TAMPEREEN TEKNILLINEN YLIOPISTO
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PRODUCT DEVELOPMENT OF A HOOKLIFT BY UTILIZING DESIGN FOR SIX SIGMA PRINCIPLES

Master of Science Thesis

Examiner: PhD. Jarkko Pakkanen
Examiner and topic approved on 31 January 2018

ABSTRACT

Jonne Heino: Product Development of a Hooklift by Utilizing Design for Six Sigma Principles
Tampere University of Technology
Master of Science Thesis, 77 pages, 8 Appendix pages
February 2018
Master's Degree Programme in Mechanical Engineering
Major: Machine Design and Product Development
Examiner: Ph.D. Jarkko Pakkanen

Keywords: Design for Six Sigma, Product development, Concept design, The European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR), Quality Function Deployment (QFD), Analytic Hierarchy Process (AHP)

The purpose of this thesis is to support an ongoing product development project in the case company. The thesis is examines if the product requirements are fulfilled after certain updates have been made to the product. Especially the requirements that are set by the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) are in the center of the focus in this thesis. For those elements, which do not meet the product requirements, the thesis aims to create optimized design solutions that fulfill the product requirements by utilizing Design for Six Sigma principles.

The thesis consists of three main sections: theory, current state analysis and making improvements to remedy the discovered problems. In the theory section, the thesis introduces the ADR requirements for a hooklift and Design for Six Sigma principles and tools which are utilized in this thesis. Current state analysis strives to identify which parts of the product require improvements. The aim of the final section is to provide solutions for the identified problems.

The research method used in this thesis is action research. First, theories are clarified and research questions identified and determined. Next, data is collected, which is then analyzed in order to improve the design. According to the analysis, certain changes are made to various design elements and finally, the solutions are reviewed.

As a result of this thesis, we have clarification for the mechanical strength requirements required by ADR regulations in the context of hooklifts. Even though the ADR regulations were ambiguous to interpret or directly targeted to hooklifts, we could produce a viable interpretation of them. As an outcome of this thesis, the product is now ADR compliant, interchangeable with older model and its hook is now equipped with a safety latch. A completely new safety latch concept was created during the project which turned out to be a viable solution that can be used in the facelifted product according to the prototype testing.

Overall, the product requirements were fulfilled successfully and we can be pleased with the results. For the company, the thesis supported an ongoing project by finding solutions for the problems that occurred in the design. In the future, ADR interpretation clarifies and eases design work of products that are required to be ADR compliant.

TIIVISTELMÄ

JONNE HEINO: Koukkulaitteen tuotekehitys Design for Six Sigma periaatteita hyödyntäen
Tampereen teknillinen yliopisto
Diplomityö, 77 sivua, 8 liitesivua
Helmikuu 2018
Konetekniikan diplomi-insinöörin tutkinto-ohjelma
Pääaine: Koneensuunnittelu ja tuotekehitys
Tarkastaja: Ph.D. Jarkko Pakkanen

Avainsanat: Design for Six Sigma, tuotekehitys, konseptisuunnittelu, The European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR), Quality Function Deployment (QFD), Analytic Hierarchy Process (AHP)

Tämä diplomityö pyrkii avustamaan meneillään olevaa tuotekehitysprojektia kohdeyrityksessä. Työn tarkastelee täyttääkö tietyiltä osin muutettu tuote sille asetetut tuotevaatimukset. Erityisesti tuotevaatimukset, jotka UNECE:n sopimus vaarallisten aineiden kansainvälisistä tiekuljetuksista (ADR) säätää, ovat huomion keskipisteessä tässä työssä. Niille elementeille, jotka eivät täytä tuotevaatimuksia, työ pyrkii luomaan optimoidut tuotevaatimukset täyttävät ratkaisut käyttäen hyväksi Design for Six Sigma periaatteita.

Työ koostuu kolmesta pääosasta: teoriaosuus, nykytila-analyysi ja parannusten tekeminen havaittujen ongelmien korjaamiseksi. Teoriaosuudessa perehdytään ADR:n säätämiin vaatimuksiin koukkulaitteelle ja Design for Six Sigma periaatteisiin ja työkaluihin, joita hyödynnetään työssä. Nykytila-analyysi pyrkii tunnistamaan miltä osin tuote vaatii parannuksia. Havaituille ongelmille pyritään löytämään ratkaisut työn viimeisessä osiossa.

Tutkimusmenetelmänä työssä käytetään toimintatutkimusta. Ensin valitut teoriat selvennetään ja tutkimuskysymys tunnistetaan ja määritellään. Seuraavaksi tietoa kerätään, joka sen jälkeen analysoidaan designin parantamiseksi. Analyysin perusteella tehdään design elementteihin muutokset ja lopulta tulokset arvioidaan.

Työn tuloksena saatiin selvennys ADR säädösten vaatimiin mekaanisiin lujuusvaatimuksiin koukkulaitteita koskien. Vaikka ADR vaatimukset eivät olleet yksiselitteisiä tai koukkulaitteelle suoraan suunnattuja, käyttökelpoinen tulkinta pystyttiin tuottamaan. Työn seurauksena tuote on nyt ADR kelpoinen, vaihtokelpoinen vanhan mallin kanssa ja sen koukku on varustettu turvalukolla. Projektin aikana luotiin kokonaan uusi turvalukko konsepti, joka osoittautui käyttökelpoiseksi ratkaisuksi faceliftatussa tuotteessa prototyyppitestausten perusteella.

Kokonaisuutenaan tuotevaatimukset saatiin hyvin täytettyä ja lopputulokseen voidaan olla tyytyväisiä. Yrityksen kannalta työ tuki vahvasti meneillään olevaa projektia ja ratkaisi ongelmia, joita suunnittelussa ilmeni. ADR-tulkinta selventää ja helpottaa tulevaisuudessa uusien ADR-hyväksyttyjen tuotteiden suunnittelua.

PREFACE

This thesis is done at Raisio for Cargotec Finland Oy, Multilift.

I would like to thank Esa Mylläri for coming up with an interesting thesis opportunity and for the guidance and cooperation Pauli Siivonen. The project progressed little by little and without the guidance and support, the thesis would not have been finished this early. Thanks also to Matti Randelin for all the professional guidance with the FEM and strength analysis related issues.

Thanks to my examiner Ph.D. Jarkko Pakkanen for all the feedback and help during the thesis. The guidance was a big help along the project and it directed the thesis towards the right direction. I would also like to thank my family and friends for all the support during the years at University. Finally, I am grateful to Vilma for your continuous support through the ups and downs of the writing process.

Turku, 14.2.2018

Jonne Heino

CONTENTS

List of Symbols and abbreviations

ADR	The European Agreement concerning the International Carriage of Dangerous Goods by Road
AHP	Analytic hierarchy process
CAD	Computer-aided design/engineering
CAE	Computer-aided engineering
CHU	Container handling unit
CTS	Critical-to-Satisfaction
DFM	Design for Manufacturing
DFMEA	Design Failure Mode and Effect Analysis
DMAIC	Define, Measure, Analyze, Improve, Control
DoE	Design of Experiments
DROPS	Demountable Rack Offload and Pickup System
FEA	Finite element analysis
FEM	Finite element method
FMEA	Failure mode effect analysis
HOQ	House of Quality
MEGC	Multi element gas container
MPGM	Maximum permitted gross mass
RPN	Risk Priority Number
TRIZ	Theory of Inventive Problem Solving
UN	United Nation
UNECE	United Nations Economic Commission for Europe
QFD	Quality Function Deployment
VAK	Vaarallisten aineiden kuljetus
VOC	Voice of the customer

a	acceleration
F	force
m	mass
g	acceleration of gravity
G	force of gravity
K	stiffness matrix
u	displacement matrix

1. INTRODUCTION

In the introduction, the background, objectives and framework of the thesis are introduced. After methods are introduced, the case company and the products that concern the thesis are presented.

1.1 Background

The purpose of this thesis is to support an ongoing modernization project of a military hooklift in the case company. Some equipment has changed and they have not been analyzed yet whether they fulfill determined product requirements or not. The thesis pursues to find answers to this problem and solve the possible issues that are found out.

The case company has offered hooklifts for military purposes for several decades. A closer look at the company is provided later in chapter 1.6 of this thesis. Generally, militaries desire to retain equipment rather similar for a long time to have less variable equipment that have to be educated to people. The hooklift of this project is a popular product, which is sold to several armies around the world. The design of the product has not changed much over the past decades, which enables possibilities to create a more valuable product by modernizing it to today's standards.

Manufacturing processes have developed significantly over the past years. New and more accurate methods have allowed designing steel structures more cost efficiently. Components that are used can have nowadays more complex shapes since the data can be shared as data and not only by using drawings, for instance. More accurate laser cutting methods and considerable development of higher strength steels' weldability and ductility have enabled possibilities to achieve lighter and more cost-efficient design solutions.

The operation purpose of the hooklift has not changed much over the years. The reason for starting the modernization project is not that operation capabilities of the hooklift are not up to date. Reasons are instead that component availability has changed and cost reductions can be made by replacing the problematic components with ones with better availability and better cost-efficiently. This usually indicates lower prices for the new components as well. In addition, harmonization to the existing products can be carried out at the same time and the amount of items can be decreased.

As said, this thesis has been made to support an ongoing modernization project of a military hooklift. Design for Six Sigma (DFSS) principles and various tools that it is utilizing are used to achieve better results in satisfaction of customer demands and quality. High quality and good customer satisfaction are key factors to perform in today's world hard competition, which is why DFSS theory is a valuable approach to use in today's business.

1.2 Research objectives and problem

The objective of this work is to develop product by utilizing Design for Six Sigma tools that drive the design towards better quality without forgetting the customer needs. Customer needs have been already derived into product requirements, which are used then as a driver for the design in this thesis. The target of the product development project on behalf of the company is to increase the product value by reducing the costs in the whole lifecycle of the product. This is achieved by using components with lower costs and better availability, and by using equipment that is easier and more cost-efficient to manufacture.

As mentioned, the main research objective is to find out if the product fulfills determined product requirements and if not, improve the design so that it will. The objective is to fulfill the product requirements in a way that customer is satisfied but costs are reduced to minimum. In the product requirements, the required performance of the design is described.

Research questions of this thesis are:

- Does the product fulfill the product requirements?
    - What changes need to be done so that requirements are met?
    - What does the ADR mean?
    - How to fulfill ADR?
    - How to reach the required design performance level?

In this thesis, the whole product development loop is not performed even it is presented in the theory section. Identifying the requirements is ignored and product requirements that are provided by the case company's product management department are used. Not all the product requirements that the facelifting project consists are part of the thesis. The thesis focuses on parts of the mechanical development areas.

1.3 Research method

The research method used in this thesis is action research. The base of the action research is research that researcher does in the environment of the research object [20]. The strategy is to integrate scientific and practical actions. For action research, typical characteristics are that it is practical oriented, problem-oriented and research-object and researcher have active roles in the process [21]. Since theory and practice are combined in the action research, it is suitable research method to use in this thesis. The purpose of the thesis is to improve the product in a way that it fulfills with the product requirements. The purpose is, in other words, to make changes in the product, which is a common characteristic for the action research.

The research data is collected from studying existing designs, FEM analysis, interviews and prototype testing. Existing designs that were studied were examined mostly in electrical form to gather information. FEM analysis was carried out by using Ansys 17 program. Some interviews were made as well in order to define product requirements even more precisely for example. Prototype testing was used for verifying some design solutions.

1.4 Structure of the thesis

The thesis is divided into four sections: introduction, theory, action and conclusions. First, the reader gets an introduction to research methods and the background of the problem. Case company and its products will be introduced in this section as well. Next, in the theory section, product development and methods to do it are presented. The most important tools that will be used in this work, as well as the ADR regulations, are introduced. In section three, the presented theory is used as a support for solving the case problems. Finally, the results are concluded in the last section.

1.5 Introduction of the case company

This thesis is done for Cargotec Finland, Multilift. Multilift is part of Hiab, which is one of the three business areas that Cargotec corporation consists of. The brand of the products is Multilift, which formerly was also the name of the company. Cargotec is a Finnish listed company that offers cargo handling solutions globally for heavy industry. The company is divided into three business areas based on their core competence: Kalmar, MacGregor and Hiab. Kalmar offers products and services that are used globally in ports, terminals and distribution centers in the heavy industry. MacGregor provides solutions for offshore and marine load handling.

Hiab offers on-road cargo handling equipment such as loader cranes, tail lifts and demountables and is at the moment the market leader in the business area. The brands Hiab, Moffet, Loglift, Multilift, Del, Zepro and Waltco belong to the business area of Hiab. Brand of demountables is Multilift and it consists of three main product types/families: commercial hooklifts, skiploaders and military hooklifts.

Commercial hooklifts are products that are targeted to the consumer market. They are technologically leading and the most popular products of the company. Typical feature of a commercial hooklift is that the structure is modular. This means that a customer can configure a product that is suiting their needs best from different options.

Skiploaders are products that are used to handle waste containers by lifting them with chains. This type of waste containers, skips, are commonly used in the central Europe and therefore, the main market area for this product is there. The main benefit compared to a hooklift is that the load handling requires less space, which makes it a great equipment to use in narrow city centers. On the other hand, the operator has to always leave the cabin to attach the chains.

The last product type is military hooklifts. Typical for these hooklifts is that their delivery process has project nature. Usually a serial of them is ordered with some special requirements and redesigning of existing products is therefore most times required. Military hooklifts are commonly equipped with equipment that is not typical for commercial hooklifts such as container handling equipment.

1.6 Introduction to hooklift and container handling unit

Hooklift is an application that is installed on a truck and used for tipping and for the handling of demountable bodies. The main benefit of the hooklift is that it can handle any demountable body that is equipped with a standard loop interface. However, there are country dependend differencies in the demountable bodies as the standard varies depending on the country. Main difference between standards is that the height of the loop varies. Anyhow, the principle is that the hook can be attached to the loop without driver leaving the cabin, which makes it a convenient and popular solution.

For military hooklifts Multilift provides currently container handling unit (CHU) equipment. Container handling equipment consists of back rollers (or sliders), lift frame and lift frame stowage. Stowage is optional equipment and does not belong to this work's scope. Rear rollers and lift frame are presented later in this chapter.

1.6.1 MPH165 Hooklift

In this work, the range of hooklifts is limited to concern MPH165 hooklift, also called as DROPS (demountable rack offload and pickup system) or MkIV (Mark 4). In figure 1 can be seen a DROPS hooklift before modernizations without oil tank and control valve. MPH165 is fully targeted on military market, which means that it does not have tipping feature. It can only load and unload a demountable body or container.

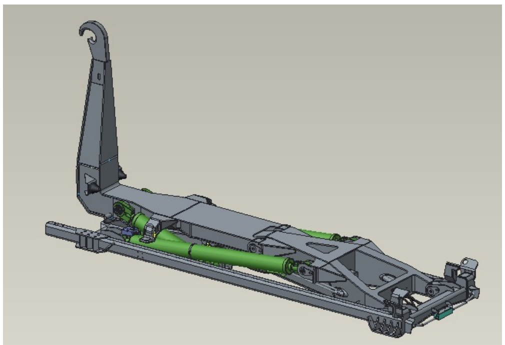


Figure 1. *MPH165 hooklift*

Lifting capacity of an MPH165 is 16500kg and it can handle either flatracks or freight containers of 20 feet long when equipped with container handling unit. The container can be either 1CC or 1C container. The 1CC container is higher than 1C but otherwise, specifications are the same.

1.6.2 Container handling unit

Container handling unit means the extra equipment that a hooklift have to be equipped with in order to handle ISO containers. In figure 2 can be seen the rear slide system that is going to be used in this work's application.

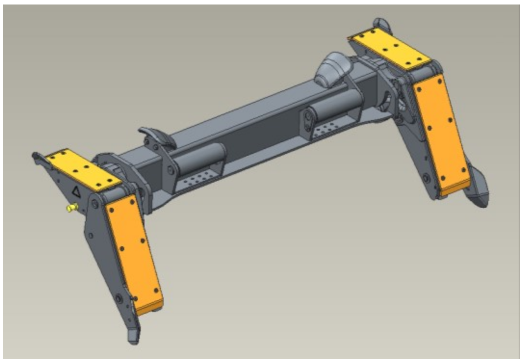


Figure 2. *Slide system of container handling unit*

The slide system is mounted on the back of a truck and its main purpose is to support container and provide sliding surface during a load/unload sequence. There is also a slide system available that is equipped with rollers instead of skids but the unit with skids is chosen to be used in this project due to better support of containers frame and lower manufacturing cost. Better support equals a longer lifetime of a container and creates customer value that way.

In figure 3 can be seen on the right-hand side the current H-type lift frame. On the left-hand side can be seen the new lift frame unit. Lift frame is an interface between ISO container and hooklift. It is attached to the front end of a container. The container can then be loaded on a truck with a hooklift. As can be seen, the new lift frame is lighter and the design is overall manufacturing wise easier to produce.

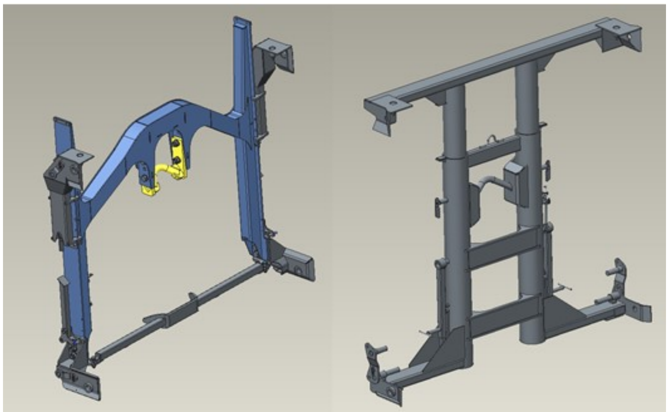


Figure 3. *Lift frame of a container handling unit (CHU)*

Current, H-type lift frame has been offered on the market for some decades. Both lift frames have adjustable height feature, which enables them to handle either 1C or 1CC containers.

1.6.3 Operating principle of a hooklift

Figure 4 illustrates the operating principle of an MPH165 hooklift. Unlike most of hooklifts available, MPH165 does not have an option for tipping but only for loading and unloading. Tipping would require that the pivot point of the middle frame would be in the back close to back rollers. However, the operational purpose of this hooklift does not require tipping option since it is used only for handling containers and flatracks.

In the figure 4 can be seen stages of a loading/unloading sequence. An unloading sequence starts with the moving of the hook arm. When hookarm is fully raised, the middle frame starts to move and hook can be operated to the rear position. At the rear position, the load can be attached to the hook and pulled on the truck.

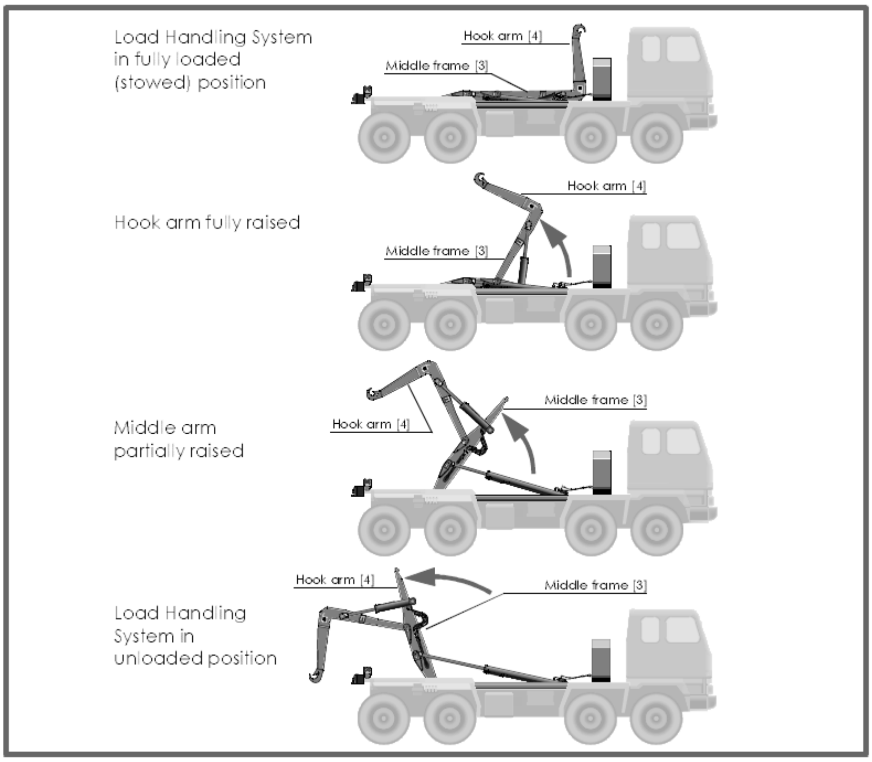


Figure 4. *Stages in the unloading sequence [6]*

1.6.4 Operating principle of the container handling unit

Container handling process can be divided into three main parts: mounting the lift frame to an ISO container, loading of the container and unloading of the container. In the first part lift frame is first mounted to a container from the top part of the frame. After that lower part of the frame is mounted to the container. In figure 5 can be seen a lift frame that is mounted to a container and the rear sliding system that is on the back of the truck prepared to provide sliding surface for the container.

Figure 5. *ISO container at the start point of a load sequence [33]*

In figure 6 can be seen the point where rear sliding system starts to provide support to the container. The hooklift in figure 5 and 6 is not an MPH165 hooklift but the operation principle is similar.

Figure 6. *ISO container at the middle point of a load sequence[33]*

1.6.5 ISO-container

ISO containers are world-widely used for efficient cargo shipping and handling. ISO-containers can be called as freight containers, shipping containers, dry bulk containers, and cargo containers. Containers are designed to store and transport material efficiently and securely. ISO 668:2013 determines standard sizes of containers that can be used for transporting goods. In 2011, the number of marine shipping containers in use in the global fleet of container equipment was roughly 18.605 million units or 28.535 million TEU. [4] One unit of TEU equals to one 20ft container. Table 1 below shows the dimensions of each container type according to ISO 668.

Table 1. *ISO freight container lengths according to ISO 668 [3]*

Freight container designation	Length		Height		Width
	mm	ft	mm	in	mm
1EEE	13 716 [a]	45 [a]	2896	9' 6"	2438
1EE			2591	8' 6"	
1AAA	12 192 [a]	40 [a]	2896	9' 6"	
1AA			2591	8' 6"	
1A			2438	8'	
1AX			< 2438	< 8'	
1BBB	9 125	30	2896	9' 6"	
1BB			2591	8' 6"	
1B			2438	8'	
1BX			< 2438	< 8'	
1CC	6 058	20	2591	8' 6"	
1C			2438	8'	
1CX			< 2438	< 8'	
1D	2 991	10	2438	8'	
1DX			< 2438	< 8'	

[a] In certain countries there are legal limitations to the overall length of vehicle and load

Containers have standard fittings in each of their corners so that they can be hoisted, stacked and secured conveniently. Corner fittings must be manufactured and designed by the ISO 1161 standard [2]. Locking the container on a platform is commonly done by using so-called twistlocks. Twistlocks are designed to be used with ISO corner fittings and are designed to be able to carry loads that container is allowed to carry according to ISO 1161 [2].

An MPH165 hooklift that is equipped with a container handling unit can handle either 1CC or 1C type of containers. The lift frame can be locked to two different operating heights so that it can be attached to either container type.

1.6.6 Flatrack

MPH165 hooklift is also designed to handle NATO flatracks, which are standardized in STANAG 2413 NATO standard [34]. Flatrack is a demountable platform that can be lifted by using a hooklift and it is commonly used in militaries to carry vehicles, goods or containers. Operating a flatrack does not require CHU equipped hooklift. The rear slide system of CHU is equipped with rollers that enable it to be used also for flatrack operating. A flatrack is secured on a hooklift by hook and so-called din locks on the back. Din-locks prevent the flatrack to move vertically up, sideward and horizontally forward.

2. PRODUCT DEVELOPMENT

2.1 Reasons to carry out product development

Product development for many companies aims to develop the products that produce the major revenue for the company. Therefore, product development aims often to create either features that create customer value or reduce the costs. The more customer demands the product the more customer is willing to pay for it. The price therefore depends on the supply and demand relationship [5].

Value of the product can be determined [5]:

- Value = benefits – liabilities

To maximize the value benefits must be maximized and liabilities minimized. In product, benefits can be categorized to functional, psychological and service and convenience benefits [5]. Functional benefits are the most obvious and easiest measurable for a product. Such functions as performance level, durability and weight are easy to measure and then compare to competitors' offering. However, the product can have the best functions available on market and still not have the biggest product value if other benefit sections are not in order. Psychological benefits such as brand reputation are playing a significant role in what a customer perceive when doing the buying decision. Service and convenience benefits include factors like availability of service/product or easiness to get correctional service in case of product problem or failure. [5]

Products liabilities are categorized into economic, psychological and service and convenience liabilities. Economic liabilities, by the name, are costs and the price of the product. The amount of value the product brings to the customer is the main thing that customer is interested in. Cost of acquisition, usage, maintenance, ownership and disposal are examples of costs that customer measures and compares to competitors products. Psychological liabilities are the same as already mentioned as benefits but opposite. A bad reputation of the brand will reduce the value of a product or reputation of low-performance service/products. Service and convenience liability include factors like liability due to lack of service, poor service or poor availability. [5]

A high product value is desirable for a company to make profit as much as possible. Profit can be determined:

- Profit = revenue – costs

Revenue is the money that is got from selling products. More revenue can be made by selling bigger volumes of products or by selling products with higher price. Depending on the product and its market, the right balance must be found between these factors to maximize the revenue. Costs are any fixed or variable cost that product creates to a company. Products development, manufacturing and the lifecycle costs are all depending on the product. With product development process, all above-mentioned costs can be affected. [5]

Product development usually aims to reduce product costs or create more customer value by adding desired properties to the product. If both of these factors can be done at the same time, we are in an ideal situation. Potential increase in customer value can be identified by innovative thinking or by capturing the voice of the customer.

2.2 Main processes of the company

Cargotec has determined its main processes and they are accessible to every employee of the company. Information is located in the QPR (Quality, Processes, and Results) portal where processes and their relations can be observed. QPR portal is a management software for measuring performance and managing processes.

The main processes of business area Hiab are illustrated in figure 7. Process consist of four main process, which each aims to better customer satisfaction with customer needs as an input. Customer satisfaction is achieved by: develop offering, create customer commitment, provide solution equipment and provide solution services.

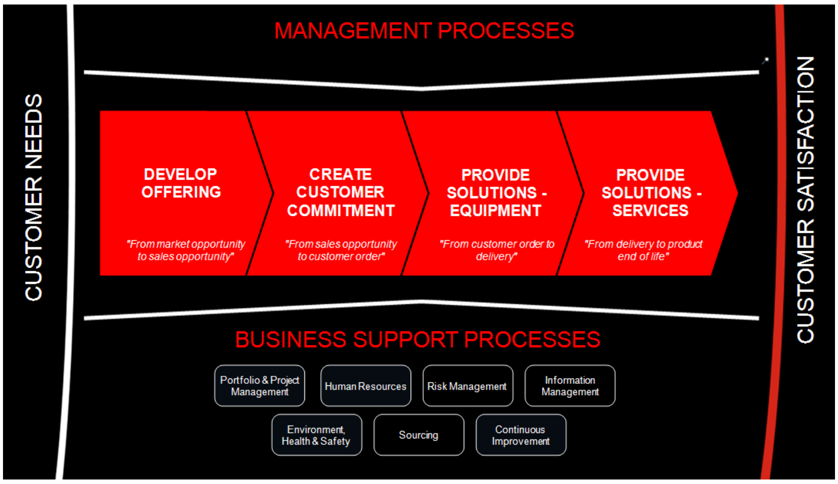


Figure 7. *Hiab management processes [10]*

Develop offering step is the closest step to product development. It is divided into three sections: new technologies process, new product process and current products process. New technologies process aims to develop new technologies to apply them into business. New technology itself is useless for business until an innovation, which utilizes it, is invented. [10]

New product process of Hiab starts with signal inputs. Input can be the strategy of the company, voice of the customer, competitive intelligence information, supply industry foresight or technology development. In today's world, development of technology is a significant driver for product development. Decreasing oil resources, for instance, drive car manufacturers to develop new solutions to substitute petrol engines. [10]

Current product process includes products lifetime care, making technical design and documentation and terminating the product. Product lifetime care gets its inputs and feedback from sales, sourcing, service, manufacturing sites and after sales. Product changes are made during the lifetime of the product according to feedback to increase the customer value without designing a completely new product. The last step for current product process is to terminate the product. When new disrupting technologies come and outdate old products, their sales volumes usually decreases and product becomes less profitable. Outdated products can be either facelifted or terminated and then replaced with a new one. [10]

2.3 Lean product development

Lean operation practices are commonly used in today's manufacturing and service businesses. Toyota, the inventor of lean has shown great performance using lean practices for manufacturing and product development [5].

Even though lean practices can be used for both, manufacturing process or product development process, there are still quite many significant differences between them. For manufacturing process, the target, what we want is easy to define and the value of the product is already known. For product development process, the value of the product is unknown until it is launched in the marketplace. For manufacturing processes, the rework is treated as a waste and on the other hand for development processes, an iterative improvement on product design is quite common. [5] Iterative work cannot therefore be treated as waste for product development.

The lean product development process is aimed to deliver greater value in the product by using less resources by [5]:

- Thoroughly capturing the voice of the customer and accurately deploying the customer value into design
- Accomplishing high product value and quality and low product cost by using the most appropriate technology and design
- Effectively transforming the voice of the customer to high-quality design with high speed and low cost
- Relentlessly decreasing the wastes in the product development process

As in lean manufacturing, the goal is to reduce waste in lean product development. However, in product development, waste is harder to define. Waste categories can be mentioned but it is hard to draw a line what is waste and what is not. Lean product development, for example, concerns unproductive meetings as waste. However, it is often hard to know beforehand whether a meeting is going to be very productive or not. In most cases, it is very individual so a universal line cannot be drawn to determine what is productive and what is not.

Lean product developing categorizes potential wastes into four categories: [5]

- Wasted sale opportunities due to poor product value
- Waste in manpower, resources and time
- Waste in knowledge and information
- Waste due to poor design

In this thesis, we are aiming to fight against making poor design and losing resources. Resources are easily lost when we have to do redesigning a lot for example. For fighting against these factors, there is a theory called Design for Six Sigma (DFSS), which focuses on product value maximization in product development. The theory will be explained later in this thesis.

The first waste category focuses on poor product value causes. The core reason for poor product value is that customer is not ready to pay the price that is expected from the product. Reasons for that might be poorly captured voice of the customer, poor innovation capabilities, poor choice of technology or poor quality/reliability of the product [5].

The second category, as mentioned, focuses on manpower, resource and time waste. Wasting manpower can be easily explained by inefficient batch queue theory. Batch queue means the jobs are coming to queue in big groups, or batches [5]. For instance, if a group of people arrives to train station's platform. The stairs get crowded and it takes some time that the way is getting clear. If the same amount of people would arrive at a little bit different times, traffic would be avoided and lead time of each person would be less to get out of the station.

For product development practices, we can assume that if a big load of work is handed to an engineer, lead time of the work will be longer compared to if the same work would be given in small pieces [5]. Knowledge of awaiting work makes many people to put their mind into them before it is necessary, which consumes thinking resources and focus from current work.

The third waste category is knowledge and information management. Product development process always creates a lot of new information and knowledge. However, not all information is useful for the process or for creating product value directly. There is always so called unused information, which is still sometimes utilized for decision making and is therefore hard to judge whether it is waste or not. Even though it is hard to judge whether information is useful or not, we can easily point out things, which are waste. Examples of waste:

- No knowledge where the information is stored
- Uncertainty, whether information is fresh or old

The first point, for example, creates a huge amount of time waste. When engineers co-operate and each of them store information to different locations, the result is that information they create is difficult to find if standardized mode of operation is not used. The second example describes time waste, where there has been some iteration loops to make the design better, but no documentation, which is the best or newest version can be found. This kind of situations create huge amount of time waste and loss of effective use of manpower.

The fourth category is about waste due to poor design. This means in this concept that design is made very complex, it has excessive design requirements or architecture of the design is poor [5]. A principle is that simple design that fulfills the functional requirements is the best design. Parts or assemblies that consist of many items that are complicated and are not necessary are considered as waste. A high amount of item numbers, for example, increases the total workload in the whole product life-cycle. Excessive design requirements can be unnecessary high tolerance or material requirements.

2.4 Design for Six Sigma

Design for Six Sigma is a theory for carrying out product development as effective as possible. It purposes making the best possible design and quality with minimum waste and that way increase the product value [5]. DFSS drives to optimize the design without forgetting the customer needs. It has various useful tools that can be used in the product development process and therefore it is chosen to be used as a base for this thesis.

The target of DFSS is to achieve Sig Sigma level of perfection at operations. A company that is working at One Sigma, for example, makes about 700 000 defects per million opportunities. Two Sigma obviously is better already and equals to 300 000 defects per million. Most companies operate at a level between three and four Sigma which equals to 67000 to 6000 defects per million. For example, operating level 3.8 Sigma means that one is operating at 99% success rate, which might sound high enough for many cases. However, for DFSS principle, it is not enough and the success rate that it is pursuing is 3.4 defects per million opportunities. [15]

In this thesis, we are not aiming to minimize the defects per million but to fulfill product requirements as well as possible by utilizing DFSS principles to achieve it effectively. The goal is to make design as effective as possible and avoiding unnecessary iteration loops. For optimizing a single design entity theory of Design for Manufacturing (DFM) could have been used to achieve a cost-efficient solution in terms of manufacturing. However, that theory does not care about the customer needs, which is why DFSS suits better for the purposes of the case.

2.4.1 DFSS process

Design and manufacturing companies usually have two modes of operation: fire prevention and firefighting [5]. In fire prevention mode one pursues to create feasible and healthy conceptual entities. In firefighting mode one pursues to carry out such problem solving that design entity can live up to its committed potentials [5]. Firefighting is noticed to consume the largest amount of resources of an organization since it easily gets stuck to loop of design-test-fix-retest. DFSS focuses on the both of these modes.

The major objective of DFSS is to “design it right the first time” to avoid painful downstream experiences. DFSS theory is based on quality engineering by Taguchi [35], TRIZ by Altshuller [36], axiomatic design principles by Suh [37], and theory of probability and statistical modelling. The term “Six Sigma” in the context of DFSS can be defined as the level at which design vulnerabilities are not effective or minimal. Two major design vulnerabilities that can affect the quality of a design entity are [5].

- Conceptual vulnerabilities that are established because of the violation of design axioms and principles
- Operational vulnerabilities due to the lack of robustness in the use environment

At early stages of product development process, if not enough information is available, most of the DFSS tools may be useless [5]. For example, if enough information at early design stage of the process is not available, we end up using traditional quality methods which can be characterized as after-the-fact practices. This mode of operation drives company towards firefighting loop, which causes low quality, high development costs, longer time to market, and marginal competitive edge. Therefore applying DFSS in the conceptual phase is a goal and can be achieved when systematic design methods are integrated with quality concepts and methods upfront [5].

It is claimed that 80 percent of the total cost is committed in the concept development phase [22]. Figure 8 illustrates the impact of design decisions/activities made during the life cycle of the product.

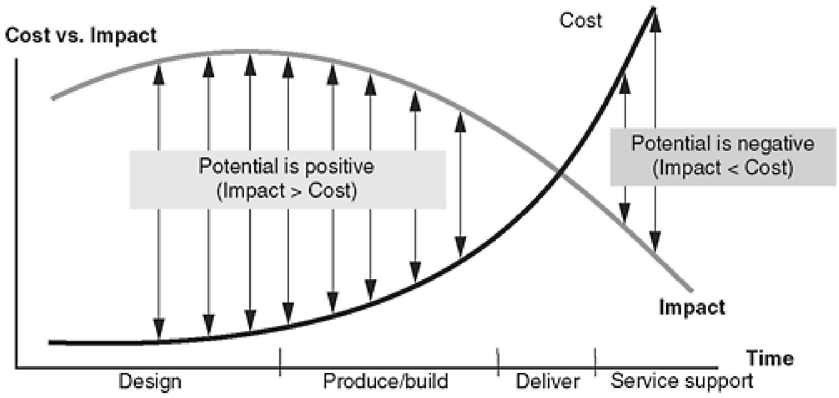


Figure 8. *Effect of design phases on life cycle [5]*

It can be seen that during the design phase, decision-making has low costs. Once the delivery phase has been reached, the costs increase exponentially and the customer potential reaches its turning point to become negative. After product deliver phase, design decision has less positive impacts than costs, which means that at this phase any redesign or corrective actions have significantly high costs and customer potential is always negative. Concisely, the earlier decisions can be made, the less the total costs of a product developing process are.

However, the theory about the 80 percent cost commitment has been questioned a lot in the literature. Some preliminary researches have shown that the rule may not hold in several industries and that the strength of the commitment may not be that outspoken [23]. In some industries, the commitment might be up to 90% while in some it can be as low as 25%. On the other hand, even though we do not know the actual correlation between the costs and the design, we can assume that when the product has a long life-cycle, the more the design effects on the upcoming costs.

The DFSS process is divided into four parts to simplify the process [5]:

- Identify requirements (I)
- Characterize the design (C)
- Optimize the design (O)
- Verify the design (V)

By following these steps, the design follows six sigma principle and takes into account the key design vulnerability possibilities. Steps seem rather similar to DMAIC processes steps that are Define, Measure, Analyze, Improve and Control. The big difference between DFSS process and DMAIC is that the last mentioned focuses on smaller design entity than DFSS. DMAIC might only work on improving a very limited subset of the critical-to-satisfactions factors and the design might end up not to be sufficient in the bigger picture [5].

2.4.2 Identify requirements

The purpose of the first step is to provide clear directions for the whole DFSS process. As all the following activities are based on the first step, targets must be made clear in order to use the resources efficiently.

The first phase starts by getting the project started on the right foot. That means approving project charter, creating a business case and completing the project plan [15]. Main milestones should be added to the project schedule to provide all participants a whole picture of deadlines. Created business case consist information of how the project will turn into value. A value adding strategy is included in the business case and can be derived from there into product requirements.

After defining and getting the project started, customer requirements can be determined. The product value can only be increased when customer requirements can be satisfied. There are in most cases more customer needs than we are able to satisfy and therefore customer needs have to be prioritized to select the most relevant needs. Customer requirements themselves cannot be used as design or product requirements but they can be transformed into them after an analysis.

Customer requirements can be obtained using various tools such as market research, interviews or for example customer feedback from the field. When starting a product development project, the best practice needs to be first selected in order to gather as reliable and useful data as possible. Successful gathering of customer needs and requirements is one of the key points to create optimized design and get the most out of the product development process.

When customer needs are obtained, they can be transformed into Voice-of-Customer (VOC). VOC is utilized then to obtain functional and measurable requirements that are used to form the product and design requirements. After enough information is gathered and a good picture of the goals and needs is formed, minimum requirements can be defined and finalized. [5]

Finalization of the requirements enables to define, critical-to-satisfaction (CTS) metrics which will be transformed into critical-to-quality, critical-to-delivery, critical-to-cost metrics and so on. These CTSs must be then quantified and an acceptable level of performance then decided for each factor. [5]

In the first step tools such as market researches, quality function deployment (QFD), Kano analysis and risk analysis are used. Details of QFD will be provided in a later chapter of this thesis.

2.4.3 Characterize the design

The second step of the DFSS process is “characterize the design”. The second phase could also be called as “develop concepts phase”. As now we have a good picture of customer needs, business requirements and critical-to-satisfaction factors (CTS), we can translate them into design/process requirements.

Concisely, the objectives of this phase are [15]:

- Identify viable concepts through creative methods
- Use logical, objective methods to evaluate alternatives
- Identify and eliminate potential product/service failures

2.4.4 Concept creation

After the product requirements are determined, we can start concept design phase which target is to find technical solutions to fulfill the requirements. Concept creation tools and creative thinking are used in this phase. Theory of innovative problem solving (TRIZ), brainstorming or axiomatic design methods are useful in order to get as many ideas as possible to concept creation [5].

Concept creation can be divided into five-step concept generation methodology [18]. The methodology breaks a complex problem into simpler subproblems. Solution concepts are then identified for the subproblems by external and internal search procedures [18]. The methodology according to Ulrich [18]:

1. Clarify the problem
2. Search externally
3. Search internally
4. Explore systematically
5. Reflect on the solutions and the process

Step 1 consists proper clarification of the problem. Problem is decomposed into simpler problems so that each of them is easier to solve and is not too complex. Next step is external search, which aims to find existing solutions both, to the overall problem and to the subproblems identified during the first step [18]. External information can be found from lead user interviews, literature, experts and benchmarking. Lead users are especially a valuable group of people to use in concept creation. Lead users bring the customer desires directly to knowledge of the engineers and many times the information is something that an engineer would not have taken into notice [17].

Step 3 is internal search, which is the use of personal and team knowledge and creativity to generate solution concepts. The search is internal when the ideas that emerge are created from knowledge already in the possession of the team. This step might be the most innovative way in any product development.

In step 4, found concepts are explored systematically. Concept classification tree and the concept combination table can be used as help, especially if there are many sub-steps and solution combinations of them. The classification tree helps to divide the possible solutions into independent categories. The combinations table guides in selectively considering combinations of fragments. [18]

The last step of the concept generation reflects the solutions and the process. Even if it is placed as the last step, it should be done throughout the whole concept generation process. The core idea is to identify opportunities for improvement in subsequent iterations or future projects.

Figure 9 illustrates how the concept selection process works in general.

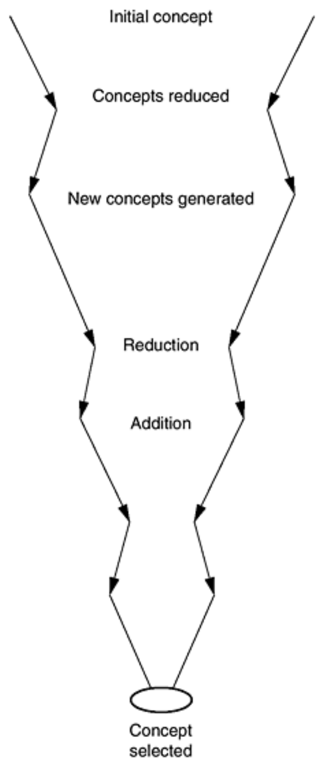


Figure 9. *Concept selection process [5]*

First, there will be many concepts created without a rough filter so that any limitations in thinking does not occur. The more concepts there is the more ideas pop up in a group brainstorming for example. Creative methods such as TRIZ, assumption busting or brainstorming are advised to be used for the concept creation. Assumption busting drives to think further of what we can do by asking "why not". The main idea behind brainstorming is to create as many concepts as possible without a filter. The main advantage of creating concepts without filter is that all concepts are accepted and we get past the obvious "safe" ideas and more innovative gems can be found [15].

Once a good amount of concepts are found they will be then reduced roughly and concepts that can satisfy customer needs best, remain for the next round. Now, when reduction is carried out, a cycle of rethinking is carried out and amount of concepts increases. They are again evaluated and winning solutions continue to next round. This cycle will be done as many times as necessary until only one concept is left and can be determined to be used.

Tools to use at this phase are:

- Design for X (DFX)
- Robust design
- Design review
- Computer-aided design/engineering (CAD/CAE)
- Simulation
- Design Failure Mode and Effect Analysis (DFMEA)

Design for X, also known as Design for Excellence aims to pursue design in terms of variable X. The “X” can have various possible values for example manufacturability, power, variability, cost, quality, environment, supply chain and reliability for example. DFX help designers structure and manage the competing needs of a product across its lifecycle [26]. Concurrent engineering requires a holistic view of the product, so DFX techniques must be integrated with broader product development and not applied in isolation [26]. Basically, the idea to get designer to consider any kind of “design for…” aspects in the early phase of the design process and not focus just to improve for example the production costs.

DFX methodologies address different issues that can occur in one or more phase of a product’s lifecycle. Problems may occur in the development phase, production phase, use phase or disposal phase. However, the problem in using DFX is that conflicts will always occur. For example, where DFM guidelines suggest a larger number of simpler components and DFA suggests a smaller number of more complex components, the problem can only be resolved by estimating the cost of each approach [26]. Comparison is hard without metrics. Measuring the performance can be sometimes hard, which leads to those decisions may rely sometimes on individuals thinking. In addition, the performance is usually hard to measure at early stages of design and therefore metrics are relative rather than absolute. [26]

The objective of DFMEA is to help the team designing the failure modes out of the project/product. In DFMEA, first, all the possible failures are defined and they get a ranking according to their severity, likelihood of occurrence and ability to detect. From ranking values, a Risk Priority Number (RPN) (Severity x Occurrence x Detection) can be calculated [27]. RPN value is a numeric representation of each failure mode's total risk. The lower an RPN value is the lower the risk is.

Possible failures can be acquired from experience, discovered in the hands of the customer or found in prototype testing. The highest leverage of DFMEA is at early stage of design when the project is still on paper and it is desired that as many failures as possible are identified before any product reaches production or a customer. [5]

In practice, we can model a cause-effect diagram called failure-tree and analyze the possibility to a failure. This is a tool especially for understanding of safety-related and catastrophic failures and their causes [5]. In the failure tree, the sub-causes to a failure are identified and each of them has a possibility of occurring. The total failure probability can be evaluated by using the sub causes.

2.4.5 Optimize the design

Concept finalization allows us to move into design optimization phase. Even though the concept design is now finalized, there is still left a lot of design parameters that can be adjusted or changed. Usually, parameter optimization phase in product DFSS projects is followed by a tolerance optimization step [5]. Sometimes if the design parameters are not controllable which happens quite often in DFSS product projects, steps 1 and 3 of DFSS might need to be repeated.

For design optimization, following DFSS tools may be used:

- Simulation tools
- Design of Experiments (DOE)
- Taguchi-method, tolerance design
- Reliability estimation

Taguchi's method means robust design optimization. It aims to control the interaction between the control and uncontrollable variables by robustification. It pursues to minimize the variation caused by uncontrollable factors. The more control over the process one has, the less variation occurs in general. Taguchi's robust design optimization process can be used to pursue high quality optimization results.

The process contains two steps: [15]

1. Minimize variability in the product or process (Robust Optimization)
2. Adjust the output to hit the highest

Process in principle means that first, the performance of the product is optimized to its maximum and then the output will be adjusted to meet all the target values and requirements.

Tolerance design is focused, like the name says, on the tolerance design and optimization. The target of tolerance design is simply to maximize their effect. Using tight tolerances in general increases costs but on the other hand, quality decreases when poor products are let through from the manufacturing process. As tight tolerances have a significant effect on the product costs, the number of design entities that require them should be minimized. Always it should be considered if tight tolerance is required or is the certain property possible to achieve using looser tolerances in terms of maximizing quality, efficiency and thrift of the design.

Optimization can be done hypothetically endlessly. The design is never perfect, which forces us to decide a level of optimization that is accepted.

2.4.6 Verify the design

Design verification is an important step to conclude the product development process. A product with no validation is always a risk to bring to the market. An untested and unverified product design have higher risk to fail or not fit to its purpose. Total costs are in most cases lower when validation is done properly.

Validation of a design can be divided into three different areas [5]:

1. Product validation
2. Manufacturing validation
3. Production validation

Product validation is divided into following aspects [5]:

- Functional performance
- Operational environmental requirements
- Reliability requirements
- Usage requirements
- Safety requirements
- Interface and compatibility
- Maintainability requirements

All products do not have to fulfill all these requirements. For a different product, different validation task is more important. Therefore, it is good idea to perform a validation requirement analysis before beginning the validation process. Same as in design, the requirements must be known.

Second validation area is manufacturing validation. The purpose of this task is to make sure that the design can be actually produced and manufacturing process has sufficient capability.

The third area is production validation. Production validation follows the manufacturing validation and focuses on verifying mass production costs, capability of process and capacity analysis of the production. Briefly, production validation aims to verify that design can be produced with sufficient low costs and quality and product can be produced with satisfied productivity level without lowering performance level of the product.

The whole DFSS validation process starts up with pilot test and refining step. According to Yang, no product or service should go directly to market without first piloting and refining. In this step, the product must be tested and design failure-mode-effect analysis carried out. The target of all this is to evaluate the real-life performance.

The second step is validation and process control. The target of this step is to make sure that product is designed and meets to it set requirements. It is important to validate that manufacturing and production are established in order to ensure that critical characteristics are always produced to the specification of the optimization phase [5].

Step three is full commercial rollout and handover to new process owner. In this step design entity is validated and process control is established and the process can be handed over to design and process owners.

In figure 10, the validation flow diagram can be seen. As the figure shows, design requirements affect validation significantly and the importance of defining them rises up once again.

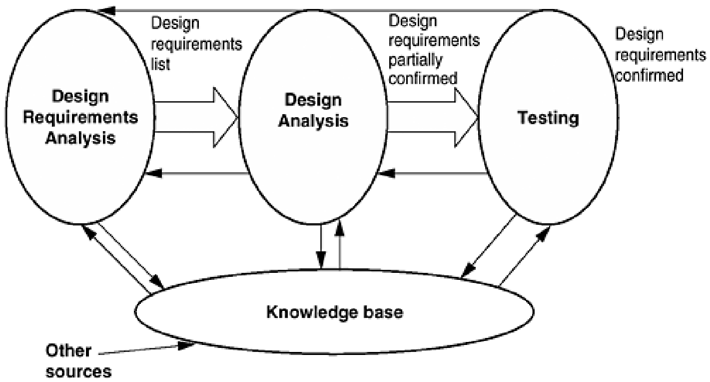


Figure 10. *Design validation flow diagram [5]*

2.5 Quality function deployment

Quality function deployment (QFD) has been developed more than 30 years ago in Japan as a quality system that focuses on delivering products and services that satisfy customers. QFD links the needs of the customer to design, development, engineering manufacturing and service functions [11]. In the QFD methodology, customers define the product using their own expressions, which rarely carry any significant technical terminology [5]. In other words, the quality is defined by the customer. Customer needs can be in QFD methodology translated into product requirements by utilizing relationship diagram, called the house of quality (HOQ)

Briefly, Quality Function Deployment is [11]:

- understanding the customer requirements
- quality systems thinking + psychology + knowledge/epistemology
- maximizing positive quality that adds value
- comprehensive quality system for customer satisfaction
- strategy to stay ahead of the game

In the QFD the target is to translate customer needs and expectations into engineering and quality characteristics which then can be visualized and ranked in the house of quality diagram. More information on the diagram is provided in the next chapter. The most significant benefit of using QFD as a design driver is that we can get information of which design elements have the greatest impact on customer requirements. With that information, it is easy to concentrate on right things and concentrate the available resources smarter in order to satisfy customer needs.

In order to successfully implement QFD, information flow has to be open between the teams that take part to the DFSS process. Market research information that is not technically or design-focused with QFD is more easily applied to incremental design than to brand creative design [5].

Figure 11 illustrates the design loop and the position of QFD in the process. The QFD is utilized in the first and second phase of DFSS process. As can be seen, customer requirements affect on all actions performed after, which gives it the most significant value in the diagram. Then QFD is applied to translate customer needs into a house of quality matrix, which drives and instructs the design to the right direction. Rest of DFSS includes product validation and optimization, which finally leads to a result that can be measured and evaluated if it is good enough in order to satisfy needs.

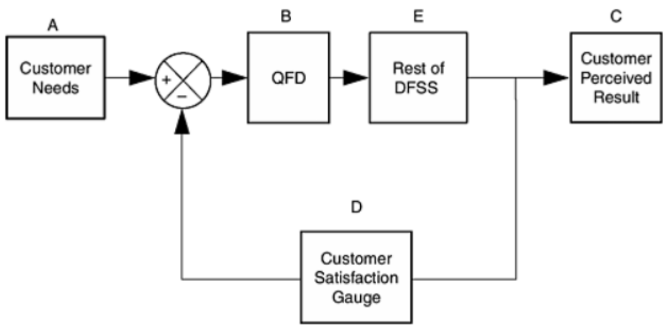


Figure 11. *QFD position in the current design loop [5]*

2.5.1 House of Quality diagram

House of Quality is a planning tool that brings engineers and customers together and integrates customer needs into the design and development cycle [16]. House of Quality is a complex looking matrix that evaluates the relationships between customer needs and engineer requirements. To each customer need, there should be at least one engineering requirement to describe means of attaining customer satisfaction.

In order to create a House of Quality we must first define following factors:

- Customer needs
- Importance ranking of customer needs (0-5)
- Engineering requirements
- Targets values for measurable engineering requirements
- Target direction of improvement

Now, we are able to create relationship matrix. Relationships between engineering requirements and customer needs are ranked as values 0, 1, 3, or 9. It is common to describe values with symbols that are shown below in table 2. Symbols are not necessary to use but usually they turn the table easier to read.

Table 2. *Relation level symbols*

Relation level 9-3-1		
●	9,0	Strong
○	3,0	Moderate
Δ	1,0	Weak

In figure 12 can be seen an example of a house of quality table. When all the necessary information has been added to the table, we get as a result importance rating of each CTSs. CTSs equal to engineering requirements and by knowing the importance in relation to satisfy customer needs, consideration of resource allocation can now be made. CTSs are usually measurable elements for which we can choose the direction of improvement and give the CTS a value.

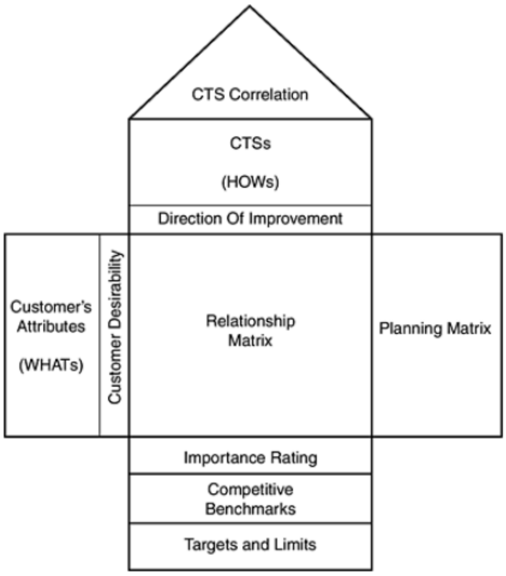


Figure 12. *An example of House of Quality matrix [11]*

The core benefit of the house of quality is to get importance rating of CTSs (HOWs). HOWs that are not so important in order to answer to customer needs can be now left for less attention, which clearly can drive the development process in the right direction and save resources. When a lot of HOWs occur, they cannot all be designed to the full performance level. In such situations QFD and the house of quality offer valuable help.

Planning matrix of figure 12 is usually used for competitor analysis. Each customer need gets an estimated performance rating and according to them, we get a picture where the own product is good compared to others and where improvement should be made. The planning matrix is optional to use in the house of quality.

HOW correlations help to understand the influence of each HOW to another. Relationship is important to understand since improving another factor might worsen other. When the roof of the house of quality is modelled, designer can easily see the influence of an improvement to other HOWs. A standard method to visualize the correlations is to use rankings that can be seen in table 3 below:

Table 3. *Standard relation describing symbols*

Correlations	
++	Strong positive
+	Medium positive
-	Medium negative
--	Strong negative

The correlation description is not absolute, and any desired method can be used that suits for the case studied.

Additional aspects that could be added to the house of quality are for example technical difficulty of implementation and target value of each engineering task (HOW).

In figure 13 can be seen a possible way to use QFD, the waterfall decomposition of QFD. The waterfall decomposition process is converting the requirement to the technical information in the design and manufacturing process through house of quality, in order to apply the requirement to the product development process that from conceptual design to the technics design stage, which includes four stages: product plan, component configuration, technics plan and manufacturing plan.

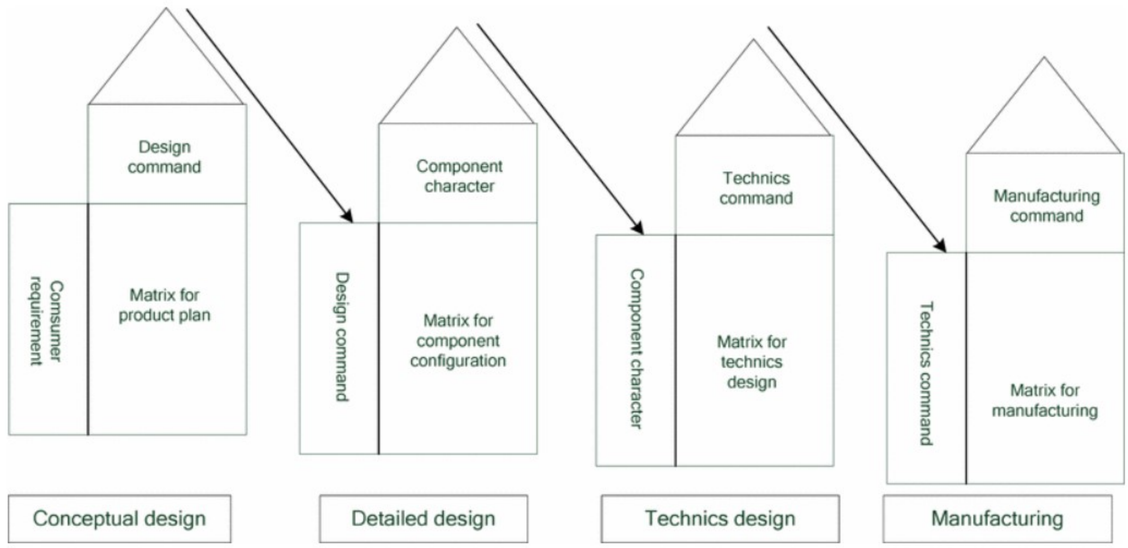


Figure 13. *The waterfall decomposition process of QFD [28]*

2.6 Analytic hierarchy process

Analytic hierarchy process (AHP) is a widely used tool among decision makers and researchers, especially for multiple criteria problems. It is based on mathematics and psychology and can be used in fields of planning, selecting an alternative, resource allocations, resolving conflict, optimization, etc. [19]. Rather than finding the globally best solution, AHP finds the best solutions that suit the goals and needs that are stated.

AHP is an Eigen value approach to the pair-wise comparisons. Pair comparison is made between each alternative by giving a number value, which describes the relationship. Comparison scales from 1/9 to 9, where 1/9 means least valued and 9 absolute more important. Value 1 indicates that comparison objectives are equal in terms of importance.

As initial information, AHP requires a problem, criterion and alternatives. In engineering, criterions can be for example customer needs or price. Alternatives are different solutions to solve the problem. Alternatives are compared by using the criterions individually. Criterions have their own weights, which indicate their importance to the decision making. Weights allow the decision maker to compare each pair in a rational and consistent way, which makes AHP a powerful tool as hierarchy gets complex.

Key steps to perform an AHP [19]:

1. State the problem
2. Broaden the objectives of the problem
3. Identify the criterion
4. Structure the problem in hierarchy of different levels
5. Compare each element in the corresponding level and calibrate them on the numerical scale. n(n – 1)/2 comparisons are required
6. Perform calculations to find the maximum Eigen value, consistency index CI, consistency ratio CR, and normalized values for each criteria/alternative
7. If the maximum Eigen value, CI, and CR are satisfactory then decision is taken based on the normalized values; else the procedure is repeated

In this thesis, the Eigen value finding process is not performed manually but with a tool [31], that solves the value automatically. Tool only requires the matrix as initial information and will then provide the solutions.

2.7 Finite element method

Structural analysis is a significant part of product development in order to create optimized designs. A structural analysis provides information if the design is capable to withstand all to it set load requirements. Structural analysis can be a great tool for optimization process when weight, costs and construction are optimization targets. In today's world where structural analysis tools are able to perform even rather complicated calculations in a short time, they can be very useful what it comes to optimization and validation of design.

Finite element method (FEM) is a dominant computational method in engineering and structural analysis. As CPUs of computers have developed, FEM together with other computational tools have been a great help to engineers to analyze and simulate the design entities before manufacturing any of them.

FEM computational procedure starts with dividing the geometry of the design entity into several subdivisions [13]. A subdivision is called an element, which consists of nodes. A model of design entity is formed by having a big amount of elements which form together a mesh which represents the geometry of the design entity. Elements can be in shape of triangle, quadrilateral, tetrahedron, or hexagon. In figure 14 can be seen possible shapes of elements.

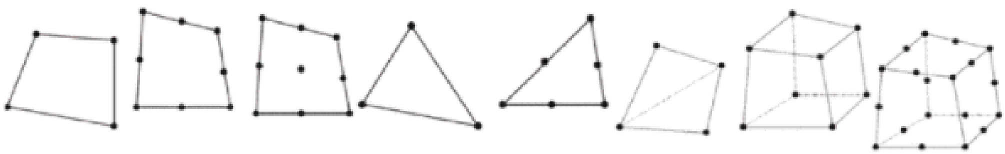


Figure 14. *Examples of elements [13]*

Finite element method can be used for stress, temperature, fluid flow, and displacement calculations for instance. Each element is a structure of nodes and the subgoal is to establish the stiffness relation for all the elements and then to the structure. The following stiffness relation serves as the basis for the matrix displacement method [14]:

$$F = K * u \tag{1}$$

where F is the matrix consisting nodal forces, K is the stiffness matrix and u is the displacement matrix that contains all the nodal displacements. A single element is the basic unit for the problem and it is coupled to the whole structure by nodes. That way we are able to solve displacement and force in every single node if the compatibility and equilibrium are fulfilled [14].

A structure can be analyzed by using FEM either by linear or non-linear analysis. Linear analysis is lighter calculation-wise as iteration loops are not always necessary to perform in order to find a solution. The linear analysis assumes material to behave elastic at any given stress level, which causes error when yield stress has been exceeded. For cases where yield strength is not exceeded or very detailed and accurate results are not required, linear analysis provides sufficient results.

Nonlinear analysis on the other hand provides more precise solutions in cases where materials yield strength is exceeded since phenomena such as plastic hardening are taken into account [14]. Analysis can be carried out with elastoplastic materials for example steel, which first behave elastic with small loads, but when load is increased further elastic limit, plastic deformation will occur.

2.8 ADR regulations

ADR is an agreement that was done at Geneva on 30 September 1957 under the auspices of the United Nations Economic Commission for Europe and it entered into force on 29 January 1968. ADR defines provisions for transporting dangerous goods on road among contracting parties. [1] It is also used as a guideline for making national regulations for transporting dangerous goods.

At the time of publishing (1st January 2017), the Contracting Parties are Albania, Andorra, Austria, Azerbaijan, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Kazakhstan, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Montenegro, Morocco, Netherlands, Norway, Poland, Portugal, the Republic of Moldova, Romania, Russian Federation, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Tajikistan, the former Yugoslav Republic of Macedonia, Tunisia, Turkey, Ukraine and United Kingdom. ADR applies to transport operations performed on the territory of at least two of the above-mentioned Contracting Parties. [1] ADR regulations are commonly used as a base of national codes of transportation of dangerous goods in Europe.

2.8.1 Strength requirements

ADR determines in the provision 9.7.3. that fastenings of the carriage shall be designed to withstand static and dynamic stresses in normal conditions of carriage, and minimum stresses as defined in provisions 6.8.2.1.2, 6.8.2.1.11 to 6.8.2.1.13, 6.8.2.1.15 and 6.8.2.1.16 in the case of tank-vehicles, battery-vehicles, and vehicles carrying demountable tanks. [1] The provisions are presented later in this thesis. The chapter 6.7 of ADR determines requirements for the design, construction, inspection and testing of portable tanks and United nation (UN) type of multi-element gas containers (MEGC). The chapter 6.8 of ADR defines provisions for design, construction, inspection and testing of demountable tanks, tank containers, tank swap bodies and MEGCs that are not UN type. Provision 9.7.3 applies to fastenings, which are used to connect vehicle and a (tank) container. According to provision 9.7.1.2, the entire unit shall meet the requirements prescribed for tank-vehicles once a demountable tank has been attached to the carrier vehicle [1]. That means that all the fastenings that play role in demountable body attachment, have to meet the requirements that are set for tank-vehicles.

The provisions that concern this project are requirements for design, construction and approval of vehicles. In other words, the fastenings have to fulfill the strength requirements that ADR sets. According to ADR, provision 6.8.2.1.2, the fastenings that are used to secure a container shall, under the maximum permissible load (MPGM), be capable of absorbing the following separately applied static forces:

a) **In the direction of travel**: twice the MPGM multiplied by the acceleration due to gravity (g)
b) **Horizontally at right angles to the direction of travel**: the MPGM (when the direction of travel is not clearly determined, the forces shall be equal to twice the MPGM) multiplied by the acceleration due to gravity
c) **Vertically upwards**: the MPGM multiplied by the acceleration due to gravity (g); and
d) **Vertically downwards**: twice the MPGM (total loading including the effect of gravity) multiplied by the acceleration due to gravity (g) [1]

Provision of point (b) requires defining the direction of travel or otherwise the force that needs to be absorbed is 2G to all horizontal directions. The direction of travel is chosen to be forward on this project since a truck can be assumed to be driven forward when transportation of carriage is performed. The truck can be driven rearwards but it is not considered as a direction of travel since the velocity stays reasonable low and does not create possibilities of big accelerations in normal driving conditions. Hypothetically thought, a truck could be loaded on a train. That way it could travel either rearward or forward but since ADR only determines regulations for on-road haulage, it can be left out from the scope and assume that sufficient additional securing is performed if a truck is mounted on a train and truck's direction of travel switches rearward for example.

Above-mentioned accelerations apply to all kind of fastenings that hold the container that is carrying dangerous goods. In addition, ADR provision 9.7.3 sets requirements for materials maximum stress and material type that can be used in construction. However, the requirements apply only for fastenings that are directly connecting a welded tank to the vehicle, or to fastenings that are under the effect of tank pressure when the test pressure is applied to the tank.

In ADR regulations goods are classified into 9 different classes. Class 1, for instance, is class of explosive substances and articles. Then there are classes for flammable materials, gases, toxic, corrosive and oxidizing substances. [1]

ADR provisions do not apply to any transportation of dangerous goods. There are exemptions related to the nature of the transport operation. For instance, provisions do not apply [1]:

- The carriage by private individuals where goods in question are packaged for retail sale and are intended for their personal or domestic use or for their leisure or sporting activities.
- Emergency transport intended to save human lives or protect the environment provided that all measures are taken to ensure that such transport is carried out in complete safety
- The carriage undertaken by enterprises which is ancillary to their main activity, such as deliveries to or returns from building or civil engineering sites, or in relation to surveying, repairs and maintenance, in quantities of not more than 450 litres per packaging, including intermediate bulk containers (IBCs) and large packagings, and within the maximum quantities specified in the provision 1.1.3.6. Measures shall be taken to prevent any leakage of contents in normal conditions of carriage. These exemptions do not apply to Class 7.
  Carriage undertaken by such enterprises for their supply or external or internal distribution does not fall within the scope of this exemption. [1]

2.8.2 Container types and condition requirements

ADR determines several different type of containers that can be used to carry dangerous goods. Most of the design requirements concern of the construction of tank shells and tank's supporting frames.

Portable tank means a multimodal tank having, when used for the carriage of gases as defined in the provision 2.2.2.1.1, a capacity of more than 450 liters in accordance with the definitions in chapter 6.7 of ADR or the International maritime code of dangerous goods (IMDG) and indicated by a portable tank instruction (T-Code) in Column (10) of Table A of Chapter 3.2. [1] Portable tank can have a frame equipped with corner casting that can be locked to or with a twistlock and it shall have equivalent strength to bulk container.

Tank-container means an article of transport equipment meeting the definition of a container, and comprising a shell and items of equipment, including the equipment to facilitate movement of the tank-container without significant change of attitude, used for the carriage of gases, liquid, powdery or granular substances and, when used for the carriage of gases as defined in 2.2.2.1.1, having a capacity of more than 0.45 m3 (450 litres). [1] An example of a tank container is presented in the figure 15.

Figure 15. *Typical tank-container for military use [24]*

Demountable tank means a tank, other than a fixed tank, a portable tank, a tank-container or an element of a battery-vehicle or a MEGC, which has a capacity of more than 450 litres, is not designed for the carriage of goods without breakage of load, and normally can only be handled when it is empty. [1]

Multiple-element gas container (MEGC) means a unit containing elements which are linked to each other by a manifold and mounted on a frame. The following elements are considered to be elements of a multiple-element gas container: cylinders, tubes, pressure drums or bundles of cylinders as well as tanks for the carriage of gases as defined in 2.2.2.1.1 having a capacity of more than 450 litres. [1]

Bulk container means a containment system (including any liner or coating) intended for the carriage of solid substances which are in direct contact with the containment system. Packagings, intermediate bulk containers (IBCs), large packagings and tanks are not included. [1]

Also, following definitions determine a bulk container [1]:

- permanent character and accordingly strong enough to be suitable for repeated use;
- specially designed to facilitate the carriage of goods by one or more means of transport without intermediate reloading
- specially designed to facilitate the carriage of goods by one or more means of transport without intermediate reloading
- fitted with devices permitting its ready handling; of a capacity of not less than 1.0 m3

Examples of bulk containers are containers, offshore bulk containers, skips, bulk bins, swap bodies, trough-shaped containers, roller containers, load compartments of vehicles. [1] This means that ISO-containers can be considered as bulk containers in ADR.

ADR provision 7.1.4 set regulations for the condition of container that carries dangerous goods. The container has to be "structurally serviceable" which means that it is free from "major defects" in its structural components, for example, its top and bottom rails. Major defects are listed below:

- dents or bends in structural members greater than 19mm in depth, regardless of length
- cracks or breaks in structural members
- more than one splice or an improper splice (e.g. a lapped splice) in top or bottom end rails or door headers or more than two splices in any one top or bottom side rail or any splice in a door sill or corner post
- door hinges and hardware that are seized, twisted, broken, missing or otherwise inoperative
- non-closing gaskets and seals; any distortion of the overall configuration sufficient to prevent proper alignment of handling equipment, mounting and securing on a chassis or vehicle
- deterioration in any component of the container, for example, rusted metal in side walls or disintegrated fiberglass is unacceptable, regardless of the material of construction

However, normal wear, including oxidization (rust), slight dents and scratches and other damage that do not affect serviceability or weather-tightness are, however, acceptable. [1]

All the above-mentioned containers can be handled with a hooklift excluding demountable tanks, which are not usually equipped with corner castings and rails or other interfaces that could be attached to hooklift or lifting frame. On the other hand, a demountable container could be for example, attached on a flatrack, which then must fulfill the ADR regulations.

2.8.3 Carriage other than by road

ADR provision 1.1.4.5 determines regulations for carriage other than by road. According to the provision: "*…any national or international regulations which, on the said section, govern the carriage of dangerous goods by the mode of transport used for conveying the road vehicle shall alone be applicable to the said section of the journey.*" [1] ADR provision states in other words that if transport operation is carried out for example by rail, the regulation there should be applied the regulation that concerns rail haulage.

Generally, ADR provisions apply only when transport operations are performed on the territory of at least two of the ADR contracting parties [1]. On the other hand, ADR is a guideline and base of the provisions for transporting of dangerous goods in many countries in Europe. For instance, in Finland, we have a law "Vaarallisten aineiden kuljetus" (VAK), which mentions ADR in the law itself.

2.8.4 Application of standards

Where the application of a standard is required and there is any conflict between the standard and the provisions of ADR, the provisions of ADR take precedence. The requirements of the standard that do not conflict with ADR shall be applied as specified, including the requirements of any other standard, or part of a standard, referenced within that standard as normative. [1]

2.8.5 ADR in the future

Currently, ADR does not clearly set any specific fastening requirements to demountable containers that are secured or transported by a truck that is equipped with a hooklift. Generally, a hooklift is not a typical equipment for transporting dangerous goods, and therefore any provision is not clearly targeted to it. On the other hand, militaries use hooklifts to transport of dangerous goods and authorities require that the whole unit is then ADR compliant.

The government of Norway has noticed the ambiguity in regulations and brought it in 2015 to a UNECE meeting as a concern [9]. The government of Norway pointed out that strength requirement of fastenings should cover all of the container types and any frames or other devices used for support of such fastenings on the vehicle. This would unequivocally concern hooklifts as well then. A proposal for changing the ADR by Norway in 2016 [8].

Norway's proposal has been adopted by the working party in the 102nd held on 2 June 2017. Provision 9.7.3. concerning the fastenings, starting from 1 January 2019 is going to be clarified in following way:

"***9.7.3*** ***Fastening***

9.7.3.1 *Fastenings shall be designed to withstand static and dynamic stresses in normal conditions of carriage. Fastenings also include any supporting frames used for mounting the structural equipment (see 1.2) to the vehicle.*

9.7.3.2 *Fastenings in the case of tank-vehicles, battery-vehicles and vehicles carrying tank-containers, demountable tanks, portable tanks, MEGCs or UN MEGCs shall be capable of absorbing, under the maximum permissible load, the following separately applied static forces:*

- In the direction of travel: twice the total mass multiplied by the acceleration due to gravity (g)1 ;
- At right angles to the direction of travel: the total mass multiplied by the acceleration due to gravity (g)1 ;
- Vertically upwards: the total mass multiplied by the acceleration due to gravity (g)1 ;
- Vertically downwards: twice the total mass multiplied by the acceleration due to gravity (g)1

NOTE: *The requirements of this paragraph do not apply to twist lock tie-down devices in compliance with ISO 1161:2016 "Series 1 freight containers -- Corner and intermediate fittings – Specifications". However, the requirements apply to any frames or other devices used for support of such fastenings on the vehicle.".* [7],[32]

The main difference that has been added is that now the ADR clearly points out that fastenings also include any supporting frames used for mounting a container. Previously it has been only matter of assuming it for example in hooklift case. Provision 9.7.3.2 would now clearly point out that ADR concerns fastenings of tank-containers, portable tanks, demountable tanks, UN-MEGCs and MEGCs, which is not directly determined in the current version of ADR.

2.9 Summary of the theory

Figure 16 below presents shortly the theories that were presented in this chapter. From the figure we can see where theories locate themselves in the big picture.

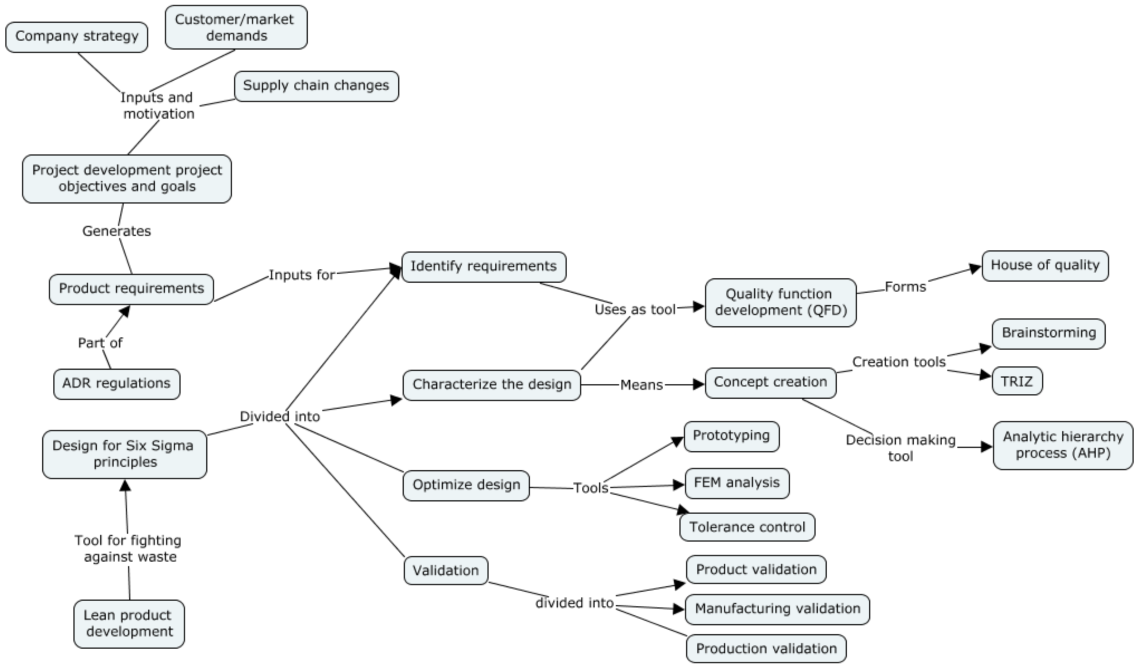


Figure 16. *Overview of the presented theories and their relations*

The whole product development process requires first motivation where it starts. Motivation factors are company strategy, customer/market demands and supply chain changes. Those factors set objectives for the project and for the product. When motivation to begin a product development project is created, a method how to carry out the process is needed. The method in the diagram is lean product development, which is base of DFSS. DFSS principles are a tool to fight against product development waste.

DFSS divides into four phases. Tools that are used in each phase are presented in figure 16. QFD is used as a tool to help to illustrate the relationshipship between each requirement and design task and element. Understanding the relationships between the design element helps to carry out design work with fewer iteration loops since the relations are considered already at the start and not after the problem is noticed.

In the second DFSS phase, brainstorming and TRIZ are utilized to create concepts. For deciding the concept that is going to be used, AHP is used to support the decision-making. It provides rational information and is, therefore, a great tool to use at this point. In figure 17 can be seen more detailed view of “characterize the design” phase of the DFSS and how it is applied to this thesis. As can be seen, the input is product requirements, which has been determined in the previous DFSS phase. The process ends to moving into the optimization phase. The process diagram illustrates the characterizing process that is carried out in this thesis. As seen in the figure, an iteration loop occurs, if improved design or a new concept does not comply with the product requirements. This loop is performed as many times as needed to fulfills the product requirements.

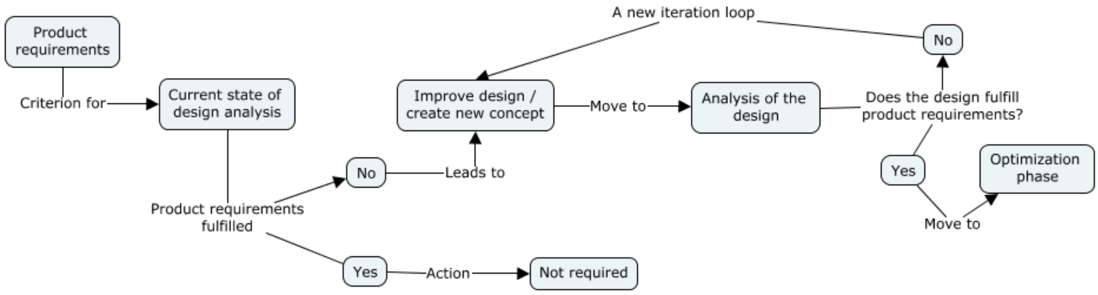


Figure 17. *Process diagram of characterize phase (C) of DFSS*

In the third phase, the design is analyzed and optimization activities are carried out. To drive the design towards optimum, FEM and prototyping are used as support and information source. In the final phase, the validation process is performed. In this thesis, the validation process is not carried out completely and it focuses on the first three phases of DFSS process.

3. PRODUCT AND DESIGN REQUIREMENTS

Before any analysis or design work can be performed, the requirements and framework have to be defined properly. The drivers for requirements are customer desires, costs, availability of parts and manufacturability improving. When we are making new design or revising older, the relationship to other parts is beneficial to know. Therefore, QFD is used to analyze the relationships.

3.1 General requirements

This thesis is focusing on fulfilling a limited amount of product requirements. The product management department has transformed customer needs into product requirements so R&D department do not have to worry about identifying the customer needs part of the process. Product requirements that consider this thesis are:

- New model should be interchangeable with the older one
- Safety latch solution must be created to the hook
- The hooklift has to be ADR compliant as well in container as in flatrack handling mode
- Reduced costs

3.2 Safety requirements

In order to improve the safety of the hooklift, it is required that a safety latch will be added to the hook. A safety latch is a commonly used solution to prevent the demountable body from releasing by accident from the hook. It is widely used in modern hooklifts and there are even pneumatic latches available, which operate automatically. However, in this hooklift, the safety latch does not have to be automatic and a manually operated latch is sufficient. The reason for that is that the latch is not required to be operated while load is on transport mode. This means that the operator does not have to climb on the truck to operate the latch but the operating can be done when the load is unloaded on the ground where latch can be safely operated without any climbing.

In table 4 can be seen product requirements for the safety latch. The information is gathered from interviews and from product requirements.

Table 4. *Safety latch product requirements*

Safety latch product requirements	
Section	**Description**
Operation requirements	Manual use is sufficient
	Latch can be manually locked either open or closed position
	Operator operates the latch from the ground when hook is at the back position and easily reachable
Manufacturing requirements	Avoid machined parts
	Avoid tight tolerances
	Minimum number of parts
	Prefer laser cut parts
Material	Steel, chain, cable can be used
	Painted, Electro galvanized + passivation
Other	Shape of the hook is not allowed to change, holes can be added
	Latch can be either fixed type or detachable

For the safety latch, the shape of the current hook is not optimal if similar latch that is used now in commercial hooklifts is going to be used. However, there is a desire not to modify the shape of the hook since it is found to be convenient for grabbing demountables. The current shape of the hook is not very sensitive to at which height it is adjusted before grabbing demountables which makes it convenient to use.

Manufacturing requirements are not strict for the safety latch. The desire is to have a reasonable simple latch design and therefore machining, tight tolerances and many parts are pursued to be avoided. Machined parts with high tolerances are not desirable but if such things are applied to design, some other significant benefits are expected to be achieved. For example, if the reliability or durability can be increased significantly with such design, machining and tighter tolerances are free to be used. Many item numbers on the other hand increases the work of after sales and assembly line, which increases the costs later in the lifecycle.

3.3 ADR requirements

ADR sets requirements for the strength of fastenings as mentioned in chapter 2.8 of this thesis. Rear skids have been already analyzed to comply with the ADR regulations and therefore they are left out from analyzes. In this work's analysis, the same amount of force is absorbed by the rear skids as in their calculation. Both flatrack and container carriage have to fulfill the ADR provisions. ADR requirements divide into two top level:

- Strength requirements for flatrack fastenings
- Strength requirements for container fastenings

Strength requirements divide into different load cases depending on the direction of the force. The amount of force applied to the structure is determined by the ADR regulations.

3.4 Interchangeability requirements

The new hooklift and CHU model are required to be interchangeable with the old hooklift and CHU. Interchangeability requirement has been identified by the sales company and product management department. In principle, interchangeability means that the new hooklift has to be able to operate an old lift frame and vice versa. Factors that effect on the operate ability are listed below:

- The new lift frame has to be able to be secured by using ratchets that have twistlocks
- New lift frame should fit to old hooklifts ratchets and vice versa
- Geometry of the lift frame shall be rather similar to avoid any collisions when using different lift frames
- Container locking geometry has to be same between the new and old lift frame so that either model of rear sliders can be used to secure the container

3.5 Relationship between product requirements and design variables

After identifying the product requirements, a design relationship map can be modelled to assist the designer to understand correlation between each requirement and task. For the new design, correlation between the design variables is an important factor to be aware of when pursuing the best possible overall solution. Requirements are first modelled as a mind map, which is then easy to turn into design relationship matrix. Mindmap can be seen in figure 18 below.

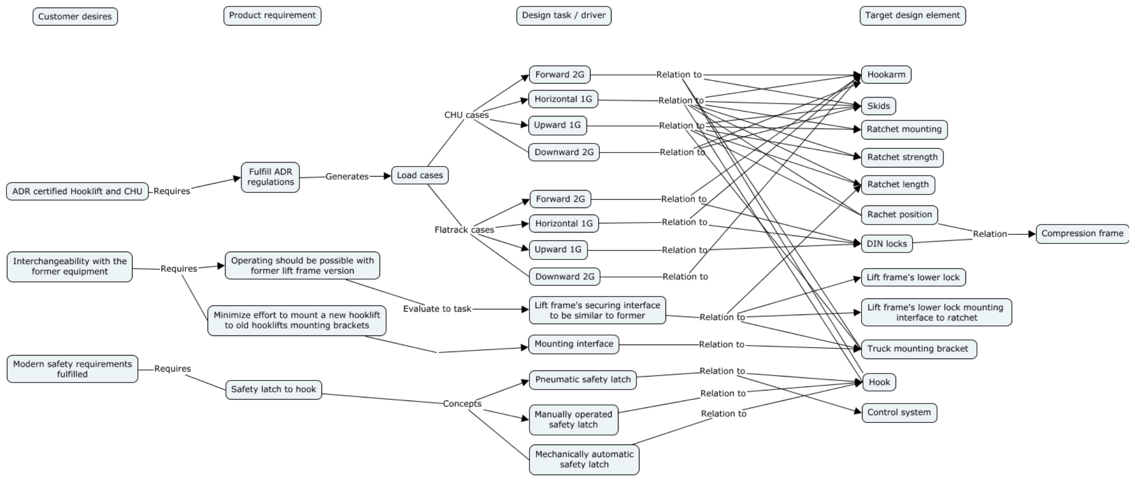
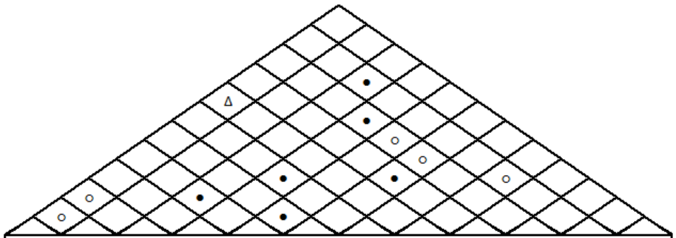


Figure 18. *Relationships between design requirements and design objects*

Table 5 illustrates house of quality table that has been derived from the mind map. In the house of quality, each product requirement has their own importance coefficient. Also, each product requirement has couple of design objects that pursues to satisfy them. Product requirements are ranked by thinking the critical-to-satisfaction factor of each of them. The more important the product requirement is, in general, the more value it has. Values are determined by the designer. For load cases downward is given only a value 1 for coefficient since it is not believed to affect the design that much or to be the critical requirement that drives the design.

Table 5. *Design variable and task relationship matrix (House of quality)*



Relation level 9-3-1		
●	9,0	Strong
○	3,0	Moderate
Δ	1,0	Weak

↑	Maximize
↓	Minimize

		Importance to coefficient	Relative importance	Hookarm strength	Hook	Skids strength	Ratchet strength	Ratchet length	Ratchet's mounting position	Srength of ratchet's mounting to compression frame	DIN lock's strength	Lift frame's lower lock strength	Lower lock's mounting interface with ratchet	Truck mounting bracket strength	Control system
	Product requirement	Scale 0-5	%	↑	x	↑	↑	↓	x	↑	↑	↑	x	↑	x
CHU load cases	Absorb forward 2G	5,0	11,90 %	●	○	●								○	
CHU load cases	Absorb horizontal 1G	4,0	9,52 %			●	●	Δ	○	●		●	○		
CHU load cases	Absorb upward 1G	4,0	9,52 %			●	●	Δ	●	●		●	●	○	
CHU load cases	Absorb downward 2G	1,0	2,38 %	○	Δ	●								Δ	
Flatrack load cases	Absorb forward 2G	5,0	11,90 %	Δ							●			●	
Flatrack load cases	Absorb horizontal 1G	4,0	9,52 %	Δ							●				
Flatrack load cases	Absorb upward 1G	3,0	7,14 %								●				
Flatrack load cases	Absorb downward 2G	1,0	2,38 %	○	Δ	●								Δ	
	Interchangeability with old DROPS	5,0	11,90 %	Δ	○	○		●	●	Δ		●	●	○	
	Safety latch	5,0	11,90 %	Δ	●										○
	Manufacturing price	5,0	11,90 %	●	Δ	○	Δ	Δ	Δ	Δ	○	○	○	○	●
	Impotance of the engineering attributes	42	100 %	2,7	2,0	3,9	1,8	1,4	2,3	2,0	2,9	3,1	2,6	2,5	1,4
	Relative importance of attributes			9,6 %	6,8 %	13,7 %	6,4 %	4,8 %	8,1 %	6,8 %	10,2 %	11,0 %	9,0 %	8,6 %	5,0 %
	Importance level (1-5)			4	3	5	3	2	3	3	4	4	4	4	2

Design objects

Desired direction of improvements are presented with arrows for each design objective that is measurable. Relationships between product requirements and design objects are modelled by using symbols. Each symbol represents a level of relation between the objects. A blank box equals no relationship between the object and requirement.

The correlations between design objects are described in the roof of house of quality table. The same symbols are used as in the previous relation description. The reason for not using standard negative/positive symbols is that in this context, we are more interested just, which design objects have relations to another and how strong is the relation.

Finally, we receive importance value of each design objective. Values are calculated by using the relative importance of product requirement as a weight factor and then summing up the relation values multiplied by each weight. After that, the importance value is transformed into relative importance to make it easier to compare. In the figure 19 can be seen the design objectives sorted by the importance.

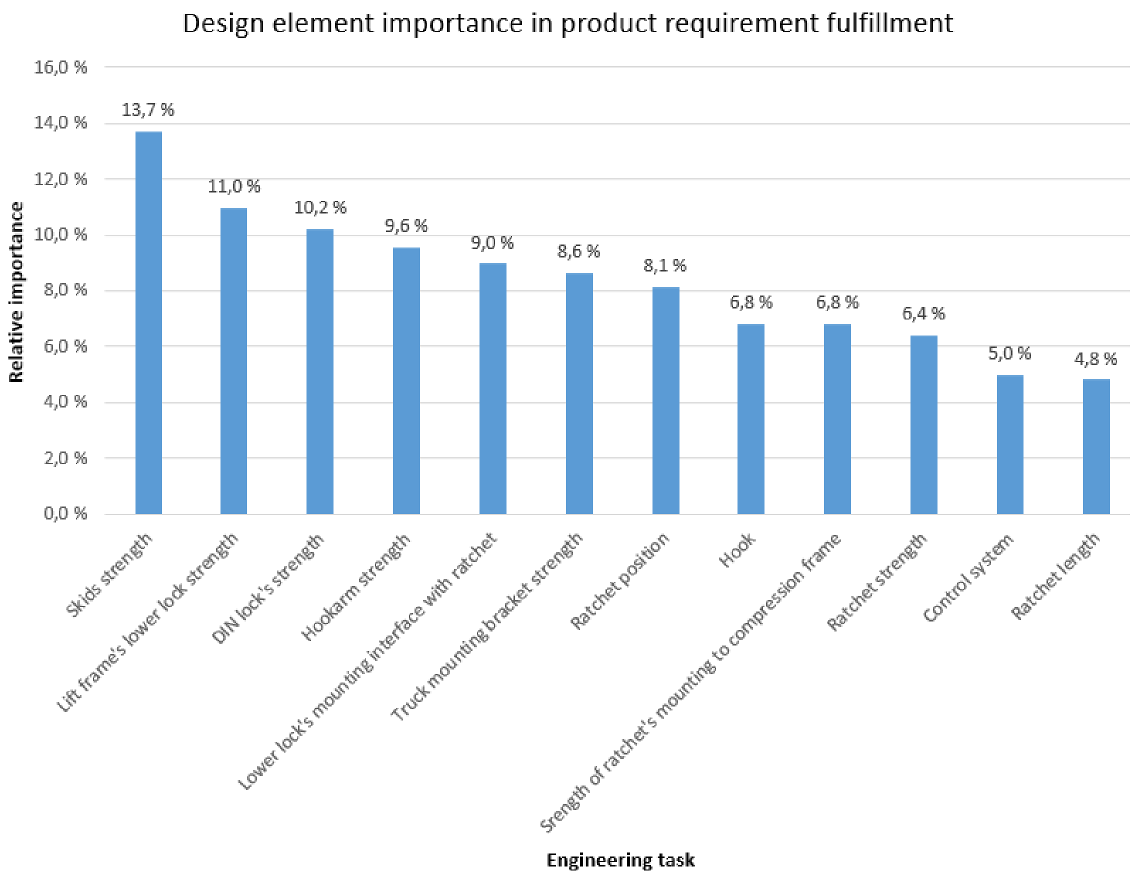


Figure 19. *Engineering tasks sorted by the importance level*

Importance indicates the amount of relation in order to satisfy the product requirements. According to the chart in figure 19, the strength of the skids is the most important factor and has most relations to the engineering tasks or design objects. The strength of the lower lock has second biggest value followed by the din locks.

Results of the house of quality give an overview of the influence potential of each design objective to the product requirements. The benefit of knowing this is that now more resources can be used to the high-value objects and designer notices that the higher the value is the more the design element affects to the fulfillment of requirements. In other words, high value objects are more critical to more elements.

3.6 Product value influences

The reason behind each product requirement is that the value of the product would increase. Product value increases by increasing the customer value and by decreasing overall costs. Customer value is a bit hard to define or present in a numeric form. In general, customer value can be defined: "*A consumer's assessment of the overall capacity of a product to satisfy his or her needs* [11]." On the other hand, satisfaction can be divided into factors such as customer effort score, service experience, net promoter score or user experience and context of use [25].

Anyhow, the product value in this project is pursued to be increased by following features:

- New lift frame and rear slide system
- Safety latch
- ADR compliant equipment
- Interchangeability

The listed features are not only part of the improvements of the whole project. Above mentioned are included in the scope of this thesis.

New lift frame and a rear sliding system increase the value by lowering the overall costs that they cause in the whole lifecycle. They offer the same features to the customer as the previous models but for the company, they are more cost-efficient to manufacture and purchase. In addition, delivery time is expected to be shorter due to harmonization possibilities to other existing products. Design of the new lift frame and the sliding system is more suitable for the modern manufacturing processes and therefore it is more cost-efficient than the older design. For example, laser cutting accuracy has increased over the years, which has enabled designers to create the design so that laser cutting can be effectively utilized.

Rear slide system with skids is a new solution in container handling. The old roller type system is more expensive to manufacture and it has been noticed to damage the rails of a container over the time by bending the rail. In the new sliding system, the skids provide a flat support surface for the container and therefore damages the rails less. On the other hand, friction increases in the load cycles, but not that much that capacity of the equipment would lower.

Safety latch increases the safety level of the product. Today’s standards require the product to be very safe, which is why a safety latch had to be designed. For the customer it is great solution especially in the lift frame operation where the risk of dropping the frame is high.

ADR compliance is a basic requirement for military equipment. It is hard to calculate the value it brings but even easier to calculate loses if the equipment is not ADR compliant since no military wants to get an equipment that is not ADR compliant.

Interchangeability increases the customer value of the product as it can be used to operate older CHU equipment without a problem. For a customer that has older MPH165 equipment, interchangeability brings great value, since any hooklift can be used with any lift frame without worrying which model of the hooklift is in the use.

4. DEFINITION OF CURRENT STATE OF DESIGN

To be able to make the product better, the current state of the design has to be known. The current design can then be compared to the newer one and benefits and product value can then be better understood.

4.1 Hooklift and new equipment

Hooklift is equipped with a new type of rear sliding system and a new type of lift frame. Sliding system already fulfills the product requirements which forces us to focus more on the new lift frame. The idea is that the mechanical design of the hooklift remains in outline rather unmodified and only necessary modifications are desired to be made.

4.2 Ratchets and securing of the lift frame

The current designs of the lift frame and its ratchets are from a former project. Currently, the designs are not completely validated and, for example, the ratchet mounting and some parts of the lift frame are not in use in any equipment yet. The ratchet design of the older DROPS is not desired to be used in the new model since a more cost-efficient solution is desired. The design of the new ratchet solution is not perfect from the operating point of view yet. The lift frame cannot be secured completely with the current solution. Lift frame still remains loose even though the ratchets are tightened up completely. The reason is that the lift frame is quite flexible and the chosen ratchets cannot be tightened up enough with current geometry since the “legs” of the lift frame starts to bend. Ratchet is in the end tightened up to its maximum. In the figure 20 can be seen the current solution of ratchet mounting.

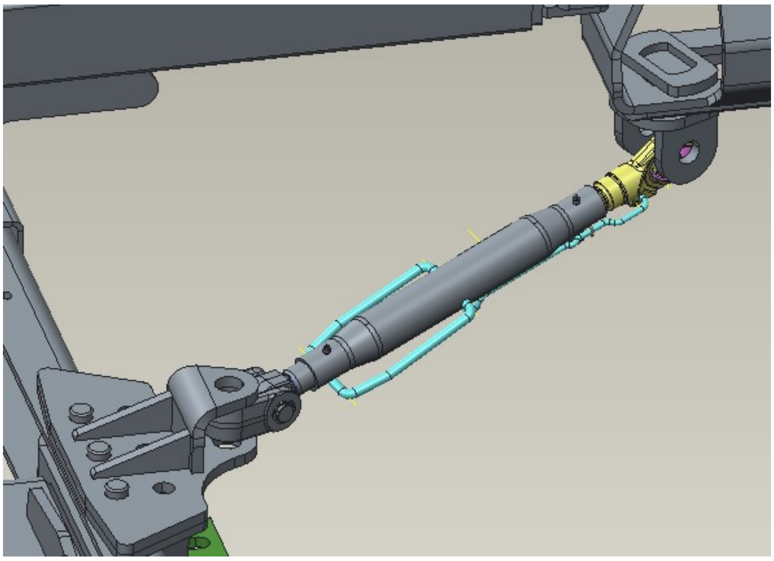


Figure 20. *Current design for securing the lift frame*

The used ratchet is a top link that is used commonly in agricultural tractors. The ratchet can be tightened up by twisting the middle section of it.

In table 6 can be seen the technical data of the new ratchet. The ratchet is a category 2 top link which maximum capacity is 120kN. Category of the ratchet indicates its capacity that it can handle. In higher capacities the size of the shaft and ratchet increases.

Table 6. *Properties of the ratchet*

Ratchet properties	
Top link category	Cat 2.
Maximum capacity	120kN
Minimum length	532mm
Maximum length	755mm
Swivel end mounting hole diameter	28mm
Ball end mounting hole diameter	25,4 (1 inch)

The minimum length of the ratchet is 532mm which is according to testing, too long for the current mounting position.

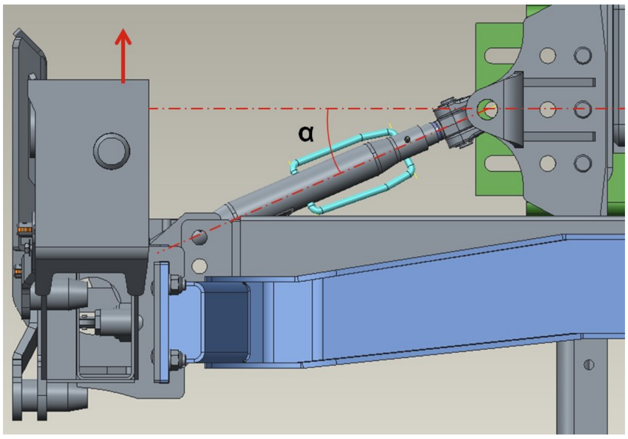


Figure 21. *Lift frame's angle in relation to ratchets from above*

As can be seen from figure 21, the ratchet has an angle rearward. Now, when the ratchet is tightened up the lift frame moves rearwards until it reaches the same line that the ratchet is mounted to. Only after that, it starts to tighten up. The current ratchet is too long to be able to lock the lifting frame completely. Another thing that is identified is that ratchets have to be tightened up quite a lot before frame starts to tighten up and finally with the current ratchet length / mounting position does not.

Attaching ratchets to the lift frame is performed with a specific mounting bracket that can be seen in figure 22. The bracket is designed to fit in a twistlock hole and to the Walterscheid's ratchet.

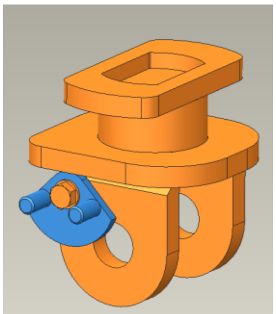


Figure 22. *The current state of twistlock interface*

The old, H-type lift frame has a twistlock interface and therefore the twistlock interface is desired to the new one as well in order to retain the interchangeability. Currently, the new lift frame is equipped with the twistlock interface as well but the strength is unknown. Old DROPS hooklifts are equipped with ratchets that have twistlocks on the other end and they can only be attached to a twistlock shaped hole.

4.3 Lift frame and locks

In figure 3 can be seen the lift frame that is used in this project. Noticeable is that the structure of the new frame is much more elastic compared to former design. Currently, the frame is too elastic so that it could be secured with ratchets that are mounted on the current position. Therefore, there is a steel beam connecting the legs of the frame. Beam prevents “legs” to move towards each other when ratchets are tightened up.

Figure 23 shows the current state of lift frame’s lower lock. The lock has, as mentioned, a twistlock interface. The interface is already designed so that it is in the same position as in H-type lift frame so position wise designer does not have to worry about it. The strength of the structure is unknown what it comes to the ratchet mounting.

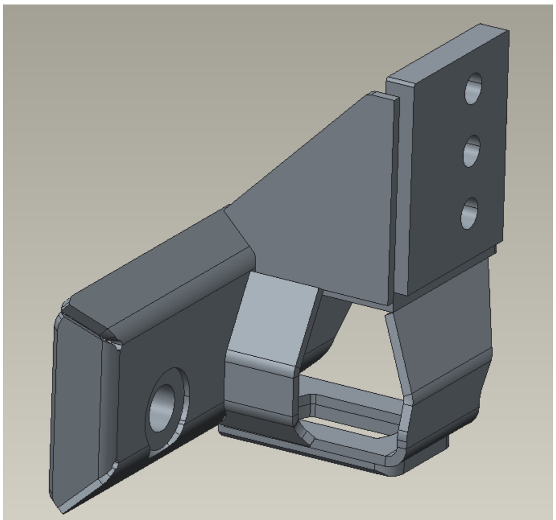


Figure 23. *Current state of a lower lock*

5. DESIGN ANALYSIS OF CURRENT STATE

In this chapter, the current state of design is analyzed. The target is to find out which parts of the product already fulfill product requirements and which parts require modifications. The current state of design is presented in the previous chapter.

Product requirements to be analyzed:

- Safety latch
- Mechanical structure fulfills the ADR regulations
- Product is interchangeable with older DROPS equipment

5.1 Interchangeability

The new MPH165 and its CHU has a requirement to be interchangeable with old models. Interchangeability means in this context that customer who has an old equipment and wants to buy more can buy the facelifted model and operate with it an old lift frame or replace an older hooklift model easily without major modifications to truck mounting.

The new model shall be able to operate the old lift frame and vice versa. Securing the lift frame to the transportation mode as well as operating it have to be possible to perform with either hooklift model.

Currently, the lift frame is interchangeable to the older one. However, securing the frame does not work conveniently with the new ratchets. The lift frame still moves a lot even though the ratchets are tighten up completely. As already mentioned in chapter 4.2, the mounting point has to be moved more forward in order to secure the frame properly.

5.2 Container handling load cases

ADR sets requirements for the fastenings to be capable of absorbing static forces that were defined previously in chapter 2.8. Both container and the flatrack fastenings have to fulfill the regulations. ADR study for skids has been already carried out and it can be left out of the scope of this work's analysis.

Before any analysis can be done the fixing points must be defined. Mounting of a flatrack and container is different and therefore the study has to be done separately for both applications. In every container load case, the force is applied to the center of a container, which is assumed to be the center of gravity.

Figure 24 and 25 illustrate load ADR load cases. The direction of travel is to the left-hand side in figure 24. As figure 24 shows, the container is fastened from the corner fittings by rear slide unit (skids) and by the lift frame on the front.

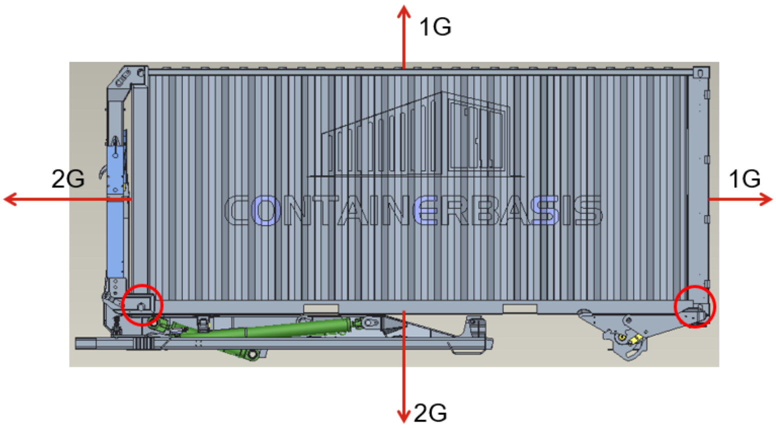


Figure 24. *ADR forces and the mounting points*

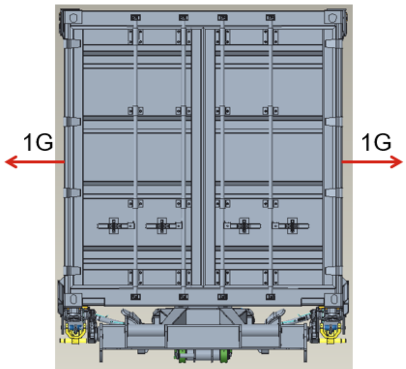


Figure 25. *Horizontal ADR forces*

Ratchets are attached to the lift frame's lower locks and they prevent the container to jump and move sideward. On the back, the container is secured from its lower corner fittings to rear sliding systems twistlocks.

5.2.1 Load case 1: forward

In this load case, a force of 2G is applied forward. According to the ADR, static force of 2G is applied to the direction of travel when it is defined.

In the container handling application, the load is carried following way:

- 50% of the load is absorbed by the hookarm and lift frame
- 50% of the load is carried by rear skids and their twistlocks

Lift frame and skids have already been analyzed, which leave us only the hookarm to be analyzed.

Figure 26 shows the inspected sections of the hookarm. Sections are chosen to be the two most critical sections.

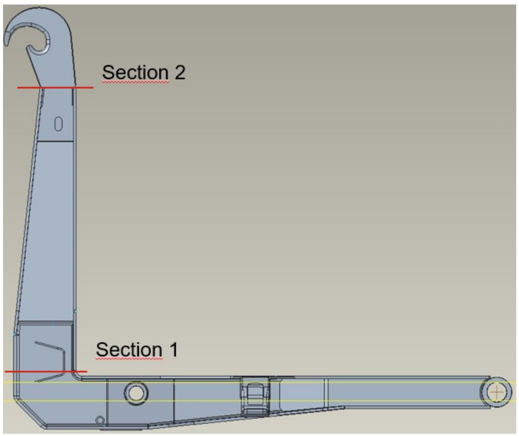


Figure 26. *Inspected sections of hookarm*

Section 1 is the point where stiffness is at its maximum and section 2 where the area is at the minimum. Maximum stress at section 1 is far from the permissible maximum. At section 2, maximum stress is almost at the same level as in section 1.

Calculations reveal that hookarm is strong enough to fulfill ADR requirements of this load case. Any reinforcement design is not necessary to be made strength-wise.

5.2.2 Load case 2: rearward

In the load case 2, force of 1G is applied backward. It is absorbed in following way:

- 50% of the load is absorbed by the hookarm and lift frame
- 50% of the load is absorbed by the rear skids and their twistlocks

In the load case 1, the hookarm was already analyzed. In load case 2, the force is carried as well with the hookarm and as the applied force is half of the first one, no further analysis is necessary to be done.

5.2.3 Load case 3: sideward

In the load case 3, a sideward force of 1G is applied. The load will be absorbed in the following way:

- 50% of the load is absorbed by the rear skids and their twistlocks
- 50% of the load is absorbed by one of the ratchets

The container is held in this load case by the ratchets and rear skids. Twistlock type of ratchet mounting is capable of absorbing the force only in one direction as lock has a clearance to the other way.

The maximum load that ratchet can carry is determined to be 120kN. The sideward force that a ratchet has to hold is 1G/2, which equals with maximum load 81kN. Calculations reveal that current solution generates a force of 178kN to the ratchet, which exceeds the maximum by a lot. Some changes are required to the ratchet's strength or position in order to handle the force.

5.2.4 Load case 4: upward

In the load case 4, a vertical force of 1G is applied and the load will be absorbed in the following way:

- 50% of the load is absorbed by the rear skids
- 25% of the load absorbed by each ratchet

According to the calculations, the current ratchet mounting solution is unable to carry the load. The current solution generates a force that exceeds the permissible maximum. Clearly, ratchet design must be re-considered. There are several actions that can be considered to improve the ratchet design in order to fulfill the ADR force requirement. Of course, lift frame's lower lock and the twistlock have to be also analyzed, but as ratchet solution is far from fulfilling requirements, there is no use of analyzing lower locks and the twistlock yet since the force is going to change.

Ratchet design can be improved by following actions:

- Improve ratchet strength
- Change the ratchet position (angle)

Improving the ratchet's strength might solve one problem but as the force is high already, it might not be the best option in this case. Smarter would be to increase the angle of the ratchet in order to reduce the force of the ratchet. Also, it is already identified that ratchet mounting position has to be moved forward to improve other factors. Therefore, it is smart to consider if ratchet force can be reduced sufficiently with the position change as well. According to the calculations, the angle of the ratchet would need to increase a little and it would require that the mounting position would need to be moved vertically lower.

5.2.5 Load case 5: downward

In the load case 5, a force of 2G is applied downwards.

- 50% of the load is absorbed by hookarm and lift frame
- 50% of the load is absorbed by the rear skids and their twistlocks

Rear skids have been already studied to handle the force. For the hookarm, the analysis is unnecessary to do, as the load is applied to the strongest direction of the hookarm. Therefore, we assume that structure is ok.

5.3 Flatrack load cases

Flatrack load cases differ from CHU cases in such a way that the critical forces are carried by the hook and din-locks instead of ratchets and rear skids. In flatrack load cases, very conservative approach is used. Amount of loads are in some load cases extreme. For example in load case 6 forward, the support of hookarm is not taken into account in the calculations.

5.3.1 Load case 6: forward

Force of 2G is applied to forwards in this load case. The load is carried by:

- 100% of the force to din locks

Force is in reality carried by the hookarm as well, but it is very hard to estimate the amount that it absorbs. The loop of the flatrack could slip over the thumb of the hook and then the load would be carried entirely by the DIN locks. Therefore, we assume that 100% of the load is carried by the DIN locks. In addition, in the load case 1, we already proved that the hookarm is able to carry easily force of 1G.

As can be seen in figure 27, the load affects heaviest to the round plate that is supporting the din lock casting.

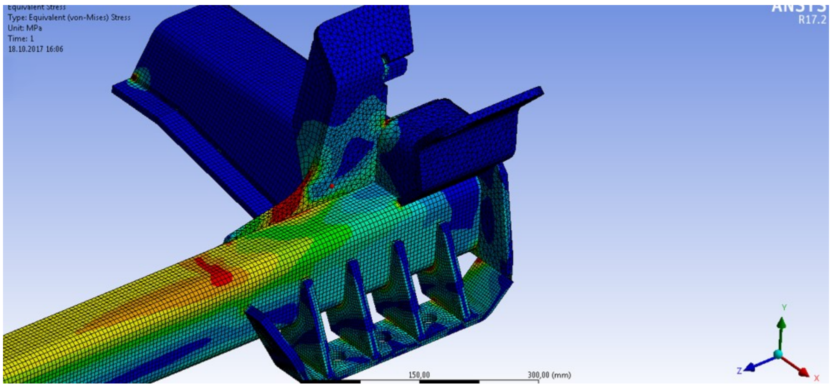


Figure 27. *Current state of design*

The U-beam seems to be under high stress as well. The structure would need some changes according to this calculation if we want to prevent plastic deformation. A more detailed analysis should be carried out in this case to get more detailed information. In more detailed analysis, bolts and the supporting surface should be modelled as well to verify the validity of the results.

It has been identified that truck mounting is going to be changed. Now the mounting is not at the same level with the front mounting, which is confusing. Therefore, a mounting bracket, which is similar to the front mounting plate, is going to be used in the next analysis.

5.3.2 Load case 7: rearward

In the load case 7, a force of 1G is applied rearwards. It is carried in the following way:

- 100% of the load to hookarm

As the rearward force might create a moment that lifts the hookarm, the hydraulics must be analyzed. The hookarm is held still by hydraulic cylinders that are locked with load control valves. The load control valves have pressure relief level, which shall not be exceeded in order to prevent possible load escaping. According to calculations, the pressure in the main cylinders exceeds slightly the setup of the pressure relief valve. However, it can be assumed that load does not escape as calculations do not include friction, pressure loses or the fact that at some point, very soon after release, the hook will be the load carrying component and not the rail supports. That would increase the moment resisting the rotation and pressure would reduce under the set limit in main cylinders.

Strength of the hookarm was already studied in the load case 1. Applied force was 1G, the same as in this load case. Therefore, we can state that hookarm has sufficient strength.

5.3.3 Load case 8: sideward

In the load case 8, a force of 1G is applied sidewards. It is carried in following way:

- 50% of the load to DIN locks
- 50% of the load to middle frame of the hook
- 100% of the moment load to DIN locks

Middle frame of the hookarm is a strong component and it is left out from the calculations as it is not assumed to be the weakest link of the structure in this load case. The weakest component is assumed to be the truck mounting or the DIN lock itself.

Rather high center of gravity in the flatrack calculations causes a force upwards to din lock. Direct sideward force of G/4 affects the lock in addition. Figure 28 shows the stresses caused by these forces.

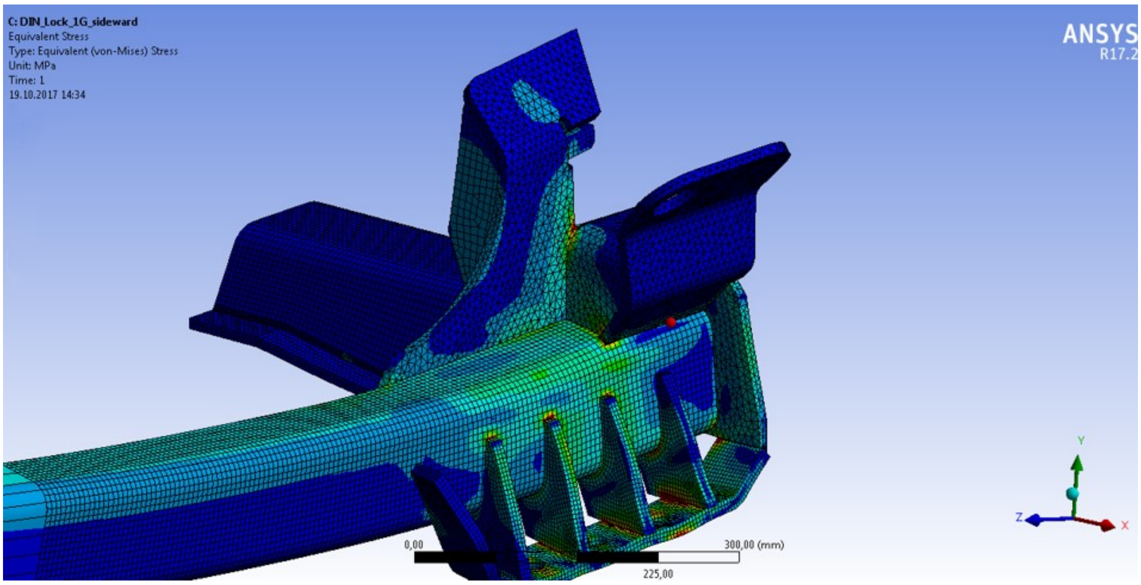


Figure 28. *Results of finite element analysis*

As can be seen, the highest stresses are at the edges of welds. However, stresses do not exceed the yield strengths or for welds, the tensile strength. Therefore can be said that the structure is ok.

5.3.4 Load case 9: upward

In this load case, the force of 1G is divided to each din lock. G/2 is applied to each of them. Finite element analysis reveals that stresses in the whole structure are moderate. No further actions are therefore required.

5.3.5 Load case 10: downward

In this load case, a load of 2G is applied downward. It is carried in the following way:

- 50% load to the sliding system
- 50% to the hookarm

The case is rather similar as already analyzed CHU load case 5. The only difference is that load is now carried by the rail rollers. They are clearly stronger than the skids that hold a container and it can be assumed that 2G force downwards is easily absorbed.

5.4 Summary of the analysis of ADR load cases

The analysis revealed that the most critical load cases for container were 2G force to forward and 1G sideward. For flatrack, the structure seemed better and only action required is a more detailed analysis to the structure to make sure that changes are required. Table 7 summarizes the analysis of the strength analysis.

Table 7. *Summary of the current state of ADR load cases*

	Load case	Force	Action
Container	Forward	2G	No action required
	Rearward	1G	No action required
	Sideward	1G	Stress level of ratchets exceeds the yield strength
	Upward	1G	Stress level of ratchet exceeds the yield strength
	Downward	2G	No action required
Flatrack	Forward	2G	Stress level exceeds the yield stress, consider changes
	Rearward	1G	No action required
	Sideward	1G	No action required
	Upward	1G	No action required
	Downward	2G	No action required

6. CONCEPT CREATION, ANALYSIS AND SELECTION

In this chapter, concepts for identified problems and for solving them are created and then analyzed. The previous chapter revealed issues in the design that are now going to be solved in this chapter.

6.1 Safety latch

According to product requirements, safety latch must be added to the hooklift to fulfill modern safety requirements. The type of safety latch is not defined in the product requirements but it should be cost-efficient and easy to use. Safety latch will be used when the hooklift is driven to the unload position. At that position, safety latch can be operated easy and safe, operator standing on the ground. In addition, the safety latch will be used only with lifting frame according to the product requirements.

Safety latch for hooklift itself is not an innovation. Therefore, existing safety latch concepts are first studied. Plenty of variable solutions are already available on market. For so-called commercial hooklifts, the customer can select a pneumatic safety latch that is operated with a remote controller or a mechanically automatic safety latch, which works by utilizing the earth's gravity. Pneumatic safety latch would be the best option what it comes to easy to use factor but the fact that it would require a completely new hook design is a disadvantage of it. Gravity assisted automatically operating mechanical latch would be an inexpensive solution.

The concept creation process starts by creating as many concepts as possible. According to Yang [5], brainstorming is a powerful tool to create many concepts. The idea is to create concepts without any filter at first. For creating safety latch concepts, a brainstorming session was held in a group of three people and following ideas were received from the session.

Final concept ideas:

1. Pneumatic safety latch
2. Gravity assisted safety latch
3. Chain or a securing cable
4. Detachable latch
5. Manual, hook fixed latch

The ideas represent different solutions of a safety latch in terms of operation principle. Safety latches can be categorized into automatically-, semi-automatically-, and manually operated concepts. The pneumatic safety latch is the only solution that can be made fully automatic. However, according to product requirements, an automatic solution is not required, which might make the pneumatic latch a bit too “high-tech” solution for the purpose.

Gravity assisted safety latch is a semi-automatic safety latch. Working principle is that the latch opens when the hook is upside down automatically. When the hook is in the normal position, gravity will move the latch to the locked position. This kind of solution is not the safest option when operating with a lift frame since the highest risk of dropping the frame from the hook is at the position where the hook is upside down.

Chain or securing cable is a concept where a chain or cable is attached to the hook. Securing would be accomplished by making a loop around the bail bar with the cable. Securing, in this case, would be a bit “loose” but costs of the concept is very low compared to others. However, this kind of securing would look a bit unprofessional and there is always a risk that cable or chain sticks to something.

Detachable latch concept is as the name says, completely detachable. The hook would not require any changes with this concept but using it is a bit complicated compared to other concepts. It would require a stowage somewhere in the hooklift as well. Since it is not mounted to the hook, there is a risk of losing the latch by dropping it somewhere, in the snow for example. This kind of latch is easy to forget to use as well.

The last concept is manual hook fixed latch. The latch would be attached to the hook and operated manually. The concept could be made with rather low costs depending on the design. Compared to the concept three, this would look more professional and would provide a “proper” securing.

6.1.1 Concept selection

Now, we have five solid concepts that could each be the best solution. However, the most suitable concept must be chosen, which then can be developed and optimized. To support the decision-making, we will use AHP to receive rational and consistent results.

For the AHP we have selected following criterions:

- Manufacturing price
- Ease of use
- Durability
- Simplicity
- Safety

The criterions describe the requirements that we value in the safety latch design. After a pair-wise comparison, we receive weights to each of them, which can be seen in table 7 below.

Table 8. *Importance factors of criterion*

Criterion	Importance
Manufacturing price	0,310
Ease of use	0,274
Durability	0,053
Simplicity	0,090
Safety	0,274

Table 7 shows that manufacturing price is the most valued criterion followed by ease of use and safety. Safety is an obvious feature for a safety latch and the reason why it is not the most valuable criterion is that all the concepts fulfill the required safety level already. Therefore, safety does not have to be the number one driver for the latch design. Safety criterion in this context includes features like ease of forgetting to use, reliability and probability of failing. For example, the detachable safety latch is easy to forget to use while pneumatic safety latch is always on automatically. Possible malfunction of a pneumatic latch, on the other hand, is harder to notice compared to a manually operated latch.

Durability and simplicity are less valued criterions than the three already mentioned but are still important factors for this comparison. By simplicity, we mean either how simple and easy the latch is to manufacture, or how many other aspects it affects when designed. For example, a pneumatic latch has an influence at least to the hook, hookarm and control system, which makes it rather complicated solution. A chain or securing cable, on the other hand, is a very simple solution as it requires itself not many parts nor has an influence on many parts.

Durability means the capability of the solution to remain workable. Target durability is that latch does not have to be replaced during the whole life cycle of the hooklift and it remains in working condition in the whole lifecycle. Sensitivity to failure due to rust or collisions is also included in durability criterion.

Next, concept alternatives are compared by using the criterions. Each alternative then gets a weight value of each criterion. Finally, the weights are summed and we can present the result as figure 29 shows.

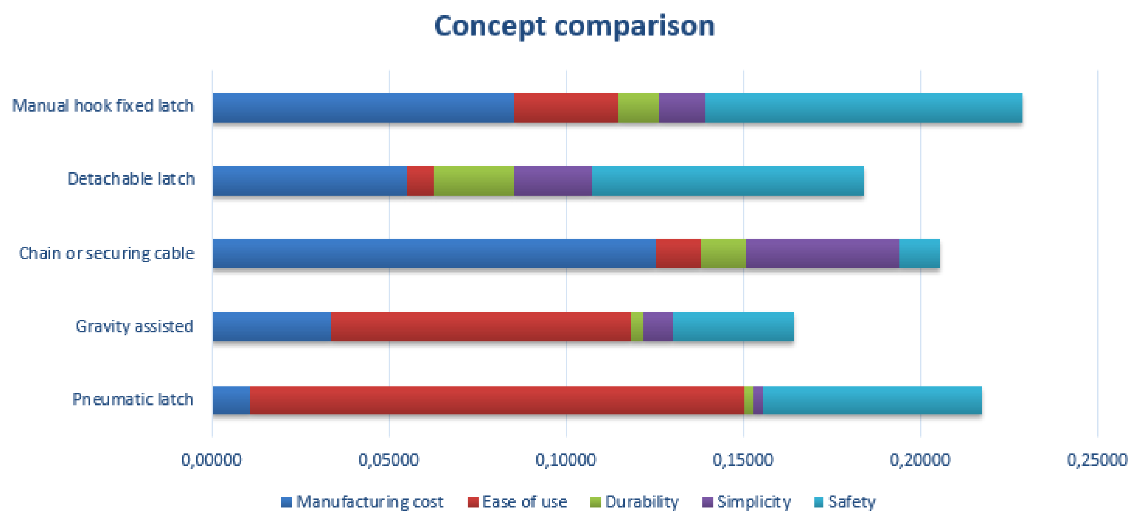


Figure 29. *AHP comparison results*

Figure 29 shows the comparison results from AHP analysis. The more the value is, the better the concept is. Noticeable is that pneumatic safety latch has significantly many points on “ease of use” factor. The chain concept, on the other hand, is cheapest and simplest solution, and therefore it has quite high points.

The highest overall points have received the “manual hook fixed latch” concept. It has the best safety and is the second cheapest option of all. It loses in simplicity to chain and detachable concept but not too much. From manually operated latch solutions, it is easiest to use which is a significant feature. The AHP material can be found in appendix B.

6.1.2 Design of safety latch

Now when the concept is selected, the design of the safety latch itself can be started. There are two different ideas to execute the latch:

- Sliding thumb
- Rotating latch

After sketching, it can be noticed that both of these concepts can be made rather easily. However, a sliding thumb would thicken the front of the hook and be more sensitive to rust and collisions. It would have also lower strength than a rotational latch. Therefore, the rotational latch is chosen as continuing concept. The rotational latch will require making three holes to the hook, which will be used as locking and pivotal points.

Now when the rotational latch is chosen, an initial design must be created. In order to meet the internal and external customer needs as well as possible, House of Quality is utilized and it can be found in the appendix A. In figure 30 can be seen the results of it.

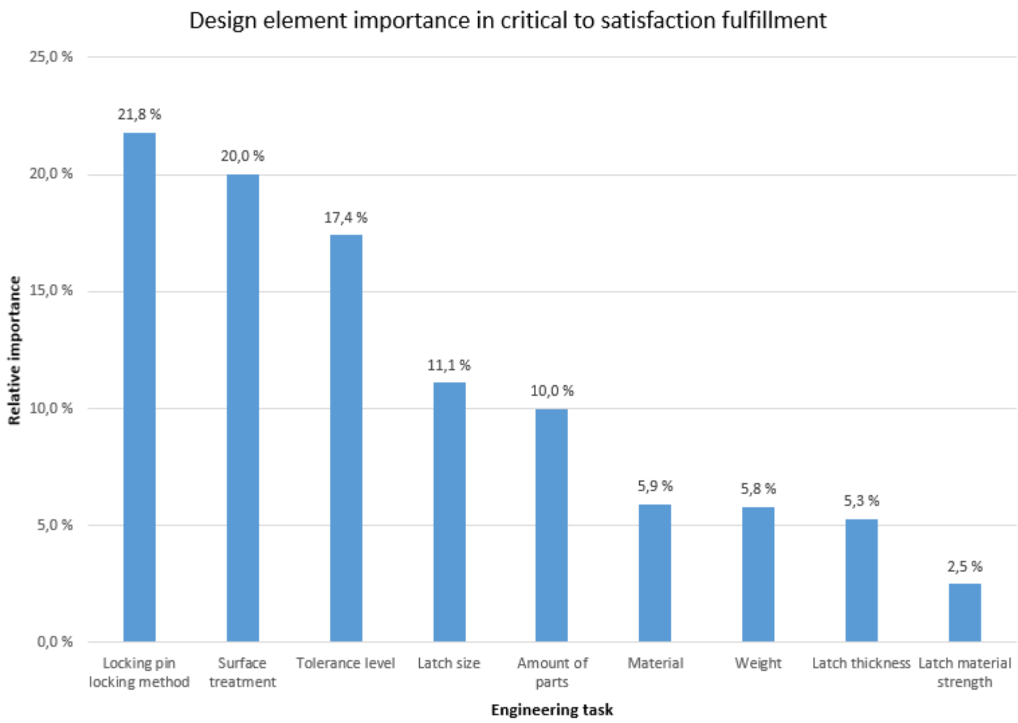


Figure 30. *Importance levels to satisfy needs from HOQ of safety latch*

As can be seen, locking pin design has the highest effect on satisfying the specified needs. Tolerance level and surface treatment seem to be very important as well, and therefore they are considered especially carefully.

First, the length of the latch and position of the holes are determined. Location of bail bar's loop is the driving factor for the decision-making of the holes' locations. It turns out that one of the holes must be made to rather end of the hook. Therefore, no bigger than 11mm holes are recommended to use. The pivotal hole will be located as close to thumbs top as possible in order to minimize the length of the latch.

Next step is to consider the locking and operating of the latch. Latch is planned to be made by using two plates, one to each side of the hook. However, it must be considered if they have to be connected to each other. Connected plates would improve the ease of use factor as the user can operate the latch only by moving the latch from one side of the hook. The possible connection could be done by:

- Welding the rotation axis to plates
- Using keyway locking
- Welding a uniting plate between the plates

If rotation axis is welded, the safety latch cannot be replaced without grinding which can be a problem at some point in the lifecycle. On the other hand, using a keyway locking, would require high tolerance manufacturing and would be too expensive for the purposes. The last way would be to weld a uniting plate between the latches. However, that would require making a groove to the hook, which is not desired option.

Since none of the above-mentioned options seems to be a viable option in order to connect latches, separate latches have to be considered. The only issue is that now the user would need to move the latch separately on both sides, which lowers the ease of use factor. On the other hand, it is not such a time consuming or tricky task to do. According to the estimations, individually moving latches would save a lot of costs, which drives us to select not connected latches at the expense of ease of use.

After the geometry of the latch is roughly known, we can start figuring out how the locking would be done. There are three simple and possible ways to use:

- Bolt locking
- A shaft that is locked with snap lock pin on the other side
- A shaft which can be locked from the same side as pushed in

The easiest way would be to use a normal bolt to lock the latches. However, it is not very professional or convenient way since bolt cannot tighten up without tools, and gets easily lost. On the other hand, the bolt could be replaced with a shaft that is locked with a locking pin from the other side. The third option is to create a system where a shaft is used but the system could be locked from the same side of the hook as operator stands.

In the figure 31 can be seen a draft design of a safety latch. The latch can be operated from one side of the hook and the locking pin does not cause any collision with the current latch shape when the latch is not in use.

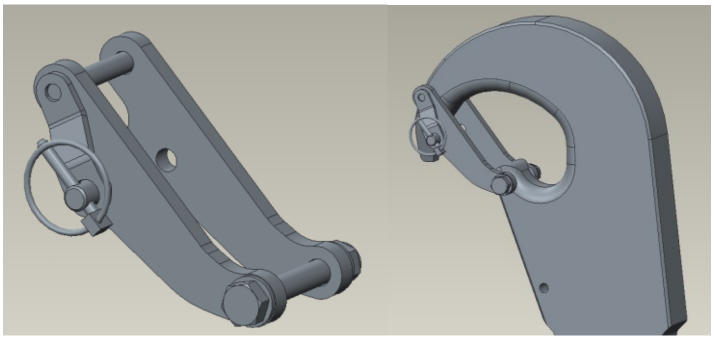


Figure 31. *Selected safety latch concept*

The surface treatment of the safety latch was forbidden to be shiny. Therefore, a green passivated electrogalvanized zinc treatment was chosen to be used. Painting was not desired as it would wear off very quickly due to the contacting faces. In the literature for atmospheric zinc corrosion rates from 0,13μm/year to 13 μm/year are reported. For example, in Helsinki the rate is 1,3μm/year [29]. On the other hand, in Spain, a 20-year service life would be achieved in a rural environment by using the coating thickness specified by the company’s standard [30].

According to the information, it is hard to say if the used zinc layer is enough to last the 20 year life cycle requirement. Therefore, tolerances are adjusted so that the rust will not jam the structure and latch will remain serviceable even if it rusts.

6.2 Ratchet mounting

According to the current design analysis carried out in the chapter 5.2.4, a ratchet cannot absorb the ADR forces. It has been identified that easiest way to fix this is to increase the angle of the ratchet vertically. Angle can be increased by lowering the ratchet's lower mounting point by around 60mm. New mounting point is determined to be at the same line with the lift frame, which means it is moved forward.

The mounting point can be made in many ways. Drivers for mounting point ADR forces and cost efficiency. Cost efficient solution is a concept where amount of welding and the number of items is low. According to the drivers, the possibility of using bolt mounting is studied. However, it is noticed that a hydraulic pipe goes inside the compression frame and makes bolt mounting hard to make. The connection to compression frame shall be made therefore by welding.

Concepts for ratchet's lower mounting:

- U-profile welded to compression frame
- L-plate and straight plate
- Truck mounting bracket's plate extended + L-plate

U-profile concept's significant benefit is that it is very cost-efficient. The number of items is very low and manufacturing easy, which makes the concept cheap. However, strength-wise, it is not very viable option. Bends lower the strength of the structure and make the welding hard when the profile is positioned to the same level with compression frame's profile at the top.

The second, L-plate concept seems very viable strength and -cost -wise. The concept requires only two plates and welding is quite easy to compression frame in this option. The strength of this concept can be improved by having a wider top plate. Force is quite high to the lower mounting, which is why third concept is created. The third concept is the same as second apart from that the top plate is replaced with an extended truck mounting bracket's top plate. This will improve the bending stiffness and reduces the number of parts.

In the figure 32 can be seen the FEM calculation results of the ratchet mounting concept when the force of load case 4 is applied. Calculations reveal that there is a critical area at L-plates lower welding area. High stresses are highest at the welds seam and exceed the tensile strength of the material. The shaft experiences quite high bending stress, which needs to be lower as well.

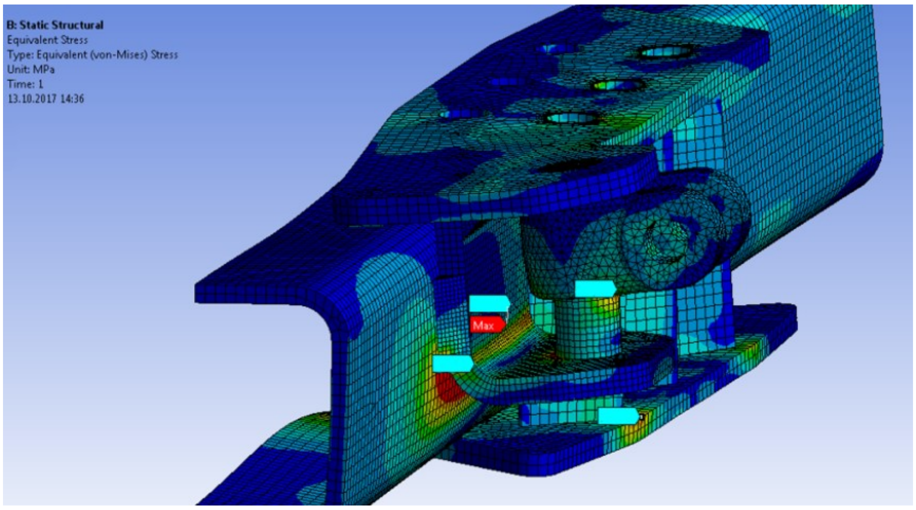


Figure 32. *Load case 4: Upward, First iteration*

To lower high stresses, bending of the structure needs to be lowered. As a solution, reinforcement plates, which are attached to the L-plate's sides, are added. To lower the bending of the shaft, we will shorten it. In the first version, the shaft is clearly unnecessary long, which causes high bending stress to the shaft. After these changes, a FEM analysis is carried out again. The results of the second calculation show that critical stress areas have now moderate stresses and strength of the structure is sufficient now.

In the figure 33 can be seen the final design of the ratchet mounting. To ease the assembly for welding, positioning holes were added also. This accelerates the welding process, which reduces costs.

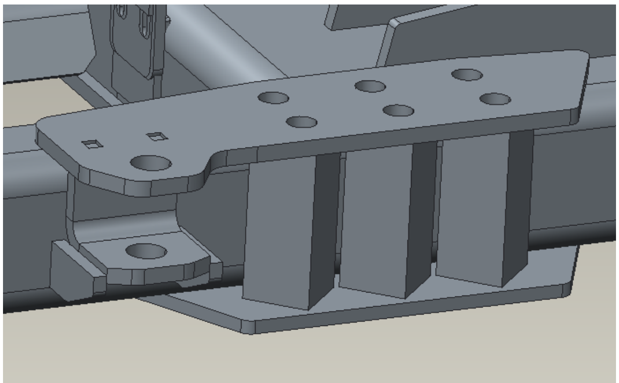


Figure 33. *Final design of the ratchet mounting*

6.3 Lower lock of lift frame and twistlock

The lower lock was not analyzed earlier because it was identified that the mounting position is not currently viable. Now, when the design for ratchet's mounting is done, we can move to the strength analysis of lower lock. For the connection between the lower lock and the ratchet, we use twistlock, which was presented earlier. The load of the analysis is based on the load case 4, which is considered as the most critical case.

The first calculation gives us results that can be seen in figure 34 below.

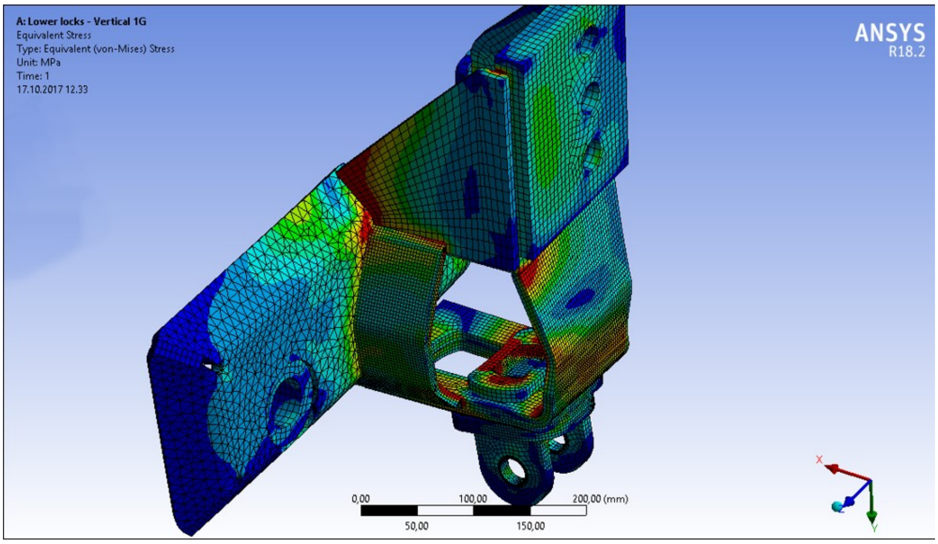


Figure 34. *Initial design under load case 4 forces*

As can be seen, the lower lock and twistlock both consist critical areas. The strength of the lower lock has a couple of weak points and some kind of reinforcement is definitely necessary to be done for the structure. Twistlock seems also quite critical. Especially the top plate and its welding seems to experience high stresses. The structure of the lower lock is open, which is the reason why the structure is rather flexible and a lot of bending occurs. Reducing bending of the lower lock is possible to do by widening the current reinforcement plate and by adding one on the opposite side as well.

To improve the strength of the twistlock, we must increase the stiffness of the top plate. Stiffness can be increased by adding material either by increasing the thickness of the plate or by changing the shape of the hole inside the plate, or by using higher strength steel. The table 8 below shows how changing the shape of the hole to a round 36mm diameter hole would affect the stiffness over the distance. Currently, the width of the hole is 36,5mm but it is not round shape so the results are comparable.

Table 9. *Section modulus comparison of top plates*

	Section modulus W (mm^3)		
	Current (t=12mm)	**Concept (t=12mm)**	**Delta W**
Middle plane	564	576	2,1 %
Offset 10mm	564	2004	255,3 %
Offset 15mm	564	2673	373,9 %
Offset 20mm	4000	4000	0,0 %

According to the table, the stiffness increases significantly if a plate with a circle hole is used. The idea behind the hole is that the shaft goes through which will, in addition to the plate geometry, increase the stiffness of the whole top plate assembly's structure.

Using higher strength steel as a top plate material for twistlock is not chosen since the welding properties suffer from it. Preheating requirement for welding would increase the manufacturing costs and narrow possible manufacturer selection. Also, S500 steel is already used, which has rather high strength compared to the traditional S355 structural steel.

For next iteration, following changes are made:

- Top plate changed to 15mm thick and hole shape has been changed round
- A plate added to lower lock and the existing reinforcement plate extended

FEM analysis shows that improvements were effective. Stresses in the whole lower lock structure reduced significantly. Neither of the reinforcement plates has high stresses anymore. The only critical area is left to the lower plate that has a twistlock hole. This area will still need redesigning.

Twistlock strength has improved significantly. The structure seems rather good apart from the top plate, which still has too high stresses. Stress level has reduced considerably at the weld, which confirms that the current hole solution is much better strength wise.

Figure 35 below shows the final design of the lower lock. As can be seen, major change is that the reinforcement plate has been added to the back side and plate on the front has been extended.

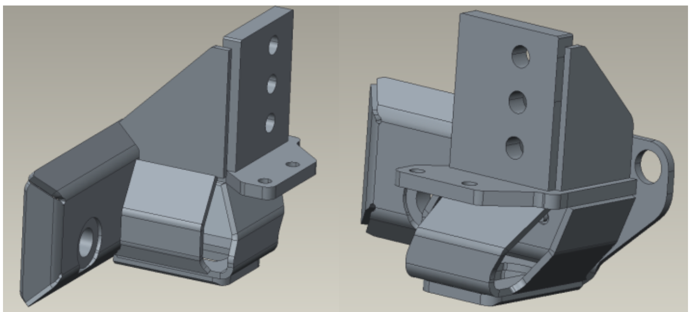


Figure 35. *Final design of the lift frame's lower lock*

Figure 36 illustrates the final design of the twistlock. The top plate is finally 20mm thick, which is 8mm thicker than in the original design. The shape of the hole has been modified to round.

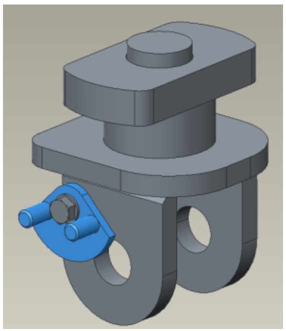


Figure 36. *Final design of the twistlock*

With this design, the twistlock has adequate strength and is strong enough to absorb loads required by the ADR.

6.4 Truck mounting bracket and DIN lock

The rear truck mounting bracket was replaced with a new one, which is now at the same level with the bracket in the front. The design is already in use in another variant of DROPS. The most critical load cases for the din locks are load case 6 and 8, which are the 2G forward and 1G sideward. According to the FE analysis, the structure is capable of absorbing the forces in both load cases but plastic deformation is expected in the bolt, which is most rear and in the mounting plate. In figure 37 can be seen the FE analysis of the structure. Detailed view reveals that in one of the bolts the stress level exceeds the yield strength of it. According to the linear analysis tensile strength is exceeded only locally and not over the thickness of the bolt. For more detailed stress calculation, a nonlinear analysis would be required.

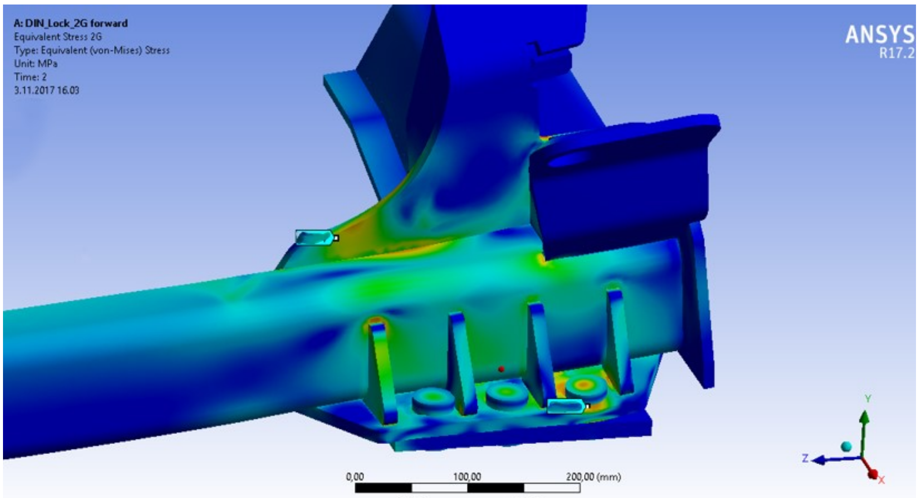


Figure 37. *Load case 6: 2G forward*

Even though plastic deformation is expected, the structure is capable of absorbing the force. According to the linear analysis, it can be said that the stress level will not exceed the tensile stress over the thickness and the structure will be capable of absorbing the force. In the previous analysis, the U-beam was experiencing high stress as well, now it seems that the stress level is moderate in the U-beam and no actions are required concerning it. Figure 38 shows the new structure of the truck mounting plate.

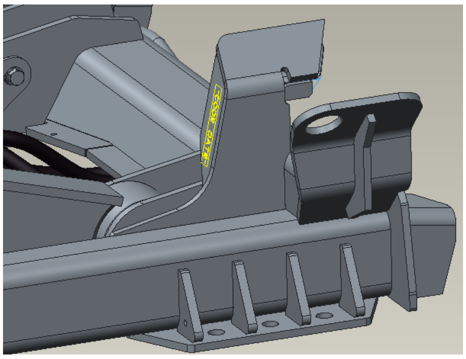


Figure 38. *New mounting bracket*

7. REVIEW OF RESULTS

As the result of product development process, the hooklift is now ADR compliant, it has a safety latch and it is interchangeable with the older DROPS hooklifts and CHUs. ADR affected the most to the design and it can be considered as the biggest driver behind the improvements. Overall, the product development process succeeded pretty well. New design solutions fulfilled the product requirements quite well and the final design solutions seemed viable. Validation of the design is not completely done yet and so it remains as a task for the future.

New design was made to the following objects:

- Lower locks of the lift frame
- Twistlock
- Ratchet mounting
- Safety latch
- Truck mounting bracket

Lower locks of the lift frame were reinforced and the biggest change was that a reinforcement plate was added to the structure. Reinforcement plate made the structure closed, which improved significantly the strength of the structure. However, the closed structure worsened the accessibility to weld all the plates from inside as well. Cost wise, any significant changes did not occur.

The design of the ratchet mounting bracket changed significantly. The new bracket has a new approach compared to the old ones in a way that it is not detachable. By not having a detachable bracket, it was possible to minimize the number of parts to the minimum. In addition, design parameters were able to be reduced. Cost wise this is a very efficient way since the manufacturing cost is rather low and it enables easier retro fitting possibility.

The strength analysis of twistlock revealed issues in the original design of the lock. According to the FE analysis, high stresses occur in the top plate and in the welds of the structure. In order to reduce the stresses in the welds enough, the shape of the holes where welds are was changed to a normal hole. The shaft was extended so that it went all the way through to the holes and welds were moved that way away from the area that experienced most bending. The top plate thickness was also increased to increase the section modulus.

The outcome of the actions resulted in a viable solution. The strength of the structure increased significantly and it can now handle the ADR loads. The weight of the new twistlock increased by 35%, which was not desired aspect but necessary since the interchangeability was retained by using these twistlocks. Weldability of the structure suffered slightly from the modification. The weld around the shaft and the weld for the “legs” of the twistlock will clash a little. In addition, the shaft reduces the space that is available for fitting the electrode near the seam.

The complete ratchet module overall was replaced with a new one. According to the estimations, the cost compared to the former module would lower by 25%. The ratchet module includes a new ratchet, a new lower mounting bracket, a new twistlock interface and a new ratchet holder during the transportation mode.

The new safety latch design ended up to be simple and manually operated as desired. The concept got overall the highest score in AHP since it did not have low points on any criterions. Therefore, it was logical to select it as the concept for further development.

Other potential concepts for the safety latch were a detachable latch, gravity assisted latch, a securing chain or cable and pneumatic safety latch. The pneumatic latch got second highest points. The reason is that ease of use was ranked quite high and the pneumatic latch was clearly all the way easiest to use compared to any other latch. However, the pneumatic latch was excessively too expensive to implement and design, which was finally the reason that it did not come into consideration selecting it.

The securing cable or chain concept got also quite high total points. However, it got unnecessary high points since it was so much cheaper and simpler than any other concept. Nevertheless, since the safety of it was not that good it came not in consideration to select. In addition, the concept would not look very professional. Professional look could have been also one of the criterions in the AHP. It would have then described better the desired traits from the latch.

For the selected concept, any extra features were not designed as the main drivers behind the design was low costs. Modifications to the current hook were avoided as much as possible as well. Finally, only three holes were added to the hook for the safety latch mounting and any shape modifications were not made. A prototype from the concept was build and it was tested in use. Testing confirmed that concept was a viable solution. However, according to prototype testing, it is hard to know how corrosion will effect on the structure over the time. The structure has rather loose tolerances, which should help that the latch is not so sensitive to jamming due the corrosion, but on the other hand, loose tolerances can make the structure more fragile and sensitive to hits. Especially the other side latch will be more sensitive to collision because of the loose tolerances. Nonetheless, the testing showed the latch does not experience such hits and collisions that often that it should be an aspect to be concerned of.

For the future, customer feedback should be gathered of the latch. Especially the locking system behavior over the time and hits is an interesting an aspect. Other future tasks remain to be validation of manufacturability of each improvement and validation of them working in the real environment. For example, the ratchet mounting bracket that is used while ratchets are not in use has not been tested in the real environment. It is not completely clear if the ratchet can be operated conveniently with the current dimensioning. A possible improvement to the ratchet would to replace the tightening rod of the ratchet to a different kind of rod. For space saving purposes, a rod that goes through to the center tube and can be switched from the side to another would be convenient solution to be used.

8. CONCLUSIONS

The objectives of this thesis were to fulfill product requirements and to clarify the meaning of ADR in context of hooklifts from the mechanical point of view. The product requirements in the framework of this thesis consisted of three basic requirements: interchangeability, ADR compliancy and safety latch. In order to fulfill them and to perform efficient product development, Design for Six Sigma principles were chosen to be used to achieve it.

ADR regulations required clarification as there had been several different interpretations of them over the years in the case company. The ADR regulations does not directly refer in any section to hooklifts but only to twistlock secured demountables or fixed type tanks and their fastenings. Therefore, there had been several interpretations of the requirements. During the research, it was found that Norway had noticed the same ambiguity concerning hooklifts and the government of Norway had made a proposal to clarify the ADR.

The product development work in this thesis consist of four parts. First, the product requirements that create the framework for the design were determined. In the second phase the current state of design were analyzed. Target of the analysis was to find out whether the current state of design fulfilled the product requirements or not. After that, improvements were done to the elements that required it and evaluation was carried out again. After requirements were fulfilled, optimization was carried out to the design elements to create even better quality and cost-efficient design.

DFSS principles and tools could be utilized to support the product development process quite well. All the product requirements and their relation to design tasks were modelled by using QFD to analyze their relationships. The relative importance levels of design tasks could be evaluated with the QFD and the most significant and critical design elements could be identified. In safety latch concept design phase, innovating tools such as brainstorming and benchmarking were used in order to create safety latch concepts. Finally, the decisions were made with assistance of AHP, which provided rational comparison results according to the determined criterion. After selection, the chosen concept was transferred to real design and prototype testing and optimization actions were carried out.

All in all, the product requirements within the framework were fulfilled well. Facelifted MPH165 is now mechanically ADR compliant, interchangeable with the older equipment and equipped with a safety latch. Since complete validation of the design could not been carried out within the time frame, it remains as a future task. Feedback from the manufacturers and customers will provide the final evaluation of the design quality. In the future, DFSS tools such as QFD could be utilized in the upcoming projects in the case company. By utilizing QFD, potential to better customer satisfaction and more efficient usage of resources could be achieved.

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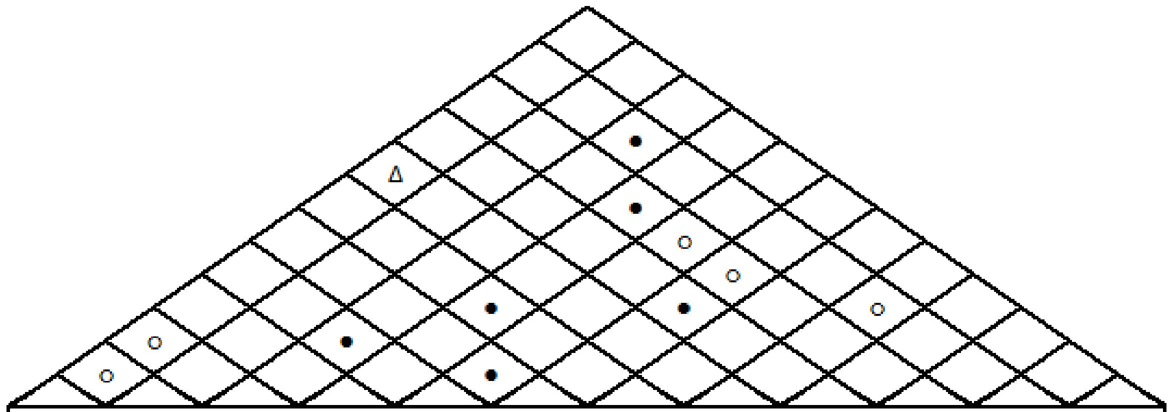
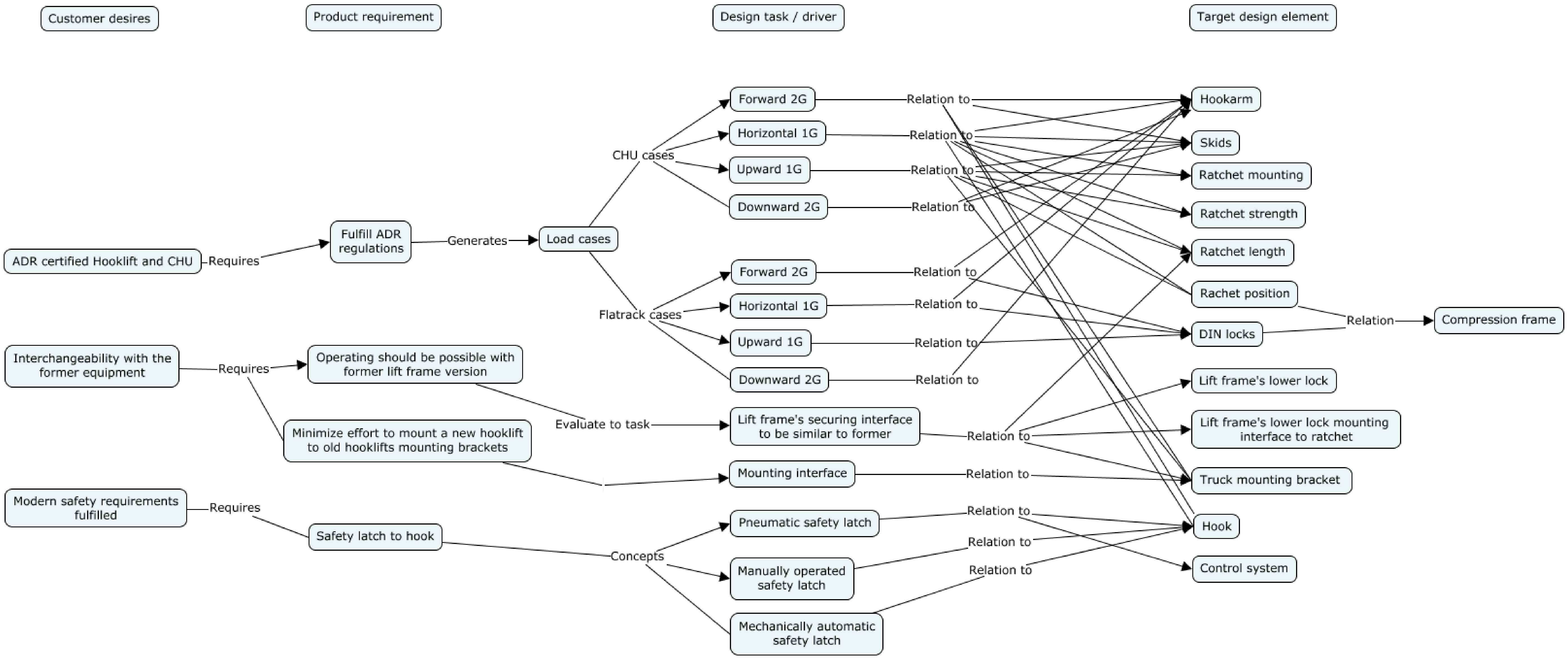
APPENDIX A: HOUSE OF QUALITY

Relation level 9-3-1		
●	9,0	Strong
○	3,0	Moderate
Δ	1,0	Weak

↑	Maximize
↓	Minimize



		Importance to coefficient	Relative importance	Hookarm strength	Hook	Skids strength	Ratchet strength	Ratchet length	Ratchet's mounting position	Srength of ratchet's mounting to compression frame	DIN lock's strength	Lift frame's lower lock strength	Lower lock's mounting interface with ratchet	Truck mounting bracket strength	Control system
				Design objects											
	Product requirement	Scale 0-5	%	↑	x	↑	↑	↓	x	↑	↑	↑	x	↑	x
CHU load cases	Absorb forward 2G	5,0	11,90 %	●	○	●								○	
	Absorb horizontal 1G	4,0	9,52 %			●	●	Δ	○	●		●	○		
	Absorb upward 1G	4,0	9,52 %			●	●	Δ	●	●		●	●	○	
	Absorb downward 2G	1,0	2,38 %	○	Δ	●								Δ	
Flatrack load cases	Absorb forward 2G	5,0	11,90 %	Δ							●			●	
	Absorb horizontal 1G	4,0	9,52 %	Δ							●				
	Absorb upward 1G	3,0	7,14 %								●				
	Absorb downward 2G	1,0	2,38 %	○	Δ	●								Δ	
	Interchangeability with old DROPS	5,0	11,90 %	Δ	○	○		●	●	Δ		●	●	○	
	Safety latch	5,0	11,90 %	Δ	●										○
	Manufacturing price	5,0	11,90 %	●	Δ	○	Δ	Δ	Δ	Δ	○	○	○	○	●
	Impotance of the engineering attributes	42	100 %	2,7	2,0	3,9	1,8	1,4	2,3	2,0	2,9	3,1	2,6	2,5	1,4
	Relative importance of attributes			9,6 %	6,8 %	13,7 %	6,4 %	4,8 %	8,1 %	6,8 %	10,2 %	11,0 %	9,0 %	8,6 %	5,0 %
	Importance level (1-5)			4	3	5	3	2	3	3	4	4	4	4	2

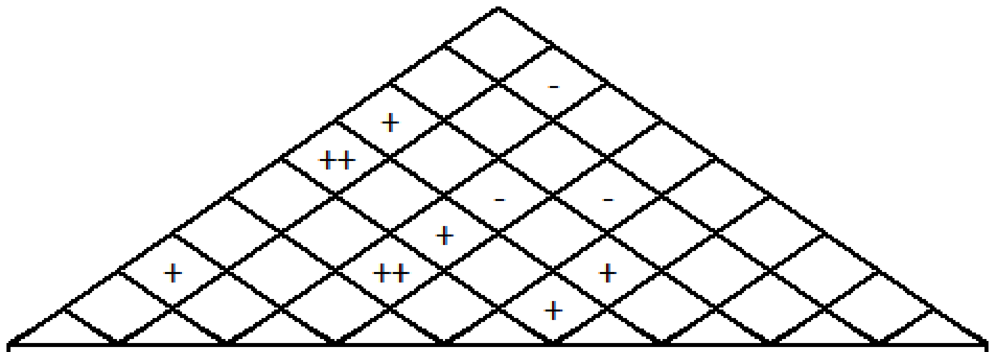


Customer desires
Product requirement
Design task / driver
Target design element
ADR certified Hooklift and CHU
Requires
Fulfill ADR regulations
Generates
Load cases
CHU cases
Forward 2G
Horizontal 1G
Upward 1G
Downward 2G
Flatrack cases
Forward 2G
Horizontal 1G
Upward 1G
Downward 2G
Relation to
Hookarm
Skids
Ratchet mounting
Ratchet strength
Ratchet length
Rachet position
DIN locks
Relation
Compression frame
Interchangeability with the former equipment
Requires
Operating should be possible with former lift frame version
Minimize effort to mount a new hooklift to old hooklifts mounting brackets
Evaluate to task
Lift frame's securing interface to be similar to former
Mounting interface
Lift frame's lower lock
Lift frame's lower lock mounting interface to ratchet
Truck mounting bracket
Modern safety requirements fulfilled
Requires
Safety latch to hook
Concepts
Pneumatic safety latch
Manually operated safety latch
Mechanically automatic safety latch
Hook
Control system

Correlations	
++	Strong positive
+	Medium positive
-	Medium negative
--	Strong negative

Relation level 9-3-1		
●	9,0	Strong
○	3,0	Moderate
Δ	1,0	Weak

↑	Maximize
↓	Minimize



		Importance to coefficient	Relative importance	Material	Surface treatment	Weight	Amount of parts	Latch size	Latch's yield strength	Latch thickness	Locking pin locking method	Tolerance level
				Design objects								
	Customer needs	Scale 0-5	%			↓	↓	↓	↑	↓		↓
Operational	Easy to operate	5,0	14,29 %			○	Δ	●		○	●	
	Good reliability	4,0	11,43 %		○		○		○		○	●
	Good durability	3,0	8,57 %	○	○						○	○
			0,00 %									
Manufacturing	Easy to assemble	3,0	8,57 %			Δ	○	○			○	○
	Low number of parts	3,0	8,57 %				●				○	
	No shiny color	4,0	11,43 %	Δ	●							
			0,00 %									
Other	Low costs	5,0	14,29 %	○	○	Δ	○	Δ	Δ	Δ	○	○
	Looks and feels professional	4,0	11,43 %	○	●	○		○		○	●	○
	Does not jam because of rust	4,0	11,43 %		●	Δ		Δ		Δ	○	●
	Impotance of the engineering attributes	35	100 %	1,1	4,1	1,1	1,9	2,1	0,5	1,0	4,2	3,3
	Relative importance of attributes			5,9 %	21,1 %	5,7 %	10,0 %	11,0 %	2,5 %	5,3 %	21,5 %	17,1 %
	Importance level (1-5)			2	5	2	3	3	1	2	5	4

APPENDIX B: AHP MATERIAL

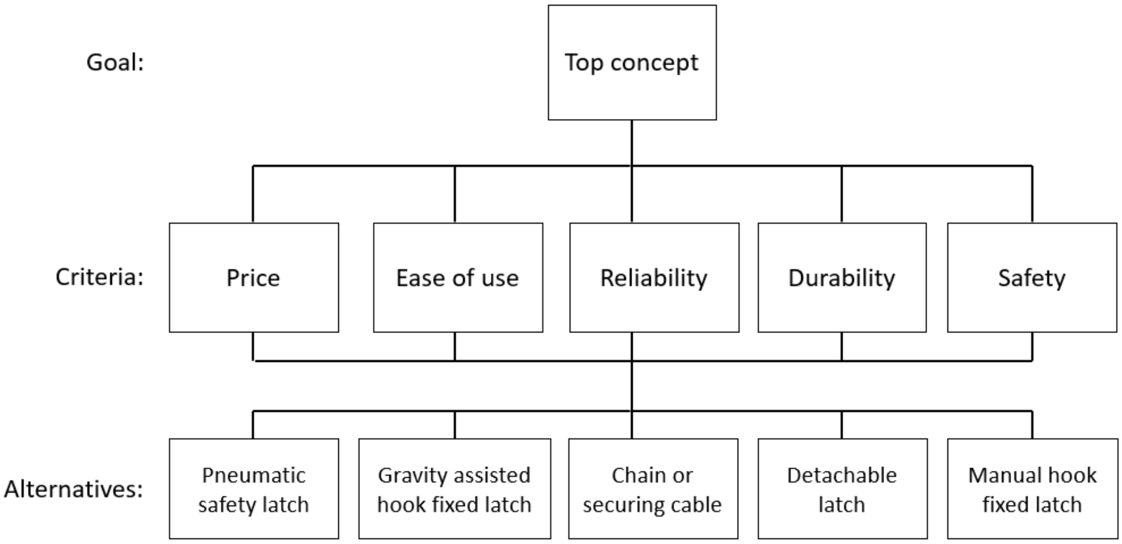


Figure 1: Shows hierarchy of AHP analysis

Table 1: Symbols used in the criteria matrices

A	Manufacturing price
B	Ease of use
C	Durability
D	Simplicity
E	Safety

	Absolutely More Important		Very Strongly More Important		Strongly More Important		Weekly More Important		Equally		Weekly More Important		Strongly More Important		Very Strongly More Important		Absolutely More Important	
	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	
A								2										B
A					5													C
A					5													D
A										1/2								E
B					5													C
B				6														D
B									1									E
C											1/3							D
C											1/3							E
D										1/2								E

Figure 2: Matrix of criteria

Table 2: Symbols that are used in the figure 3-7

A	Pneumatic latch
B	Gravity assisted
C	Chain or securing cable
D	Detachable latch
E	Manual hook fixed latch

	Absolutely More Important		Very Strongly More Important		Strongly More Important		Weekly More Important		Equally		Weekly More Important		Strongly More Important		Very Strongly More Important		Absolutely More Important	
	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	
A															1/7			B
A															1/7			C
A														1/6				D
A														1/6				E
B													1/5					C
B											1/3							D
B												1/4						E
C							3											D
C								2										E
D										1/2								E

Figure 3: Matrix of manufacturing price

	Absolutely More Important		Very Strongly More Important		Strongly More Important		Weekly More Important		Equally		Weekly More Important		Strongly More Important		Very Strongly More Important		Absolutely More Important	
	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	
A								2										B
A	9																	C
A	9																	D
A			7															E
B				6														C
B		8																D
B			7															E
C								2										D
C												1/4						E
D															1/7			E

Figure 4: Matrix of Ease of use

	Absolutely More Important		Very Strongly More Important		Strongly More Important		Weekly More Important		Equally		Weekly More Important		Strongly More Important		Very Strongly More Important		Absolutely More Important	
	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	
A										1/2								B
A												1/4						C
A															1/7			D
A														1/6				E
B											1/3							C
B															1/7			D
B														1/6				E
C										1/2								D
C								2										E
D							3											E

Figure 5: Matrix of durability

	Absolutely More Important		Very Strongly More Important		Strongly More Important		Weekly More Important		Equally		Weekly More Important		Strongly More Important		Very Strongly More Important		Absolutely More Important	
	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	
A														1/6				B
A																	1/9	C
A															1/7			D
A														1/6				E
B													1/5					C
B												1/4						D
B										1/2								E
C							3											D
C						4												E
D								2										E

Figure 6: Matrix of simplicity

	Absolutely More Important		Very Strongly More Important		Strongly More Important		Weekly More Important		Equally		Weekly More Important		Strongly More Important		Very Strongly More Important		Absolutely More Important	
	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	
A							3											B
A			7															C
A										1/2								D
A										1/2								E
B					5													C
B										1/2								D
B											1/3							E
C												1/4						D
C															1/7			E
D									1									E

Figure 7: Matrix of safety

Table 3: Weights of the criterion and alternatives

	Manufacturing cost	Ease of use	Durability	Simplicity	Safety
Weights	**0,310277**	**0,273514**	**0,052864**	**0,089586**	**0,273758**
Pneumatic latch	0,035323	0,509227	0,046756	0,030184	0,226568
Gravity assisted	0,108830	0,308735	0,063461	0,096323	0,124477
Chain or securing cable	0,403456	0,047043	0,240027	0,483865	0,040936
Detachable latch	0,177234	0,027362	0,433363	0,245109	0,280479
Manual hook fixed latch	0,275157	0,107633	0,216394	0,144519	0,327539

Table 4: Global evaluation results of the weights

	Manufacturing cost	Ease of use	Durability	Simplicity	Safety	Global evaluation
Pneumatic latch	0,01096	0,13928	0,00247	0,00270	0,06202	0,21744
Gravity assisted	0,03377	0,08444	0,00335	0,00863	0,03408	0,16427
Chain or securing cable	0,12518	0,01287	0,01269	0,04335	0,01121	0,20529
Detachable latch	0,05499	0,00748	0,02291	0,02196	0,07678	0,18413
Manual hook fixed latch	0,08537	0,02944	0,01144	0,01295	0,08967	0,22887

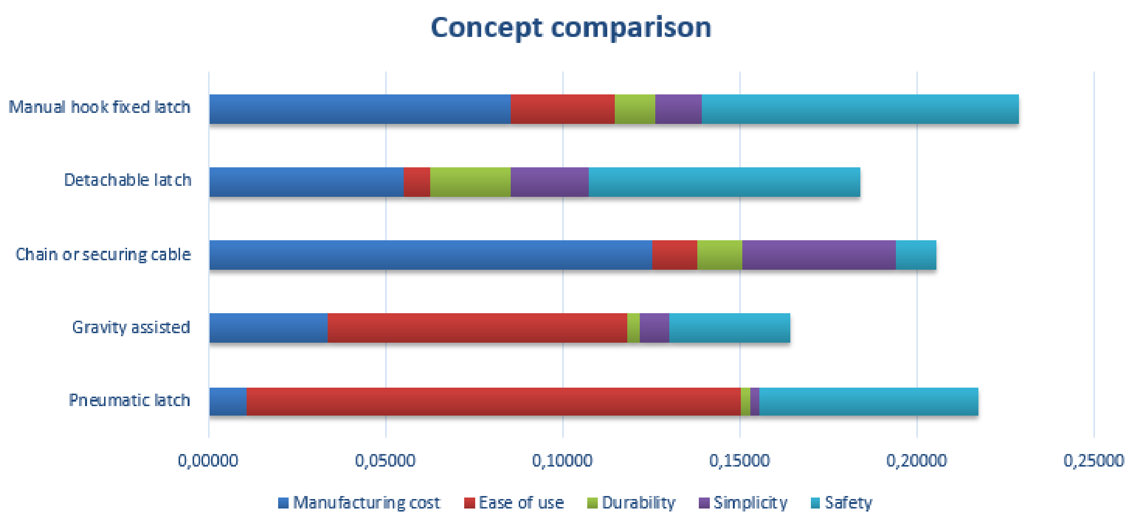


Figure 8: Global evaluation results graphically presented