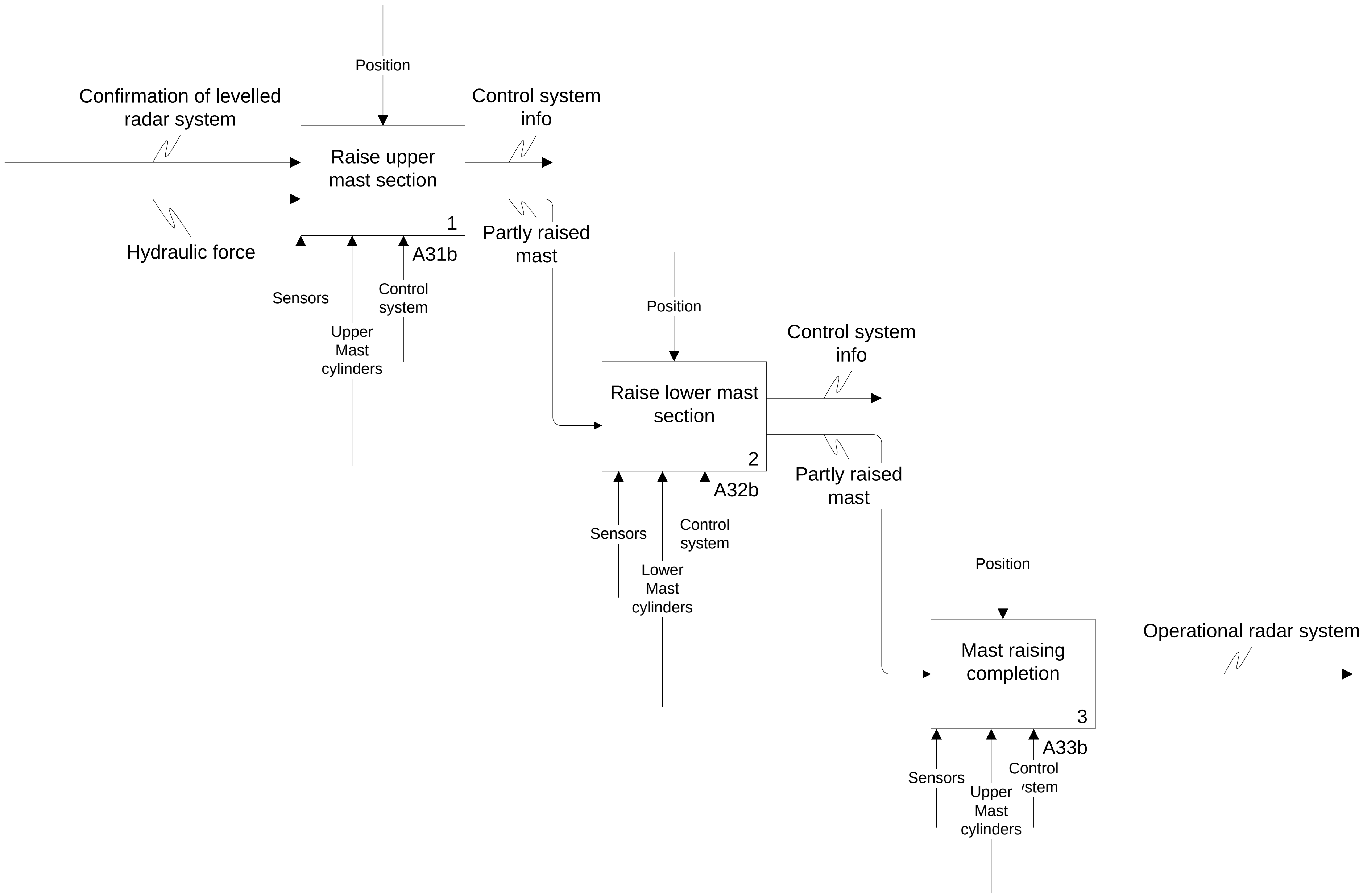
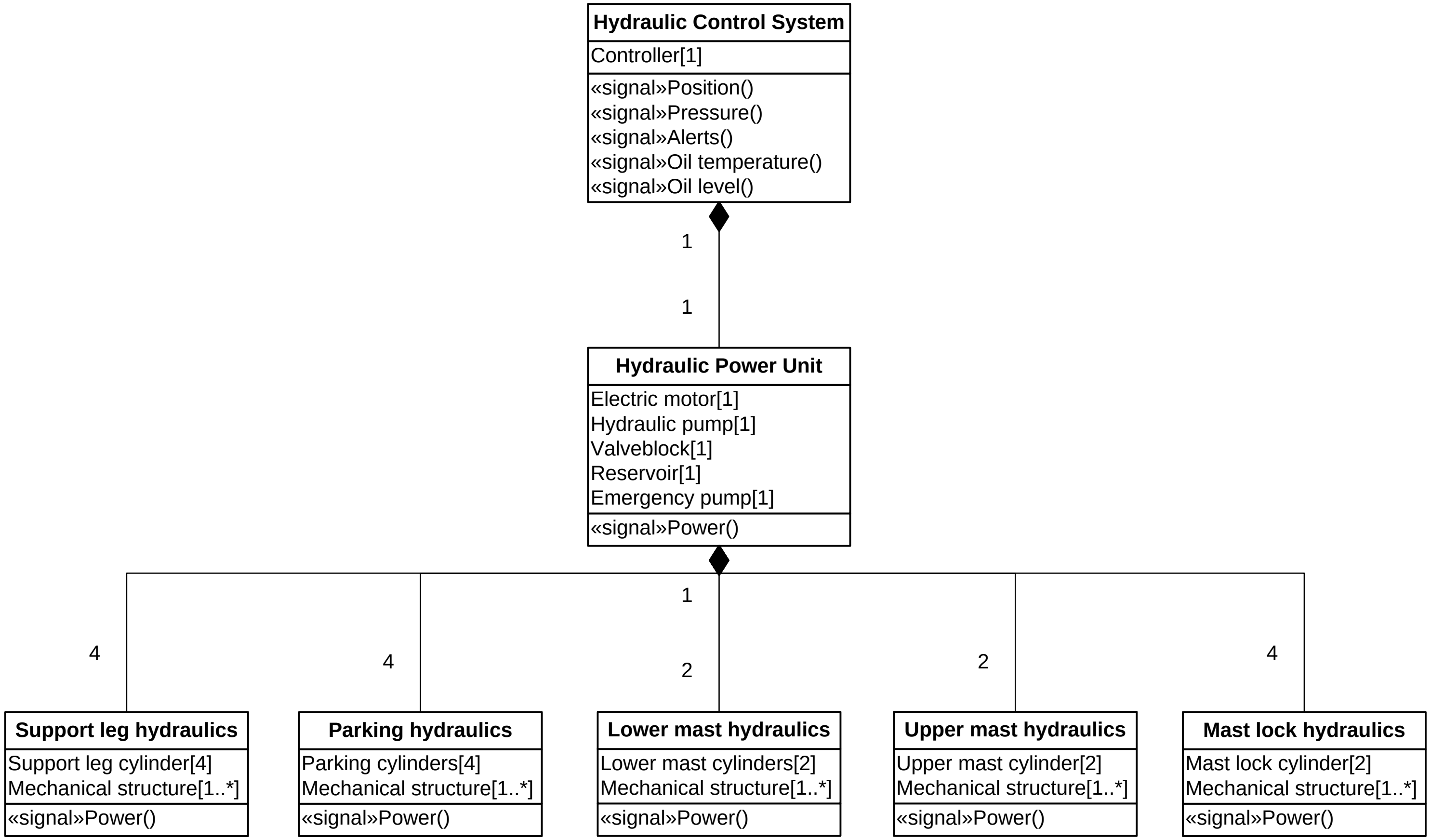


NODE: A3	TITLE: Mast operation	NO.: 2

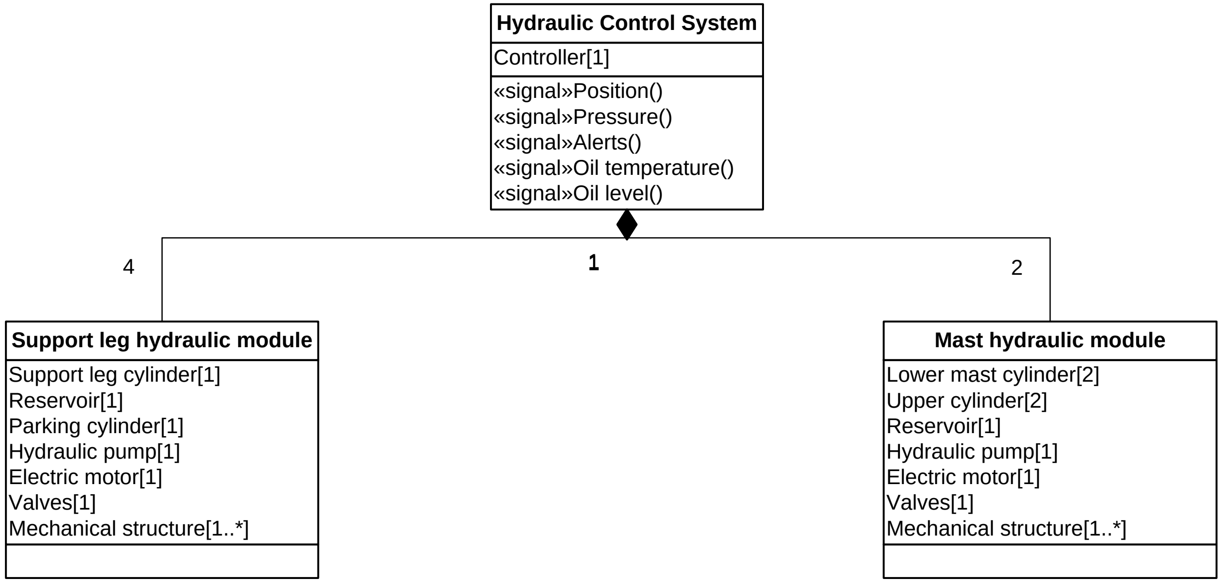
System architecture – Giraffe GAMB hydraulic system

Wednesday, May 25, 2011



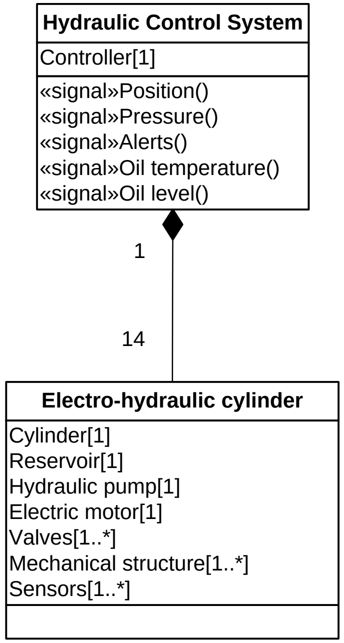
System architecture – Distributed hydraulic system

Wednesday, May 25, 2011



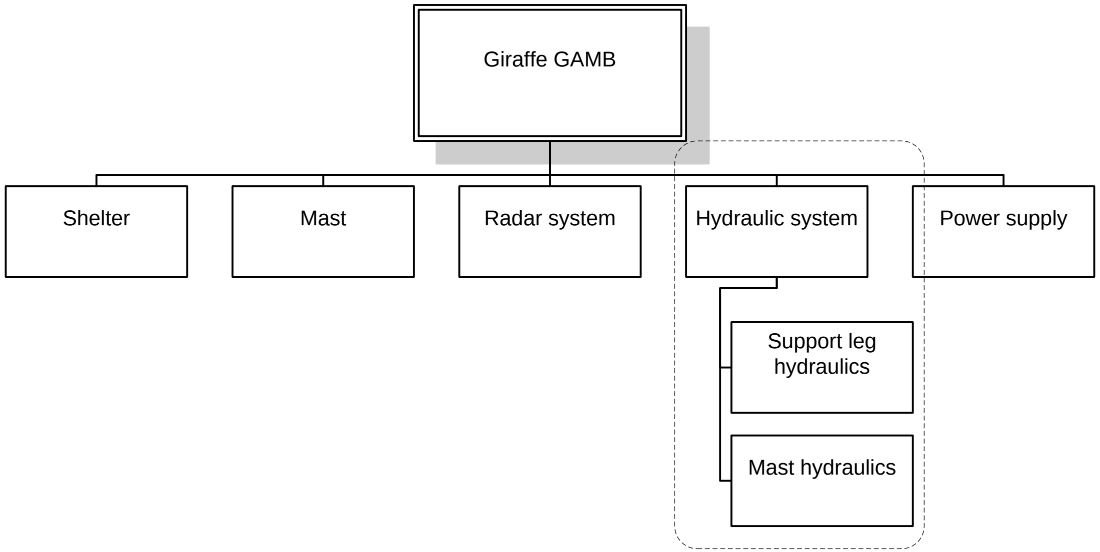
System architecture – Distributed hydraulic system

Wednesday, May 25, 2011



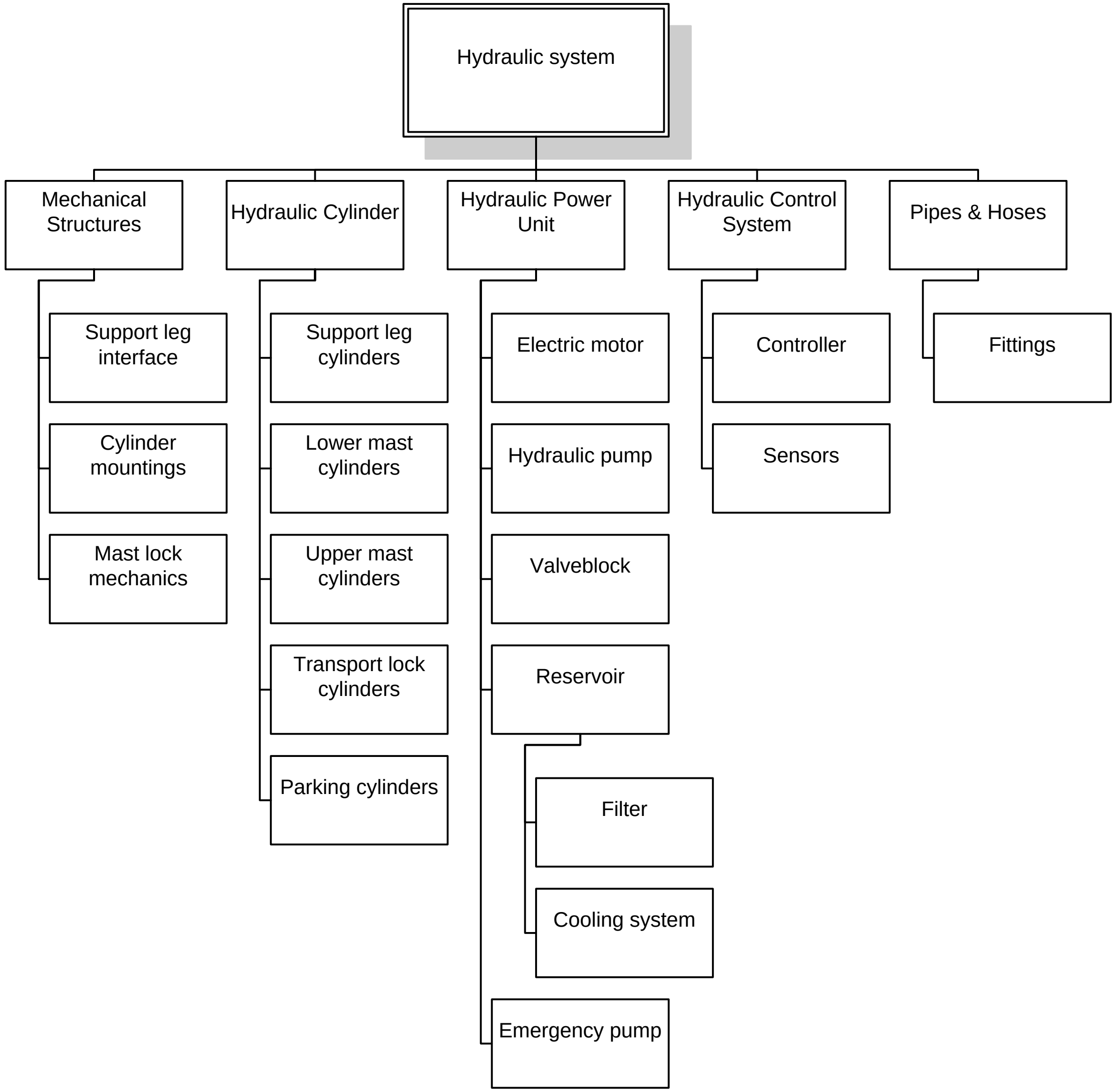
System architecture - Giraffe GAMB

Wednesday, May 25, 2011



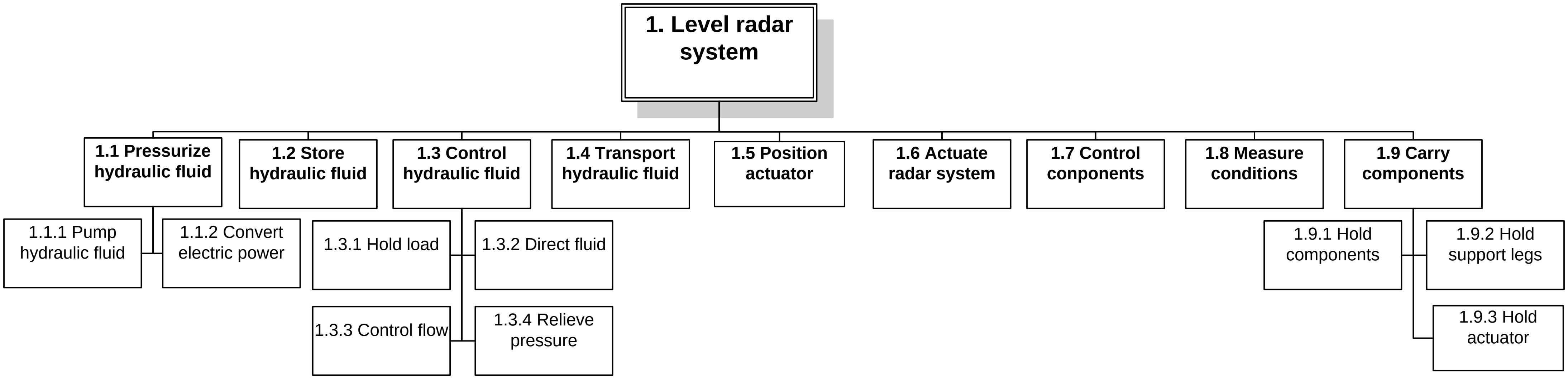
System architecture – Hydraulic system

Wednesday, May 25, 2011



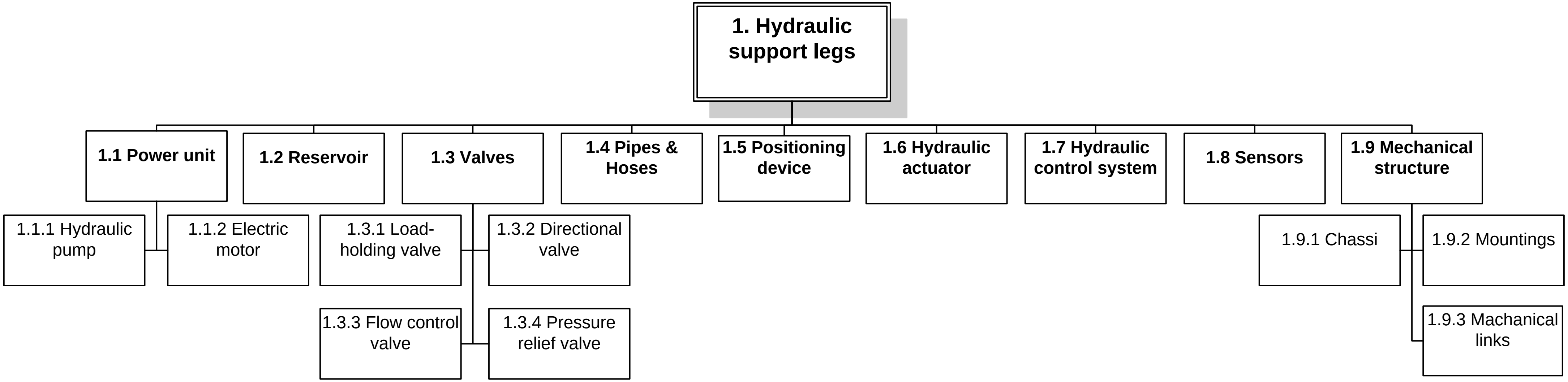
Functional requirements – Support leg unit

Wednesday, May 25, 2011



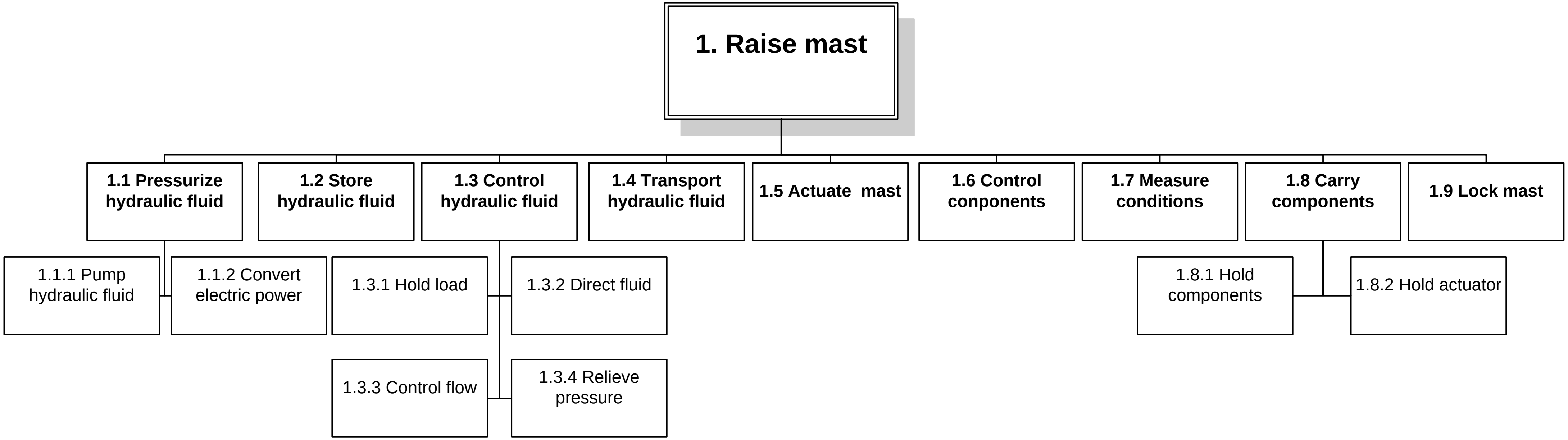
Design parameters – Support leg unit

Wednesday, May 25, 2011



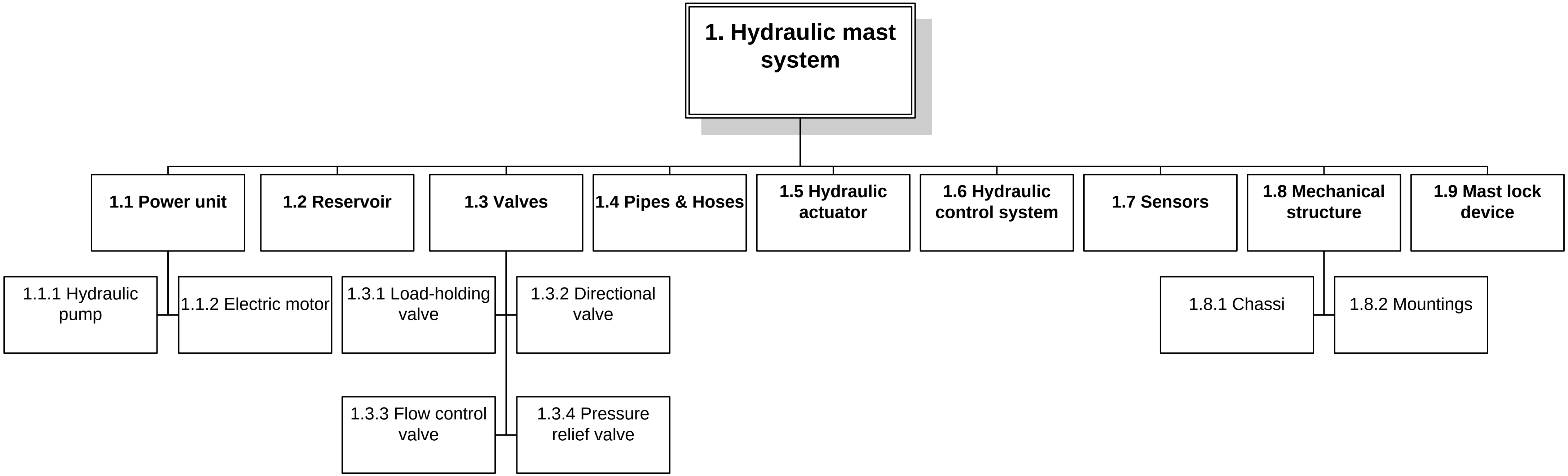
Functional requirements – Mast unit

Wednesday, May 25, 2011



Design parameters – Mast unit

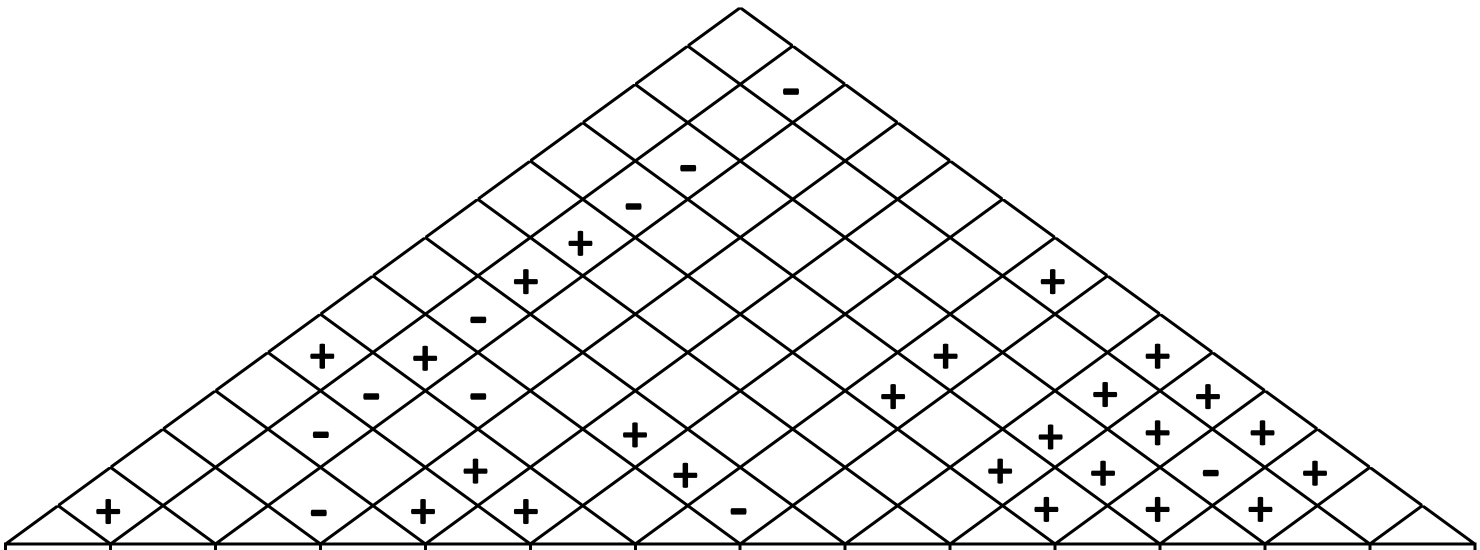
Wednesday, May 25, 2011



Quality Function Deployment

Correlation
+ Positive correlation (Supportive)
- Negative correlation (Counteracting/Trade-off)

Dependency matrix



Link
9 Strong
3 Medium
1 Weak
- None

Customer requirements \ Design criterias	Weight	Component weights	System cost	Stroke speed	Component temperature intervals	Component robustness	Material	System power requirement	Cylinder perssure	Installation time	Maintenance & service time	Degree of distribution	Control system configuration	Degree of number of components	Emergency control configuration
Customer requirements	**Weight**	kg	SEK	mm/s	[]°C	-	-	W	bar	h	h	%	-	%	-
No weight increase	5	9	3	1		1	9		1	1	1	9	1	3	1
No cost increase	3	3	9	3	9	9	9	3	3	3	3	9	9	9	3
No increase in deployment time	4	3		9	3			9	3			3	9		1
Temperature resistant	5		3	1	9	3	9		3						
Shock resistant	5	3	3			9	9								
Corrosion resistant	5		3			3	9				1		1		1
No increase in power consumption	3	9	3	3	3			9	9		1	9	1		3
Withstand GAMB specified forces	5	9		3	3	3		9	9		1	1		1	9
Easy installation	4	3	1						1	9		9	9	3	3
Easy maintenance & service	4	3	1		1				1		9	9	9	3	3
Modular solution	4	1	3							9	9	9	3	9	3
Easy controls	4		3	3	3						3	3	9	1	1
Lower complexity	4	1	3		3					9	9	9	9	9	3
Emergency operation possible	5		3					3	1			3	9		9
Goal values		≤ Ref.	≤ Ref.	= Ref.	-46 to +72° C	≥ Ref.		≤ Ref.	= Ref.	≤ Ref.	≤ Ref.	≥ 30 %	CAN bus	< Ref	
Technical weighting (link x weight)		185	155	91	136	122	207	132	126	122	147	287	277	147	174
Rank		**4**	**6**	14	9	12	**3**	10	11	12	7	**1**	**2**	7	**5**

Top 6	
Degree of distribution	≥ 30 %
Control system configuration	CAN bus
Material	*
Component weight	≤ Ref.
Emergency control configuration	*
System cost	≤ Ref.

Appendix III - Risk Analysis

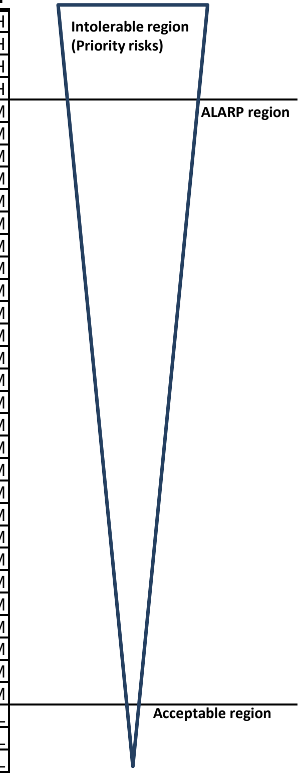
FMEA - Operator safety

	Failure mode	Effects	Causes	Initial risk estimation: Severity (1-5)	Probability (1-5)	Detectability (1-5)	RPN	Risk class	Action
1. Operator safety									
1.1	Moving the power pack	Crushing injuries from dropped power pack	Breakage on lifting/moving equipment when lifting and moving the aggregate during installation and service	6	2	7	84	L	Follow user instructions, use provided tools
1.2	Lifting the power pack	Crushing injuries from dropped power pack	Power pack is dropped because of insufficient mechanical strength in fastens	6	2	7	84	L	Follow user instructions, calculate mechanical strength on fastens
1.3	Working close to sharp edges	Cutting injuries	Cutting on sharp edges/points on metal sheets	4	7	3	84	M	Avoid sharp edges, protect sharp edges
1.4	Working close to electrical equipment	Electrical shocks, injiries	Electrical shocks from equipment	8	5	4	160	M	Hide electronic equipment
1.5	Hot equipment close to operators	Burn injuries	Burn injuries from hot equipment	4	6	4	96	M	Hide hot equipment
1.6	Working close to noisy equipment	Hearing injuries	Noisy equipment installed close to operator	6	6	2	72	M	Place away from operational position, use noise reduction materials
1.7	Working close to noisy equipment	Hearing injuries	Lack of sound-proofing	6	2	2	24	L	Place away from operational position, use noise reduction materials
1.8	Deployment in conjunction with people	Crushing injuries from support leg	Misunderstanding between operators	9	3	3	81	M	Communicate during deployment, use predetermined positions
1.9	Deployment in conjunction with people	Crushing injuries from support leg	Support leg moves unexpected due to mechanical failure	9	2	7	126	M	Check design with experts
1.10	Deployment in conjunction with people	Crushing injuries from support leg	Support leg moves unexpected due to hydraulic failure (broken pips, hoses or couplings)	9	2	7	126	M	Check design with experts
1.11	Deployment in conjunction with people	Crushing injuries from support leg	Support leg moves unexpected due to control system failure	9	2	7	126	M	Check design with experts
1.12	Deployment in conjunction with people	Crushing injuries from support leg	Lack of experience/education	9	2	3	54	M	Educate operators
1.13	Working close to the shelter and support leg cylinder collapses	Crushing injuries from shelter	Mechanical failure and shelter tips over	10	2	9	180	M	Check design with experts
1.14	Working close to the shelter and support leg cylinder collapses	Crushing injuries from shelter	Hydraulic failure and shelter tips over	10	2	9	180	M	Check design with experts
1.15	Working close to the shelter and support leg cylinder collapses	Crushing injuries from shelter	Control system failure and shelter tips over	10	2	9	180	M	Check design with experts
1.16	Troubleshoot the hydraulic system	Pinhole leak injuries	Searching for leakage with bare hands	9	5	3	135	H	Educate operators and maintenance staff about the risks, always use approved gloves
1.17	Maintain the hydraulic system	Pinhole leak injuries	Searching for leakage with bare hands	9	5	3	135	H	Educate operators and maintenance staff about the risks, always use approved gloves
1.18	Maintaining pressurized hydraulic system	Human injuries	Suddenly released potential energy	9	7	4	252	H	Educate operators and maintenance staff about the risks, never work with a pressurized system
1.19	Maintain the hydraulic system	Polluted by oil	Contact or inhalation of second hand polluted hydraulic oil	7	2	8	112	M	Educate operators and maintenance staff about the risks with second hand oil

	Failure mode	Effects	Causes	Initial risk estimation: Severity (1-5)	Probability (1-5)	Detectability (1-5)	RPN	Risk class	Action
1.20	Working close to a pressurized hydraulic system	Human injuries	Pressurized hydraulic accumulators brakes or potential energy is suddenly released	8	2	9	144	M	Educate operators and maintenance staff about the risks, never work with a pressurized system
1.21	Working in contact to the hydraulic systems	Polluted by oil	Contact or inhalation of second hand polluted hydraulic oil	7	2	8	112	M	Educate operators and maintenance staff about the risks with second hand oil
1.22	Working in conjunction with the hydraulic system	Human injuries related to fall	Slip, fall or stumble because of oil leakage	5	5	4	100	M	Minimize oil leakage, use warning signs and marks, inform the importance of being careful around hydraulic systems
1.23	Working in conjunction with the hydraulic system	Human injuries	Unpredictable failures because of wrong dimensioning or installing	8	5	8	320	M	Follow all the instructions and recommendations from manufactures and test run the equipment before installing
1.24	Working on top of the shelter	Human injuries from moving mast	Safety switch does not work (Wrong mounted/installed)	8	3	9	216	M	Test safety switch regularly
1.25	Working on top of the shelter	Human injuries from moving mast	Safety switch is broken	8	2	9	144	M	Test safety switch regularly
1.26	Working on top of the shelter	Human injuries from moving mast	Misunderstanding between operators	8	4	9	288	M	Always communicate before operation
1.27	Working on top of the shelter	Human injuries from moving mast	Hydraulic control system failure	8	2	9	144	M	Check design with experts
1.28	Working on top of the shelter	Human injuries from moving mast	Hydraulic system failure	8	2	9	144	M	Check design with experts
1.29	Working on top of the shelter	Human injuries from moving mast	Mechanical structure failure	8	2	9	144	M	Check design with experts
1.30	Operating the hydraulic system	Human injuries from moving hydraulics	Inexperienced operators	8	4	2	64	M	Educate operators
1.31	Operating the hydraulic system	Human injuries from moving hydraulics	Alienage people comes too close when system is operating	8	5	3	120	M	Use safety markings and signals when operating
1.32	Alienage people comes to close when system is operating	Human injuries from moving hydraulics	Lack of safety markings and signals	8	6	2	96	M	Use safety markings and signals when operating
1.33	Oil leakage in the hydraulic system	Human injuries from fire/explosion	Fire from oil mist	9	2	6	108	M	Use safety markings and signals when operating
1.34	Oil leakage in the hydraulic system	Human injuries from fire/explosion	Accumulator explosion in case of fire	9	7	3	189	H	Use safety markings and signals when operating

Risk Classification - Operator Safety

No.			Failure mode	RPN
1.16	Troubleshoot the hydraulic system	due to	Searching for leakage with bare hands	H
1.17	Maintain the hydraulic system	due to	Searching for leakage with bare hands	H
1.18	Maintaining pressurized hydraulic system	due to	Suddenly released potential energy	H
1.34	Oil leakage in the hydraulic system	due to	Accumulator explosion in case of fire	H
1.3	Working close to sharp edges	due to	Cutting on sharp edges/points on metal sheets	M
1.4	Working close to electrical equipment	due to	Electrical shocks from equipment	M
1.5	Hot equipment close to operators	due to	Burn injuries from hot equipment	M
1.6	Working close to noisy equipment	due to	Noisy equipment installed close to operator	M
1.8	Deployment in conjunction with people	due to	Misunderstanding between operators	M
1.9	Deployment in conjunction with people	due to	Support leg moves unexpected due to mechanical failure	M
1.10	Deployment in conjunction with people	due to	Support leg moves unexpected due to hydraulic failure (broken pips, hoses or couplings)	M
1.11	Deployment in conjunction with people	due to	Support leg moves unexpected due to control system failure	M
1.12	Deployment in conjunction with people	due to	Lack of experience/education	M
1.13	Working close to the shelter and support leg cylinder collapses	due to	Mechanical failure and shelter tips over	M
1.14	Working close to the shelter and support leg cylinder collapses	due to	Hydraulic failure and shelter tips over	M
1.15	Working close to the shelter and support leg cylinder collapses	due to	Control system failure and shelter tips over	M
1.19	Maintain the hydraulic system	due to	Contact or inhalation of second hand polluted hydraulic oil	M
1.20	Working close to a pressurized hydraulic system	due to	Pressurized hydraulic accumulators brakes or potential energy is suddenly released	M
1.21	Working in contact to the hydraulic systems	due to	Contact or inhalation of second hand polluted hydraulic oil	M
1.22	Working in conjunction with the hydraulic system	due to	Slip, fall or stumble because of oil leakage	M
1.23	Working in conjunction with the hydraulic system	due to	Unpredictable failures because of wrong dimensioning or installing	M
1.24	Working on top of the shelter	due to	Safety switch does not work (Wrong mounted/installed)	M
1.25	Working on top of the shelter	due to	Safety switch is broken	M
1.26	Working on top of the shelter	due to	Misunderstanding between operators	M
1.27	Working on top of the shelter	due to	Hydraulic control system failure	M
1.28	Working on top of the shelter	due to	Hydraulic system failure	M
1.29	Working on top of the shelter	due to	Mechanical structure failure	M
1.30	Operating the hydraulic system	due to	Inexperienced operators	M
1.31	Operating the hydraulic system	due to	Alienage people comes too close when system is operating	M
1.32	Alienage people comes to close when system is operating	due to	Lack of safety markings and signals	M
1.33	Oil leakage in the hydraulic system	due to	Fire from oil mist	M
1.1	Moving the power pack	due to	Breakage on lifting/moving equipment when lifting and moving the aggregate during installation and service	L
1.2	Lifting the power pack	due to	Power pack is dropped because of insufficient mechanical strength in fastens	L
1.7	Working close to noisy equipment	due to	Lack of sound-proofing	L



Risk Classification Matrix - Operator Safety

Severity \ Probability	1	2-3	4-6	7-8	9-10
1	1(L)	2(L)	4(L)	7(L)	11(M)
2-3	3(L)	5(L)	8(L)	12(M)	16(M)
4-6	6(L)	9(L)	13(M)	17(M)	20(H)
7-8	10(L)	14(M)	18(M)	21(H)	23(H)
9-10	15(M)	19(M)	22(H)	24(H)	25(H)

Risk index	Actions required	Risk level
1-10	Risk can be accepted	Low(L)
10-19	Must be reduced	Medium(M)
20-25	Riquires priority actions	High(H)

Risk Priority Ranking - Operator Safety

No.	Failure mode			RPN
1.23	Working in conjunction with the hydraulic system	due to	Unpredictable failures because of wrong dimensioning or installing	320
1.26	Working on top of the shelter	due to	Misunderstanding between operators	288
1.18	Maintaining pressurized hydraulic system	due to	Suddenly released potential energy	252
1.24	Working on top of the shelter	due to	Safety switch does not work (Wrong mounted/installed)	216
1.34	Oil leakage in the hydraulic system	due to	Accumulator explosion in case of fire	189
1.13	Working close to the shelter and support leg cylinder collapses	due to	Mechanical failure and shelter tips over	180
1.14	Working close to the shelter and support leg cylinder collapses	due to	Hydraulic failure and shelter tips over	180
1.15	Working close to the shelter and support leg cylinder collapses	due to	Control system failure and shelter tips over	180
1.4	Working close to electrical equipment	due to	Electrical shocks from equipment	160
1.20	Working close to a pressurized hydraulic system	due to	Pressurized hydraulic accumulators brakes or potential energy is suddenly released	144
1.25	Working on top of the shelter	due to	Safety switch is broken	144
1.27	Working on top of the shelter	due to	Hydraulic control system failure	144
1.28	Working on top of the shelter	due to	Hydraulic system failure	144
1.29	Working on top of the shelter	due to	Mechanical structure failure	144
1.16	Troubleshoot the hydraulic system	due to	Searching for leakage with bare hands	135
1.17	Maintain the hydraulic system	due to	Searching for leakage with bare hands	135
1.9	Deployment in conjunction with people	due to	Support leg moves unexpected due to mechanical failure	126
1.10	Deployment in conjunction with people	due to	Support leg moves unexpected due to hydraulic failure (broken pips, hoses or couplings)	126
1.11	Deployment in conjunction with people	due to	Support leg moves unexpected due to control system failure	126
1.31	Operating the hydraulic system	due to	Alienage people comes too close when system is operating	120
1.19	Maintain the hydraulic system	due to	Contact or inhalation of second hand polluted hydraulic oil	112
1.21	Working in contact to the hydraulic systems	due to	Contact or inhalation of second hand polluted hydraulic oil	112
1.33	Oil leakage in the hydraulic system	due to	Fire from oil mist	108
1.22	Working in conjunction with the hydraulic system	due to	Slip, fall or stumble because of oil leakage	100
1.5	Hot equipment close to operators	due to	Burn injuries from hot equipment	96
1.32	Alienage people comes to close when system is operating	due to	Lack of safety markings and signals	96
1.1	Moving the power pack	due to	Breakage on lifting/moving equipment when lifting and moving the aggregate during installation and service	84
1.2	Lifting the power pack	due to	Power pack is dropped because of insufficient mechanical strength in fastens	84
1.3	Working close to sharp edges	due to	Cutting on sharp edges/points on metal sheets	84
1.8	Deployment in conjunction with people	due to	Misunderstanding between operators	81
1.6	Working close to noisy equipment	due to	Noisy equipment installed close to operator	72
1.30	Operating the hydraulic system	due to	Inexperienced operators	64
1.12	Deployment in conjunction with people	due to	Lack of experience/education	54
1.7	Working close to noisy equipment	due to	Lack of sound-proofing	24

FMEA - System reliability

	Failure mode	Effect: Local	Effect: Higher level	Effect: End	Causes	Indications	Safeguards	S	P	D	RPN	Action
1. Machine												
	Pump											
1.1	Pump fails to function	No oil flow	Pressure drop	Cylinders changes position	Electrical failure, overload, heat; wear	Power (current), temperature	Electrical safeguard (switch); Alarm	7	3	5	**105**	Position in enclosed space; Use electrical safeguard; Periodical maintenance; Design for effective cooling.
1.2	Pump fails to function	No oil flow	Pressure drop	Cylinders changes position	Mechanical failure, overload, heat, dirt, wear	Pressure, flow, temperature	Pressure sensors; Temperature sensors; Filters	7	3	6	**126**	Position in enclosed space; Use sensors to control properties; Periodical maintenance; Change/clean filters schematically
1.3	Pump fails to function	No oil flow	Pressure drop	Cylinders changes position	Inadequate maintenance	Irregular/varying operation	Maintenance protocols	7	4	5	**140**	Perform maintenance periodically and use maintenance protocols/checklists
	Electric motor											
1.4	Electric motor fails to function	Pump can not operate	Pressure drop	Cylinders changes position	Electrical failure, overload, heat, wear	Power (current), temperature	Electrical safeguard (switch); Alarm	7	3	6	**126**	Position in enclosed space; Use electrical safeguard; Periodical maintenance; Design for effective cooling.
1.5	Electric motor fails to function	Pump can not operate	Pressure drop	Cylinders changes position	Mechanical failure, overload, heat, wear	Rpm, temperature	Temperature sensors; Rpm control	7	3	5	**105**	Position in enclosed space; Use sensors to control properties; Perform periodical maintenance
1.6	Electric motor fails to function	Pump can not operate	Pressure drop	Cylinders changes position	Inadequate maintenance	Irregular/varying operation	Maintenance protocols	7	4	5	**140**	Perform maintenance periodically and use maintenance protocols/checklists
1.7	Irregular operation of electric motor	Pump will operate irregular	Improper control of flow	Unstable operation of hydraulic system	Loose electrical contact	Irregular/varying operation	Alarm; Design; Maintenance protocols	5	6	6	**180**	Use quality connections; Protect/enclose cables and connections; Periodical maintenance; Show alarm to operator
1.8	Irregular operation of electric motor	Pump will operate irregular	Improper control of flow	Unstable operation of hydraulic system	Irregular power supply	Irregular/varying operation	Alarm; Design; Maintenance protocols	5	2	3	**30**	Use electrical safeguard; Periodical maintenance; Show alarm to operator
1.9	Irregular operation of electric motor	Pump will operate irregular	Improper control of flow	Unstable operation of hydraulic system	Inadequate maintenance	Irregular/varying operation	Maintenance protocols	5	5	5	**125**	Perform maintenance periodically and use maintenance protocols/checklists

	Failure mode	Effect: Local	Effect: Higher level	Effect: End	Causes	Indications	Safeguards	S	P	D	RPN	Action
	Control system											
1.10	Control system malfunction	Incorrect / no signals are sent / translated	Incorrect operation properties	Hydraulic system can not operate properly	Incorrect programming	Irregular/Incorrect operation	Testing	8	2	2	**32**	Use testing protocols/checklists
1.11	Control system malfunction	Incorrect / no signals are sent / translated	Incorrect operation properties	Hydraulic system can not operate properly	Incorrect configuration of sensors	Irregular/Incorrect operation	Testing	8	4	3	**96**	Use testing protocols/checklists
1.12	Control system malfunction	Incorrect / no signals are sent / translated	Incorrect operation properties	Hydraulic system can not operate properly	Connection play (bad/no electrical contact)	Irregular/Incorrect operation	Alarm; Design; Maintenance protocols	8	5	4	**160**	Use quality connections; Protect/enclose cables and connections; Periodical maintenance; Show alarm to operator
1.13	Control system malfunction	Incorrect / no signals are sent / translated	Incorrect operation properties	Hydraulic system can not operate properly	Inadequate diagnostics/maintenance	Irregular/Incorrect operation	Maintenance protocols	8	4	5	**160**	Perform maintenance periodically and use maintenance protocols/checklists
1.14	Control system failure	No signals are sent / recieved	No information transfer in hydraulic system	Hydraulic system can not operate	Electrical failure, overload, heat	System down	Electrical safeguard (switch); Alarm	7	4	5	**140**	Use electrical safeguard; Periodical maintenance; Design for effective cooling.
1.15	Control system failure	No signals are sent / recieved	No information transfer in hydraulic system	Hydraulic system can not operate	Control system component failure	System down	Alarm; Maintenance protocols	7	5	6	**210**	Perform periodical maintenance; Show alarm to operator
1.16	Control system failure	No signals are sent / recieved	No information transfer in hydraulic system	Hydraulic system can not operate	Inadequate diagnostics/maintenance	System down	Maintenance protocols	7	5	6	**210**	Perform maintenance periodically and use maintenance protocols/checklists
	Cylinder											
1.17	Cylinder breaks	Oil leaks out	Cylinder pressure is lost	Cylinder can not hold load	Overpressure	Pressure measurements	Valves, pressure sensors	9	2	3	**54**	Use pressure relief valves; Use pressure sensors fo cylinder
1.18	Cylinder lose pressure	Cylinder can not hold load	Oil flows back due to back-loading	Unstable shelter and breakage of hydraulic components	Leakage (Broken coupling/hose/pipes/seals; Mechanical play)	Pressure measurements	Valves, pressure sensors	7	4	6	**168**	Use pressure sensors for cylinder; Use overcenter valves
	Reservoir											
1.19	Reservoir breaks	Oil leaks out	No oil is available to the pump	Cylinders can not get actuated	Corrosion or other environmental wear	Visible damage	Coating	7	7	7	**343**	Position in enclosed space; Treat reservoir for corrosion: Perform periodical maintenance
1.20	Reservoir breaks	Oil leaks out	No oil is available to the pump	Cylinders can not get actuated	Badly mounted / breakage of couplings	Load/Pressure	Mounting instructions, design	7	5	4	**140**	Use quality couplings; Follow follow supplier instructions in design; Perform periodical maintenance; Test solution
1.21	Reservoir breaks	Oil leaks out	No oil is available to the pump	Cylinders can not get actuated	Inadequate maintenance	Visible damage	Maintenance protocols	7	5	5	**175**	Perform maintenance periodically and use maintenance protocols/checklists

	Failure mode	Effect: Local	Effect: Higher level	Effect: End	Causes	Indications	Safeguards	S	P	D	RPN	Action
	Pipes & Hoses											
1.22	Pipe/hose breakage	Oil leaks out	Pressure drops in system	Actuator loose pressure; Pump gets damaged (no oil supply)	Physical wear from movements (abrading)	Visible damage (cracks etc.)	Design, Safety valves	7	8	7	**392**	Design for movement; Follow supplier coupling instructions; Use load-holding valves/check valves
1.23	Pipe/hose breakage	Oil leaks out	Pressure drops in system	Actuator loose pressure; Pump gets damaged (no oil supply)	Inadequate maintenance	Visible damage (cracks etc.)	Maintenance protocols, Safety valves	7	5	4	**140**	Perform maintenance periodically; Use load-holding valves/check valves
	Electrical cables											
1.24	Electrical cable breakage	Electrical signals can not be transferred properly	Insufficient control of system	Unable to operate system correctly	Physical wear due to environmental effects/movements	Visible damage (cracks etc.)	Coating; Enclosure; Position	6	7	7	**294**	Use protective coating; Enclose cables; Position in unsensitive areas
1.25	Electrical cable breakage	Electrical signals can not be transferred properly	Insufficient control of system	Unable to operate system correctly	Inadequate maintenance	Visible damage (cracks etc.)	Maintenance protocols	6	5	5	**150**	Perform maintenance periodically and use maintenance protocols/checklists
	Mechanical structure											
1.26	Mechanical structure breaks	Loads can not be held	Components / subsystems collapse	Instability of radar system	Overload (badly dimensioned)	Structures bending, Initiating cracks	Mechanical calculations	9	4	4	**144**	Perform calculations in design; Model structure and test in simulaitions; Perform periodical crack/damage inspections
1.27	Mechanical structure breaks	Loads can not be held	Components / subsystems collapse	Instability of radar system	Cracks or other physical wear	Visible damage	Mechanical calculations, Inspection	9	5	5	**225**	Perform calculations in design; Model structure and test in simulaitions; Perform periodical crack/damage inspections
1.28	Mechanical structure breaks	Loads can not be held	Components / subsystems collapse	Instability of radar system	Inadequate maintenance	Visible damage	Maintenance protocols	9	5	5	**225**	Perform maintenance periodically and use maintenance protocols/checklists
	Valves											
1.29	Valve fails to function	Valve can not perform its function properly	Unstable / Inapropriate flow control	Unstable operation of hydraulic system	Internal component failure	Irregular/Incorrect operation	Maintenance protocols	6	3	5	**90**	Perform maintenance periodically and use maintenance protocols/checklists
1.30	Valve fails to function	Valve can not perform its function properly	Unstable / Inapropriate flow control	Unstable operation of hydraulic system	Interference from accretions etc. (clogging)	Irregular/Incorrect operation	Filters, Reservoir	6	4	5	**120**	Perform maintenance periodically and use maintenance protocols/checklists; Change/Clean filters
1.31	Valve fails to function	Valve can not perform its function properly	Unstable / Inapropriate flow control	Unstable operation of hydraulic system	Inadequate maintenance	Irregular/Incorrect operation	Maintenance protocols	6	5	5	**150**	Perform maintenance periodically and use maintenance protocols/checklists

	Failure mode	Effect: Local	Effect: Higher level	Effect: End	Causes	Indications	Safeguards	S	P	D	RPN	Action
	Filters											
1.32	Filter clogging	Oil can not flow properly to and from reservoir	Irregular flow rate	Unstable operation of hydraulic system	Dirt in system	Visible dirt	Filters	6	8	6	**288**	Change of filters
1.33	Filter clogging	Oil can not flow properly to and from reservoir	Irregular flow rate	Unstable operation of hydraulic system	Inadequate maintenance	Visible dirt	Maintenance protocols	6	3	5	**90**	Perform maintenance periodically and use maintenance protocols/checklists
	Seals											
1.34	Seal rupture	Oil leaks out	Pressure drops in system	Hydraulic system can not function properly	Temperature influence	Visible damage (cracks etc.)	Maintenance, new seals	6	8	5	**240**	Perform maintenance periodically and use maintenance protocols/checklists; Change seals
1.35	Seal rupture	Oil leaks out	Pressure drops in system	Hydraulic system can not function properly	Aging	Visible damage (cracks etc.)	Maintenance; new seals	6	7	3	**126**	Perform maintenance periodically and use maintenance protocols/checklists; Change seals
1.36	Seal rupture	Oil leaks out	Pressure drops in system	Hydraulic system can not function properly	Inadequate maintenance	Visible damage (cracks etc.)	Maintenance protocols	6	8	5	**240**	Perform maintenance periodically and use maintenance protocols/checklists
	Couplings											
1.37	Coupling breakage	Oil leaks out	Pressure drops in system	Hydraulic system can not function properly	Incorrect mounting	Visible damage; Pressure measurements	Design; Test	7	2	4	**56**	Design following mounting instructions provided by supplier; Test system
1.38	Coupling breakage	Oil leaks out	Pressure drops in system	Hydraulic system can not function properly	Physical wear (corrosion, violance)	Visible damage; Pressure measurements	Coating; Enclosure; Position	7	7	5	**245**	Use protective coating on components; Enlose components where possible
	Power supply											
1.39	Power loss	No power supplied to components	System can not operate	Functions cannot be performed	Electrical failure; overload, heat	Power indication	Emergency power supply	8	4	6	**192**	Perform maintenance for electrical failure periodically and use maintenance protocols/checklists

		Effect						Risk assessment				
	Failure mode	**Local**	**Higher level**	**End**	**Causes**	**Indications**	**Safeguards**	**S**	**P**	**D**	**RPN**	**Action**
2. Man												
2.1	Hose gets disconnected	Oil leaks out	Pressure drops in system	Hydraulic system can not function properly	Physical violence (accidential disconnection)	Loose hose; Oil leaking	Resistant couplings; Education	6	2	8	**96**	Use quality couplings; Design to avoid problem (hide)
2.2	System is incorrect dimensioned	Component overload	Component breaks	Hydraulic system malfunction	Unclear instructions from supplier	Irregular/Incorrect operation	Testing protocols	9	3	4	**108**	Test and verify with supplier
2.3	System is incorrect dimensioned	Component overload	Component breaks	Hydraulic system malfunction	Insufficient designer knowledge	Irregular/Incorrect operation	Education	9	3	4	**108**	Educate designers or consult experts
2.4	System is incorrect dimensioned	Component overload	Component breaks	Hydraulic system malfunction	Insufficient product testing	Irregular/Incorrect operation	Testing protocols	9	4	6	**216**	Perform tests using in depth testing protocols
2.5	System is incorrect dimensioned	Component overload	Component breaks	Hydraulic system malfunction	Incorrect assumptions	Irregular/Incorrect operation	Education	9	3	4	**108**	Educate designers or consult experts
2.6	Cylinders are improperly mounted	Unwanted loads on cylinder	Unwanted loads on mechanical structure	Cylinder/Structure breakage	Insufficient designer knowledge	Irregular/Incorrect operation	Education	8	3	4	**96**	Educate designers or consult experts
2.7	Cylinders are improperly mounted	Unwanted loads on cylinder	Unwanted loads on mechanical structure	Cylinder/Structure breakage	Unclear instructions from supplier	Irregular/Incorrect operation	Testing protocols	8	3	4	**96**	Test and verify with supplier
2.8	Cylinder pressure on rod side is not accounted for when dimensioning	Under-dimensioned cylinder	Cylinder breakage	Hydraulic system failure	Insufficient designer knowledge	Irregular/Incorrect operation	Education	8	3	4	**96**	Educate designers or consult experts
2.9	Improper coupling of pipes/hoses	Physical wear on components / Mechanical play	Coupling breakage	Oil leakage	Unclear instructions from supplier	Leaking oil	Testing protocols	6	3	4	**72**	Test and verify with supplier
2.10	Improper coupling of pipes/hoses	Physical wear on components / Mechanical play	Coupling breakage	Oil leakage	Insufficient designer knowledge	Leaking oil	Education	6	3	4	**72**	Educate designers or consult experts
2.11	Rough handling of components	Component wear	Component breaks	Hydraulic system malfunction	Inattentive/negliant service operator	Visible damage	Education	3	5	4	**60**	Educate designers or consult experts
3. Milleu												
3.1	High temperature	Improper oil viscosity	Unstable flow properties	Hydraulic system malfunction	Deployment of radar system in high temperature area	Temperature measurements	Temperature sensors; Design; Cooling system	7	9	8	**504**	Use sensors to measure temp.; Strive for heat emitting design; Use cooling system if necessary
3.2	Low temperature	Improper oil viscosity	Unstable flow properties	Hydraulic system malfunction	Deployment of radar system in low temperature area	Temperature measurements	Temperature sensors; Design; Warm-up	7	9	8	**504**	Use sensors to measure temp.; Protect components; Use heat to warm up components
3.2	Environmental wear	Wear on components	Component failure	Hydraulic system malfunction	Deployment of radar system in rough areas	System condition measurements	Sensors; Protective coating; Enclosure; Position	7	9	8	**504**	Design to protect components (enclose); Position in unsensitive area
3.3	Dirt in system	Component damage	Interference in operation properties	Hydraulic system malfunction	Deployment of radar system in sandy and dusty (rough) areas	Visible dirt	Inspection; Filters	7	7	7	**343**	Perform maintenance for electrical failure periodically and use maintenance protocols/checklists; Change/Clean filters
3.4	Vibrations	Component damage	Component failure	Hydraulic system malfunction	Power pack operation related vibrations spreads to other components (resonance)	Loose mountings; Visible damage	Design; Mountings	5	8	7	**280**	Damping design; Use quality mountings; Periodical maintenance with protocols
3.5	Moisture	Component damage	Component failure	Hydraulic system malfunction	Deployment of radar system in costal/moist areas	Visible corrosion	Inspection; Protective coating; Enclosure; Position	6	9	8	**432**	Protect components by enclosing them; Use protective treatment; Periodical maintenance/inspection with protocols

	Failure mode	Effect: Local	Effect: Higher level	Effect: End	Causes	Indications	Safeguards	S	P	D	RPN	Action
4. Measurements												
4.1	Incorrect sensor positioning	Inaccurate motion control	Improper deployment	Radar unit can not transmit properly	Incorrect sensor configuration	Visible incorrect positions; Irregular operation	Testing; Design	8	3	2	**48**	Design to ease positioning; Test system and use protocols/checklists;
4.2	Incorrect sensor positioning	Inaccurate motion control	Improper deployment	Radar unit can not transmit properly	Dust/dirt on sensor	Visible incorrect positions; Irregular operation	Inspection	8	7	7	**392**	Periodic inspection prior to start-up
4.3	Incorrect sensor positioning	Inaccurate motion control	Improper deployment	Radar unit can not transmit properly	Inadequate maintenance	Visible incorrect positions; Irregular operation	Maintenance protocols	8	2	5	**80**	Perform maintenance periodically and use maintenance protocols/checklists
4.4	Incorrect oil temperature sensing	Inaccurate flow control	Incorrect operation	Incorrect deployment	Incorrect sensor configuration	Irregular operation	Configuration protocols	6	6	3	**108**	Test configurations and verify feedback
4.5	Incorrect oil temperature sensing	Inaccurate flow control	Incorrect operation	Incorrect deployment	Broken sensor	Irregular operation	Periodical maintenance intervals; Fault signals	6	6	2	**72**	Perform periodical maintenance with protocols/checklists; Use fault signals if sensor broken
4.6	Incorrect oil level sensing	Minimum oil level missed	Air in system	Incorrect flow properties	Incorrect sensor configuration	Irregular operation	Configuration protocols	6	6	3	**108**	Test configurations and verify feedback
4.7	Incorrect oil level sensing	Minimum oil level missed	Air in system	Incorrect flow properties	Broken sensor	Irregular operation	Periodical maintenance intervals; Fault signals	6	6	2	**72**	Perform periodical maintenance with protocols/checklists; Use fault signals if sensor broken
4.8	Incorrect oil level sensing	Minimum oil level missed	Air in system	Incorrect flow properties	Dirt or other interference on/in sensor	Irregular operation	Periodical maintenance intervals; Fault signals	6	7	7	**294**	Perform periodical maintenance with protocols/checklists; Use fault signals if sensor broken
4.9	Incorrect pressure sensing	Wrong pressure in system	Incorrect operation properties	Bad operation performance	Incorrect sensor configuration	Irregular operation	Configuration protocols	6	6	3	**108**	Test configurations and verify feedback
4.10	Incorrect pressure sensing	Wrong pressure in system	Incorrect operation properties	Bad operation performance	Broken sensor	Irregular operation	Periodical maintenance intervals; Fault signals	6	6	2	**72**	Perform periodical maintenance with protocols/checklists; Use fault signals if sensor broken
4.11	Incorrect position of support leg prior to actuation	Shelter cannot be levelled properly	Mast can not be raised	Radar system can not transmit	No positioning system	Unstable radar system	Sequence control	9	8	1	**72**	Design control system for sequence control; Use sensors and feedback to control system; Test and verify system
4.12	Incorrect position of support leg prior to actuation	Shelter cannot be levelled properly	Mast can not be raised	Radar system can not transmit	Incorrect sensor configuration	Unstable radar system	Sequence control	9	5	3	**135**	Test and verify system
4.13	Mast is raised prior to levelled radar system	Instability of radar system	Radar system tips over	Damage to radar system	No positioning system	Unstable radar system	Sequence control	9	8	1	**72**	Design control system for sequence control; Use sensors and feedback to control system; Test and verify system

	Failure mode	Effect: Local	Effect: Higher level	Effect: End	Causes	Indications	Safeguards	S	P	D	RPN	Action
4.14	Mast is raised prior to levelled radar system	Instability of radar system	Radar system tips over	Damage to radar system	No sequence control system	Unstable radar system	Sequence control	9	8	1	**72**	Design control system for sequence control with feedback sensors; Test and verify system
4.15	Mast is raised prior to levelled radar system	Instability of radar system	Radar system tips over	Damage to radar system	Incorrect sensor configuration	Unstable radar system	Sequence control	9	6	3	**162**	Test and verify system
4.16	Mast is raised prior to levelled radar system	Instability of radar system	Radar system tips over	Damage to radar system	Incorrect control system configuration	Unstable radar system	Sequence control	9	6	3	**162**	Test and verify system
4.17	Mast not fastened during transport	Mast moves freely	Vibrations and shaking affects mast	Damage to mast	No transport lock function	Noise during transport	Design	6	9	2	**108**	Design lock function on mast
4.18	Support legs not fastened during transport	Support leg structure and cylinder moves freely	Vibrations and shaking affects support legs	Damage to support legs	No transport lock function	Noise during transport	Design	6	9	2	**108**	Design lock function on support legs
5. Maintenance												
5.1	Inadequate maintenance	Component wear	Component failure	Hydraulic system malfunction	Irregular maintenance intervals	Visible component wear	Periodic maintenance intervals	9	7	5	**315**	Perform maintenance periodically and with protocols/checklists
5.2	Inadequate maintenance	Component wear	Component failure	Hydraulic system malfunction	Lack of maintenance procedures	Visible component wear	Maintenance procedures	9	7	4	**252**	Conduct thorough maintenance checklists
5.3	Inadequate maintenance	Component wear	Component failure	Hydraulic system malfunction	Unclear maintenance procedures	Visible component wear	Maintenance procedures	9	6	4	**216**	Review protocols by objective part and operator (consultation)
6. Mechanisms												
6.1	Air in oil	Cavitation	Damage on components	Hydraulic system malfunction	Too high flow rate	Irregular/Incorrect operation	Filter; Flow rate design	6	7	7	**294**	Design for flow rate; Use diffusor if necessary; Change/Clean filters continously
6.2	Air in oil	Cavitation	Damage on components	Hydraulic system malfunction	Too small reservoir (oil has not time to "rest")	Irregular/Incorrect operation	Filter; Reservoir design	6	7	7	**294**	Adjust reservoir size to needed flow rate; Change/Clean filters continously
6.3	Heated oil	Changed oil viscosity	Complex control of flow properties	Hydraulic system malfunction	Too intense working cycles compared to the dimensioned components (pump, motor, reservoir)	Irregular/Incorrect operation	Design; Heat emiiting structure; Reservoir	4	7	5	**140**	Design system for low heat production; Dimension reservoir to adjust cooling
6.4	Pressure drop	Temporary operation interference	Pressure shock	Unstable cylinder operation	Inappropriate flow rate	Irregular/Incorrect operation	Design	4	9	5	**180**	Safety valves (stop valves)
6.5	Pressure drop	Temporary operation interference	Pressure shock	Unstable cylinder operation	High temperature	Irregular/Incorrect operation	Design, Cooling	4	9	5	**180**	Safety valves (stop valves)
6.6	Hysteresis	Different flow property values from same input	Irregular flow / pressure	Irregular operation	Component built-in phenomenon	Irregular/Incorrect operation	Design	4	9	5	**180**	Use components with low hysterisis

(S, P, D, RPN: Risk assessment)

Risk Priority Ranking - System Reliability

No.	Failure mode			RPN
3.1	High temperature	due to	Deployment of radar system in high temperature area	**504**
3.2	Low temperature	due to	Deployment of radar system in low temperature area	**504**
3.2	Environmental wear	due to	Deployment of radar system in rough areas	**504**
3.5	Moisture	due to	Deployment of radar system in costal/moist areas	**432**
4.2	Incorrect sensor positioning	due to	Dust/dirt on sensor	**392**
1.22	Pipe/hose breakage	due to	Physical wear from movements (abrading)	**392**
1.19	Reservoir breaks	due to	Corrosion or other environmental wear	**343**
3.3	Dirt in system	due to	Deployment of radar system in sandy and dusty (rough) areas	**343**
5.1	Inadequate maintenance	due to	Irregular maintenance intervals	**315**
6.1	Air in oil	due to	Too high flow rate	**294**
6.2	Air in oil	due to	Too small reservoir (oil has not time to "rest")	**294**
4.8	Incorrect oil level sensing	due to	Dirt or other interference on/in sensor	**294**
1.24	Electrical cable breakage	due to	Physical wear due to environmental effects/movements	**294**
1.32	Filter clogging	due to	Dirt in system	**288**
3.4	Vibrations	due to	Powerpack operation related vibrations spreads to other comp.	**280**
5.2	Inadequate maintenance	due to	Lack of maintenance procedures	**252**
1.38	Coupling breakage	due to	Physical wear (corrosion, violance)	**245**
1.34	Seal rupture	due to	Temperature influence	**240**
1.36	Seal rupture	due to	Inadequate maintenance	**240**
1.27	Mechanical structure breaks	due to	Cracks or other physical wear	**225**
1.28	Mechanical structure breaks	due to	Inadequate maintenance	**225**
5.3	Inadequate maintenance	due to	Unclear maintenance procedures	**216**
2.4	System is incorrect dimensioned	due to	Insufficient product testing	**216**
1.15	Control system failure	due to	Control system component failure	**210**
1.16	Control system failure	due to	Inadequate diagnostics/maintenance	**210**
1.39	Power loss	due to	Electrical failure; overload, heat	**192**
1.7	Irregular operation of electric motor	due to	Loose electrical contact	**180**
6.4	Pressure drop	due to	Inappropriate flow rate	**180**
6.5	Pressure drop	due to	High temperature	**180**
6.6	Hysteresis	due to	Component built-in phenomenon	**180**
1.21	Reservoir breaks	due to	Inadequate maintenance	**175**
1.18	Cylinder lose pressure	due to	Leakage (Broken coupling/hose/pipes/seals; Mechanical play)	**168**
4.15	Mast is raised prior to levelled radar system	due to	Incorrect sensor configuration	**162**
4.16	Mast is raised prior to levelled radar system	due to	Incorrect control system configuration	**162**
1.12	Control system malfunction	due to	Connection play (bad/no electrical contact)	**160**
1.13	Control system malfunction	due to	Inadequate diagnostics/maintenance	**160**
1.25	Electrical cable breakage	due to	Inadequate maintenance	**150**
1.31	Valve fails to function	due to	Inadequate maintenance	**150**
1.26	Mechanical structure breaks	due to	Overload (badly dimensioned)	**144**
6.3	Heated oil	due to	Too intense work cycles compared to dimensioned components	**140**
1.23	Pipe/hose breakage	due to	Inadequate maintenance	**140**
1.20	Reservoir breaks	due to	Badly mounted / breakage of couplings	**140**
1.14	Control system failure	due to	Electrical failure, overload, heat	**140**
1.3	Pump fails to function	due to	Inadequate maintenance	**140**
1.6	Electric motor fails to function	due to	Inadequate maintenance	**140**
4.12	Incorrect position of support leg prior to actuation	due to	Incorrect sensor configuration	**135**
1.35	Seal rupture	due to	Aging	**126**
1.4	Electric motor fails to function	due to	Electrical failure, overload, heat, wear	**126**
1.2	Pump fails to function	due to	Mechanical failure, overload, heat, dirt, wear	**126**
1.9	Irregular operation of electric motor	due to	Inadequate maintenance	**125**
1.30	Valve fails to function	due to	Interference from accretions etc. (clogging)	**120**
4.17	Mast not fastened during transport	due to	No transport lock function	**108**
4.18	Support legs not fastened during transport	due to	No transport lock function	**108**
4.9	Incorrect pressure sensing	due to	Incorrect sensor configuration	**108**
4.6	Incorrect oil level sensing	due to	Incorrect sensor configuration	**108**
4.4	Incorrect oil temperature sensing	due to	Incorrect sensor configuration	**108**
2.2	System is incorrect dimensioned	due to	Unclear instructions from supplier	**108**
2.3	System is incorrect dimensioned	due to	Insufficient designer knowledge	**108**
2.5	System is incorrect dimensioned	due to	Incorrect assumptions	**108**
1.1	Pump fails to function	due to	Electrical failure, overload, heat; wear	**105**
1.5	Electric motor fails to function	due to	Mechanical failure, overload, heat, wear	**105**

1.11	Control system malfunction	due to	Incorrect configuration of sensors	**96**
2.1	Hose gets disconnected	due to	Physical violence (accidential disconnection)	**96**
2.6	Cylinders are improperly mounted	due to	Insufficient designer knowledge	**96**
2.7	Cylinders are improperly mounted	due to	Unclear instructions from supplier	**96**
2.8	Cylinder pressure on rod side is not accounted for	due to	Insufficient designer knowledge	**96**
1.29	Valve fails to function	due to	Internal component failure	**90**
1.33	Filter clogging	due to	Inadequate maintenance	**90**
4.3	Incorrect sensor positioning	due to	Inadequate maintenance	**80**
4.5	Incorrect oil temperature sensing	due to	Broken sensor	**72**
4.7	Incorrect oil level sensing	due to	Broken sensor	**72**
4.10	Incorrect pressure sensing	due to	Broken sensor	**72**
4.11	Incorrect position of support leg prior to actuation	due to	No positioning system	**72**
4.13	Mast is raised prior to levelled radar system	due to	No positioning system	**72**
4.14	Mast is raised prior to levelled radar system	due to	No sequence control system	**72**
2.9	Improper coupling of pipes/hoses	due to	Unclear instructions from supplier	**72**
2.10	Improper coupling of pipes/hoses	due to	Insufficient designer knowledge	**72**
2.11	Rough handling of components	due to	Inattentive/negliant service operator	**60**
1.37	Coupling breakage	due to	Incorrect mounting	**56**
1.17	Cylinder breaks	due to	Overpressure	**54**
1.10	Control system malfunction	due to	Incorrect programming	**32**
1.8	Irregular operation of electric motor	due to	Irregular power supply	**30**

Variation Mode and Effect Analysis (VMEA) - System reliability

Key Product Characteristic [KPC]	Sub-KPC	KPC sensitivity to Sub-KPC [a]	No.	Noise Factor [NF]	Sub-KPC sensitivity to NF [b]	NF Variation size [c]	VRPN [$a^2 \times b^2 \times c^2$]	∑VRPN
Machine	Machine	8	1.1 - 1.3	Pump failure	9	4	82944	65044
			1.4 - 1.6	Electrical motor failure	9	4	82944	
			1.7 - 1.9	Irregular motor operation	6	4	36864	
			1.10 - 1.13	Control system malfunction	7	5	78400	
			1.14 - 1.16	Control system failure	9	4	82944	
			1.17	Cylinder breakage	9	2	20736	
			1.18	Cylinder pressure loss	7	4	50176	
			1.19 - 1.21	Reservoir breakage	9	2	20736	
			1.22 - 1.23	Pipe/Hose breakage	7	5	78400	
			1.24 - 1.25	Electrical cable breakage	7	5	78400	
			1.26 - 1.28	Mechanical structure breakage	7	4	50176	
			1.29 - 1.31	Valve malfunction	7	5	78400	
			1.32 - 1.33	Filter clogging	6	6	82944	
			1.34 - 1.36	Seal rupture	6	4	36864	
			1.37 - 1.38	Coupling breakage	7	4	50176	
			1.39	Power loss	9	5	129600	
	Man	7	2.1	Accidental hose disconnection	4	3	7056	16444
			2.2 - 2.5, 2.8	Incorrect system dimensioning	7	3	21609	
			2.6 - 2.7	Improper cylinder mounting	6	3	15876	
			2.9 - 2.10	Improper pipe/hose coupling	5	5	30625	
			2.11	Rough component handling	3	4	7056	
	Milleu	9	3.1	High temperature	8	7	254016	158099
			3.2	Low temperature	8	7	254016	
			3.3	Environmental wear	6	7	142884	
			3.4	Dirt in system	7	5	99225	
			3.5	Vibrations	5	7	99225	
			3.6	Moisture	5	7	99225	
	Measurements	8	4.1 - 4.3	Incorrect sensor positioning	9	5	129600	78048
			4.4 - 4.5	Incorrect oil temperature sensing	6	6	82944	
			4.6 - 4.8	Incorrect oil level sensing	7	6	112896	
			4.9 - 4.10	Incorrect pressure sensing	7	6	112896	
			4.11 - 4.12	Incorrect position of support leg prior to actuation	9	4	82944	
			4.13 - 4.16	Mast is raised prior to levelled radar system	9	3	46656	
			4.17	Mast not fastened for transport	7	3	28224	
			4.18	Support legs not fastened for transport	7	3	28224	
	Maintenance	7	5.1 - 5.3	Inadequate maintenance	8	7	153664	153664
	Mechanisms	7	6.1 - 6.2	Air in oil	7	7	117649	78278
			6.3	Heated oil	5	5	30625	
			6.4	Pressure drop	6	7	86436	
			6.5	Hysterisis	5	8	78400	
							Σ	549576

Sensitivity Factor Ranking - System reliability

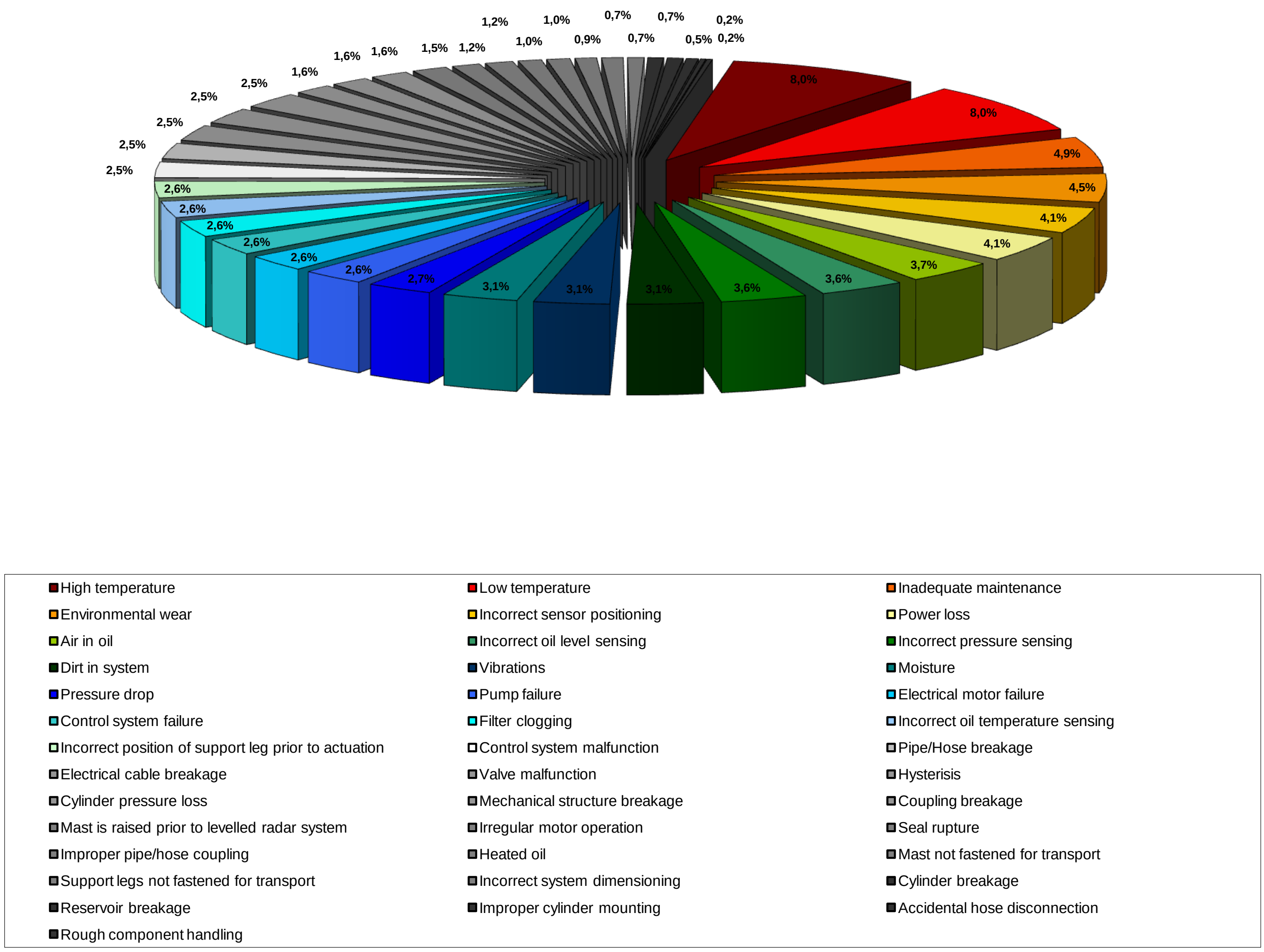
Ranked sensitivity factors

No.	Noice factor	%	VRPN
3.1	High temperature	8,03	254016
3.2	Low temperature	8,03	254016
5.1 - 5.3	Inadequate maintenance	4,86	153664
3.3	Environmental wear	4,52	142884
4.1 - 4.3	Incorrect sensor positioning	4,1	129600
1.39	Power loss	4,1	129600
6.1 - 6.2	Air in oil	3,72	117649
4.6 - 4.8	Incorrect oil level sensing	3,57	112896
4.9 - 4.10	Incorrect pressure sensing	3,57	112896
3.4	Dirt in system	3,14	99225
3.5	Vibrations	3,14	99225
3.6	Moisture	3,14	99225
6.4	Pressure drop	2,73	86436
1.1 - 1.3	Pump failure	2,62	82944
1.4 - 1.6	Electrical motor failure	2,62	82944
1.14 - 1.16	Control system failure	2,62	82944
1.32 - 1.33	Filter clogging	2,62	82944
4.4 - 4.5	Incorrect oil temperature sensing	2,62	82944
4.11 - 4.12	Incorrect position of support leg prior to actuation	2,62	82944
1.10 - 1.13	Control system malfunction	2,48	78400
1.22 - 1.23	Pipe/Hose breakage	2,48	78400
1.24 - 1.25	Electrical cable breakage	2,48	78400
1.29 - 1.31	Valve malfunction	2,48	78400
6.5	Hysterisis	2,48	78400
1.18	Cylinder pressure loss	1,59	50176
1.26 - 1.28	Mechanical structure breakage	1,59	50176
1.37 - 1.38	Coupling breakage	1,59	50176
4.13 - 4.16	Mast is raised prior to levelled radar system	1,48	46656
1.7 - 1.9	Irregular motor operation	1,17	36864
1.34 - 1.36	Seal rupture	1,17	36864
2.9 - 2.10	Improper pipe/hose coupling	0,97	30625
6.3	Heated oil	0,97	30625
4.17	Mast not fastened for transport	0,89	28224
4.18	Support legs not fastened for transport	0,89	28224
2.2 - 2.5, 2.8	Incorrect system dimensioning	0,68	21609
1.17	Cylinder breakage	0,66	20736
1.19 - 1.21	Reservoir breakage	0,66	20736
2.6 - 2.7	Improper cylinder mounting	0,5	15876
2.1	Accidental hose disconnection	0,22	7056
2.11	Rough component handling	0,22	7056
			3162675

Ranked Sub-KPC's

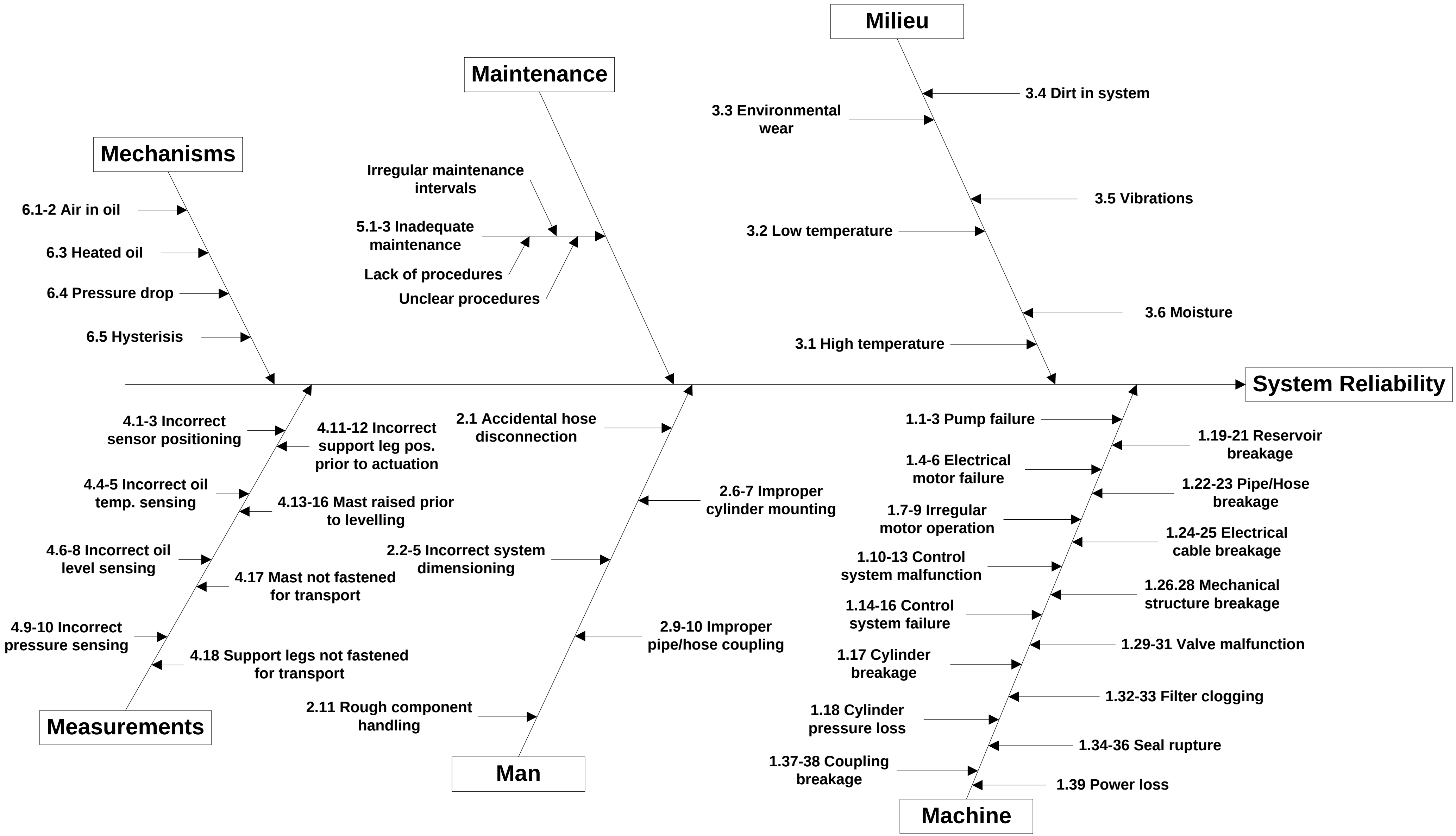
	Sub-KPC	%	ΣVRPN
	Milleu	28,8	**158099**
	Maintenance	28	**153664**
	Mechanicms	14,2	**78278**
	Measurements	14,2	**78048**
	Machine	11,8	**65044**
	Man	2,99	**16444**
		Σ	**549576**

Sensitivity factors - System reliability

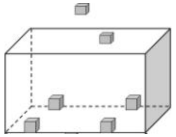
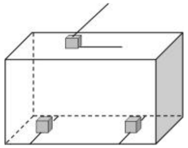
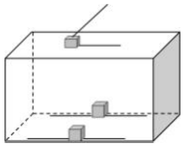
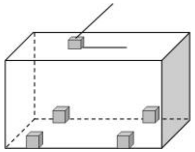
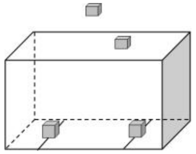
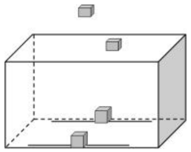
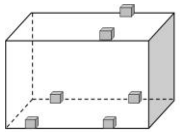
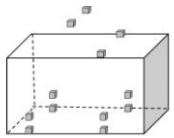
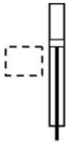
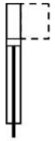


Cause and Effect Diagram (Ishikawa)

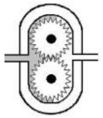
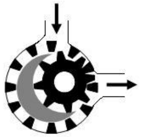
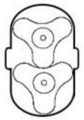
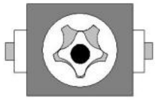
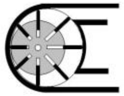
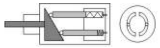
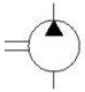
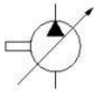
Monday, March 14, 2011

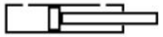
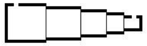
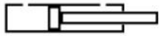
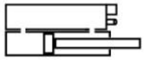
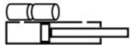
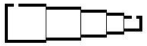
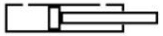
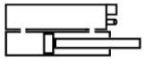
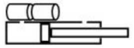
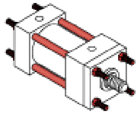
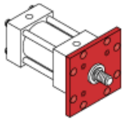
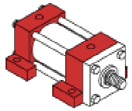
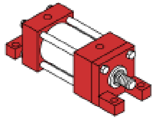
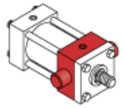
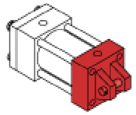
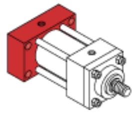
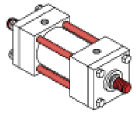


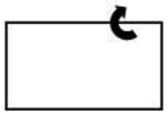
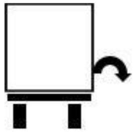
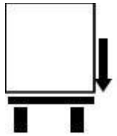
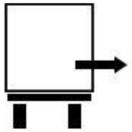
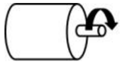
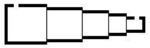
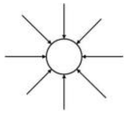
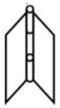
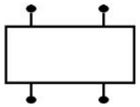
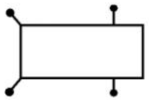
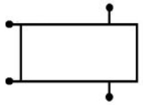
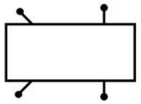
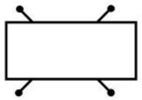
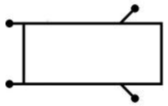
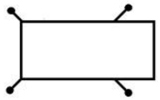
Appendix IV - Brainstorming

	Subfunction /Component	A	B	C	D	E	F	G	H	I
		List of generated alternative ideas								
1	**General**									
1.1	Hydraulic circuit	Closed	Open: Closedcenter	Open: Opencenter						
1.2	Hydraulic module distribution									
1.3	Hydraulic power unit position (support leg space)	 Side	 Above	 Beneath	 Behind	 On	Outside support leg space	Mixed positions		
1.4	Hydraulic power unit position (mast)	On side of mast	Under roof	On mast	On cylinder	Under mast	Inside shelter			
2	**Hydraulic control system**									
2.1	Control components	CANbus	Profibus	Existing						

3	**Operation controls**					
3.1	Operate system	 Remote control	 Operator panel			
3.2	Operate manually	 Hand levers	 Remote control	 Operator panel		
3.3	Emergency operation	Hand pump	Valves	Accumulator	Hydraulic pump	Portable pump unit (plug-in)
3.2	Convert electric energy	AC motor	DC motor			
3.3	Electric motor characteristics	Constant EM power & torque	Varying EM power & torque			

4	**Power unit**								
4.1	Hydraulic power unit distribution	Complete power pack	Separate positions	Power pack on cylinder (integrated)	Electro-hydrostatic actuator (EHA)				
4.2	Pump hydraulic fluid	Pump	Accumulator & Pump						
4.3	Hydraulic pump type	 External gear	 Internal gear	 Lobe	 Gerotor	 Vane	 Radial piston	 Axial piston	Accumulator + Pump
4.4	Deplacement	 Fixed	 Variable						
4.5	Convert electric power	AC motor	DC motor						
4.6	Powering hydraulic pump	Constant EM power & torque	Varying EM power & torque						

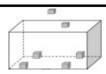
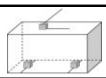
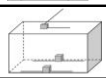
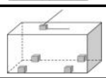
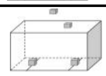
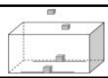
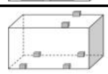
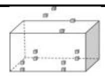
5	**Hydraulic actuator**									
5.1	Cylinder principles	 Single acting	 Double acting							
5.2	Hydraulic cylinder type	 Tie rod	 Welded							
5.3	Actuate mast	 Telescopic	 Differential	 Servo	 Duplex	 Tandem	 Rephasing	 EHA	 Integrated	 Standard
5.4	Actuate radar system	 Telescopic	 Differential	 Servo	 Duplex	 Tandem	 Rephasing	 EHA	 Integrated	 Standard
5.5	Cylinder mountings	 Tie-rod	 Flange	 Side	 Lug	 Trunnion	 Clevis	 Solid flange	 Rod-end	Special
6	**Lock/ Positioning device**									
6.1	Lock mast	Hydraulic actuator	Electrical actuator							
6.2	Position support legs	Hydraulic actuator	Electrical actuator							

7	**Reservoir**									
7.1	Store hydraulic fluid	Vacuum reservoir	Open reservoir	Closed system (no main reservoir)	Pressurized reservoir	Use extension cylinder as reservoir				
8	**Mechanical structure**									
8.1	Support leg positioning principle	 Fold sideways	 Fold down	 Push down	 Push out					
8.2	Hold support legs (mechanical link)	Folding ”Side wings”	Folding cylinder	Folding truss structure	Folding flaps	Rotating frame	Mobile crane – beam principle	Push down mechanical leg		
8.3	Positioning tools	 Rotator	 Cylinder	 Telescopic	 ”Piggyback”	 Gear rack	 Screw	 Gravity	 Sax lift	 Hinge
8.4	Support leg positions									
8.5	Mast raising principle	Existing	Telescopic cylinder & structure							

Appendix V - Evaluation & Elimination

Screening 1 - Pre-evaluation

Pre-evaluation matrix - General

	Alternatives	Reasonable reliability	Economically reasonable	Application suitability	Reasonable maintainability	Acceptable efficiency	Reasonable complexity	Acceptable accuracy	Variation flexibility	Reasonable serviceability	Reasonable space reqiorements	Further development / Elimination
		Acceptance criteria										
	Hydrauli circuit											
1.1.A	Closed	+	+	-			+					NO
1.1.B	Open - Closed center	+	+	-			+					NO
1.1.C	Open - Open center	+	+	+			+					GO
	Hydraulic module distribution											
1.2.A		+	+	+	+	+	-	+	+	+	+	NO
1.2.B		+	+	-	+	+	-	+	-	+	+	NO
1.2.C		+	+	+	+	+	+	+	+	+	+	GO
1.2.D		+	+	+	+	+	+	+	+	+	+	GO
1.2.E		+	+	-	+	+	-	+	-	+	+	NO
1.2.F		+	+	+	+	+	-	+	+	+	+	NO
1.2.G		+	+	+	+	+	+	+	+	+	+	GO
1.2.H		+	+	+	+	+	+	+	+	+	+	GO
	Hydraulic power unit position (support leg space)											
1.3.A	On the side of cylinder	+		+	+		+			+	+	GO
1.3.B	Above cylinder	+		+	+		+			+	+	GO
1.3.C	Beneath cylinder	+		+	+		+			+	+	GO
1.3.D	Behind cylinder	+		-	-		+			-	+	NO
1.3.E	On cylinder	+		+	+		+			+	+	GO
1.3.F	Outside support leg space	+		+	+		+			+	+	GO
1.3.G	Mixed positions	+		+	+		+			+	+	GO

	Hydraulic power unit position (mast)											
1.4.A	On the side of non-operational mast	+		+	+		+			+	+	GO
1.4.B	Under roof	+		+	+		+			+	+	GO
1.4.C	On mast	+		+	+		+			+	+	GO
1.4.D	On cylinder	-		-	+		+			+	+	NO
1.4.E	Under mast	+		-	-		+			-	+	NO
1.4.E	Inside shelter	+		-	+		+			+	+	NO

Pre-evaluation matrix - Hydraulic control system

		Acceptance criteria										
	Alternative	Reasonable reliability	Economically reasonable	Application suitability	Reasonable maintainability	Acceptable efficiency	Reasonable complexity	Acceptable accuracy	Variation flexibility	Reasonable serviceability	Reasonable space reqiorements	Further development / Elimination
	Function: Control components (communication interface)											
2.1.A	CANbus	+	+	+	+	+	+	+	+	+	+	GO
2.1.B	Profibus	+	+	-	+	+	+	+	+	+	+	NO
2.1.C	Existing	+	+	+	+	+	+	+	+	+	+	GO

Pre-evaluation matrix - Operation controls

	Alternative	Acceptance criteria										
		Reasonable reliability	Economically reasonable	Application suitability	Reasonable maintainability	Acceptable efficiency	Reasonable complexity	Acceptable accuracy	Variation flexibility	Reasonable serviceability	Reasonable space reqiorements	Further development / Elimination
	Function: Operate system											
3.1.A	Remote control	+	+	+	+		+	+	+	+	+	GO
3.1.B	Panel	+	+	+	+		+	+	+	+	+	GO
	Function: Operate manually											
3.2.A	Remote control	+	+	-	+		-	+	+	+	+	NO
3.2.B	Panel	+	+	-	+		+	+	+	+	+	NO
3.2.C	Levers	+	+	+	+		+	+	+	+	+	GO
3.2.D	Electronic switch/regulator	+	+	+	+		+	+	+	+	+	GO
	Function: Emergency operation											
3.3.A	Hand pump	+	+	-		-	+	-		+	+	NO
3.3.B	Valves (mast)	+	+	+		+	+	+		+	+	GO
3.3.C	Accumulator	+	+	+		+	+	+		+	+	GO
3.3.D	Hydraulic pump	+	+	+		+	+	+		+	+	GO
3.3.E	Portable pump unit (plug-in)	+	+	+		+	+	+		+	+	GO
3.3.F	Electrically driven hand pump	+	+	+		+	+	+		+	+	GO

Pre-evaluation matrix - Power unit

	Alternative	Reasonable reliability	Economically reasonable	Application suitability	Reasonable maintainability	Acceptable efficiency	Reasonable complexity	Acceptable accuracy	Variation flexibility	Reasonable serviceability	Reasonable space reqiorements	Further development / Elimination
		Acceptance criteria										
	Function: Pressurize hydraulic fluid											
4.1.A	Complete power pack	+	+	+	+	+	+		+	+	+	GO
4.1.B	Separate positions	+	+	+	+	+	+		+	+	+	GO
4.1.C	Power pack on cylinder (integrated)	+	+	+	+	+	+		+	+	+	GO
4.1.D	Electrohydrostatic actuator (EHA)	+	-	+	+	+	+		+	+	+	NO
4.1.E	Electrohydraulic pump	+	+	+	+	+	+		+	+	+	GO
	Function: Pump hydraulic fluid											
4.2.A	Pump only	+	+	+	+	+	+	+	+	+	+	GO
4.2.B	Accumulator & Pump	+	+	+	+	+	+	+	+	+	+	GO
	Pump type											
4.3.A	External gear	+	+	+		+	+	+	+		+	GO
4.3.B	Internal gear	+	+	+		+	+	+	+		+	GO
4.3.C	Lobe	+	+	-		+	+	+	+		+	NO
4.3.D	Gerotor	+	+	-		+	+	+	+		+	NO
4.3.E	Vane	+	+	-		+	+	+	+		+	NO
4.3.F	Radial piston	+	+	+		+	+	+	+		+	GO
4.3.G	Axial piston	+	+	+		+	+	+	+		+	GO
	Deplacement											
4.4.A	Fixed	+	+	+		+	+	+	+			GO
4.4.B	Variable	+	-	-		+	+	+	+			NO
	Function: Convert electric power											
4.5.A	AC motor	+	+	+	+	+	+	+	+	+	+	GO
4.5.B	DC motor	+	+	-	+	+	+	+	+	+	+	NO
	Powering pump device											
4.6.A	Constant power & torque	+	-	-		+	+	+				NO
4.6.B	Varying power & torque	+	+	+		+	+	+				GO

Pre-evaluation matrix - Hydraulic actuator

	Alternative	Acceptance criteria: Reasonable reliability	Economically reasonable	Application suitability	Reasonable maintainability	Acceptable efficiency	Reasonable complexity	Acceptable accuracy	Variation flexibility	Reasonable serviceability	Reasonable space reqiorements	Further development / Elimination
	Cylinder principle											
5.1.A	Single acting	+	+	-	+	+	+	+	-	+	+	NO
5.1.B	Double acting	+	+	+	+	+	+	+	+	+	+	GO
	Hydraulic cylinder type											
5.2.A	Tie rod	+	+	-	+	+	+	+	+	+	+	NO
5.2.B	Welded	+	+	+	+	+	+	+	+	+	+	GO
	Function: Actuate mast (cylinder variant)											
5.3.A	Telescopic	+	+	+	+			+	+	+	+	GO
5.3.B	Differential	+	+	+	+			+	+	+	+	GO
5.3.C	Servo (Electrohydraulic, EH)	+	+	+	+			+	+	+	+	GO
5.3.D	Duplex	+	+	-	+			+	+	+	+	NO
5.3.E	Tandem	+	+	-	+			+	+	+	+	NO
5.3.F	Rephasing	+	+	-	+			+	+	+	+	NO
5.3.G	Electrohydrostatic actuation, EHA	+	-	-	+			+	+	+	+	NO
5.3.H	Integrated	+	+	+	+			+	+	+	+	GO
5.3.I	Standard	+	+	+	+			+	+	+	+	GO
	Function: Actuate radar system (cylinder variant)											
5.4.A	Telescopic	-	+	-	+			+	+	+	+	NO
5.4.B	Differential	+	+	+	+			+	+	+	+	GO
5.4.C	Servo (Electrohydraulic, EH)	+	+	+	+			+	+	+	+	GO
5.4.D	Duplex	+	+	-	+			+	+	+	+	NO
5.4.E	Tandem	+	+	-	+			+	+	+	+	NO
5.4.F	Rephasing	+	+	-	+			+	+	+	+	NO
5.4.G	Electrohydrostatic actuation, EHA	+	-	-	+			+	+	+	+	NO
5.4.H	Integrated	+	+	+	+			+	+	+	+	GO
5.4.I	Standard	+	+	+	+			+	+	+	+	GO

Pre-evaluation matrix - Lock & Positioning device

	Alternative	Reasonable reliability	Economically reasonable	Application suitability	Reasonable maintainability	Acceptable efficiency	Reasonable complexity	Acceptable accuracy	Variation flexibility	Reasonable serviceability	Reasonable space reqiorements	Further development / Elimination
		Acceptance criteria										
	Function: Lock mast											
6.1.A	Hydraulic actuator	+	+	+	+	+	+	+		+	+	GO
6.1.B	Electric actuator	+	+	+	+	+	+	+		+	+	GO
	Function: Position support legs											
6.2.A	Hydraulic actuator	+	+	+	+	+	+	+		+	+	GO
6.2.B	Electric actuator	+	+	+	+	+	+	+		+	+	GO
6.2.C	Electrohydraulic cylinder (Integrated)	+	+	+	+	+	+	+		+	+	GO

Pre-evaluation matrix - Reservoir

	Alternative	Reasonable reliability	Economically reasonable	Application suitability	Reasonable maintainability	Acceptable efficiency	Reasonable complexity	Acceptable accuracy	Variation flexibility	Reasonable serviceability	Reasonable space reqiorements	Further development / Elimination
		Acceptance criteria										
	Function: Store hydraulic fluid											
7.1.A	Vacuum reservoir	+	-	-	+		-			+	+	NO
7.1.B	Open reservoir	+	+	+	+		+			+	+	GO
7.1.C	Closed system (no main reservoir)	+	+	-	+		+			+	+	NO
7.1.D	Pressurized reservoir	+	-	-	+		-			+	+	NO
7.1.E	Use extension cylinder as reservior	+	+	+	+		+			+	+	GO

Pre-evaluation matrix - Mechanical structure

	Alternative	Reasonable reliability	Economically reasonable	Application suitability	Reasonable maintainability	Acceptable mechanical prop.	Reasonable complexity	Acceptable accuracy	Variation flexibility	Reasonable serviceability	Reasonable space reqiorements	Further development / Elimination
	Support leg positioning principle											
8.1.A	Fold sideways	+	+	-		+	+		-	+	+	NO
8.1.B	Fold down	+	+	+		+	+		+	+	+	GO
8.1.C	Push down	+	+	-		+	+		+	+	+	NO
8.1.D	Push out	-	+	-		+	+		-	-	-	NO
	Function: Hold support legs											
8.2.A	"Side wings"	+	+	+		+	+		+	+	+	GO
8.2.B	Cylinder	-	+	+		-	+		+	+	+	NO
8.2.C	Truss structure	+	+	+		+	+		+	+	+	GO
8.2.D	Flaps	+	+	+		+	+		+	+	+	GO
8.2.E	Rotating frame	+	+	-		-	+		-	+	+	NO
8.2.F	Mobile crane beam principle	+	+	-		+	+		-	-	-	NO
8.2.G	Push down mechanical leg	-	+	+		-	+		+	-	+	NO
	Positioning tools											
8.3.A	Rotator	+	+	+		+	+	+	+		+	GO
8.3.B	Hydraulic cylinder	+	+	+		+	+	+	+		+	GO
8.3.C	Telescopic	-	-	-		-	-	+	+		+	NO
8.3.D	Piggyback cylinder	+	-	-		+	-	+	-		-	NO
8.3.E	Gear rack	+	+	+		+	+	+	+		+	GO
8.3.F	Electrical screw	+	+	+		+	+	+	+		+	GO
8.3.G	Gravity	-	+	-		-	+	-	-		+	NO
8.3.H	Saxlift	+	+	-		+	+	+	-		+	NO
8.3.I	Hinge	+	+	-		+	+	+	+		+	NO
	Mast raising principle											
8.5.A	Existing	+	+	+	+	+	+	+	+	+	+	GO
8.5.B	Use telescopic cylinder	-	+	-	+	+	+	+	+	+	-	NO

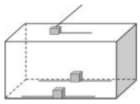
Result - Screening 1

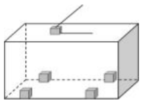
General

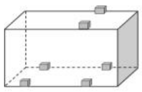
Hydrauli circuit

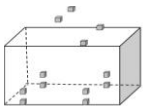
Open - Open center

Hydraulic module distribution

1 

2 

3 

4 

Hydraulic power unit position (support leg space)

On side of cylinder
Above cylinder
Beneath cylinder
On cylinder
Outside SL space
Mixed positions

Hydraulic power unit position (mast)

On the side of mast
Under roof
On mast

Hydraulic control system

Function: Control components (interface)

CANbus
Existing

Operation controls

Function: Operate system

Remote control
Panel

Function: Operate manually

Levers
Electronic switch/regulator

Function: Emergency operation

Valves (mast)
Accumulator
Hydraulic pump
Portable pump unit
Electrically driven hand pump

Power unit

Function: Pressurize hydraulic fluid

Power pack
Separate positions
EH Pump + Separate reservoir
Power pack on cylinder (Integrated)

Function: Pump hydraulic fluid

Pump only
Accumulator & Pump

Pump type

External gear
Internal gear
Radial piston
Axial piston

Deplacement

Fixed

Function: Convert electrical power (el. motor)

AC motor

Function: Powering pump device

Varying power & torque
Fixed power & torque

Hydraulic actuator

Cylinder principle

Double acting

Hydraulic cylinder type

Welded

Function: Actuate mast (cylinder variant)

Telescopic
Differential
Servo (EH)
Standard
Integrated

Function: Actuate radar system (cylinder variant)

Differential
Servo (EH)
Standard
Integrated

Lock & Positioning device

Function: Lock mast

Hydraulic cylinder
Electric actuator

Function: Position support legs

Hydraulic cylinder
Electric actuator
Electrohydraulic cylinder

Reservoir

Function: Store hydraulic fluid

Open reservoir
Use extension cylinder

Mechanical structure

Support leg positioning principle

Fold down

Function: Hold support legs

Folding "Side wings"
Folding truss structure
Folding Flaps (existing)

Positioning tools

Rotator
Hydraulic actuator
Gear rack
Electric screw

Mast raising principle

Existing

Screening 2 - Pugh matrices

Hydraulic pump

Creators: Holm J; Hultgren T   Date: 2011-03-29

Criteria	**Axial piston**	**Gear**	**Radial piston**
Efficiency	Reference	-	0
Cost		+	0
Suitability		+	0
Size		+	0
Complexity		+	0
Maintainability		+	0
Reliability		-	0
Total value	**0**	**3**	**0**
Further evaluation?	NO	YES	NO

Emergency operation

Creators: Holm J; Hultgren T   Date: 2011-03-29

Criteria	**Hydraulic pump**	**Valves (mast)**	**Accumulator**	**Portable pump unit**	**El. Hand pump**
Reliability	Reference	0	0	0	0
Economy		+	+	+	+
Standardization		-	0	0	0
Power consumption		+	+	0	+
Space requirements		+	+	+	+
Complexity		+	0	0	+
Control		-	-	-	0
Maintainability		0	0	0	+
Serviceability		-	0	0	+
Weight		+	+	+	+
Manual operability		-	-	-	+
Modularity		+	0	+	0
Total value	**0**	**2**	**2**	**2**	**8**
Further evaluation?	YES	YES	YES	YES	YES

Actuate mast

Creators: Holm J; Hultgren T   Date: 2011-03-29

Criteria	**Standard**	**Differential**	**Electrohydraulic (Servo)**	**Telescopic**	**Integrated**
Efficiency	Reference	+	+	0	+
Cost		-	-	-	-
Power consumption		-	0	-	0
Control		0	+	0	+
Suitability		-	+	0	-
Size		0	-	+	0
Complexity		-	-	-	-
Maintainability		0	0	-	0
Reliability		0	0	-	0
Total value	**0**	**-3**	**0**	-4	-1
Further evaluation?	YES	NO	YES	NO	YES

Actuate radar system

Creators: Holm J; Hultgren T   Date: 2011-03-29

Criteria	**Standard**	**Electrohydraulic (Servo)**	**Differential**	**Integrated**
Efficiency	Reference	+	+	+
Cost		-	-	-
Power consumption		0	-	0
Control		+	0	+
Suitability		+	-	-
Size		-	0	0
Complexity		-	-	-
Maintainability		0	0	0
Reliability		0	0	0
Total value	**0**	**0**	**-3**	-1
Further evaluation?	YES	YES	NO	YES

Convert electrical power

Creators: Holm J; Hultgren T   Date: 2011-03-29

Criteria	AC motor	DC motor
Efficiency	Reference	-
Cost		0
Suitability		-
Size		+
Complexity		+
Maintainability		-
Reliability		0
Total value	**0**	**-1**
Further evaluation?	YES	NO

Powering pump device

Creators: Holm J; Hultgren T   Date: 2011-03-29

Criteria	Fixed rpm	Variable rpm
Efficiency	Reference	+
Cost		+
Control		+
Suitability		+
Complexity		0
Maintainability		0
Reliability		-
Total value	**0**	**3**
Further evaluation?	NO	YES

Distribution

Creators: Holm J; Hultgren T Date: 2011-03-29

Criteria	1	2	3	4
Efficiency	Reference	+	+	+
Cost		0	0	-
Suitability		+	+	+
Size		-	-	-
Complexity		+	+	+
Maintainability		0	0	0
Reliability		+	+	+
Total value	**0**	**2**	**2**	**1**
Further evaluation?	**NO**	**YES**	**YES**	**YES**

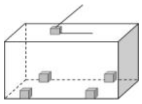
Result - Screening 2

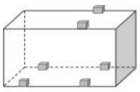
Pre-evaluation result - General

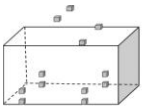
Hydrauli circuit

Open - Open center

Hydraulic module distribution

2 

3 

4 

Hydraulic power unit position (support leg space)

On side of cylinder
Above cylinder
Beneath cylinder
On cylinder
Outside SL space
Mixed positions

Hydraulic power unit position (mast)

On the side of mast
Under roof
On mast

Hydraulic control system

Function: Control components (interface)

CANbus
Existing

Operation controls

Function: Operate system

Remote control
Panel

Function: Operate manually

Levers
Electronic switch/regulator

Function: Emergency operation

Valves (mast)
Accumulator
Hydraulic pump
Portable pump unit
Electrically driven hand pump
Valves + Hand pump

Power unit

Function: Pressurize hydraulic fluid

Power pack
EH Pump + Separate reservoir
Power pack on cylinder (Integrated)

Function: Pump hydraulic fluid

Pump only
Accumulator & Pump

Pump type

External gear
Internal gear

Deplacement

Fixed
Variable

Function: Convert electrical power (el. motor)

AC motor

Function: Powering pump device

Varying power & torque

Hydraulic actuator

Cylinder principle

Double acting

Hydraulic cylinder type

Welded

Function: Actuate mast (cylinder variant)

Servo (EH)
Standard
Integrated

Function: Actuate radar system (cylinder variant)

Servo (EH)
Standard
Integrated

Lock & Positioning device

Function: Lock mast

Hydraulic cylinder
Electric linear actuator

Function: Position support legs

Hydraulic cylinder
Electric linear actuator

Reservoir

Function: Store hydraulic fluid

Open reservoir
Use extension cylinder

Mechanical structure

Support leg positioning principle

Fold down

Function: Hold support legs

Folding "Side wings"
Folding truss structure
Folding Flaps (existing)

Positioning tools

Rotator
Hydraulic actuator
Gear rack
Electric screw

Mast raising principle

Existing

Screening 3 - Kesselring matrices

Emergency operation

Date: 2011-03-29

Creators: Holm J; Hultgren T

wf = weight factor; w = weight; t = total score

Criteria		**Alternatives**													
		Ideal		**Hydraulic pump**		**Valves**		**Accumulator**		**Portable unit**		**El. Hand pump**		**Valve + Hand pump**	
	wf	w	t	w	t	w	t	w	t	w	t	w	t	w	t
Reliability	5	5	25	4	20	4	20	4	20	4	20	4	20	4	20
Economy	3	5	15	3	9	5	15	4	12	4	12	4	12	5	15
Standardization	4	5	20	5	20	4	16	5	20	3	12	3	12	3	12
Power saving	3	5	15	3	9	5	15	4	12	4	12	4	12	4	12
Space requirements	4	5	20	2	8	5	20	4	16	5	20	4	16	5	20
Complexity	4	5	20	3	12	4	16	3	12	3	12	4	16	4	16
Control	5	5	25	5	25	3	15	3	15	3	15	4	20	3	15
Maintainability	4	5	20	3	12	3	12	2	8	5	20	4	16	3	12
Serviceability	4	5	20	3	12	3	12	3	12	5	20	4	16	3	12
Weight	3	5	15	2	6	5	15	4	12	4	12	4	12	4	12
Operability	5	5	25	5	25	3	15	4	20	2	10	3	15	3	15
Manual operability	4	5	20	4	16	4	16	3	12	4	16	5	20	4	16
Modularity	4	5	20	3	12	5	20	3	12	5	20	4	16	3	12
Total		65	260	45	186	53	207	46	183	51	201	51	203	48	189
Relative total		1	**1**	0,69	**0,72**	0,82	**0,80**	0,71	**0,70**	0,78	**0,77**	0,78	**0,78**	0,74	**0,73**
Mean		5	20,00	3,46	14,31	4,08	15,92308	3,54	14,08	3,92	15,46	3,92	15,62	3,69	14,54
Median		5	20	3	12	4	15	4	12	4	15	4	16	4	15
Ranking				**5**		**1**		**6**		**3**		**2**		**4**	
Decision		An extra hydraulic pump on each function is eliminated together with the alternative Accumulator. Remaining options will act as alternatives for further evaluation if the decision is to adapt a distributed system.													

Hydraulic actuator

Date: 2011-03-29

Creators: Holm J; Hultgren T

wf = weight factor;   w = weight;   t = total score

Criteria		**Alternatives**							
		Ideal		**Standard**		**Servo**		**Integrated (EHC)**	
	wf	w	t	w	t	w	t	w	t
Cost/Benefit	4	5	15	4	16	2	8	4	16
Control	5	5	25	3	15	4	20	4	20
Suitability	5	5	25	5	25	5	25	5	25
Complexity	4	5	20	5	20	4	16	5	20
Maintainability	4	5	20	4	16	3	12	4	16
Reliability	5	5	25	4	20	4	20	3	15
Total		30	130	25	112	22	101	25	112
Relative total		1	**1**	0,83	**0,86**	0,73	**0,78**	0,83	**0,86**
Mean		5	21,67	4,17	18,67	3,67	16,83333	4,17	18,67
Median		5	22,5	4	18	4	18	4	18
Ranking				**1**		**3**		**1**	
Decision		Servo cylinders are eliminated due to high cost and higher complexity. Standard cylinders and integrated (EHC) cylinders are adapted in concepts.							

Result - Concept proposals

Function/Characteristic	Concept "PowerPack"	
General		
Hydraulic circuit	Open - Open center	
Hydraulic module distribution	6 units	
Hydraulic control system		
Function: Control components	Existing	Option: CANbus
Operation controls		
Function: Operate system	Panel	Option: Remote control
Function: Operate manually	Levers	
Function: Emergency operation (SL)	Portable pump unit	Option: El. hand pump
Function: Emergency operation (mast)	Portable pump unit	Option: El. hand pump
Power unit	CA / KE series	Option: Single components (mast)
Function: Pressurize hydraulic fluid	Power pack	Option: EH Pump
Function: Pump hydraulic fluid	Pump only	
Pump type	External gear	
Deplacement (SL)	Fixed - 3.75 - 4.2 cm^3/rev	(Recommendation)
Deplacement (mast)	Fixed - 20 - 22.5 cm^3/rev	(Recommendation)
Function: Convert electrical power (SL)	3 x 230/400 V AC motor - 1.1 kW	
Function: Convert electrical power (mast)	3 x 230/400 V AC motor - 1.5 kW	Option: 4 kW; Bosch Rexroth ZL
Function: Powering pump device	Varying torque & speed	(Standalone freq. converter)
Hydraulic actuator		
Cylinder principle	Double acting	
Cylinder type	Welded	
Function: Actuate mast	Standard	
Function: Actuate radar system	Standard	
Lock & Positioning device		
Function: Lock mast	Hydraulic cylinder	
Function: Position support legs	Hydraulic cylinder	
Reservoir		
Store hydraulic fluid (SL module)	Open reservoir - approx. 6-7 l	Option: Use extension cylinder
Store hydraulic fluid (mast module)	Open reservoir - approx. 13 l	
Valves		
Function: Hold load	Load-holding valve	Option: EH valve
Function: Direct fluid	Proportional directional valves	Option: EH valve
Function: Control flow	Flow control valve	Option: EH valve
Function: Releve pressure	Pressure relief valve	Option: EH valve
Pipes & Hoses		
Transport fluid	Hoses	
Sensors		
Measure oil temperature	Electronic temperature sensor	
Measure pressure	Pressure transducer	
Measure oil level	TBD	Option: Visually on reservoir
Measure position	Position transducer	

Function/Characteristic	Concept "EHC"	
General		
Hydraulic circuit	Open - Open center	
Hydraulic module distribution	14 units	
Hydraulic control system		
Function: Control components	Existing	
Operation controls		
Function: Operate system	Panel	
Function: Operate manually	Electr. switch/regulator	
Function: Emergency operation (mast)	Electric AC/DC converter	
	Portable drive unit on motor shaft	Option: Hand pump w. fast couplings
Function: Emergency operation (SL)	Electric AC/DC converter	(Few other alternatives)
	Portable drive unit on motor shaft	Option: Hand pump w. fast couplings
Power unit		
Function: Pressurize hydraulic fluid	"Electro-Hydraulic Cylinder"	
Function: Pump hydraulic fluid	Pump only	
Pump type	Bi-directional gear pump	(Hydraulic gear motor)
Deplacement (SL)	Fixed	
Deplacement (mast)	Fixed	
Function: Convert electrical power (SL)	3 x 230/400 V AC motor - 3 kW*	*(Specified by supplier, assumption)
Function: Convert electrical power (mast)	3 x 230/400 V AC motor - 7.5 kW*	*(Specified by supplier, assumption)
Function: Powering pump device	Varying torque & speed	(Standalone freq. converter)
Hydraulic actuator		
Cylinder principle	Double acting	
Cylinder type	Welded	
Function: Actuate mast	"Electro-Hydraulic Cylinder"	
Function: Actuate radar system	"Electro-Hydraulic Cylinder"	
Lock & Positioning device		
Function: Lock mast	"Electro-Hydraulic Cylinder" - 350W	Option: Linear actuator
Function: Position support legs	"Electro-Hydraulic Cylinder" - 350W	Option: Linear actuator
Reservoir		
Store hydraulic fluid (SL module)	Open reservoir - approx. 6 l/cyl.	(Cover around cylinder body)
Store hydraulic fluid (mast module)	Open reservoir - approx. 5 l/cyl.	
Store hydraulic fluid (lock module)	Open reservoir - approx. 0.3 l/cyl.	
Store hydraulic fluid (position module)	Open reservoir - approx. 2 l/cyl.	
Valves		
Function: Hold load	Solenoid valve	(Magnetic lock)
Function: Direct fluid	None	
Function: Control flow	None	
Function: Releve pressure	Pressure relief valve	
Pipes & Hoses		
Transport fluid	None	
Sensors		
Measure oil temperature	Electronic temperature sensor	
Measure pressure	Pressure transducer	
Measure oil level	TBD	Option: Visually on cylinder
Measure position	Position transducer	

Appendix VI - Calculations

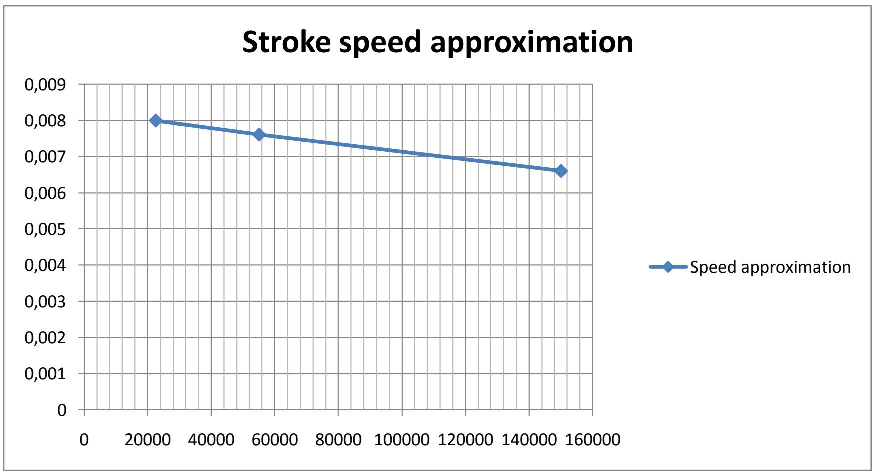
Time measurements (Giraffe AMB)

Support leg without load (850mm)	Down 1 leg	 2 legs	 4 legs	Up 1 leg	 2 legs	 4 legs
Measurement 1 (s)	66			39,5		
Measurement 2 (s)	65			39,5		
Measurement 3 (lever) (s)	66			33,2		
Measurement 4 (s)		66			58	
Measurement 5 (s)			86			55
Speed (m/s)	**0,012879**	**0,012879**	**0,009884**	**0,021519**	**0,014655**	**0,015455**
Area (m2)	0,012271484	0,012271484	0,012271484	0,005909764	0,005909764	0,005909764
Flow rate (l/min)	**9,48**	**9,48**	**7,28**	**7,63**	**5,20**	**5,48**

Support leg with load (207mm)	Down 4 legs
Measurement 1 (s)	25,9
Speed (m/s)	**0,007992278**
Full stroke (s)	106,352657
Area (m2)	0,01227148
Flow rate (l/min)	**5,88**

Note: Load = Only shelter (approx. 22,5 kN)

Parking cylinder	Down 1 leg	 2 legs	 4 legs	Up 1 leg	 2 legs	 4 legs
Measurement 1 (s)	33			29		
Speed (m/s)	**0,011818182**			**0,013448276**		
Area (m2)	0,001256636			0,001256636		
Flow rate (l/min)	**0,89**			**1,01**		



22500	0,007992
55000	0,007604
150000	0,0066

Power calculations (distributed hydraulic system)

Support leg cylinders	Push				Pull			
	Stroke 850 (Normal op.)	Stroke 850 (Max load)	Stroke 850 (Shelter only)	Stroke 850 (Max load) Set power	Stroke 850 (Normal op.)	Stroke 850 (Max load)	Stroke 850 (Shelter only)	Stroke 850 (Max load) Set power
Assumed truck height	1,5 m							
Lenght between rod head and shelter floor	1,264 m (see doc. 2_15510-UAZ10170_22 - en - B.pdf)							
Stroke without external load (m)	0,236 m							
"Unloaded" stroke								
t (s)	23,87697289	23,87697289	23,87697289	17,37642188	23,87697289	23,87697289	23,87697289	17,25460778
s (m)	0,236	0,236	0,236	0,236	0,236	0,236	0,236	0,236
v (m/s)	0,009884	0,009884	0,009884	0,013581622	0,009884	0,009884	0,009884	0,013677506
r (m)	0,0625	0,0625	0,0625	0,0625	0,0625	0,0625	0,0625	0,0625
A1 (m2)	0,012271484	0,012271484	0,012271484	0,012271484	0,012271484	0,012271484	0,012271484	0,012271484
A2 (m2)	0,005909947	0,005909947	0,005909947	0,005909947	0,005909947	0,005909947	0,005909947	0,005909947
V (m3)	0,00289607	0,00289607	0,00289607	0,00289607	0,00289607	0,00289607	0,00289607	0,00289607
Vd (Difference volume, m3)	0,001501323	0,001501323	0,001501323	0,001501323	0,001501323	0,001501323	0,001501323	0,001501323
Q (m3/s)	0,000121291	0,000121291	0,000121291	0,000166667	5,84139E-05	5,84139E-05	5,84139E-05	8,08333E-05
Q (l/min)	7,277481094	7,277481094	7,277481094	10	3,504834895	3,504834895	3,504834895	4,85
F (N)	61357,42188	61357,42188	61357,42188	61357,42188	29549,73438	29549,73438	29549,73438	29549,73438
p (Pa)	5000000	5000000	5000000	5000000	5000000	5000000	5000000	5000000
Phyd (W)	606,4567578	606,4567578	606,4567578	833,3333333	292,0695746	292,0695746	292,0695746	404,1666667
η (%)	0,95	0,95	0,95	0,95	0,95	0,95	0,95	0,95
Pin (W)	638,3755345	638,3755345	638,3755345	877,1929825	307,4416574	307,4416574	307,4416574	425,4385965
P,source (W)	797,9694182	797,9694182	797,9694182	1096,491228	384,3020718	384,3020718	384,3020718	531,7982456
I,source (A)	1,393346286	1,393346286	1,393346286	1,914599665	0,671035571	0,671035571	0,671035571	0,928580837
4 support legs (W)	**3191,877673**	**3191,877673**	**3191,877673**	**4385,964912**	**1537,208287**	**1537,208287**	**1537,208287**	**2127,192982**
4 support legs (A)	**5,573385145**	**5,573385145**	**5,573385145**	**7,658398659**	**2,684142286**	**2,684142286**	**2,684142286**	**3,71432335**

Power calculations (distributed hydraulic system)

Loaded stroke	Push				Pull			
t (s)	80,72883146	80,72883146	76,82394305	93,03030303	80,72883146	80,72883146	76,82394305	58,2989899
s (m)	0,614	0,614	0,614	0,614	0,614	0,614	0,614	0,614
v (m/s)	0,007605709	0,007605709	0,0079923	0,0066	0,007605709	0,007605709	0,0079923	0,010531915
r (m)	0,0625	0,0625	0,0625	0,0625	0,0625	0,0625	0,0625	0,0625
A1 (m2)	0,012271484	0,012271484	0,012271484	0,012271484	0,012271484	0,012271484	0,012271484	0,012271484
A2 (m2)	0,005909947	0,005909947	0,005909947	0,005909947	0,005909947	0,005909947	0,005909947	0,005909947
V (m3)	0,010430762	0,007534691	0,007534691	0,007534691	0,007534691	0,007534691	0,007534691	0,007534691
Vd (Difference volume, m3)	0,005407307	0,003905984	0,003905984	0,003905984	0,003905984	0,003905984	0,003905984	0,003905984
Q (m3/s)	9,33333E-05	9,33333E-05	9,80774E-05	8,09918E-05	4,49493E-05	4,49493E-05	4,72341E-05	6,22431E-05
Q (l/min)	5,600000349	5,600000349	5,884643074	4,859507813	2,696960168	2,696960168	2,834044105	3,734583451
F (N)	55000	150000	22500	150000	20500	94000	20500	94000
p (Pa)	4481935,381	12223460,13	1833519,02	12223460,13	3468728,304	15905388,32	3468728,304	15905388,32
Phyd (W)	418,313995	1140,85635	179,82675	990	155,9170345	714,936646	163,84215	990
η (%)	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9
Pin (W)	464,7933278	1267,618167	199,8075	1100	173,2411494	794,3740511	182,0468333	1100
P,source (W)	580,9916597	1584,522708	249,759375	1375	216,5514368	992,9675639	227,5585417	1375
I,source (A)	1,014478191	2,766758701	0,436108565	2,40090798	0,378123689	1,733835453	0,397343359	2,40090798
4 support legs (W)	**2323,966639**	**6338,090833**	**999,0375**	**5500**	**866,2057472**	**3971,870256**	**910,2341667**	**5500**
4 support legs (A)	**4,057912762**	**11,06703481**	**1,744434259**	**9,603631919**	**1,512494757**	**6,935341812**	**1,589373436**	**9,603631919**

Power calculations (distributed hydraulic system)

Upper Mast cyilnders	Push				Pull			
	Stroke 1457	Stroke 1457	Stroke 1457	Stroke 1457	Stroke 1457	Stroke 1457	Stroke 1457	Stroke 1457
	Mean load (2 cyl)	Max load	Mean load (1 cyl)	Max (set power)	Mean load (2 cyl)	Max load	Mean load (1 cyl)	Max (set power)
t (s)	33	33	33	97,13333333	33	33	33	54,24788741
s (m)	1,457	1,457	1,457	1,457	1,457	1,457	1,457	1,457
v (m/s)	0,044151515	0,044151515	0,044151515	0,015	0,044151515	0,044151515	0,044151515	0,026858189
r (m)	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
A1 (m2)	0,00785375	0,00785375	0,00785375	0,00785375	0,00785375	0,00785375	0,00785375	0,00785375
A2 (m2)	0,0050264	0,0050264	0,0050264	0,0050264	0,0050264	0,0050264	0,0050264	0,0050264
V (m3)	0,011442914	0,011442914	0,011442914	0,011442914	0,011442914	0,011442914	0,011442914	0,011442914
Difference volume	0,004119449	0,004119449	0,004119449	0,004119449	0,004119449	0,004119449	0,004119449	0,004119449
Q (m3/s)	0,000346755	0,000346755	0,000346755	0,000117806	0,000443846	0,000221923	0,000221923	0,000135
Q (l/min)	41,61059545	20,80529773	20,80529773	7,068375	26,63078109	13,31539055	13,31539055	8,1
F (N)	43000	90000	21500	90000				
p (Pa)	5475091,517	11459493,87	2737545,758	11459493,87		10000000		10000000
Phyd (W)	1898,515152	3973,636364	949,2575758	1350	0	2219,231758	0	1350
η (%)	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9
Pin (W)	2109,461279	4415,151515	1054,73064	1500	0	2465,813064	0	1500
P,source (W)	2636,826599	5518,939394	1318,4133	1875	0	3082,26633	0	1875
I,source (A)	4,604202199	9,636702277	2,302101099	3,273965427	0	5,381991147	0	3,273965427
2 upper mast cyl (W)	**x**	**11037,87879**	**2636,826599**	**3750**	**x**	**6164,53266**	**0**	**3750**
2 upper mast cyl (A)	**9,208404398**	**19,27340455**	**4,604202199**	**6,547930854**	**0**	**10,76398229**	**0**	**6,547930854**

Lower Mast cyilnders	Push				Pull			
	Stroke 1457	Stroke 1457	Stroke 1457	Stroke 1457	Stroke 1457	Stroke 1457	Stroke 1457	Stroke 1457
	Mean load (2 cyl)	Max load	Mean load (1 cyl)	Max (set power)	Mean load (2 cyl)	Max load	Mean load (1 cyl)	Max (set power)
t (s)	33	33	33	48,56666667	33	33	33	10,84957748
s (m)	1,457	1,457	1,457	1,457	1,457	1,457	1,457	1,457
v (m/s)	0,044151515	0,044151515	0,044151515	0,03	0,044151515	0,044151515	0,044151515	0,134290944
r (m)	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
A1 (m2)	0,00785375	0,00785375	0,00785375	0,00785375	0,00785375	0,00785375	0,00785375	0,00785375
A2 (m2)	0,0050264	0,0050264	0,0050264	0,0050264	0,0050264	0,0050264	0,0050264	0,0050264
V (m3)	0,011442914	0,011442914	0,011442914	0,011442914	0,011442914	0,011442914	0,011442914	0,011442914
Difference volume	0,004119449	0,004119449	0,004119449	0,004119449	0,004119449	0,004119449	0,004119449	0,004119449
Q (m3/s)	0,00069351	0,000346755	0,000346755	0,000235613	0,000443846	0,000221923	0,000221923	0,000675
Q (l/min)	41,61059545	20,80529773	20,80529773	14,13675	26,63078109	13,31539055	13,31539055	40,5
F (N)	31000	60000	15500	60000				
p (Pa)	3947159	7639662,582	1973579,5	7639662,582	0	2000000	0	2000000
Phyd (W)	2737,393939	2649,090909	684,3484848	1800	0	443,8463515	0	1350
η (%)	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9
Pin (W)	3041,548822	2943,434343	760,3872054	2000	0	493,1626128	0	1500
P,source (W)	3801,936027	3679,292929	950,4840067	2500	0	616,453266	0	1875
I,source (A)	6,638617124	6,424468185	1,659654281	4,365287236	0	1,076398229	0	3,273965427
2 lower mast cyl (W)	**x**	**7358,585859**	**1900,968013**	**5000**	**x**	**1232,906532**	**0**	**3750**
2 lower mast cyl (A)	**13,27723425**	**12,84893637**	**3,319308562**	**8,730574472**	**0**	**2,152796459**	**0**	**6,547930854**

Power calculations (distributed hydraulic system)

	Push				Pull			
Parking cylinders	**Stroke 393**	**Stroke 393**	**Stroke 393**	**Stroke 393**	**Stroke 393**	**Stroke 393**	**Stroke 393**	**Stroke 393**
	Set load	**Max load**	**Set load**	**Set load**	**Set load**	**Max load**	**Set load**	**Set load**
t (s)	29	29	29	29	29	29	29	29
s (m)	0,39	0,39	0,39	0,39	0,39	0,39	0,39	0,39
v (m/s)	0,013448276	0,013448276	0,013448276	0,013448276	0,013448276	0,013448276	0,013448276	0,013448276
r (m)	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02
A1 (m2)	0,0012566	0,0012566	0,0012566	0,0012566	0,0012566	0,0012566	0,0012566	0,0012566
A2 (m2)	0,000765741	0,000765741	0,000765741	0,000765741	0,000765741	0,000765741	0,000765741	0,000765741
V (m3)	0,000490074	0,000490074	0,000490074	0,000490074	0,000490074	0,000490074	0,000490074	0,000490074
Difference volume	0,000191435	0,000191435	0,000191435	0,000191435	0,000191435	0,000191435	0,000191435	0,000191435
Q (m3/s)	1,02979E-05	1,02979E-05	1,02979E-05	1,02979E-05	1,68991E-05	1,68991E-05	1,68991E-05	1,68991E-05
Q (l/min)	0,61787347	0,61787347	0,61787347	0,61787347	1,013946207	1,013946207	1,013946207	1,013946207
F (N)	4000	20000	4000	4000	3000	20000	3000	3000
p (Pa)	3183192,742	15915963,71	3183192,742	3183192,742	2387394,557	15915963,71	2387394,557	2387394,557
Phyd (W)	32,78017241	163,9008621	32,78017241	32,78017241	40,34482759	268,9655172	40,34482759	40,34482759
η (%)	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9
Pin (W)	36,42241379	182,112069	36,42241379	36,42241379	44,82758621	298,8505747	44,82758621	44,82758621
P,source (W)	45,52801724	227,6400862	45,52801724	45,52801724	56,03448276	373,5632184	56,03448276	56,03448276
I,source (A)	0,079497149	0,397485745	0,079497149	0,079497149	0,097842645	0,6522843	0,097842645	0,097842645
4 Parking cylinders (W)	**182,112069**	**910,5603448**	**182,112069**	**182,112069**	**224,137931**	**1494,252874**	**224,137931**	**224,137931**
4 Parking cylinders (A)	**0,317988596**	**1,58994298**	**0,317988596**	**0,317988596**	**0,39137058**	**2,609137198**	**0,39137058**	**0,39137058**

Lock cylinders	**Stroke 80**	**Stroke 80**	**Stroke 80**	**Stroke 80**	**Stroke 80**	**Stroke 80**	**Stroke 80**	**Stroke 80**
	Set load	**Set load**	**Set load**	**Set load**	**Set load**	**Set load**	**Set load**	**Set load**
t (s)	6	6	6	6	6	6	6	6
s (m)	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08
v (m/s)	0,013333333	0,013333333	0,013333333	0,013333333	0,013333333	0,013333333	0,013333333	0,013333333
r (m)	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02
A1 (m2)	0,0012566	0,0012566	0,0012566	0,0012566	0,0012566	0,0012566	0,0012566	0,0012566
A2 (m2)	0,00094245	0,00094245	0,00094245	0,00094245	0,00094245	0,00094245	0,00094245	0,00094245
V (m3)	0,000100528	0,000100528	0,000100528	0,000100528	0,000100528	0,000100528	0,000100528	0,000100528
Difference volume	0,000025132	0,000025132	0,000025132	0,000025132	0,000025132	0,000025132	0,000025132	0,000025132
Q (m3/s)	0,000012566	0,000012566	0,000012566	0,000012566	1,67547E-05	1,67547E-05	1,67547E-05	1,67547E-05
Q (l/min)	0,75396	0,75396	0,75396	0,75396	1,00528	1,00528	1,00528	1,00528
F (N)	2000	2000	2000	2000	3000	3000	3000	3000
p (Pa)	1591596,371	1591596,371	1591596,371	1591596,371	2387394,557	2387394,557	2387394,557	2387394,557
Phyd (W)	20	20	20	20	40	40	40	40
η (%)	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9
Pin (W)	22,222	22,222	22,222	22,222	44,444	44,444	44,444	44,444
P,source (W)	27,778	27,778	27,778	27,778	55,556	55,556	55,556	55,556
I,source (A)	0,049	0,049	0,049	0,049	0,097	0,097	0,097	0,097
2 lower mast cyl (W)	**55,556**	**55,556**	**55,556**	**55,556**	**111,111**	**111,111**	**111,111**	**111,111**
2 lower mast cyl (A)	**0,097**	**0,097**	**0,097**	**0,097**	**0,194**	**0,194**	**0,194**	**0,194**

Power calculations (distributed hydraulic system)

	Push				Pull			
Energy								
Existing (kW)	7,2	7,2	7,2	7,2	7,2	7,2	7,2	7,2
Support leg cylinders	**Stroke 850 (Normal op.)**	**Stroke 850 (Max load)**	**Stroke 850 (Shelter only)**	**Stroke 850 (Max load) Set power**	**Stroke 850 (Normal op.)**	**Stroke 850 (Max load)**	**Stroke 850 (Shelter only)**	**Stroke 850 (Max load) Set power**
Mast cyilnders	**Stroke 1457 Mean load**	**Stroke 1457 Max load**	**Stroke 1457 Mean load**	**Stroke 1457 Max (set power)**	**Stroke 1457 Mean load**	**Stroke 1457 Max load**	**Stroke 1457 Mean load**	**Stroke 1457 Max (set power)**
Power cons. savings (%) (By largest, simultaneously operated, motor capacity)	**20,00**	**x**	**20,00**	**20,00**	**20,00**	**x**	**20,00**	**20,00**
Power cons. savings (%) (By largest P during normal op.)								
Unloaded SL stroke	**55,67**	**55,67**	**55,67**	**x**	**78,65**	**44,85**	**78,65**	**x**
Loaded SL stroke	**67,72**	**11,97**	**86,13**	**23,61**	**88,26**	**44,83**	**87,67**	**67,72**
Upper mast stroke	**63,38**	**-53,31**	**63,38**	**30,56**	**x**	**x**	**x**	**x**
Lower mast stroke	**73,61**	**-2,20**	**73,61**	**30,56**	**x**	**x**	**x**	**x**
Time								
Total operation time (s) (pauses excl.)	205,6058043	205,6058043	201,7009159	291,1067249	205,6058043	205,6058043	201,7009159	175,6510626
Time margin (s) (levelling, operator work, tuning etc)	394,3941957	394,3941957	398,2990841	308,8932751	394,3941957	394,3941957	398,2990841	424,3489374
Margin in minutes (min)	6,57	6,57	6,64	5,15	6,57	6,57	6,64	7,07

Selection material - Motor & Pump

$$p = \frac{F}{A \cdot 100000}$$

$$P = \frac{Q \cdot p}{600 \cdot \eta_t}$$

$$n = \frac{Q \cdot 1000}{D \cdot \eta_v}$$

$$M = \frac{D \cdot p \cdot 1{,}59}{\eta_{hm}}$$

$$Q = \frac{D \cdot n \cdot \eta_v}{1000}$$

$$t = \frac{s}{20 \cdot \pi}$$

$$D = \frac{Q \cdot 1000}{n \cdot \eta_v}$$

F = Force (N)
p = Pressure (bar)
n = Rotation speed (rpm)
Q = Flow rate (l/min)
D = Deplacement (cm^3/rev)
P = Power (kW)
M = Torque (Nm)
t = Time (s)
s = Lenght/Stroke (m)
v = Actuating speed (m/s)
A = Effective area (m^2)
η_v = Volymetric efficiency (0,95)
η_{hm} = Hydromechanical efficiency 95)
η_t = total efficiency (0,9)

A1 (Support leg cylinder) [m^2]	0,012271484
A2 (Mast cylinder) [m2]	0,00785375

Mast cylinders

4kW; D = x cm^3/rev

	Working load		Max load (Set power (P))		Max load		With accumulator	
	Lower cylinders	Upper cylinders	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder
F	15500	21500	60000	90000	60000	90000	50000	50000
p	19,736	27,375	76,397	114,595	76,397	114,595	63,664	63,664
n	1410	1355,769231	958,3085337	638,8723558	1410	1410	1152,061121	1152,061121
Q	41,60	40,00	28,27	18,85	41,60	41,60	33,93	33,93
D	31,056	31,056	31,056	31,056	31,056	31,056	31,000	31,000
P	1,520	2,028	4,000	4,000	5,885	8,828	4,000	4,000
M	10,258	14,229	39,710	59,565	39,710	59,565	33,031	33,031
t	33,01	34,33	48,57	72,85	33,01	33,01	40,47	40,47

3kW; D = x cm^3/rev

	Working load		Max load (Set power (P))		Max load		With accumulator	
	Lower cylinders	Upper cylinders	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder
F (N)	15500	21500	60000	90000	60000	90000	50000	50000
p (bar)	19,736	27,375	76,397	114,595	76,397	114,595	63,664	63,664
n (rpm)	1430	1375	728,9261719	485,9507813	1430	1430	864,0458404	864,0458404
Q (l/min)	41,60	40,00	21,21	14,14	41,60	41,60	25,45	25,45
D (cm3/rev)	30,622	30,622	30,622	30,622	30,622	30,622	31,000	31,000
P (kW)	1,520	2,028	3,000	3,000	5,885	8,828	3,000	3,000
M (Nm)	10,115	14,030	39,154	58,732	39,154	58,732	33,031	33,031
t (s)	33,01	34,33	64,76	97,13	33,01	33,01	50,26	50,26
							100,52	

2,2kW; D = x cm^3/rev

	Working load		Max load (Set power (P))		Max load		With accumulator	
	Lower cylinders	Upper cylinders	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder
F (N)	15500	21500	60000	90000	60000	90000	50000	50000
p (bar)	19,736	27,375	76,397	114,595	76,397	114,595	63,664	63,664
n (rpm)	1435	1379,807692	536,4149008	357,6099339	1435	1435	633,6336163	633,6336163
Q (l/min)	41,60	40,00	15,55	10,37	41,60	41,60	18,66	18,66
D (cm3/rev)	30,515	30,515	30,515	30,515	30,515	30,515	31,000	31,000
P (kW)	1,520	2,028	2,200	2,200	5,885	8,828	2,200	2,200
M (Nm)	10,080	13,981	39,018	58,527	39,018	58,527	33,031	33,031
t (s)	33,01	34,33	88,30	132,45	33,01	33,01	73,59	73,59

4kW; D = 32 cm^3/rev

	Working load		Max load (Set power (P))		Max load		With accumulator	
	Lower cylinders	Upper cylinders	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder
F (N)	15500	21500	60000	90000	60000	90000	50000	50000
p (bar)	19,736	27,375	76,397	114,595	76,397	114,595	63,664	63,664
n (rpm)	1368,421053	1315,789474	930,0493421	620,0328947	1368,421053	1368,421053	1116,059211	1116,059211
Q (l/min)	41,60	40,00	28,27	18,85	41,60	41,60	33,93	33,93
D (cm3/rev)	32,000	32,000	32,000	32,000	32,000	32,000	32,000	32,000
P (kW)	1,520	2,028	4,000	4,000	5,885	8,828	4,000	4,000
M (Nm)	10,570	14,662	40,916	61,375	40,916	61,375	34,097	34,097
t (s)	33,01	34,33	48,57	72,85	33,01	33,01	40,47	40,47

3kW; D = 32 cm^3/rev

	Working load		Max load (Set power (P))		Max load		With accumulator	
	Lower cylinders	Upper cylinders	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder
F (N)	15500	21500	60000	90000	60000	90000	50000	50000
p (bar)	19,736	27,375	76,397	114,595	76,397	114,595	63,664	63,664
n (rpm)	1368,421053	1315,789474	697,5370066	465,0246711	1368,421053	1368,421053	837,0444079	837,0444079
Q (l/min)	41,60	40,00	21,21	14,14	41,60	41,60	25,45	25,45
D (cm3/rev)	32,000	32,000	32,000	32,000	32,000	32,000	32,000	32,000
P (kW)	1,520	2,028	3,000	3,000	5,885	8,828	3,000	3,000
M (Nm)	10,570	14,662	40,916	61,375	40,916	61,375	34,097	34,097
t (s)	33,01	34,33	64,76	97,13	33,01	33,01	53,96	53,96

2,2kW; D = 32 cm^3/rev

	Working load		Max load (Set power (P))		Max load		With accumulator	
	Lower cylinders	Upper cylinders	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder
F (N)	15500	21500	60000	90000	60000	90000	50000	50000
p (bar)	19,736	27,375	76,397	114,595	76,397	114,595	63,664	63,664
n (rpm)	1368,421053	1315,789474	511,5271382	341,0180921	1368,421053	1368,421053	613,8325658	613,8325658
Q (l/min)	41,60	40,00	15,55	10,37	41,60	41,60	18,66	18,66
D (cm3/rev)	32,000	32,000	32,000	32,000	32,000	32,000	32,000	32,000
P (kW)	1,520	2,028	2,200	2,200	5,885	8,828	2,200	2,200
M (Nm)	10,570	14,662	40,916	61,375	40,916	61,375	34,097	34,097
t (s)	33,01	34,33	88,30	132,45	33,01	33,01	73,59	73,59

4kW; D = 28 cm^3/rev

	Working load		Max load (Set power (P))		Max load		With accumulator	
	Lower cylinders	Upper cylinders	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder
F (N)	15500	21500	60000	90000	60000	90000	50000	50000
p (bar)	19,736	27,375	76,397	114,595	76,397	114,595	63,664	63,664
n (rpm)	1563,909774	1503,759398	1062,913534	708,6090226	1563,909774	1563,909774	1275,496241	1275,496241
Q (l/min)	41,60	40,00	28,27	18,85	41,60	41,60	33,93	33,93
D (cm3/rev)	28,000	28,000	28,000	28,000	28,000	28,000	28,000	28,000
P (kW)	1,520	2,028	4,000	4,000	5,885	8,828	4,000	4,000
M (Nm)	9,249	12,829	35,802	53,703	35,802	53,703	29,835	29,835
t (s)	33,01	34,33	48,57	72,85	33,01	33,01	40,47	40,47

3kW; D = 28 cm^3/rev

	Working load		Max load (Set power (P))		Max load		With accumulator	
	Lower cylinders	Upper cylinders	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder
F (N)	15500	21500	60000	90000	60000	90000	50000	50000
p (bar)	19,736	27,375	76,397	114,595	76,397	114,595	63,664	63,664
n (rpm)	1563,909774	1503,759398	797,1851504	531,4567669	1563,909774	1563,909774	956,6221805	956,6221805
Q (l/min)	41,60	40,00	21,21	14,14	41,60	41,60	25,45	25,45
D (cm3/rev)	28,000	28,000	28,000	28,000	28,000	28,000	28,000	28,000
P (kW)	1,520	2,028	3,000	3,000	5,885	8,828	3,000	3,000
M (Nm)	9,249	12,829	35,802	53,703	35,802	53,703	29,835	29,835
t (s)	33,01	34,33	64,76	97,13	33,01	33,01	53,96	53,96

2,2kW; D = 28 cm^3/rev

	Working load		Max load (Set power (P))		Max load		With accumulator	
	Lower cylinders	Upper cylinders	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder
F (N)	15500	21500	60000	90000	60000	90000	50000	50000
p (bar)	19,736	27,375	76,397	114,595	76,397	114,595	63,664	63,664
n (rpm)	1563,909774	1503,759398	584,6024436	389,7349624	1563,909774	1563,909774	701,5229323	701,5229323
Q (l/min)	41,60	40,00	15,55	10,37	41,60	41,60	18,66	18,66
D (cm3/rev)	28,000	28,000	28,000	28,000	28,000	28,000	28,000	28,000
P (kW)	1,520	2,028	2,200	2,200	5,885	8,828	2,200	2,200
M (Nm)	9,249	12,829	35,802	53,703	35,802	53,703	29,835	29,835
t (s)	33,01	34,33	88,30	132,45	33,01	33,01	73,59	73,59

4kW; D = 24 cm³/rev

	Working load		Max load (Set power (P))		Max load		With accumulator	
	Lower cylinders	Upper cylinders	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder
F (N)	15500	21500	60000	90000	60000	90000	50000	50000
p (bar)	19,736	27,375	76,397	114,595	76,397	114,595	63,664	63,664
n (rpm)	1824,561404	1754,385965	1240,065789	826,7105263	1824,561404	1824,561404	1488,078947	1488,078947
Q (l/min)	41,60	40,00	28,27	18,85	41,60	41,60	33,93	33,93
D (cm3/rev)	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000
P (kW)	1,520	2,028	4,000	4,000	5,885	8,828	4,000	4,000
M (Nm)	7,928	10,996	30,687	46,031	30,687	46,031	25,573	25,573
t (s)	33,01	34,33	48,57	72,85	33,01	33,01	40,47	40,47

3kW; D = 24 cm³/rev

	Working load		Max load (Set power (P))		Max load		With accumulator	
	Lower cylinders	Upper cylinders	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder
F (N)	15500	21500	60000	90000	60000	90000	50000	50000
p (bar)	19,736	27,375	76,397	114,595	76,397	114,595	63,664	63,664
n (rpm)	1824,561404	1754,385965	930,0493421	620,0328947	1824,561404	1824,561404	1116,059211	1116,059211
Q (l/min)	41,60	40,00	21,21	14,14	41,60	41,60	25,45	25,45
D (cm3/rev)	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000
P (kW)	1,520	2,028	3,000	3,000	5,885	8,828	3,000	3,000
M (Nm)	7,928	10,996	30,687	46,031	30,687	46,031	25,573	25,573
t (s)	33,01	34,33	64,76	97,13	33,01	33,01	53,96	53,96

2,2kW; D = 24 cm³/rev

	Working load		Max load (Set power (P))		Max load		With accumulator	
	Lower cylinders	Upper cylinders	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder
F (N)	15500	21500	60000	90000	60000	90000	50000	50000
p (bar)	19,736	27,375	76,397	114,595	76,397	114,595	63,664	63,664
n (rpm)	1824,561404	1754,385965	682,0361842	454,6907895	1824,561404	1824,561404	818,4434211	818,4434211
Q (l/min)	41,60	40,00	15,55	10,37	41,60	41,60	18,66	18,66
D (cm3/rev)	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000
P (kW)	1,520	2,028	2,200	2,200	5,885	8,828	2,200	2,200
M (Nm)	7,928	10,996	30,687	46,031	30,687	46,031	25,573	25,573
t (s)	33,01	34,33	88,30	132,45	33,01	33,01	73,59	73,59

4kW; D = 20 cm^3/rev

	Working load		Max load (Set power (P))		Max load		With accumulator	
	Lower cylinders	Upper cylinders	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder
F (N)	15500	21500	60000	90000	60000	90000	50000	50000
p (bar)	19,736	27,375	76,397	114,595	76,397	114,595	63,664	63,664
n (rpm)	2189,473684	2105,263158	1488,078947	992,0526316	2189,473684	2189,473684	1785,694737	1785,694737
Q (l/min)	41,60	40,00	28,27	18,85	41,60	41,60	33,93	33,93
D (cm3/rev)	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000
P (kW)	1,520	2,028	4,000	4,000	5,885	8,828	4,000	4,000
M (Nm)	6,606	9,164	25,573	38,359	25,573	38,359	21,311	21,311
t (s)	33,01	34,33	48,57	72,85	33,01	33,01	40,47	40,47

3kW; D = 20 cm^3/rev

	Working load		Max load (Set power (P))		Max load		With accumulator	
	Lower cylinders	Upper cylinders	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder
F (N)	15500	21500	60000	90000	60000	90000	50000	50000
p (bar)	19,736	27,375	76,397	114,595	76,397	114,595	63,664	63,664
n (rpm)	2189,473684	2105,263158	1116,059211	744,0394737	2189,473684	2189,473684	1339,271053	1339,271053
Q (l/min)	41,60	40,00	21,21	14,14	41,60	41,60	25,45	25,45
D (cm3/rev)	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000
P (kW)	1,520	2,028	3,000	3,000	5,885	8,828	3,000	3,000
M (Nm)	6,606	9,164	25,573	38,359	25,573	38,359	21,311	21,311
t (s)	33,01	34,33	64,76	97,13	33,01	33,01	53,96	53,96

2,2kW; D = 20 cm^3/rev

	Working load		Max load (Set power (P))		Max load		With accumulator	
	Lower cylinders	Upper cylinders	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder
F (N)	15500	21500	60000	90000	60000	90000	50000	50000
p (bar)	19,736	27,375	76,397	114,595	76,397	114,595	63,664	63,664
n (rpm)	2189,473684	2105,263158	818,4434211	545,6289474	2189,473684	2189,473684	873,0063158	873,0063158
Q (l/min)	41,60	40,00	15,55	10,37	41,60	41,60	18,66	18,66
D (cm3/rev)	20,000	20,000	20,000	20,000	20,000	20,000	22,500	22,500
P (kW)	1,520	2,028	2,200	2,200	5,885	8,828	2,200	2,200
M (Nm)	6,606	9,164	25,573	38,359	25,573	38,359	23,974	23,974
t (s)	33,01	34,33	88,30	132,45	33,01	33,01	73,59	73,59

4kW; D = 18 cm^3/rev

	Working load		Max load (Set power (P))		Max load		With accumulator	
	Lower cylinders	Upper cylinders	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder
F (N)	15500	21500	60000	90000	60000	90000	50000	50000
p (bar)	19,736	27,375	76,397	114,595	76,397	114,595	63,664	63,664
n (rpm)	2432,748538	2339,181287	1653,421053	1102,280702	2432,748538	2432,748538	1984,105263	1984,105263
Q (l/min)	41,60	40,00	28,27	18,85	41,60	41,60	33,93	33,93
D (cm3/rev)	18,000	18,000	18,000	18,000	18,000	18,000	18,000	18,000
P (kW)	1,520	2,028	4,000	4,000	5,885	8,828	4,000	4,000
M (Nm)	5,946	8,247	23,015	34,523	23,015	34,523	19,180	19,180
t (s)	33,01	34,33	48,57	72,85	33,01	33,01	40,47	40,47

3kW; D = 18 cm^3/rev

	Working load		Max load (Set power (P))		Max load		With accumulator	
	Lower cylinders	Upper cylinders	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder
F (N)	15500	21500	60000	90000	60000	90000	50000	50000
p (bar)	19,736	27,375	76,397	114,595	76,397	114,595	63,664	63,664
n (rpm)	2432,748538	2339,181287	1240,065789	826,7105263	2432,748538	2432,748538	1488,078947	1488,078947
Q (l/min)	41,60	40,00	21,21	14,14	41,60	41,60	25,45	25,45
D (cm3/rev)	18,000	18,000	18,000	18,000	18,000	18,000	18,000	18,000
P (kW)	1,520	2,028	3,000	3,000	5,885	8,828	3,000	3,000
M (Nm)	5,946	8,247	23,015	34,523	23,015	34,523	19,180	19,180
t (s)	33,01	34,33	64,76	97,13	33,01	33,01	53,96	53,96

2,2kW; D = 18 cm^3/rev

	Working load		Max load (Set power (P))		Max load		With accumulator	
	Lower cylinders	Upper cylinders	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder
F (N)	15500	21500	60000	90000	60000	90000	50000	50000
p (bar)	19,736	27,375	76,397	114,595	76,397	114,595	63,664	63,664
n (rpm)	2432,748538	2339,181287	909,3815789	606,254386	2432,748538	2432,748538	1091,257895	1091,257895
Q (l/min)	41,60	40,00	15,55	10,37	41,60	41,60	18,66	18,66
D (cm3/rev)	18,000	18,000	18,000	18,000	18,000	18,000	18,000	18,000
P (kW)	1,520	2,028	2,200	2,200	5,885	8,828	2,200	2,200
M (Nm)	5,946	8,247	23,015	34,523	23,015	34,523	19,180	19,180
t (s)	33,01	34,33	88,30	132,45	33,01	33,01	73,59	73,59

With two power units, one at each mast side.

1,5 kW; D = 9,9 cm^3/rev

	Working load		Max load (Set power (P))		Max load		With accumulator	
	Lower cylinders	Upper cylinders	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder	Lower cylinder	Upper cylinder
F (N)	15500	21500	60000	90000	60000	90000	50000	50000
p (bar)	19,736	27,375	76,397	114,595	76,397	114,595	63,664	63,664
n (rpm)	2211,58958	2211,58958	1653,421053	1102,280702	2211,58958	2211,58958	1091,257895	1091,257895
Q (l/min)	20,80	20,80	15,55	10,37	20,80	20,80	18,66	18,66
D (cm3/rev)	9,900	9,900	9,900	9,900	9,900	9,900	18,000	18,000
P (kW)	0,760	1,054	2,200	2,200	2,943	4,414	2,200	2,200
M (Nm)	3,270	4,536	12,659	18,988	12,659	18,988	19,180	19,180
t (s)	33,01	33,01	44,15	66,23	33,01	33,01	36,79	36,79

Electric motor	Rated torque	Specified rpm	M_{st} (start) Nm	M_s (sadel) Nm	M_k (cut) Nm	Pressure	Ref.
2,2 kW - 4 poles - AC 3~230/400V	14,90	1410	44,70	40,23	46,19		VEM AB - K21R-100L4
3 kW - 4 poles - AC 3~230/400V	20,03	1430	46,08	42,07	56,10		VEM AB - K21R-100LX4
4 kW - 4 poles - AC 3~230/400V	26,62	1435	69,21	66,55	85,18		VEM AB - K21R-112M4

Hydraulic pump	Deplacement	p (min/max)	Min rpm (<100bar)	Min rpm (100-180 bar)	Max speed
Bosch - N series Gear pump	20	230/270	500 rpm	600 rpm	3000 rpm
Bosch - N series Gear pump	22,5	230/270	500 rpm	600 rpm	3000 rpm
Bosch - N series Gear pump	25	230/270	500 rpm	600 rpm	3000 rpm
Bosch - N series Gear pump	28	210/250	500 rpm	600 rpm	2800 rpm
Bosch - N series Gear pump	32	180/220	500 rpm	600 rpm	2800 rpm
HYDAC - PGE103-2000	20	x/220	750 rpm	750 rpm	3000 rpm
HYDAC - PGE103-2250	22,5	x/220	750 rpm	750 rpm	3000 rpm
HYDAC - PGE103-2500	25	x/220	750 rpm	750 rpm	3000 rpm
HYDAC - PGE103-2800	28	x/220	750 rpm	750 rpm	3000 rpm
HYDAC - PGE103-3200	32	x/220	750 rpm	750 rpm	3000 rpm

Support leg cylinders

D = x cm3/rev

1,1kW Leg	Unloaded	Shelter only (S)	Mean (S+T)	Max (Set power)	Max (no limit)
F (N)	61357,42	22500	55000	150000	150000
p (bar)	50,000	18,335	44,819	122,235	122,235
n (rpm)	2066,468144	1670,847389	1435	1379,777107	1590,027701
Q (l/min)	7,28	5,88	5,60	4,86	5,60
D (cm3/rev)	3,707	3,707	3,707	3,707	3,707
P (kW)	0,674	0,200	0,465	1,100	1,268
M (Nm)	3,102	1,138	2,781	7,585	7,585
t (s)	23,88	76,82	80,73	93,03	80,73

D = 3,2 cm3/rev

1,1kW Mast	Unloaded	Shelter only (S)	Mean (S+T)	Max (Set power)	Max (no limit)
F (N)	61357,42	22500	55000	150000	150000
p (bar)	50,000	18,335	44,819	122,235	122,235
n (rpm)	2394,078947	1935,737829	1842,105263	1598,522258	1842,105263
Q (l/min)	7,28	5,88	5,60	4,86	5,60
D (cm3/rev)	3,200	3,200	3,200	3,200	3,200
P (kW)	0,674	0,200	0,465	1,100	1,268
M (Nm)	2,678	0,982	2,400	6,547	6,547
t (s)	23,88	76,82	80,73	93,03	80,73

D = 3,75 cm3/rev

1,1kW Mast	Unloaded	Shelter only (S)	Mean (S+T)	Max (Set power)	Max (no limit)
F (N)	61357,42	22500	55000	150000	150000
p (bar)	50,000	18,335	44,819	122,235	122,235
n (rpm)	2042,947368	1651,829614	1571,929825	1364,072327	1571,929825
Q (l/min)	7,28	5,88	5,60	4,86	5,60
D (cm3/rev)	3,750	3,750	3,750	3,750	3,750
P (kW)	0,674	0,200	2,200	1,100	1,268
M (Nm)	3,138	1,151	2,813	7,672	7,672
t (s)	23,88	76,82	80,73	93,03	80,73

D = 4,2 cm3/rev

1,1kW Leg	Unloaded	Shelter only (S)	Mean (S+T)	Max (Set power)	Max (no limit)
F (N)	61357,42	22500	55000	150000	150000
p (bar)	50,000	18,335	44,819	122,235	122,235
n (rpm)	1824,06015	1474,84787	1403,508772	1217,92172	1403,508772
Q (l/min)	7,28	5,88	5,60	4,86	5,60
D (cm3/rev)	4,200	4,200	4,200	4,200	4,200
P (kW)	0,674	0,200	0,465	1,100	1,268
M (Nm)	3,515	1,289	3,151	8,592	8,592
t (s)	23,88	76,82	80,73	93,03	80,73

D = 4,75 cm3/rev

1,1kW Leg	Unloaded	Shelter only (S)	Mean (S+T)	Max (Set power)	Max (no limit)
F (N)	61357,42	22500	55000	150000	150000
p (bar)	50,000	18,335	44,819	122,235	122,235
n (rpm)	1612,853186	1304,076011	1240,99723	1076,899205	1240,99723
Q (l/min)	7,28	5,88	5,60	4,86	5,60
D (cm3/rev)	4,750	4,750	4,750	4,750	4,750
P (kW)	0,674	0,200	0,465	1,100	1,268
M (Nm)	3,975	1,458	3,563	9,718	9,718
t (s)	23,88	76,82	80,73	93,03	80,73

D = 4,8 cm3/rev

1,1kW Leg	Unloaded	Shelter only (S)	Mean (S+T)	Max (Set power)	Max (no limit)
F (N)	61357,42	22500	55000	150000	150000
p (bar)	50,000	18,335	44,819	122,235	122,235
n (rpm)	1596,052632	1290,491886	1228,070175	1065,681505	1228,070175
Q (l/min)	7,28	5,88	5,60	4,86	5,60
D (cm3/rev)	4,800	4,800	4,800	4,800	4,800
P (kW)	0,674	0,200	0,465	1,100	1,268
M (Nm)	4,017	1,473	3,601	9,820	9,820
t (s)	23,88	76,82	80,73	93,03	80,73

Set working rpm (Mean load); D = 3,2 cm3/rev

1,1kW Mast	Unloaded	Shelter only (S)	Mean (S+T)	Max (Set power)	Max (no limit)
F (N)	61357,42	22500	55000	150000	150000
p (bar)	50,000	18,335	44,819	122,235	122,235
n (rpm)	2394,078947	1935,737829	1400	1598,522258	1842,105263
Q (l/min)	7,28	5,88	4,26	4,86	5,60
D (cm3/rev)	3,200	3,200	3,200	3,200	3,200
P (kW)	0,674	0,200	0,353	1,100	1,268
M (Nm)	2,678	0,982	2,400	6,547	6,547
t (s)	23,88	76,82	106,22	93,03	80,73

Set working rpm (Mean load); D = 3,75 cm3/rev

1,1kW Mast	Unloaded	Shelter only (S)	Mean (S+T)	Max (Set power)	Max (no limit)
F (N)	61357,42	22500	55000	150000	150000
p (bar)	50,000	18,335	44,819	122,235	122,235
n (rpm)	2042,947368	1651,829614	1400	1364,072327	1571,929825
Q (l/min)	7,28	5,88	4,99	4,86	5,60
D (cm3/rev)	3,750	3,750	3,750	3,750	3,750
P (kW)	0,674	0,200	2,200	1,100	1,268
M (Nm)	3,138	1,151	2,813	7,672	7,672
t (s)	23,88	76,82	90,64	93,03	80,73

Set working rpm (Mean load); D = 4,2 cm3/rev

1,1kW Leg	Unloaded	Shelter only (S)	Mean (S+T)	Max (Set power)	Max (no limit)
F (N)	61357,42	22500	55000	150000	150000
p (bar)	50,000	18,335	44,819	122,235	122,235
n (rpm)	1824,06015	1474,84787	1400	1217,92172	1403,508772
Q (l/min)	7,28	5,88	5,59	4,86	5,60
D (cm3/rev)	4,200	4,200	4,200	4,200	4,200
P (kW)	0,674	0,200	0,464	1,100	1,268
M (Nm)	3,515	1,289	3,151	8,592	8,592
t (s)	23,88	76,82	80,93	93,03	80,73

Set working rpm (Mean load); D = 4,75 cm3/rev

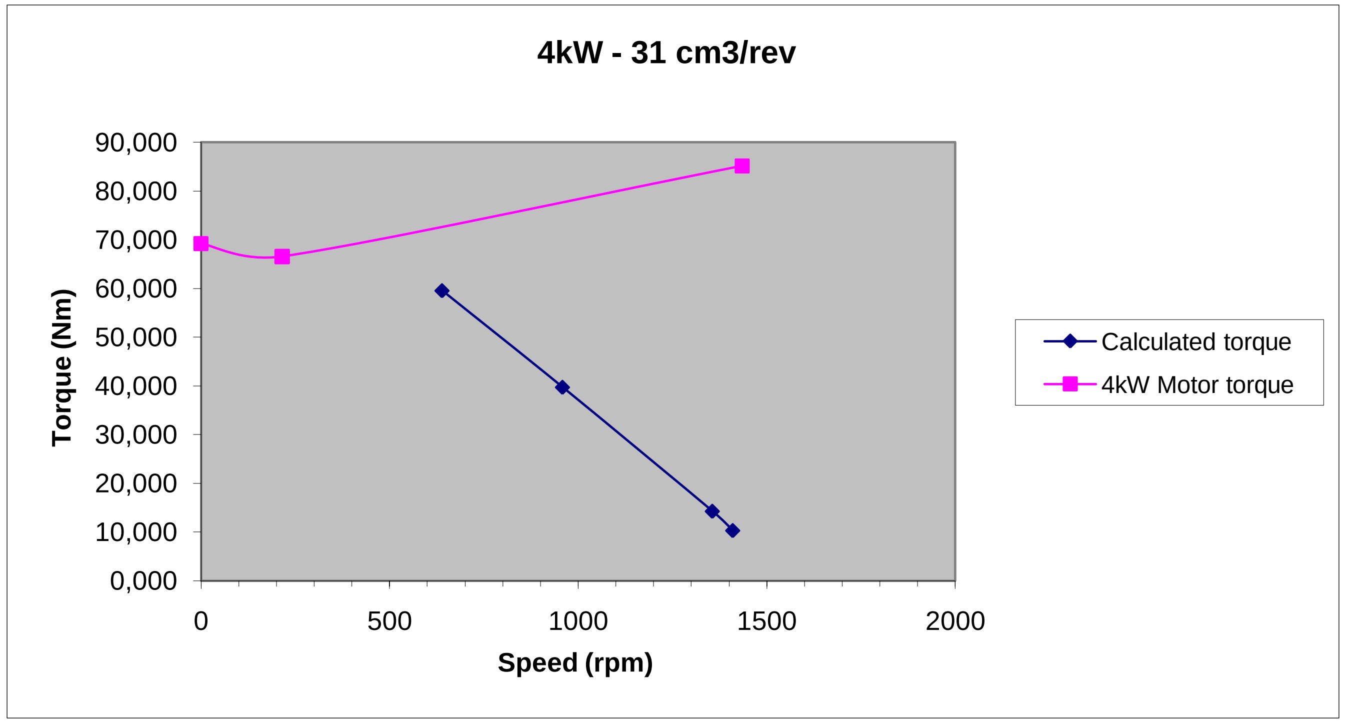
1,1kW Leg	Unloaded	Shelter only (S)	Mean (S+T)	Max (Set power)	Max (no limit)
F (N)	61357,42	22500	55000	150000	150000
p (bar)	50,000	18,335	44,819	122,235	122,235
n (rpm)	1612,853186	1304,076011	1400	1076,899205	1240,99723
Q (l/min)	7,28	5,88	6,32	4,86	5,60
D (cm3/rev)	4,750	4,750	4,750	4,750	4,750
P (kW)	0,674	0,200	0,524	1,100	1,268
M (Nm)	3,975	1,458	3,563	9,718	9,718
t (s)	23,88	76,82	71,56	93,03	80,73

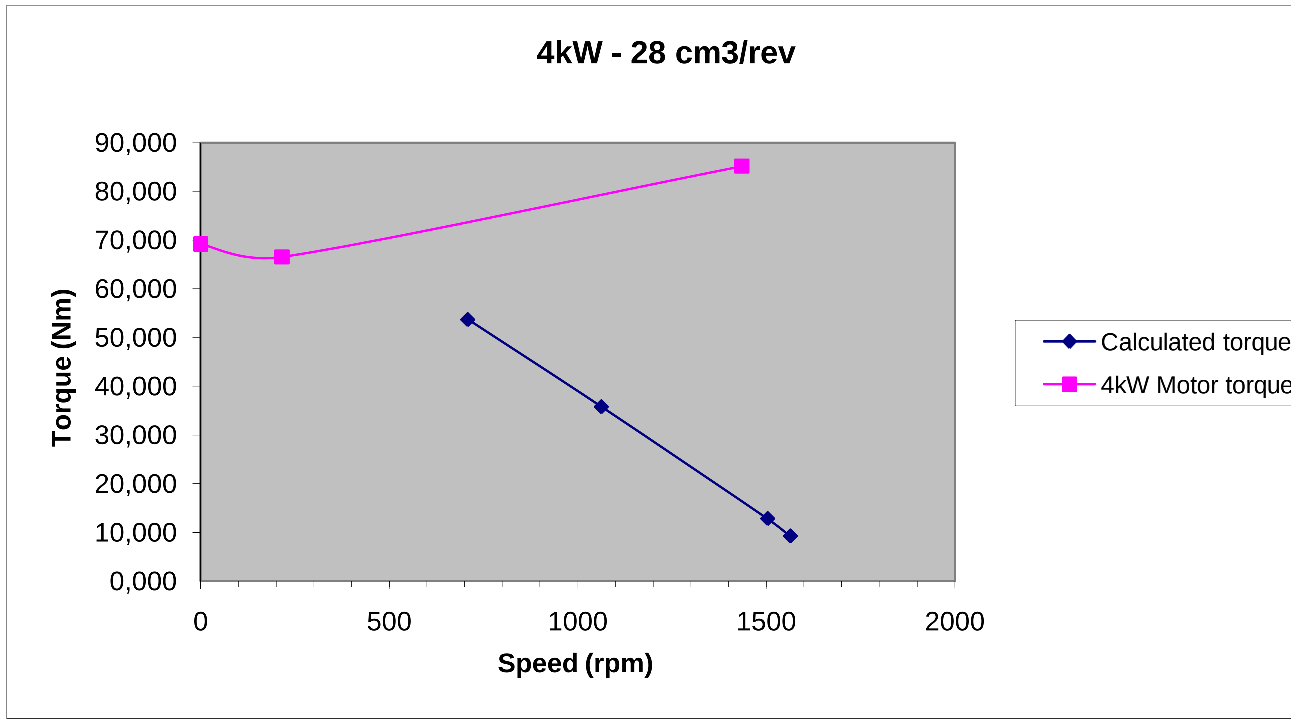
Set working rpm (Mean load); D = 4,8 cm3/rev

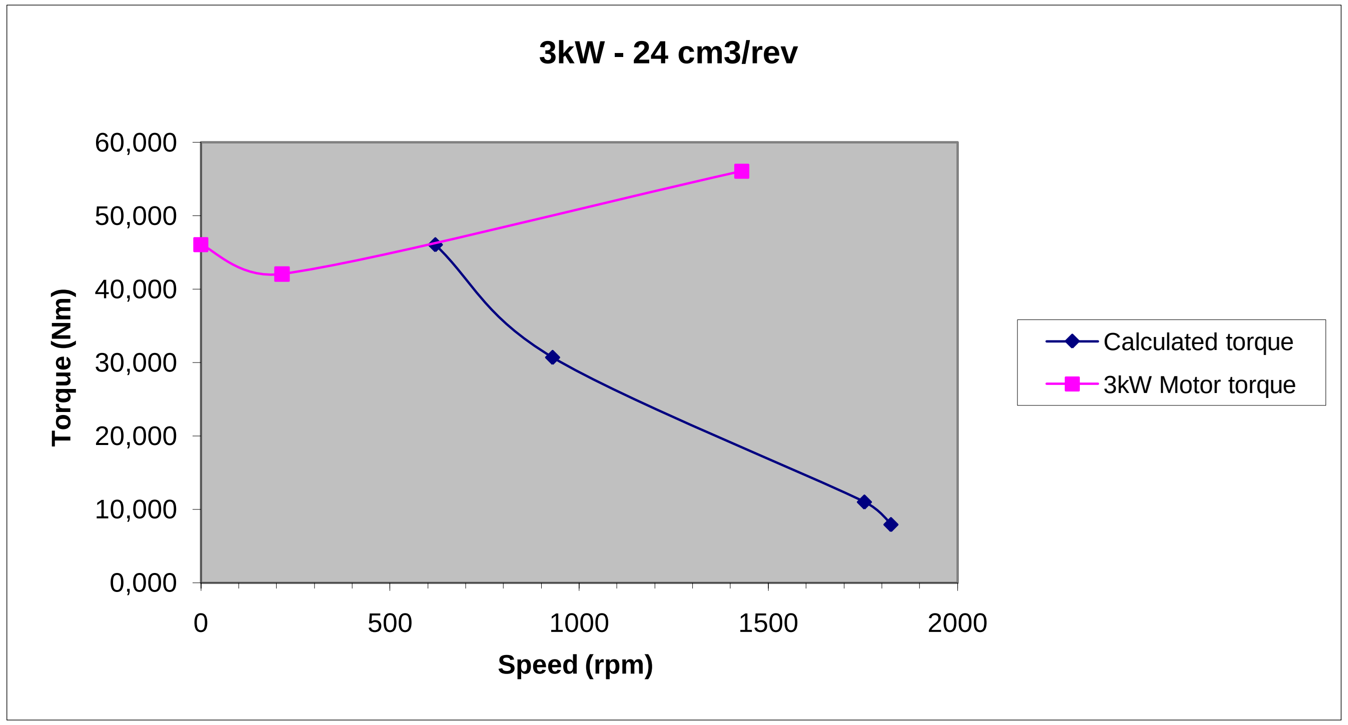
1,1kW Leg	Unloaded	Shelter only (S)	Mean (S+T)	Max (Set power)	Max (no limit)
F (N)	61357,42	22500	55000	150000	150000
p (bar)	50,000	18,335	44,819	122,235	122,235
n (rpm)	1596,052632	1290,491886	1400	1065,681505	1228,070175
Q (l/min)	7,28	5,88	6,38	4,86	5,60
D (cm3/rev)	4,800	4,800	4,800	4,800	4,800
P (kW)	0,674	0,200	0,530	1,100	1,268
M (Nm)	4,017	1,473	3,601	9,820	9,820
t (s)	23,88	76,82	70,81	93,03	80,73

Electric motor	Rated torque	Specified rpm	M_{st} (start) Nm	M_s (saddle) Nm	M_k (cut) Nm	Pressure (bar)	Ref.
1,1 kW - 4 poles - AC 3~230/400V	7,45	1410	17,14	16,39	18,63	-	VEM AB - K21R-90S4
1,5 kW - 4 poles - AC 3~230/400V	10,23	1400	25,58	24,56	26,60	-	VEM AB - K21R-90L4
1,1 kW - 4 poles - AC 3~230/400V - Powerpack	7,50	1400	-	-	-	-	HydroSwede - M-090 S
1,5 kW - 4 poles - AC 3~230/400V - Powerpack	10,23	1400	-	-	-	-	HydroSwede - M-090 L
1,1 kW - 4 poles - AC 3~230/400V - Powerpack	7,50	1400 other on req.	-	-	-	140/170	HYDAC - CA power module
1,5 kW - 4 poles - AC 3~230/400V - Powerpack	10,23	1400 other on req.	-	-	-	185/230	HYDAC - CA power module
1,1 kW - 4 poles - AC 3~230/400V - Powerpack	7,24	1450	-	-	-	-	Bosch K-KE-KS - 406

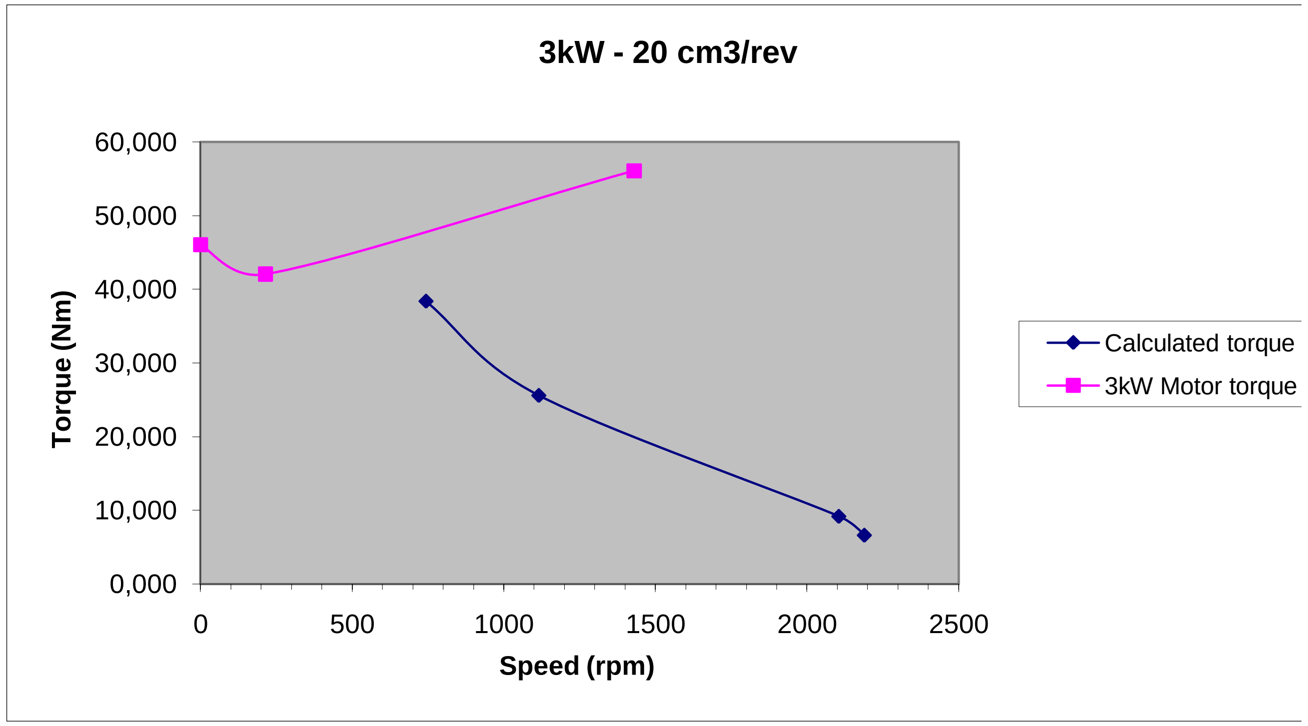
Hydraulic pump	Deplacement	p (cont/int)	Min rpm	Max speed	
HYDAC - CA power module	3,75	170/230	-	-	170/1,1kW; 230/1,5kW
HYDAC - CA power module	4,75	140/185	-	-	140/1,1kW; 185/1,5kW
HydraSwede - TP3 - P1 - 3.2D	3,2	200/230	-	-	
HydraSwede - TP3 - P1 - 3.7D	3,7	200/231	-	-	
HydraSwede - TP3 - P1 - 4.2D	4,2	180/210	-	-	
Bosch K-KE-KS -15	3,2	210/250	-	-	
Bosch K-KE-KS -16	3,7	210/250	-	-	
Bosch K-KE-KS -17	4,2	210/250	-	-	
Bosch K-KE-KS -18	4,8	190/230	-	-	
HYDAC - PGE101-365	3,65	x/220	750	3500	
HYDAC - PGE101-420	4,2	x/220	750	3500	
HYDAC - PGE102-450	4,5	x/220	750	3500	


4kW - 31 cm3/rev
Torque (Nm)
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0,000
0
500
1000
1500
2000
Speed (rpm)
Calculated torque
4kW Motor torque

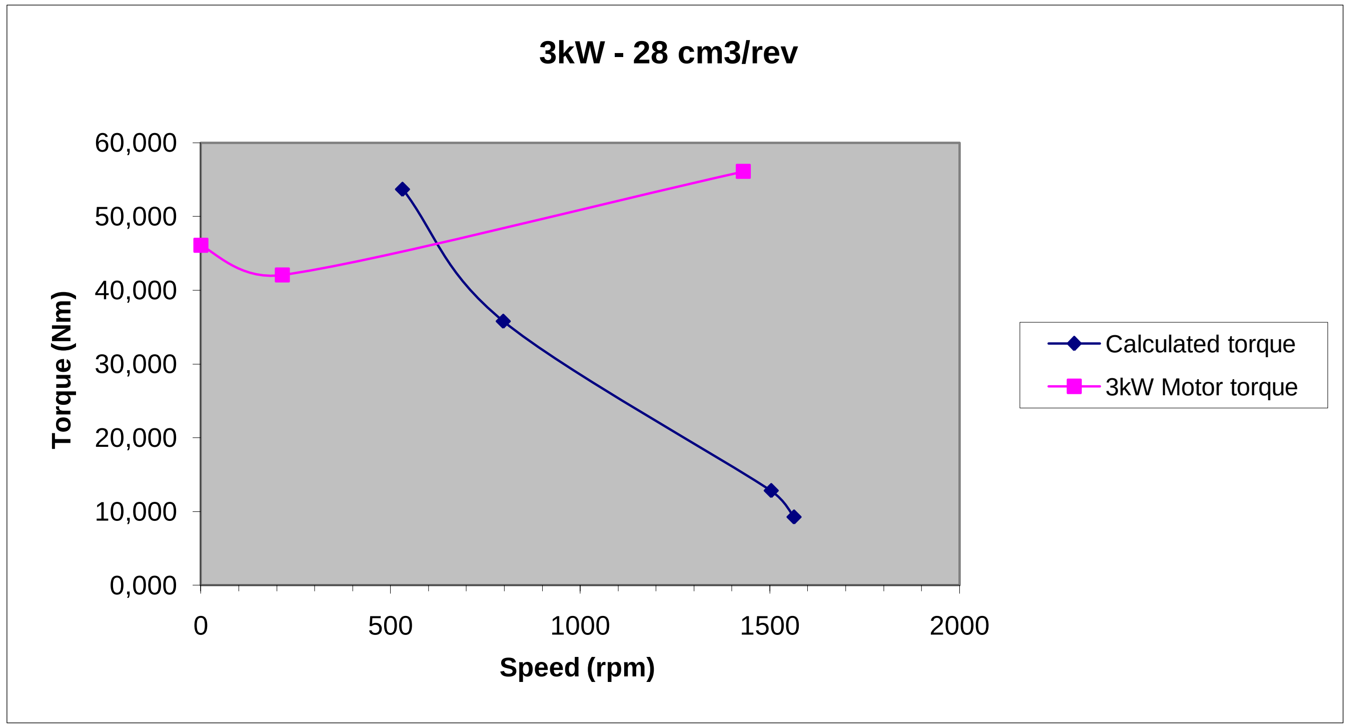

4kW - 28 cm3/rev
Torque (Nm)
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0,000
0
500
1000
1500
2000
Speed (rpm)
Calculated torque
4kW Motor torque

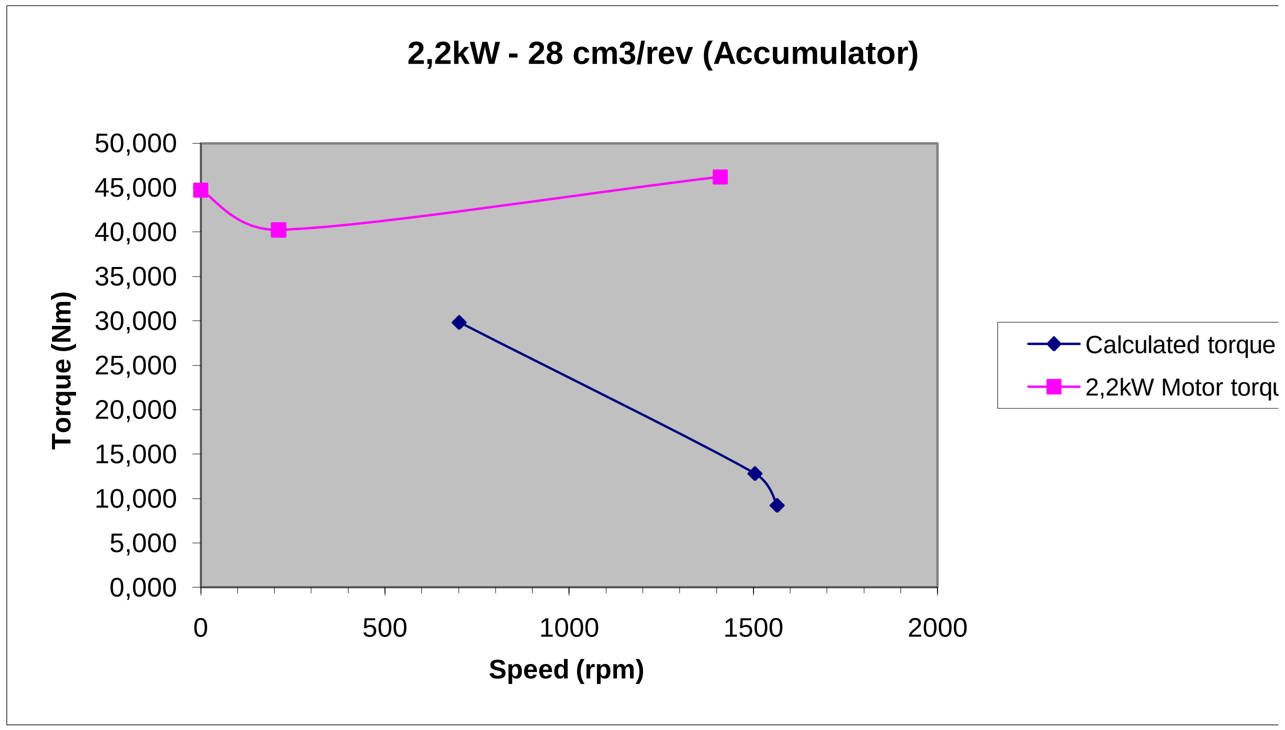


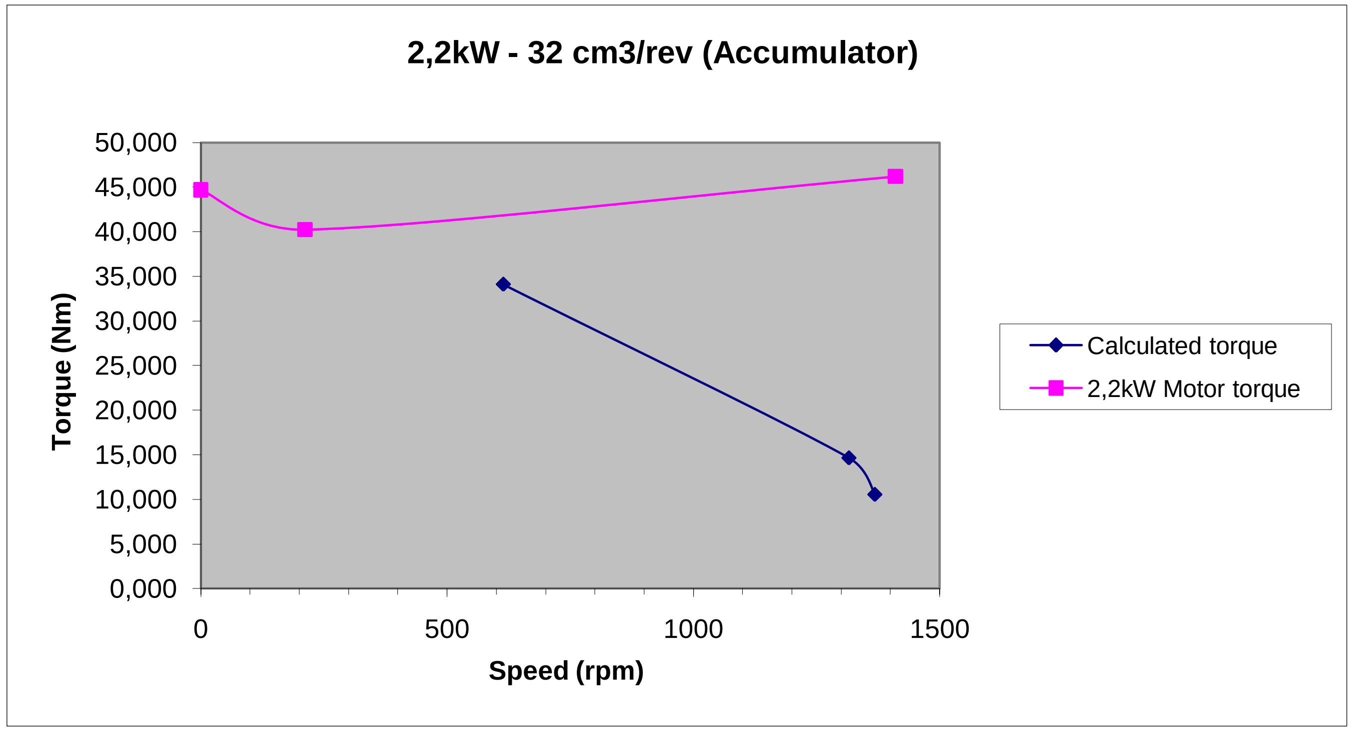
3kW - 24 cm3/rev
Torque (Nm)
60,000
50,000
40,000
30,000
20,000
10,000
0,000
0
500
1000
1500
2000
Speed (rpm)
Calculated torque
3kW Motor torque

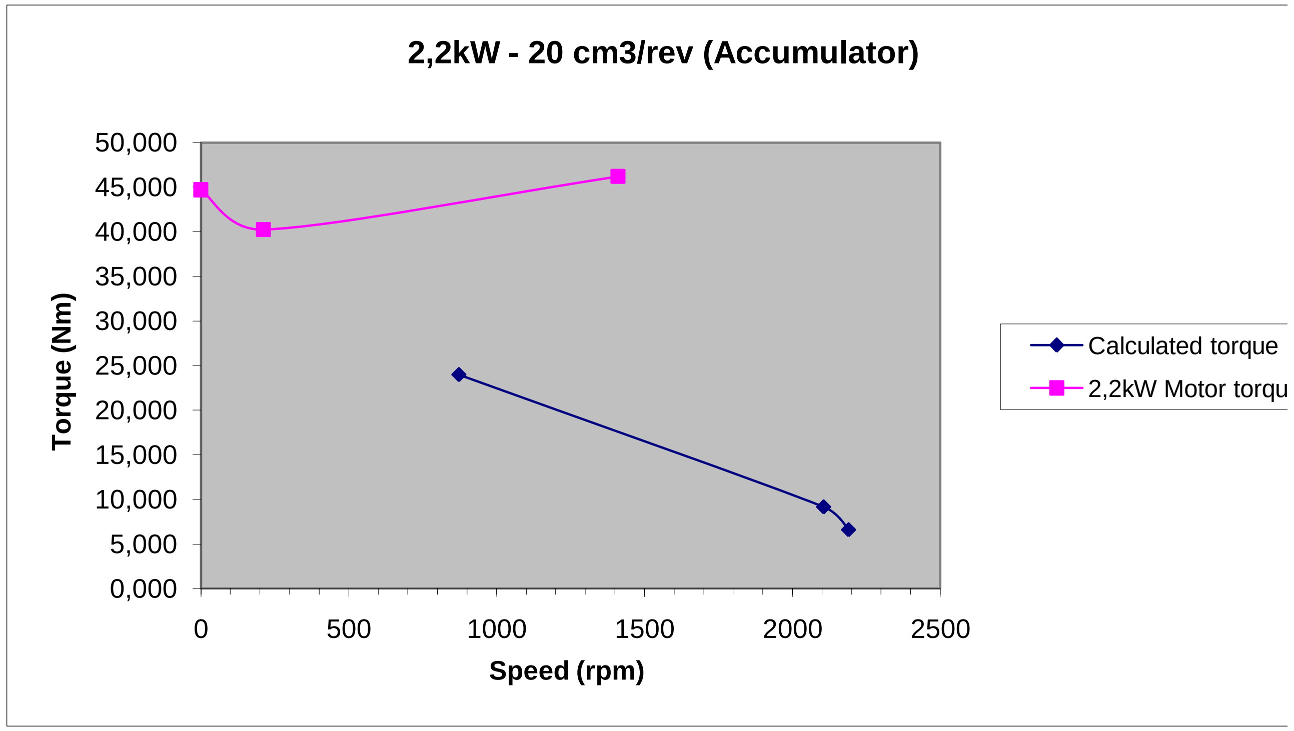


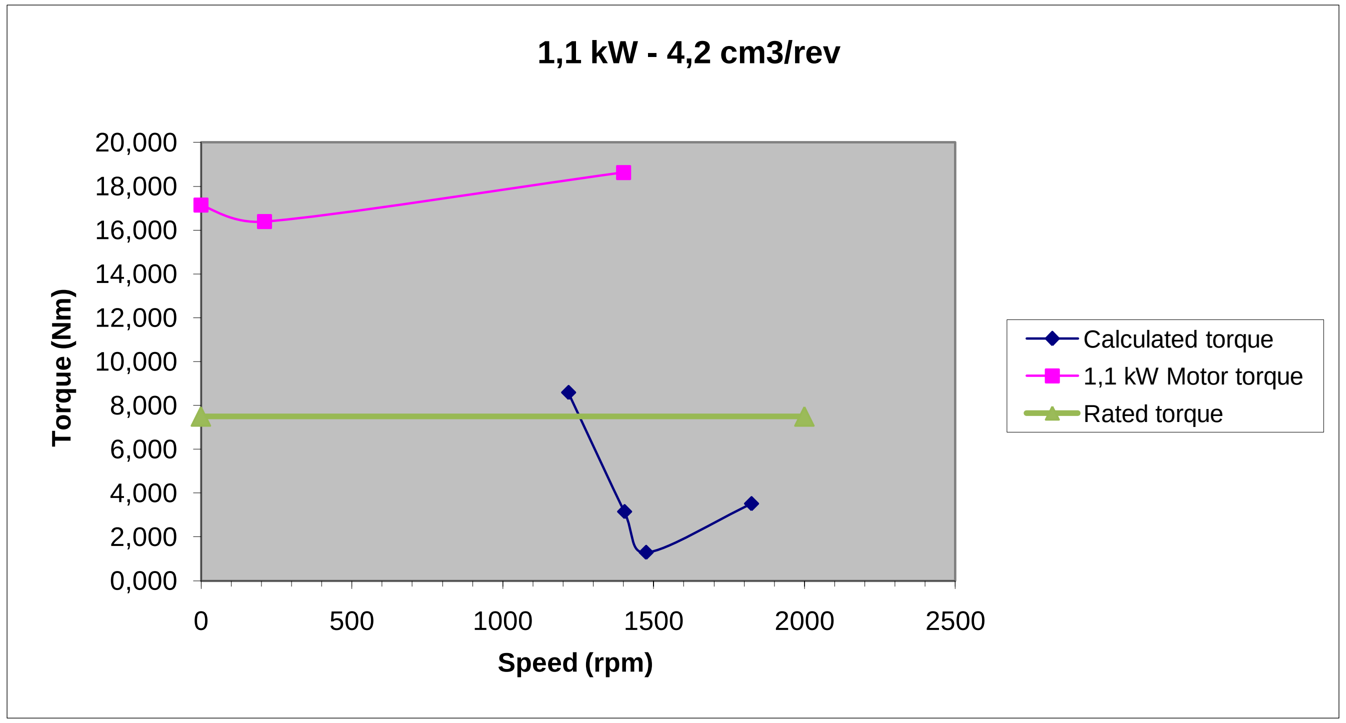
3kW - 20 cm3/rev
Torque (Nm)
60,000
50,000
40,000
30,000
20,000
10,000
0,000
0
500
1000
1500
2000
2500
Speed (rpm)
Calculated torque
3kW Motor torque

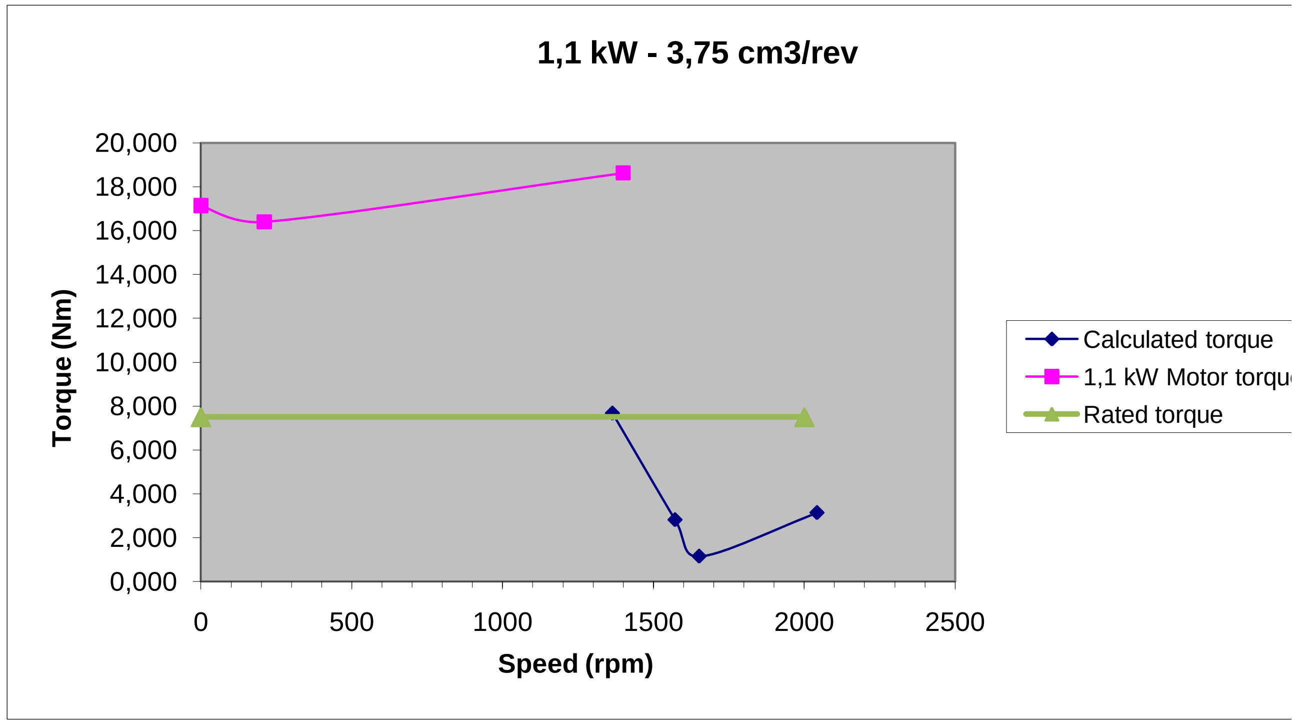

3kW - 28 cm3/rev
Torque (Nm)
60,000
50,000
40,000
30,000
20,000
10,000
0,000
0
500
1000
1500
2000
Speed (rpm)
Calculated torque
3kW Motor torque

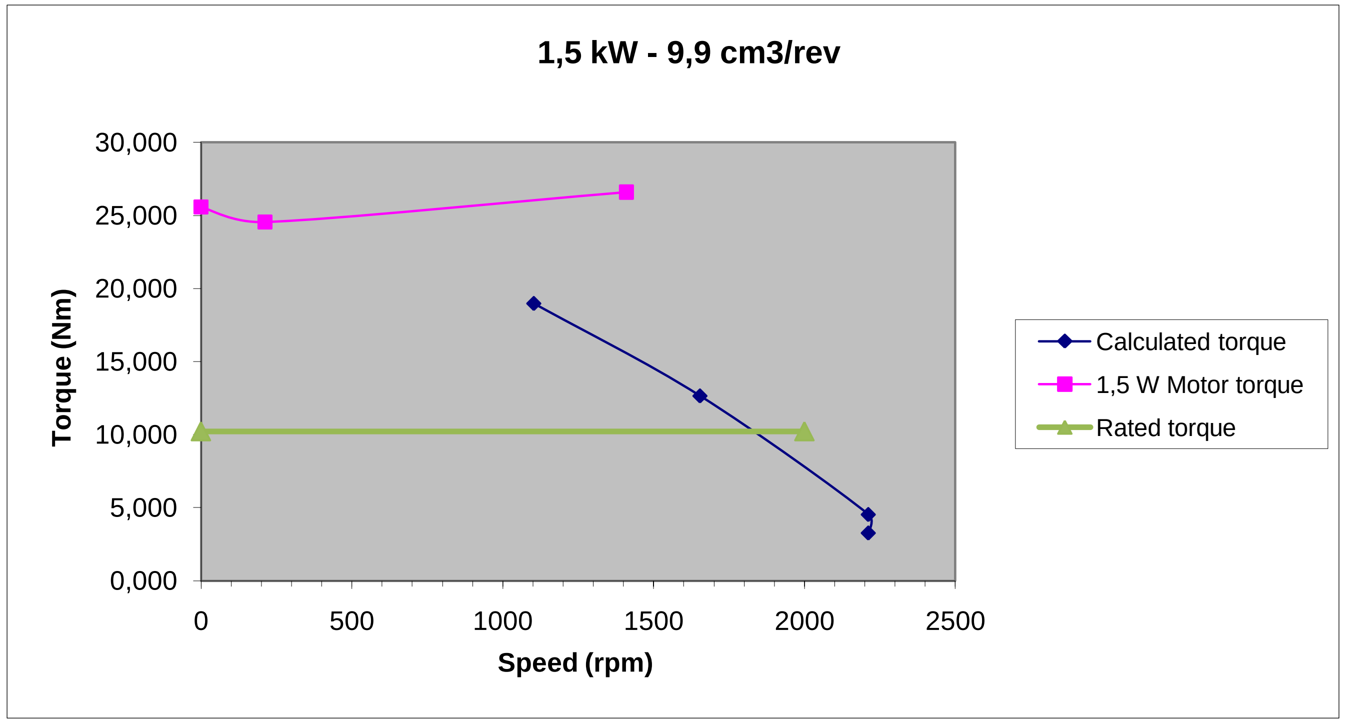

2,2kW - 28 cm3/rev (Accumulator)
Torque (Nm)
50,000
45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0,000
0
500
1000
1500
2000
Speed (rpm)
Calculated torque


2,2kW - 32 cm3/rev (Accumulator)
Torque (Nm)
50,000
45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0,000
0
500
1000
1500
Speed (rpm)
Calculated torque
2,2kW Motor torque


2,2kW - 20 cm3/rev (Accumulator)
Torque (Nm)
50,000
45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0,000
0
500
1000
1500
2000
2500
Speed (rpm)
Calculated torque
2,2kW Motor torqu


1,1 kW - 4,2 cm3/rev
20,000
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0,000
Torque (Nm)
0
500
1000
1500
2000
2500
Speed (rpm)
Calculated torque
1,1 kW Motor torque
Rated torque


1,1 kW - 3,75 cm3/rev
20,000
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0,000
Torque (Nm)
0
500
1000
1500
2000
2500
Speed (rpm)
Calculated torque
Rated torque


1,5 kW - 9,9 cm3/rev
Torque (Nm)
30,000
25,000
20,000
15,000
10,000
5,000
0,000
0
500
1000
1500
2000
2500
Speed (rpm)
Calculated torque
1,5 W Motor torque
Rated torque

Appendix VII - Cost & Weight

Cost specification

						Concept EHC		Concept PowerPack		Existing system	
Component	**Component id**	**Data**	**Price(SEK)**	**Source**	**Additional information**	**Quantity**	**Total price (SEK)**	**Quantity**	**Total price (SEK)**	**Quantity**	**Total price (SEK)**
Complete power pack				Cost interval: 6 500 - 20 000 SEK							
	Hydac - CA	D=3.75cm³/rev, 1.1kW, reservoir=7l	0	Victor Lubian; Hydac AB		0	0	0	0	0	0
	Bosch Rexroth - KE (SL)	D=4.2cm³/rev, 1.1kW, Reservoir= 7 l	20000	15000 from conversation with Håkan Ahlgren, Hydac AB, a factor 1.33 are used as backup		0	0	4	80000	0	0
	Bosch Rexroth - KE (Mast)	D=9.9cm3/rev, 1.5 kW, Reservoir = 13 l	20000	15000 from conversation with Håkan Ahlgren, Hydac AB, a factor 1.33 are used as backup		0	0	2	40000	0	0
	Saturn mini power pack (SL)	D=3.75cm³/rev, 1.1kW, reservoir=7l	7000	6536 SEK; Approximated offer by KRAMP (KRAMP GRENE), Use 7000 SEK	Based on exchange rate 1EUR=8,915SEK 2011-05-25	0	0	4	28000		0
	Saturn mini power pack (SL)	x	8000	Assumed cost increase of 1000 SEK for motor, pump and reservoir		0	0	2	16000	0	0
	Bosch Rexroth - ZL	D=22.5cm3/rev, 4 kW, Reservoir = 25 l		x	Option	0	0	0	0	0	0
Backup system											
	Hand pump		6530	http://www.pmckatalogen.no/view.aspx?ProductId=112001-2-1&menyCategory=1,1	Based on exchange rate 1NOK=1,17SEK 2011-05-20	0	0	0	0		0
	Bosch Rexroth - KE	D=9.9cm3/rev, 1.5 kW, Reservoir = 13 l	20000	15000 from conversation with Håkan Ahlgren, Hydac AB, a factor 1.33 are used as backup		0	0	2	40000		0
Frequency control				Cost interval: 1 000 - 14 000 SEK/motor							
	For motor - K21R132S4		8000	VEM Sweden AB, sales support 040-6712900		0	0	0	0	0	0
	For motor - K21R112M4		7000	VEM Sweden AB, sales support 040-6712900		0	0	0	0	0	0
	For motor - WE1R112M4		5000	VEM Sweden AB, sales support 040-6712900	For 1.1 kW motor, for up to 5 motors (≈ 1000SEK/motor)	3	15000	3	15000		
	VLT Decentral drive FCD 302		14110	Drivhuset AB, (Danfoss) sales support, Håkan Andersson		14	197540	6	84660	0	0
Reservoir											
	x	x		x		0	0		0		0
Mast cylinder											
	101/KFU901047/1	Mast cylinder kit, painted	34000	PMC Hydraulics offer 2010-11-11		0	0	4	136000	4	136000
Mast lock cylinder											
	104/KFU901047/1	Mast lock cylinder, painted	6700	PMC Hydraulics offer 2010-11-11		0	0	2	13400	2	13400
Parking cylinder											
	105/KFU901047/1	Parking cylinder, mounted valve, painted	10150	PMC Hydraulics offer 2010-11-11		0	0	4	40600	4	40600

Support leg cylinder

	102(3)/KFU901047/1	Support leg cylinder, painted	79900	PMC Hydraulics offer 2010-11-11		0	0	4	319600	4	319600

Pipes

	109/KFU901047/1	Pipe set GAMB	85500	PMC Hydraulics offer 2010-11-11		0	0	0	0	1	85500

Oil

	Rando HDZ LT 32	For applications in nature, min temp -42	40,5321274	http://www.fleetfactors.co.uk/lubricants-c8/industrial-oils-c19/rando-hdz-lt-32-p453		104,72	4244,40	104,72	4244,40	122,5	4965,185607

Hoses

	107/KFU901047/1	Hose set hydraulic unit	5500			0	0	1	5500	1	5500
	108/KFU901047/1	Hose set shelter	24200			0	0	1	24200	1	24200

Hydraulic control unit

	201/HCS-001		107800	Syncore Technologies AB Offer 2010-09-28		1	107800	1	107800	1	107800
		Inclinometer	12995	Syncore Technologies AB Offer 2010-09-29		1	12995	1	12995	1	12995

Hydraulic unit

	106/KFU901047/1	Hydraulic unit, baffle-plates included, painted	256000	PMC Hydraulics offer 2010-11-11		0	0	0	0	1	256000

Filter

						0	0	0	0	0	0
											0

Valves

	Valve kit existing system		13690	PMC Hydraulics offer 2010-11-11		0	0	0	0	1	13690

Accumulator

						0	0	0	0	0	0

Pressure sensor

	Pressure sensor		5085			10	50850	10	50850	10	50850

Electro hydraulic cylinder SL

	Electro hydraulic cylinder	d=125mm s=850mm	39000	Kent Börjesson Teknik AB		4	156000	0	0	0	0

Electro hydraulic cylinder mast

	Electro hydraulic cylinder	d=100mm s=1457mm	39000	Kent Börjesson Teknik AB		4	156000	0	0	0	0

Electro hydraulic cylinder Parking

	Electro hydraulic cylinder	d=40mm s=393mm	18000	Kent Börjesson Teknik AB		4	72000	0	0	0	0

Electric linear actuator

	Electric linear actuator econom 2	s=390mm, 3*400V	20480	Offer mekanex 2011-04-15		0	0	0	0	0	0
	Electric linear actuator econom 0	s=80mm, 3*400V	7192	Offer mekanex 2011-04-15		0	0	0	0	0	0

Electro hydraulic cylinder mast lock

	Electro hydraulic cylinder	d=40mm s=80mm	17000	Kent Börjesson Teknik AB		2	34000	0	0	0	0

Additional costs

	Installation GAMB	Assembly of pipes on shelter	14425	PMC Hydraulics offer 2010-11-11			0		0	1	14425
	Installation GAMB	Assembly of pipes on mast	8415	PMC Hydraulics offer 2010-11-11			0		0	1	8415
	Installation GAMB	Assembly of hoses on mast and shelter	6000	PMC Hydraulics offer 2010-11-11			0	1	6000	1	6000
	Installation GAMB	Assembly of hoses between hydraulic unit and shelter	2510	PMC Hydraulics offer 2010-11-11			0	1	2510	1	2510
	Installation GAMB	Startup 1, test	18107	PMC Hydraulics offer 2010-11-11		1	18107	1	18107	1	18107
	Installation GAMB	Startup 2, test	13290	PMC Hydraulics offer 2010-11-11		1	13290	1	13290	1	13290

Total price (high level)	**822826,4031**	**999756,4031**	**1133847,186**
Margin	311020,7825	134090,7825	
%	27,4	11,8	
Total price (low level)	**640286,40**	**854096,4031**	**1133847,186**
Margin	493560,78	279750,7825	
%	43,5	24,7	
Total cost margin	**27 - 43 %**	**12 - 25 %**	

Cost	640 000 - 820 000 SEK	860 000 - 1 000 000 SEK
Margin	310 000 - 490 000 SEK	130 000 - 280 000 SEK

Weight specification

Name	Weight	Source	Concept EHC	Concept PowerPack	Existing system
Power pack KE - Bosch 1,1kW	14,5	Assumed from Hydac data-sheet, incl control (control (valves) = 9/6 kg = 1,5kg)		58	
Power pack KE - Bosch 1,5 kW	16	Assumed from Hydac data-sheet, incl control (control (valves) = 9/6 kg = 1,5kg)		32	
Power pack ZL - Bosch 4kW	x				
Power pach CA - Hydac 1,1kW	14,5	Hydac datasheet - E5305-2-12-10_CA.pdf; 1.1-1.5 kW = 13-14.5 kg excl. oil + control			
Existing power unit	165	Document 12_10262-UAZ10170_22 - sv - A			165
Backup system	32	Assumed to be equal to power pack KE 1,5 kW		32	
Valves					9
Accumulator					
Reservoir					
Mast cylinder top	88	Document 12_10262-UAZ10170_22 - sv - A		176	176
Mast cylinder lower	88	Document 12_10262-UAZ10170_22 - sv - A		176	176
Mast lock cylinder	3,5	Document 12_10262-UAZ10170_22 - sv - A		7	7
Parking cylinder	6,5	Document 12_10262-UAZ10170_22 - sv - A		26	26
Support leg cylinder	170	Document 12_10262-UAZ10170_22 - sv - A		680	680
Oil	91,9826	Document 12_10262-UAZ10170_22 - sv - A	91,98	91,98	107,6
Pipes	35	Document 12_10262-UAZ10170_22 - sv - A			35
Hoses	35	Document 12_10262-UAZ10170_22 - sv - A		35	35
Hydraulic control unit	4	Document 12_10262-UAZ10170_22 - sv - A	4	4	4
Cabling	19,9	Document 12_10262-UAZ10170_22 - sv - A	19,9	19,9	19,9
Electro hydraulic cylinder Support leg	240	Estimation from Kent Börjesson Teknik AB	960		
Electro hydraulic cylinder Mast	132	Estimation from Kent Börjesson Teknik AB	528		
Electro hydraulic cylinder Parking	9,75	Estimation from Kent Börjesson Teknik AB	39		
Electro hydraulic cylinder Mast lock	5,25	Estimation from Kent Börjesson Teknik AB	10,5		
EHC Parking + EHC Mast lock		49,5			
Linear actuator econom 2 (Mekanex AB - offer)	32	128			
Linear actuator econom 0 (Mekanex AB - offer)	13	26			
Extra weight with linear actuators		**104,5**			
Total weight hydraulic system			**1653,38**	**1337,88**	**1440,5**
Total weight with linear actuators instead			**1757,88**	**1458,88**	

Appendix VIII - Functional Specification

Category	No.	Requirement	Data	Fulfilment	"PowerPack"	"EHC"
1. Characteristics						
1.1 Performance						
1.1.1 General						
	1.1.1.1	The hydraulic system shall not affect the possibility of loading the entire radar system onto a truck.		OK/OK	Existing mechnical structures reused.	Existing mechnical structures reused.
1.1.2 Weight						
	1.1.2.1	Hydraulic system (total weight incl. mechanical structures of support legs)	1889 kg	OK/NO	Approx. 1440 kg	Approx. 1715 kg
1.1.3 Operational range						
	1.1.3.1	The system shall manage to operate i.e. lift the radar cabin to horisontal position and reverse, on all ground slopes ≤ 7° without truck.	≤ 7°	OK/OK	Existing controls reused, components dimensioned to handle these loads.	Existing controls reused, components dimensioned to handle these loads.
	1.1.3.2	The system shall manage to operate i.e. lift the radar cabin to horisontal position and reverse, on all ground slopes ≤ 5° with truck.	≤ 5°	OK/OK	see above	see above
1.1.4 Accuracy						
	1.1.4.1	The system shall automatically ensure that the resulting horisontal position of the radar cabin is within ± 0.3° i.e. that the radar system is levelled.	± 0.3°	OK/OK	Reference configuration of sensors is used with the inclinometer	Reference configuration of sensors is used with the inclinometer
1.1.5 Positional locking						
	1.1.5.1	No piston movement or slipping is allowed for the support leg and mast cylinders in any of their static positions.		OK/OK	Existing load-holding valve on cylinder & pump activation when position is lost (position sensors & inclinometer)	Existing load-holding valve on cylinder & pump activation when position is lost (position sensors & inclinometer)
	1.1.5.2	The positional locking must withstand the cylinder maximum operating and non-operating loads.		OK/?	Existing structures used	Small design modifications needed due to change of cylinders. Fulfillment not known.

Category		No.	Requirement	Data	Fulfilment	"PowerPack"	"EHC"
	1.1.6 Power loss						
		1.1.6.1	During power loss, all cylinders shall keep their positions.		OK/OK	Load-holding valve	Solenoid valve
		1.1.6.2	All cylinders must keep their non-operating load taking performance.		OK/(OK)	Existing cylinders used.	Cylinders approximately dimensioned to non-operating loads.
	1.1.7 Cylinder maximum loads						
	Support leg cylinders						
		1.1.7.1	Case 1: Maximum axial loads, non-operating mode (no electrical power), individual cylinder.	150kN	OK/(OK)	Existing cylinders used.	Cylinders approximately dimensioned to maximum loads.
		1.1.7.2	Case 1: Maximum transversal loads, non-operating mode (no electrical power), individual cylinder.	20kN	OK/(OK)	see above	see above
		1.1.7.3	Case 2: Maximum axial loads, non-operating mode (no electrical power), individual cylinder.	100kN	OK/(OK)	see above	see above
		1.1.7.4	Case 2: Maximum transversal loads, non-operating mode (no electrical power), individual cylinder.	30kN	OK/(OK)	see above	see above
	Mast cylinder(s)						
		1.1.7.6	Maximum axial loads, operating mode, individual cylinder.	95kN	OK/(OK)	Existing cylinders used.	Cylinders approximately dimensioned to maximum loads.
		1.1.7.7	Maximum axial loads, non-operating mode (no electrical power), individual cylinder.	95kN	OK/(OK)	see above	see above
	Mast transport lock						
		1.1.7.8	Maximum load, individual cylinder.	3kN	OK/OK	Existing cylinders used.	Cylinders approximately dimensioned to maximum loads & linear actuators specified to withstand load.
	Parking cylinders						
		1.1.7.9	Maximum load, individual cylinder.	20kN	OK/OK	see above	see above

Category		No.	Requirement	Data	Fulfilment	"PowerPack"	"EHC"
	1.1.8 Cylinder stiffness						
		1.1.8.1	For redesigning of mechanical structures/ interfaces, the stiffness of the entire system shall not be negatively affected.		OK/(OK)	Existing structures used.	Only small design modifications of mountings needed due to change of cylinders. Fulfillment not known but should not be a problem.
	1.1.9 Buckling						
		1.1.9.1	The support leg cylinder and piston shall be dimensioned to prevent buckling at their most extended position. Safety factor 2.0 is included. Boundary conditions according to Euler 1.	300 kN (150*SF kN)	OK/(OK)	Existing cylinders used.	No verification can be officially made, though same dimensions of the cylinders are used.
		1.1.9.2	The mast cylinders and pistons shall be dimensioned to prevent buckling at their most extended position. Safety factor 2.0 is included. Boundary conditions according to Euler 2.	110 kN (55*SF kN)	OK/(OK)	see above	see above
	1.1.10 Power usage						
		1.1.10.1	Power usage shall be minimized		OK/OK	Power usage adapted to each function's specific requirement	Power usage adapted to each function's specific requirement
		1.1.10.2	The power consumption of the system shall on avarage be	≤ 7 kW	OK/OK	Savings of up to 50-70 %	Savings of up to 50-70 %
1.2 Operation time							
				Temp.	Section	Factor	
			The required times in section 1.2.1-1.2.2 are valid within the ambient temp. range 0°C to +55°C. At ambient temp. below 0°C the times are allowed to be extended with the following factors.	-20°C	Both	x2	
				-40°C	1.2.1	x2	
					1.2.2	x4	
	1.2.1 General						
		1.2.1.1	The total time for deployment of the entire radar system shall be maximum 10 minutes with main power supply.	10 min	OK/OK	Mast operation: 120s Support leg operation: approx 335s	Mast operation: 120s Support leg operation: approx 335s
	1.2.2 Emergency operation						
		1.2.2.1	The time required from operational conditions to transport position shall be less than 30 minutes without main power supply.	30min	(OK)/(OK)	Not evaluated, though configuration possibilities exist	Not evaluated, though configuration possibilities exist

Category	No.	Requirement	Data	Fulfilment	"PowerPack"	"EHC"

2. Interfaces

2.1 Mechanical interfaces

	2.1.0.1	The interfaces of the hydraulic system including support leg cylinders, mast cylinder(s), mast transport lock and hydraulic control unit shall consist of standard components.		OK/OK	Power pack uses standard components and connections.	EHC built up of standard components and interfaces, though reservoir is customized.

2.2 Electrical interface

2.2.1.Power supply						
	2.2.1.1	The power supply driving the hydraulic pump shall comply with the nominal voltage 3x230/400V AC.	3x230/400V AC	OK/OK	Compliance	Compliance
	2.2.1.2	The hydraulic control system shall comply with the nominal voltage 28V DC.	28V DC	OK/OK	Compliance (or 24V DC)	Compliance (or 24V DC)
	2.2.1.3	The system shall have an emergency external power supply/other solutions for lowering the mast and positioning of the support legs for transport if main power loss occurs.		OK/OK	Portable power unit / Hand pump driven by portable motor	AC/DC converter to switch power source & external drive module to rotate electric motor axis.
2.2.2 Control signals to/from hydraulic control system						
	2.2.2.1	The hydraulic system shall be controlled by a bus-based control system.		(OK)/(OK)	Bus system possible for adaption to concept solutions, though costly	Bus system possible for adaption to concept solutions, though costly
	2.2.2.2	The hydraulic control system shall recieve information for:		OK/OK	Existing control system config.	Existing control system config.
		• overload condition for each support leg			Existing pressure sensors	Pressure sensors
		• mast up/down			Existing rotary & position sensors	Existing rotary & position sensors
		• safety switch when someone enters the roof			Safety switch	Safety switch
		• hydraulic faults			Sensor alarms	Sensor alarms
		• level alarms			Inclinometer	Inclinometer
		• oil pressure/level/temp in hydraulic unit			Pressure & temp sensor	Pressure & temp sensor
		• ground pressure in support leg cylinders			Pressure sensor on cylinder	Pressure sensor on cylinder
		• pressure in mast cylinder(s)			Pressure sensor on cylinder	Pressure sensor on cylinder
		• emergency stop			Button	Button
		• black out				
		• locked/open rear transport lock			Position sensor	Position sensor

Category	No.	Requirement	Data	Fulfilment	"PowerPack"	"EHC"
		• locked/open front transport lock			Position sensor	Position sensor
		• position of mast cylinder(s)			Position sensor	Position sensor
		• parking of support legs			Rotary sensor	Rotary sensor
		• rotation of mast			Rotary sensor	Rotary sensor
		• antenna parking status			Position sensors	Position sensor
		• hydraulic pump control			Frequency converter	Frequency converter
		• emergency pump control			External control	External control
		• support leg switch manual operation			Directional valve lever / switch / regulator	Button / Switch / Regulator that controls the motor

Category	No.	Requirement	Data	Fulfilment	"PowerPack"	"EHC"
3. Reliability						
3.1 Life time						
	3.1.0.1	The hydraulic system is expected to be in use for at least 20 years and with an operating profile according to section 3.2.	20 years	x/x	Evaluation have not been possible, though not likely to not meet requirement due to the nature of the application's intermittent operation.	Cannot be specified, testing needed
	3.1.0.2	The system shall be able to handle storage for 6 years with storage environment according to section 5.	6 years	x/x	see above	see above
3.2 Operating profile						
	3.2.0.1	The hydraulic system shall have the possibility to be operated manually.		OK/OK	Directional valve lever / switch / regulator	Button / Switch / Regulator that controls the motor
	3.2.0.2	The equipment shall withstand an operating profile during a period of 20 years with 10 000 operations. (one setup & one take down)	10 000 operations	x/x	Evaluation have not been possible, though not likely to not meet requirement due to the nature of the application's intermittent operation.	Evaluation have not been possible, though not likely to not meet requirement due to the nature of the application's intermittent operation.
	3.2.0.3	The equipment shall withstand to be used in deployed operational position during a period of three months continuously.	3 months	x/x	see above	see above

Category	No.	Requirement	Data	Fulfilment	"PowerPack"	"EHC"

4. Maintainability

4.1 General

Category	No.	Requirement	Data	Fulfilment	"PowerPack"	"EHC"
	4.1.0.1	The hydraulic system and control system shall be designed for simple maintenance and repair.		OK/OK	Either existing control system or CAN bus-based which is better in this sense	Either existing control system or CAN bus-based which is better in this sense
	4.1.0.2	The hydraulic system and control system shall have a modular design with replaceable units for quick change in field operation.		(OK)/(OK)	If CAN bus interface is selected	If CAN bus interface is selected
	4.1.0.3	Preventive maintenance shall be of limited range.		x/x	Evaluation have not been possible	Evaluation have not been possible

4.2 Interchangeability

Category	No.	Requirement	Data	Fulfilment	"PowerPack"	"EHC"
	4.2.0.1	Any unit shall be interchangeable without any trimming or alignment.		OK/OK	Standard components	Standard components

Category	No.	Requirement	Data	Fulfilment	"PowerPack"	"EHC"

5. Environmental requirements

5.1 Climatic environment

Category	No.	Requirement	Data	Fulfilment	"PowerPack"	"EHC"
5.1.1 General						
	5.1.1.1	The system shall be designed for coastal climate and industrial pollution.		OK/OK	Aftertreatment of power pack, otherwise the same structure and cylinders.	Solution is proven in coastal and naval environments.
5.1.2 High temp. during operation						
	5.1.2.1	The hydraulic system shall be able to operate in a maximum ambient temperature of +55°C	+55°C	(OK)/(OK)	With surface treatment etc.	With surface treatment etc.
5.1.3 High temp. during storage						
	5.1.3.1	The hydraulic system shall be able to be stored in a maximum ambient temperature of +71°C	+71°C	(OK)/(OK)	With surface treatment etc.	With surface treatment etc.
5.1.4 Low temp. during operation						
	5.1.4.1	The hydraulic system shall be able to operate in an ambient temperature of -40°C	-40°C	(OK)/(OK)	With surface treatment etc.	With surface treatment etc.
5.1.5 Low temp. during storage						
	5.1.5.1	The hydraulic system shall be able to be stored in an ambient temperature of -46°C	-46°C	(OK)/(OK)	With surface treatment etc.	With surface treatment etc.
5.1.6 Solar radiation						
	5.1.6.1	The hydraulic cylinders and other exposed components shall be designed for maximum intensity of 1120 W/m2.	1120 W/m2	x/x	Testing not possible/Not specified	Testing not possible/Not specified
5.1.7 Humidity (function & storage)						
	5.1.7.1	The hydraulic system shall withstand severe condensing humidity resulting from non-controlled temperature and humidity in tropical areas.		OK/OK	Existing structures and cylinders. Enclosed power pack.	Fully enclosed solution, except from motor. After-treatment of motor necessary.
5.1.8 Fungus						
	5.1.8.1	The hydraulic system shall not be affected by fungus growth i.e. no damage nor performance degradation.		OK/OK	Existing structures and cylinders. Enclosed power pack.	Fully enclosed solution, except from motor. After-treatment of motor necessary.

Category	No.	Requirement	Data	Fulfilment	"PowerPack"	"EHC"
5.1.9 Rain						
	5.1.9.1	The hydraulic cylinders and other exposed components shall be designed for max intensity of 100 mm/h of rain.	100 mm/h	x/x	Testing not possible/Not specified	Testing not possible/Not specified
5.1.10 Sand & Dust						
	5.1.10.1	The hydraulic cylinders and other exposed components shall be designed to withstand air containing sand and dust.		x/x	Testing not possible/Not specified	Testing not possible/Not specified
	5.1.10.2	The hydraulic cylinders and other exposed components shall be designed to prevent clogging or build up of sand and dust.		x/x	see above	see above
5.1.11 Low pressure						
	5.1.11.1	Minimum operational pressure shall be 65kPa (3500m above sea level) at maximum ambient temp. +20°C.	65 kPa	x/x	Testing not possible/Not specified	Testing not possible/Not specified
		Minimum operational pressure shall be 75kPa (2500m above sea level) at maximum ambient temp. +35°C.	75 kPa	x/x	see above	see above
		Minimum non-operational pressure shall be 19kPa (12000m above sea level).	19 kPa	x/x	see above	see above
5.1.12 Snow						
	5.1.12.1	The hydraulic cylinders and other exposed components shall during transport, storage and operation withstand snowfall corresponding to an intensity of 50mm/h in melted form.	50 mm/h (melted)	x/x	Testing not possible/Not specified	Testing not possible/Not specified
5.1.13 Hail						
	5.1.13.1	The hydraulic cylinders and other exposed components shall withstand hailstorms with hails of diameter of 10mm with full performance afterwards.	10 mm	x/x	Testing not possible/Not specified	Testing not possible/Not specified
5.1.14 Ice during storage & transportation						
	5.1.14.1	The hydraulic cylinders and other exposed components shall be designed to withstand 13 mm ice thickness.	13 mm	x/x	Testing not possible/Not specified	Testing not possible/Not specified

Category	No.	Requirement	Data	Fulfilment	"PowerPack"	"EHC"

6. Design rules and requirements

6.1 General

Category	No.	Requirement	Data	Fulfilment	"PowerPack"	"EHC"
	6.1.0.1	The hydraulic units shall have a modular design/configuration.		OK/OK	Power pack + Cylinder	All-in-one module
	6.1.0.2	The support leg hydraulic units with its components shall not, in parked position, extend from the shelter walls.		OK/(OK)	Power pack placed in shelter. Existing structure reused.	Minor modifications needed on structure, though it shall not affect the fulfillment.
	6.1.0.3	The mast cylinder hydraulic unit(s) shall not extend from the roof and not interfere with the mast's space requirements.		OK/(OK)	see above	see above

6.2 Enclosure protection

Category	No.	Requirement	Data	Fulfilment	"PowerPack"	"EHC"
	6.2.0.1	Sensitive components shall be enclosed for protection.		OK/OK	Power pack enclosed	Integrated solution, though motor extends. After-treated motor.

6.3 Connections

Category	No.	Requirement	Data	Fulfilment	"PowerPack"	"EHC"
	6.3.0.1	All connections for pipes, hoses and cables shall be easily accessible for mounting and dismounting.		OK/OK	All cables out in leg compartment	No pipes or hoses, only electric wires
	6.3.0.2	Connections shall be of standard connection types.		OK/OK	Standard connections	Standard connections
	6.3.0.3	All connections shall be secured against accidental loosening. Solded lugs are not permitted.		x/x	Partly outside thesis scope. Though standard couplings are assumed to be secure.	Partly outside thesis scope. Though standard couplings are assumed to be secure.

6.4 Dimensioning

Category	No.	Requirement	Data	Fulfilment	"PowerPack"	"EHC"
	6.4.0.1	The hydraulic system shall fit into existing dimensions of the shelter (HxWxL).	2438 x 2438 x 6058 mm	OK/OK	Power pack fits into compartment	All components on cylinder; redesign / modification shall not affect the fulfillment.
	6.4.0.2	The support legs shall not geometrically/physically, during deployment, interfere with the truck.		OK/OK	Existing structure and cylinders are used	Similar structures are used. Minor cylinder configurations.
	6.4.0.3	The bottom of the shelter shall be able to be lifted 2100 mm above ground by the support legs.	2100 mm	OK/OK	Same stroke lenght and position of cylinders.	Same stroke lenght and position of cylinders.

6.5 Materials & surface treatment

Category	No.	Requirement	Data	Fulfilment	"PowerPack"	"EHC"
	6.5.0.1	The metallic materials used in equipment shall be corrosion resistant or treated to be corrosion resistant.		OK/OK	Saab EDS	Saab EDS post treatment & Supplier specification
	6.5.0.2	Non-metallic materials like plastics, rubber etc. shall be moisture, UV, flammable and fungus resistant during its intended lifetime.		x/x	Partly outside thesis scope. Though selected components are assumed to be resistant.	Partly outside thesis scope. Though standard components are assumed to be resistant.

Category	No.	Requirement	Data	Fulfilment	"PowerPack"	"EHC"
	6.5.0.3	All materials shall be chosen considering extreme temperatures and all other environmental conditions specified in section 5.		x/x	Partly outside thesis scope. Though selection of components have been taken with this aspect mind.	Partly outside thesis scope. Though selection of components have been taken with this aspect in mind.
6.6 Mechanical components						
	6.6.0.1	All components shall be carefully chosen considering performance, environmental resistance, easy service and handling.		OK/OK	Components have been chosen with this in mind.	Components have been chosen with this in mind.
	6.6.0.2	For choice of mechanical components ISO-standard shall be used.		(OK)/(OK)	Not verified, but components are assumed to follow common industry standards.	Not verified, but components are assumed to follow common industry standards.
6.7 Cables & protection of circuits						
	6.7.0.1	The apparatus and circuits shall be arranged to facilitate their operation and maintenance, and at the same time be arranged to ensure the necessary degree of safety.		x/x	see risk analysis recommendations. Existing circuit arrangements are mainly used.	see risk analysis recommendations. Existing circuit arrangements are mainly used.
6.8 Moisture						
	6.8.0.1	The equipment shall be designed to achieve necessary ventilation. Special attention shall be paid to avoid water condensation inside structures. If necessary, there shall be holes for draining of moisture.		x/x	Not verified, though same structures are used and the power pack shall be enclosed with proper ventilation.	Not verified, though similar structures are used and the electrical motor is in open-air but surface treated.
6.9 Cleanness						
	6.9.0.1	The mechanical design shall be carried out in consideration of easy cleaning of the equipment. All components shall have a material or surface treatment resistant to deterioration.		OK/OK	The accessibility of the concept components favours cleanliness; Enclosed components and surface treatment provides resistance.	The accessibility of the concept components favours cleanliness; Enclosed components and surface treatment provides resistance.

Category	No.	Requirement	Data	Fulfilment	"PowerPack"	"EHC"

7. Product safety requirements

7.1 General

	7.1.0.1	The design of the hydraulic system shall be performed with necessary safety, to avoid damage to person, property, system and environment at prescribed use and handling.		OK/OK	see Risk analysis, appendix III	see Risk analysis, appendix III
	7.1.0.2	A Risk analysis shall be made on the system.		OK/OK	see Risk analysis, appendix X	see Risk analysis, appendix X