NTNU
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Develop a lifting and handling tool that enables weight savings on subsea xmas trees

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Sammendrag av Bacheloroppgaven

Tittel:	**Utvikling av løfteverktøy som muliggjør vektbesparing av et subsea juletre**
Dato:	20.05.2019
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Nøkkelord:	Produktutvikling, subsea, løfteoperasjoner, vekt og kostbesparing
Antall sider:	65
Antall vedlegg:	10
Tilgjengelighet:	Åpen

Sammendrag: Hensikten med bacheloroppgaven er å kunne fjerne behovet for motvekter på et subsea juletre. Imidlertid vil en slik fjerning resultere i et skjevløft av juletreet, noe som ikke er akseptabelt. Målet ble dermed å utvikle et løfteverktøy som kan kompensere for skjevheten. Resultatet ble et løfteverktøy som kan løfte utenfor senter, hvor løftepunktet kan forskyves ved hjelp av en skrue og plasseres over tyngdepunktet. Denne løsningen på problemstillingen muliggjør å løfte juletreet horisontalt selv om motvektene er fjernet, og dermed gjør det mulig å spare penger og vekt på et subsea juletre. I tillegg til dette ble det også utviklet et konsept for et løfteverktøy som kan brukes for å installere eller trekke juletreet offshore.

Summary of Graduate Project

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Abstract:

The purpose of the bachelor thesis is to remove the need of counterweights at a subsea xmas tree. However would such a removal result in a tilted lift of the XT, which is not acceptable. The main objective was thereby to develop a lifting tool to compensate for this. The result was an off center lifting tool, where the lifting point can be displaced by a screw and placed above center of gravity. This solution would result in a level lift due to the counterweight removal and enable both weight and cost savings to the xmas tree. In addition to this, a concept for a xmas tree running tool was made. This tool is dedicated for installing and retrieving of xmas trees from the seabed.

Preface

This is a technical report which describes the product development of a lifting tool, dedicated for lifting and handling of various types of subsea Xmas Tree (XT). This lifting tool, named as Xmas Tree Handling Tool (XTHT), enables both weight and cost savings to the XT. The report is conducted as a bachelor thesis in mechanical engineering field, at the Product and System Design programme, NTNU in Aalesund. The development of the XTHT is a request from Aker Solutions, which is the collaborative partner in the project.

The report covers the whole development process, as well as a business case which reflect potential weight and cost savings for Aker Solutions.

We would like thank our supervisor at NTNU Aalesund, Lars Petter Bryne, which have provided the students with instructions and helpful advice.

We would also like to thank Aker Solutions and all the personnel which have been involved in the project. We would thank Aker Solutions for providing us with a PC with our own mail address, Skype account and fully access to their internal system. This enabled easy collaboration, even though the students was located in Aalesund and Aker Solutions in Tranby. We would like to thank all involved personnel, for providing us with technical guidance at their applicable field.

We would thank our supervisor at Aker Solutions, Sverre Olsen and Daniel Vik Skogen. First of all, for creating this interesting task and giving us the opportunity. Secondary, a special thanks to Sverre Olsen which have been available throughout the whole period. He has helped us in a professional manner and guided us to the correct personnel when necessary.

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Glossary

Flow Control Module As the name implies, the FCM is provided with different equipment to monitor and control the flow from the well. This is mainly an adjustable choke valve, Multiphase flow meter [MPFM] and sensors to monitor pressure, temperature, amount of sand in the flow, leakage etc. Common for many of these, especially the choke valve, is that they get worn out over the years. Hence, this control equipment is placed on a replaceable module. 14

H4 profile The H4 profile is a locking and sealing interface towards different tools that are relevant to this connection. The H4 profile is located at the top of the spool. The H4 profile exists in many sizes, but the most common size and which is relevant for this thesis, is 18-3/4" at inner diameter. See section 5.2 for further details. 17

spool The spool is the pipe that extends above the XT roof. The H4 profile is located at the top of the spool. 5, 6, 17, 47, 62

Subsea Control Module The SCM is basically the communication center between the topside operator and the subsea XT. The SCM receives and sends fiber optical signal through a cable (umbilical). By this communication, controlling of valves and monitoring of different sensors are possible. In case of failure of the SCM, the valves at the XT shuts down, and in some cases, the SCM needs to be retrieved and replaced/maintained to restart production. 14

wellhead Top of the well and connection point towards the XT. Has a 18-3/4" H4 profile. 5

Acronyms

3D CAD 3-dimensional computer-aided design. 7

CAD Computer-aided design. iv, 7

COG Center Of Gravity. viii, 6, 22, 29, 31, 46

COM Center Of Mass. 6

CW counterweights. 1–3, 6, 9, 17, 19

DOF Degree Of Freedom. 26

FCM Flow Control Module. 15, 22

FEA Finite Element Analysis. 7

FPSO Floating Production, Storage and Offloading. 4

HSE Health, Safety and Environment. 9

HXT Horizontal Xmas Tree. 22, 35

LTRT Light Tree Running Tool. 55

MVB Master Valve Block. 62

ROV Remotely Operated Vehicle. 4, 15, 24, 25

SCM Subsea Control Module. 15, 22

SW SolidWorks. 22, 29, 34

TRT Tree Running Tool. iv, viii, 2, 7, 11, 13, 15–17, 19, 24, 25, 36

VXT Vertical Xmas Tree. 34

WLL Working Load Limit. 14, 15

XT Xmas Tree. iii, 1, 2, 4, 6, 9, 17, 19, 28, 46

XTHT Xmas Tree Handling Tool. iii, 1, 2, 5–7, 11, 36–38, 55

1 Introduction

1.1 Purpose and background

The purpose of the bachelor thesis is to remove the need of counterweights (CW) on a subsea Xmas Tree (XT). This is a request from Aker Solutions, as such a removal would result in both weight and cost reduction on every XT they manufacture.

The CW's are today used to balance the XT. They result in level lift of the XT, which is important in order to proper enter the XT's different interfaces and to secure safe lifting operations.

The terminology regarding subsea technology and XT's are further explained in the report. Figure 1 shows a XT and its counterweights.

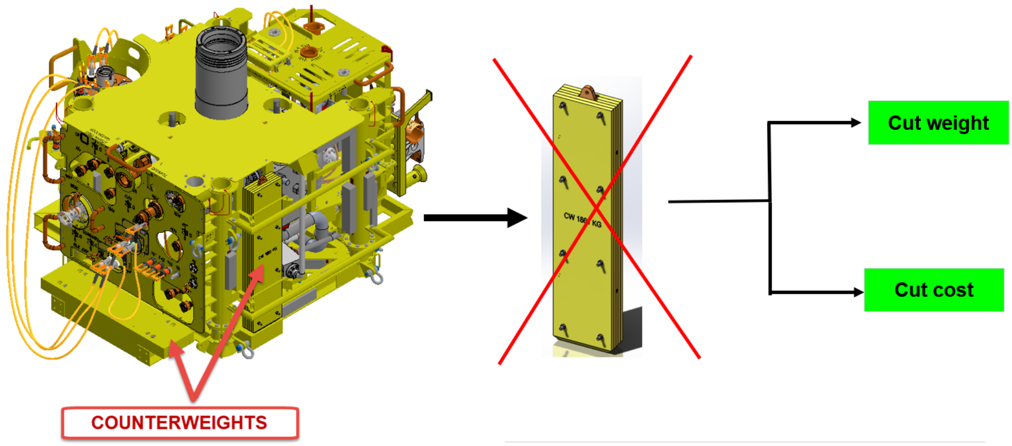


Figure 1: Purpose of CW removal

1.2 Thesis problem

The XT is lifted with a Xmas Tree Handling Tool (XTHT), which is a tool dedicated to lift and handle the XT's from a single lift point. The counterweight removal will result in an angulation of the XT during lifting, which is not acceptable. Aker Solutions wants to restore the balance by utilizing a XTHT which could compensate for the tilt. The thesis problem thereby becomes to see if this is possible, in a safe and user friendly manner.

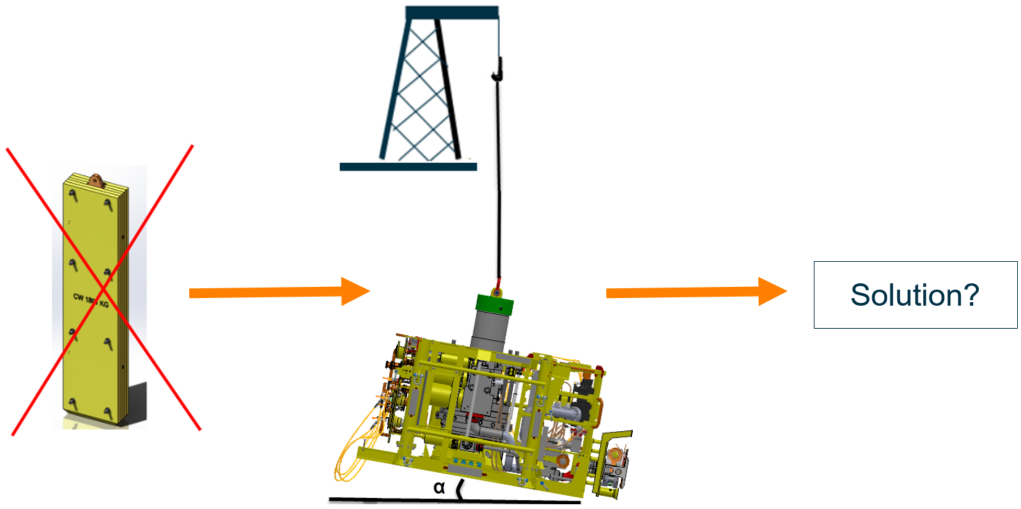


Figure 2: Thesis problem

1.3 Thesis objectives

The first objective of thesis is to find a solution to the thesis problem and perform a detailed design of the XTHT. The detailed design shall include a calculation report, product data sheet and manufacturing drawings.

Product development phases such as creating a design basis and conduct a concept phase are required before a detail design phase can begin. The following list describes the work which is required from Aker Solutions, before a detailed design development could start. The work is to be conducted in the given order.

1. Create a plan
2. Perform a business case study to estimate potential cost and weight savings.
3. Create a design basis/framework for the design
4. Conduct a concept phase, where all the ideas is documented.

The secondary objective is to create a concept for the Tree Running Tool (TRT) which could compensate for the CW removal. The TRT is a lifting tool used offshore, dedicated for installation and retrieval of XT's.

1.4 Outline

The thesis main points and structure are reflected in Table 1. The work is conducted in the given order of the topics.

Topic	Content	Purpose
Theory	- Subsea - Lifting - CAD	Covers basic theory in different subjects. This could be necessary for some readers and enhance their outcome and understandings of the reports content.
Plan		Show the planned time estimation and important goals/dates.
Business case	- Cost study - Pros & cons	To estimate potential weight and cost savings at different projects if the CW's are removed. To consider the general advantages and disadvantages due to a CW removal
Design basis	See appendix A	Framework for the design. Considers all lifting scenarios and limitations of the design.
Concept phase	- Locking - Level lift - Position verification - Anti-rotation	Brainstorming and searching of potential of solutions. Produce basic models and simple calculations to remove as much uncertainty as possible before concept selection.
Detailed design	See section 5.4.	Detailing of the selected concept. Details, calculations, manufacturing drawings, procedures etc. are made to verify the tools functionality and strength
Results		Summarize the results of the project
Discussion		Reflects the results, potential improvements and lists further work which is necessary before an implementation.
Conclusion		Provides a simple conclusion to the thesis problem.

Table 1: Thesis outline

2 Theory

The report covers disciplines and methods that could be unfamiliar to some of the readers. To follow the reports structure and intentions, the reader needs to possess basic understanding at some relevant subjects. This chapter covers basic theory at these subjects. If you are familiar with this, there is no need to read this chapter.

Note: The students were familiar with these subjects before the thesis was assigned.

2.1 Subsea technology

Subsea technology is processes or equipment in the oil and gas industry, that are situated or occurs beneath the ocean surface. The subsea technology produces oil and gas from units located at the seabed. The gas or/and oil are then transported in pressurized pipes to either onshore, existing platforms or a Floating Production, Storage and Offloading (FPSO).

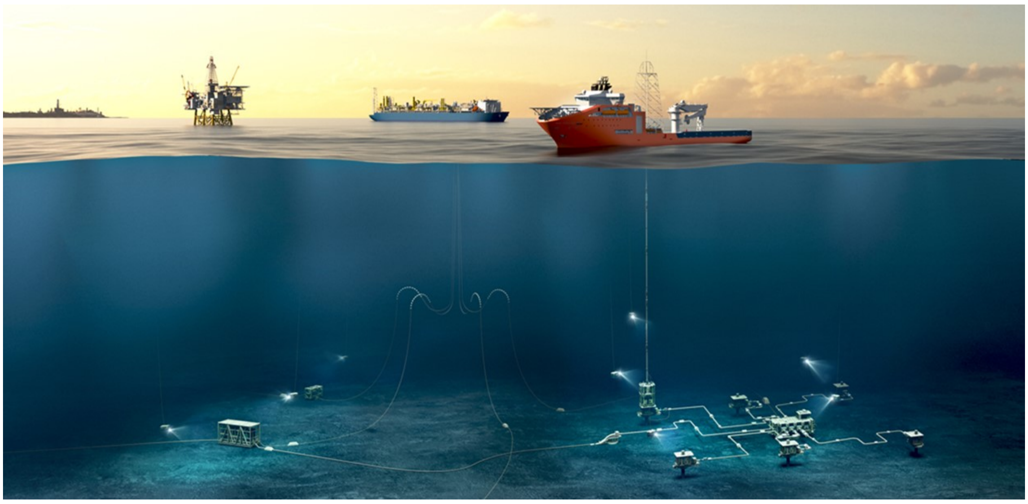


Figure 3: Overview of a subsea field, including a service vessel doing XT intervention, a FPSO and an existing platform (Source: Aker Solutions)

Subsea operations are most of all remotely operated from either onshore, a vessel or a existing platform. In some few cases, divers are involved in subsea operations, but mostly such assistance is today done by a Remotely Operated Vehicle (ROV), which is operated from a vessel or a rig.

The bachelor thesis enclosing a small area of the subsea technology. The hydrocarbons goes through a lot of different unites on its several kilometer long way from the reservoir to the its receiver. The XT is the first unit the hydrocarbons meet as they reach the seabed.

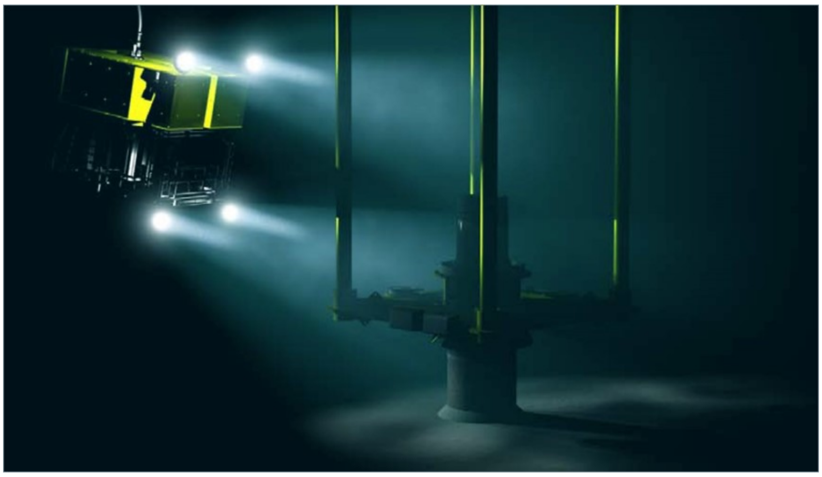


Figure 4: The figure shows a ROV and the wellhead (top of the well), before the XT is installed (Source: Aker Solutions)

Figure 5: XT mounted on the wellhead. The man is placed by the XT to give a size perspective (Source: Aker Solutions)

The XT is the control unit of the hydrocarbon production. The XT is connected to the wellhead, where it controls and monitors the production by its valves and sensors. The production crew communicates and controls the XT through an umbilical (cable), which consist of fiber optic cables and hydraulic supply lines. The XT is suited with a ROV panel, which allows the ROV to override the XT in case of intervention, installation/retrieving of XT or to function as back-up in case of emergency.

As explained in chapter 1, the bachelor thesis objective is to find a solution to perform level lifting of the XT without the use of counterweights. The most preferred lifting point is the green pipe centered at the top of the XT, referring to Figure 5. The pipe is called the spool and is also the attachment point for the current XTHT. The terminology regarding this tube is explained in the glossary, and is frequently used throughout the report.

2.2 Lifting

Lifting and lifting theory is a central subject in this report. The general operation of lifting is hazardous, as the consequences could be fatal if something goes wrong. Therefore, this thesis are based on strict standards and Aker Solutions lifting policy, which are explained more closely in section 5.2

To perform a level lift of the XT is crucial in many scenarios. The importance of this is explained more closely in section 5.2. A central term regarding level lifting and lifting in general, is Center Of Gravity (COG). The COG is an geometric property or point where the total weight of a any structure or body may thought to be located. Regarding the bachelor thesis, this point is useful when it comes to static calculations and designing of the XTHT, as the gravitational force of the complete XT assembly will act at this point.

Note: Another term is Center Of Mass (COM), which is typical preferred by physicists. To eliminate all confusion, COG and COM would have the same geometric location at an object if the object is placed in a uniform gravitational field [1]. In other words, these points are similar since the work of this thesis take place in the earths gravitational field.

To perform a straight lift without any relative motion between the lifting point and the lifted object, the lifting point has to be located above COG. As explained in section 2.1, lifting from the spool is preferred, and to lift the XT (w/o CW) horizontally from this point could thereby be done in two ways:

1. Displace the COG to its desired position by the use of CW at XTHT.
2. Lifting above COG.

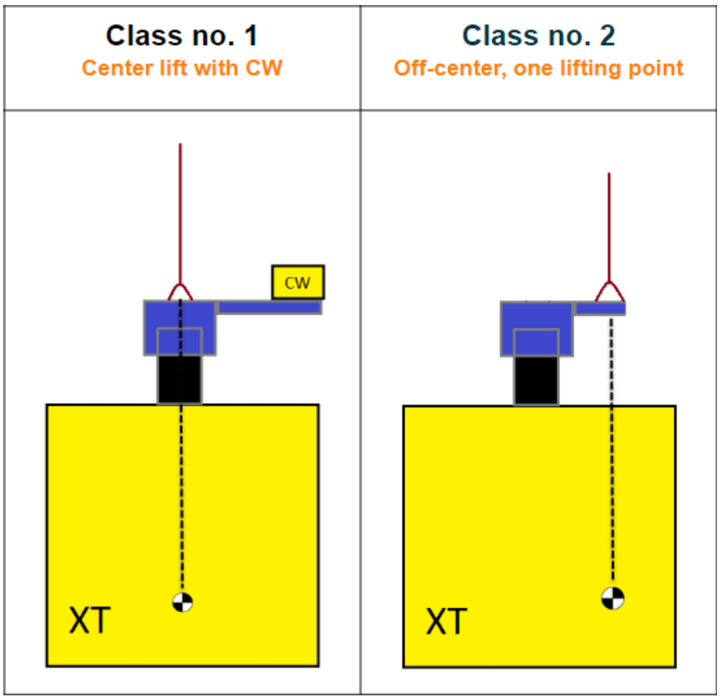


Figure 6: The figure shows the lift types explained in the enumeration above. Lifting in center and off-center from the spool.

2.3 3D CAD software

Throughout the product development of both XTHT and TRT, Siemens NX is the 3-dimensional computer-aided design (3D CAD) software used for both 3D modelling and Finite Element Analysis (FEA). 3D CAD is a technology that enables product developers and engineers to perform design, test and document three-dimensional objects [2].

This section gives a simple description of 3D modelling and FEA, to give potential readers some basic knowledge of this field.

2.3.1 3D modelling

Using the 3D modelling application of Siemens NX allows the designer to create 3D digital representations of objects. With such a 3D model, the designer could do clearly representations of the product and prepare it for further work, such as simulations, creation of photo-realistic images, manufacturing drawings and 3D printing [3].

Regarding the bachelor thesis, product development of the XTHT and TRT requires frequently usage of the 3D modelling application in Siemens NX, especially in section 5.3 (Concept phase) and section 5.4 (Detail design of XTHT).

2.3.2 Finite element analysis

Using the FEA application of Siemens NX allows the designer to perform structural or performance analysis of a product or a system in a virtual environment. The purpose is to solve a potential and uncertain issues or cases. For example, this analysis could be used to predict how a 3D model would respond to stress or other environmental factors [4].

Regarding the bachelor thesis, detailed designing of the XTHT are done with the help of the FEA application.

3 Plan

This chapter shows the plan for the project, as well as some important dates that occur throughout the thesis period. Throughout the period, every day has been been registered, with intention to compare the realistic time spent with the ordinary plan. The comparison and log is presented in appendix I - "Plan and log".

Plan		Week no.																			
Phase	**Percentage**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Administrative and planning	2 %																				
Business case/cost study	5 %																				
Design basis	10 %																				
Concept phase	15 %																				
Detailed design	40 %																				
Report	25 %																				
Finishing/buffer	3 %																				

Table 2: Project plan

Note: The faint red colour shows that documentation work and report writing is planned to be done along with the concept phase and detailed design, but not as much as in week 16 and further on.

The following table shows the most important dates and milestones.

Important milestones and dates

Milestone	Date	Location	Purpose
First presentation for class	30 January 2019	NTNU Aalesund	Introduction for class and mentors
Concept design review	Week 8	Skype	Show concepts and concept selection
Secondary presentation for class	20 March 2019	NTNU Aalesund	Progress report for class and mentors
Presentation for Aker Solutions	May	Tranby, Lier	Present our solution
Deadline	20 May 2019	NTNU Aalesund	Deliver bachelor thesis
Final presentation for class	22 May 2019	NTNU Aalesund	Present our thesis and graduation

Table 3: Important milestones and dates

4 Business case

4.1 Cost study

This chapter covers a cost study, which intents to estimate the weight and cost savings when counterweights (CW) are removed from the XT. The study includes:

- Potential weight saving [kg/XT] at the given project specific tree.
- Typical price for counterweights [NOK/kg] based on previous purchases.
- Based on amount of XT's, potential cost savings for the project.

Removing counterweights could result in a large cost and weight reduction at XT's and projects. If the final solution also result in a lighter lift, it could create opportunities to handle the XT with smaller vessels and/or in a larger weather windows. The removal will also lighten the work for the operators and create better HSE at the workplace, as assembling or disassembling of counterweights are demanding and heavy operations.

To estimate typical savings, six different projects is assigned to this cost study. The six projects are also the basement for other studies done throughout the thesis.

The following table shows how much weight that could be saved just by removing the weights, the price of buying the weights and the cost savings for a typical project.

Note: Manhours assembling the weights has not been considered in this study.

Potential savings in counterweights

Case			Overview			
Client	**Project**	**Trees**	**kg/XT**	**NOK/XT**	**NOK/kg**	**Field price**
Aker BP	Ærfugl 7x5VXT	4	3 526	105 400	30	421 600
Equinor	Troll phase 3 7x7 VXT	9	6 325	243 709	39	2 193 380
	Aasta Hansteen 7x5 HXT	8	2 328	137 000	59	1 096 000
Total	Moho 5X2 VXT	18	3 460	120 842	35	2 175 156
	Kaombo 5x2 VXT	35	3 494	77 190	22	2 701 650
DEA	Dvalin 7X5 HXT	4	5 407	183 726	34	734 904
Reliance	KG-D6 7X2HXT	8	2 521	107 923	43	863 384
Average			**3866**	**139399**	**37**	

Table 4: Potential cost and weight savings due to CW removal

Result

It is clear that there are savings on both weight and cost if counterweights are removed. The table shows that the NOK/kg and kg/XT can vary quite a bit, and the main reason for this is tight deadlines and last minute changes. The average cost saving is almost 140 000 NOK per XT, and clarifies that a tool to compensate for CW removal, could result in great cost savings for Aker Solutions.

Beside that, the table also shows that weight savings are at an average of 3.8 tonnes. A lighter XT creates new advantages, which is reflected more closely in 5. Note that a heavy lifting tool could eliminate some of these pros if the tool weight result in heavier lift compared to today's lift.

There is an expression in Aker Solutions, which says: "*Cut weight, cut costs*", and in this case, it does.

4.2 Pros and cons

This section reflects the different advantages and disadvantages regarding the removal of the counterweights. Following is a table with a list which explain the general pros and cons if the CW's are removed, not specific for any new solution.

Removal of counterweights	
Pros	**Cons**
Cost savings: No purchases of CW No manhours regarding CW Weight savings on XT: Greater weather window offshore Less impact on wellhead or other similar interfaces when XT is installed or retrieved Use of smaller cranes. Use of smaller vessels. Increased safety. Other: Reduce crushing hazards and ease the operators for heavy work in fabrication of the XT.	A different tool or system needs to compensate for the CW removal, which can lead to following cons: Expensive solution Time consuming to mount/use Advanced lifting equipment, which could lead to incorrect use. Heavier lifting equipment which eliminate some of the weight savings pros. If other equipment is used to lift the XT instead of the new tool, for example with a workover system, the position of COG could be more unfortunate and create problems.

Table 5: Pros and cons by removing counterweights

The idea of removing counterweights is something Aker Solutions has taught about for a while, and it is clear that this will be an positive implementation and result in great savings for the company.

5 Method

This chapter reflects the main work of the bachelor thesis and substantiates the results shown in chapter 6. The chapter presents the work process and describes the most important choices done throughout the bachelor thesis, as well as it reflects upon why these choices are made.

As mentioned, only the main work is covered in this chapter. A lot of work are attached as appendix and consistently referred to throughout the report.

5.1 Product development

This thesis is a work in product development. Throughout the Product- and System Design programme at NTNU Aalesund the subject "Product development" has been completed. This subject reflects the different phases and importances of product development. This bachelor thesis and development of the XTHT and Tree Running Tool (TRT) is going to be based on the knowledge acquired from this subject.

5.1.1 Product development methodology

Product development methodology is an important aspect in the field of general product development. The objective of this is to achieve development of better products in less time and with the amount of resources to be as few as possible [5]. Developing a product or a system requires a well structured and methodical process. The following process model is one of the fundamental features when is comes to product development methodology.

Figure 7: Product development workflow (Source: See reference [5])

To see

This phase intends to get an understanding of the requirement of the product to be developed. In this phase it is important to include:

- See and look for new opportunities
- See and include the users of the product
- See the different scenarios for the usage
- See and get and basic understanding of the current technology
- Get inspired

To create

The second phase is "to create", where the purpose is to find new solutions. This would be the concept phase of the process, where you searching for new solutions. The different solutions is being evaluated to find the one with the best potential, and would be based on the information gather in the “To see” phase [6].

In the concept phase it is appropriate to do hand drawings, 3D models and simple calculations to verify the functionality of the concepts. The intention of the concept phase is to find a solution that could be realized and removing uncertainty as much as possible [6].

Prepare

This phase of the process model includes iterating and detailing the of the product. The product would be a result of the selected concept chosen in the previous phase. Design of product, product data sheet, calculation report and manufacturing drawings are carried out in detail through this phase [6].

Implementation

This is the last phase of the development model, where the product is going to be realized. Manufacturing and marketing of the product starts in this phase, and is often the most expensive phase for the company.

Note: The implementation phase is not relevant for this bachelor thesis.

5.2 Design basis

The design basis corresponds to the "To see" phase in the general product development methodology described in the previous section. It explains and reflects the different challenges that are important to have in mind when designing the XTHT and the TRT. These challenges, standards and previous configurations of the tools will define the requirements for the designs. Safety, worst case scenarios and simple usage of tools must be in focus.

Figure 8: The design basis corresponds to the general "To see" phase (Source: See reference [5])

The design basis is attached as appendix A. It reflects on the concluded requirements and covers all challenges, lifting scenarios and other factors that are important to include in order to create a proper design framework.

To give a short introduction of the content, the following enumeration shows the chapters/subjects of the appendix.

1. Relevant standards and Aker Solutions documents
2. Product description
3. Selection of lifting point
4. Interfaces
5. Lifting scenarios
6. Lifting configurations
7. Center of gravity
8. Tilt angle
9. Safety and test factor
10. Failure modes
11. Materials

The two next pages show an overview for each tool, sourced from the appendix. The overviews covers the requirements which have been concluded throughout the design basis.

Note: The bachelor thesis statement says that the design basis shall be a part of the main report. However, a choice of attach it as an appendix was done due to its large size. This will make the report more comfortable to read and the objectives can easier be followed.

XT lifting and handling tool

Parameter	Value
Height	2m
Length/width	3.5m x 3.5m Within XT's outer framework
Maximum tool weight	5t
Working Load Limit (WLL)	70t
Maximum distance between spool center and COG, bird's-eye view.	0.5m
Maximum tilt angle	1.7°
Safety factor / Design load	3.99 / 280t
Test factor for tool / Test load	3 / 210t
Design life	25 years and maintainable
Temperature range	-18°C to 50°C
Main material	Alloy steel - AISI 8630 MOD 80ksi
Indicators	Lock position Unlock posistion Correct positioning of tool
Lifting point	18-3/4" H4 profile Other arrangement at XT
Lifting configurations	Complete XT Without Flow Control Module Without Subsea Control Module XT only Tool only
Important precautions	Horizontal lifting Rotation (off-center solution) Easy and safe way of: - Locking - Unlocking - Attach hook - Detach hook
Important interfaces	Hook XT Operator

Table 6: Overview of requirements for the XTHT

Tree Running tool

Parameter	Value
Height	4m
Length/width	3.5m x 3.5m (NB: See note in lifting scenario no.2) Within XT's outer framework
Maximum tool weight	Mechanical TRT - 5t Hydraulic TRT - 20t
Working Load Limit (WLL)	70t
Maximum distance between spool center hub and COG, bird's-eye view	0.5m
Maximum tilt angle	1.7°
Safety factor / Design load	3.99 / 280t
Test factor / Test load	3 / 210t
Design water depth rating	2 000m
Hydraulic operating pressure	15 000 PSI
Design pressure	5 000 PSI
Design life	25 years and maintainable
Temperature range	-18°C to 121°C
Main material	Alloy steel - AISI 8630 MOD 80ksi
Indicators	Lock position Unlock posistion Correct positioning of tool
Lifting point	18-3/4" H4 profile Other arrangement at XT
Lifting configurations	Complete XT Without FCM Without SCM XT only Tool only
Important precautions	Horizontal lifting Rotation (off-center solution) Easy and safe way of: - Locking - Unlocking - Attach hook - Detach hook
Important interfaces	Hook XT Operator ROV

Table 7: Overview of requirements for the TRT

5.3 Concept phase

This section of the method chapter covers the concept phase of product development, which corresponds to the "To create" phase described in section 5.1. Searching for new solutions has been the main goal of the concept phase, with intention to find the most potential concept.

The following concepts-area needs to be covered to create a reliable design:

- Concept for level lifting due to the CW removal
- Concept for position verification
- Concept for anti-rotation if a off-center lifting solution is selected

A total of 28 concepts including all three areas have been discussed and reviewed. All of them are covered in appendix B - "Concept phase". The report only covers the most potential concepts.

Note: Obviously, concepts for locking and unlocking the tool is an important concept area. But the locking mechanism is chosen to be the same as for today's tools and is described in section 5.3.1

This bachelor thesis should only include detailed design of the XTHT, and a concept design of the TRT. Therefore, the main focus have been to find a smart solution for the XTHT. It has also been focused on creating solutions that could satisfy subsea usage, with hope to use the same concept for both tools.

The concept phase are based on the requirements from section 5.2 - "Design basis". Throughout the concept phase, every lifting scenario have been taken into account, were the following have been the leading objectives for the tools, in prioritized order:

1. Safety
2. Functionality
3. Simple usage for the operator
4. Time efficiency
5. Cost

Figure 9: The concept phase corresponds to the general "To create" phase (Source: See reference [5])

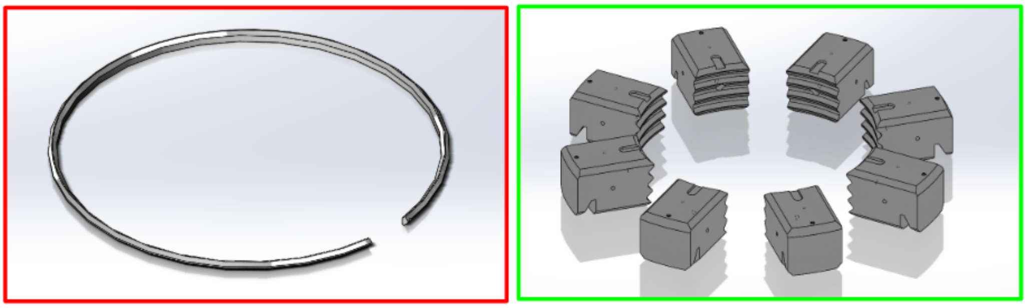
5.3.1 Locking to the XT

This section covers which locking element and locking mechanism that were chosen for the concepts. Referring to appendix A - "Detailed Design", the tools lifting point could either be the spool or other attachment points at the XT, or a combination.

In the concept phase, an early decision to use the 18-3/4" H4 profile profile as main lifting point was taken. The reason for this choice is that the attachment point could withstand great loads, as described in appendix A - "Design basis".

Locking elements

Today's tools either use locking dogs or a spilt lock ring to secure a safe and steady lifting connection to the H4 profile-profile. Figure 10 shows these two options.



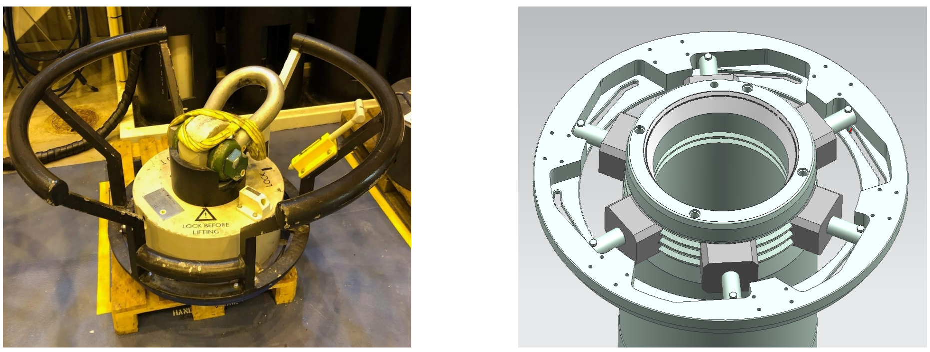
(a) Split lock ring (b) Locking dogs

Figure 10: The two types of locking element (Source: Aker Solutions)

The chosen locking element is the locking dogs. This decision is based on the greater strength and physical properties the locking dogs provide compared to the split lock ring. A new tool to compensate for counterweights (CW) removal could create a lot of new challenges, for example bending stress that occur with an off-center lifting solution. Also when it comes to maintenance, the mechanics preferred locking dogs.

Locking mechanism

Aker Solutions has different configurations of XTHT's and TRT's, and also different types of locking mechanism. Figures 11, 12 13 show the three main types:



(a) XTHT at workshop in Tranby (b) Partial view of XTHT at the spool

Figure 11: Locking ring to engage all dogs at once (Source: Aker Solutions)

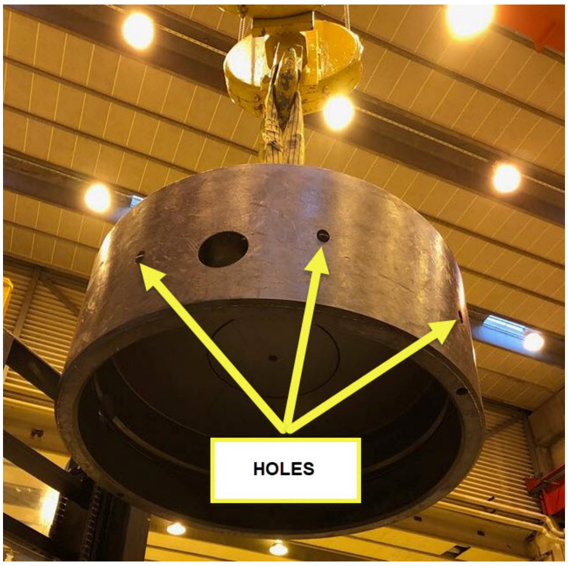


Figure 12: Locking mechanism based on having separated holes for hand tightening of locking dogs/ring (Source: Aker Solutions)

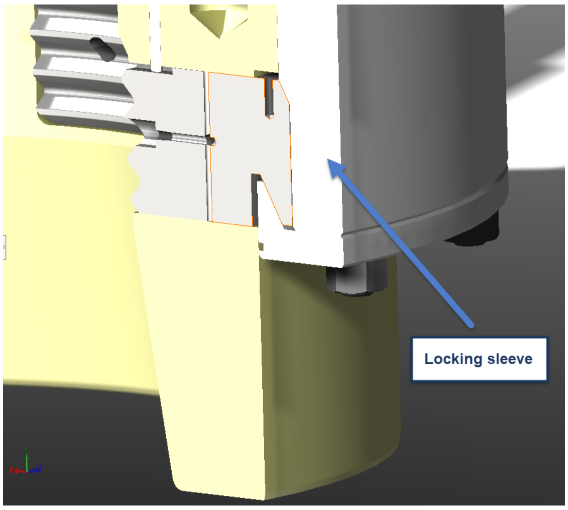


Figure 13: Principle of having a locking sleeve to engage/disengage the locking dogs. Figure shows the retracted position of the locking dogs. As hydraulic pressure is applied to cylinders (out of figure), the locking sleeve displaces further down and engage the dogs (Source: Aker Solutions)

The chosen locking mechanism for the tool is the locking ring shown in Figure 11. The basis for this choice is the simple functionality, which relieve the workers with its simple way of usage. It also creates a more safe tool with less failure modes compared to locking mechanism in Figure 12. The mechanism shown in Figure 12 has a failure mode with the separated holes, as the operator could forget to tighten a dog/bolt or not distribute evenly tension to all the dogs. When it comes to the the locking sleeve and Figure 13, it have its disadvantage by making the tool more heavy and complex.

5.3.2 Concepts for level lifting

This section covers different concepts of how to perform a level lift of the XT, due to the removal of CW. Basically there are four lifting classes that solve this issue and which the concepts could be based on, as illustrated in the figure below.

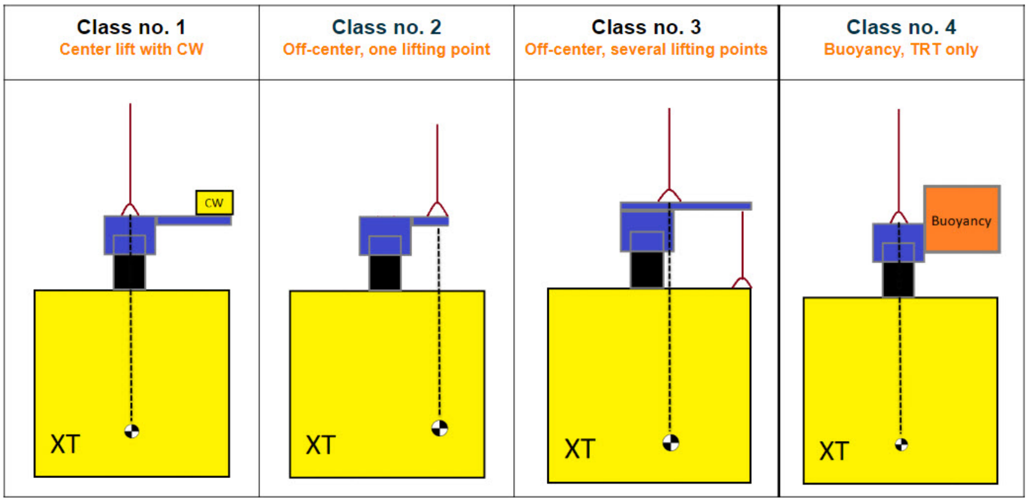


Figure 14: Figure shows the four main and possible lifting classes

Note: Class no. 4, buoyancy, is only applicable for TRT

The different concepts for level lifting are presented further on in the section, which is divided into three subsections:

- Leap ideas
- Potential concepts
- Final and selected concept

Leap ideas

An important aspect of the innovation and product development field, is to think and seek for solutions "outside the box". Changing your mindset to think more conventional and get distance from the normal thinking-patterns, could inspire to potential solutions. Ideas that are based on such thinking, are called "leap ideas".

Some leap solutions are presented in appendix B - "Concept Phase", which describe the process and reflect how one of the leap solution inspired to concepts for radius adjustment.

The following page shows a figure collection of many of the concepts that were made but not were found actual.

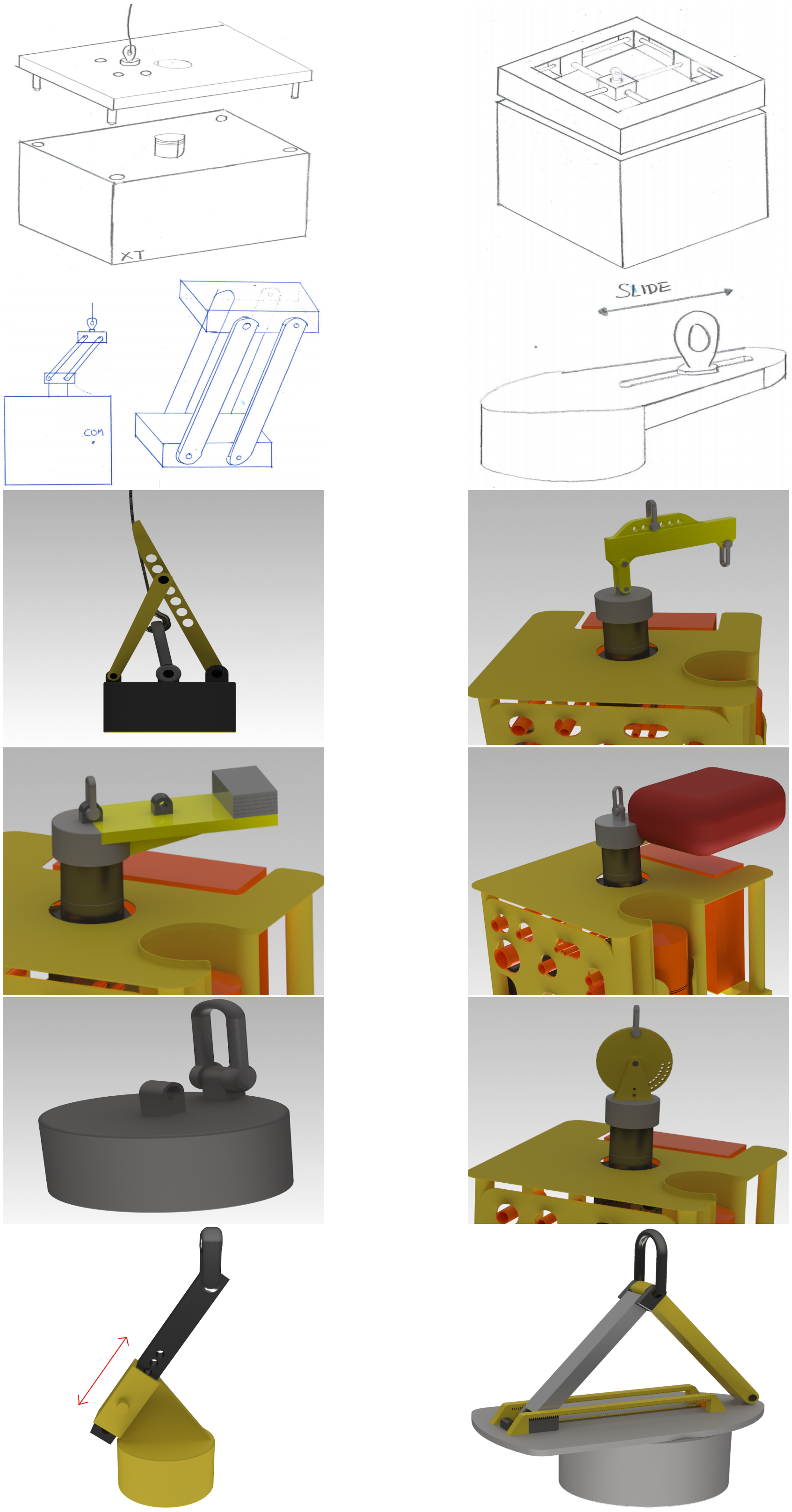


Figure 15: Collection of level lifting concepts

Potential concepts

This section covers the three most potential and preferred level lifting concepts that came to paper throughout the concept phase.

All the three concepts are based on lifting class no.2 (off-center lifting), and thereby there is a risk of the tool to start rotating on the spool if the tool is misaligned, as Figure 16 illustrates. Concepts for anti-rotation are therefore necessary, as described in the "Failure mode" section in appendix A - "Design Basis". Anti-rotation concepts are covered in section 5.3.4.

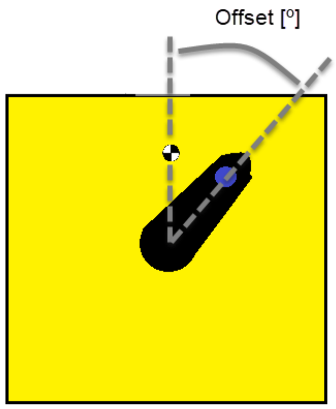


Figure 16: Misalignment of tool, bird's-eye view

Lifting off-center, also introducing extra loads to the locking dogs closest to the off-center lifting point, compared to a center lift. This is illustrated at Figure 17, demonstrating that support B needs to withstand the upward load from A to achieve equilibrium. In a center lift, both A and B would be acting downwards. This will be referred to as the "bottle-opener effect" further out in the report, as it is the same principle as when you open a bottle with a bottle opener. This case and extra loads are further analysed in appendix D - "Calculation report"

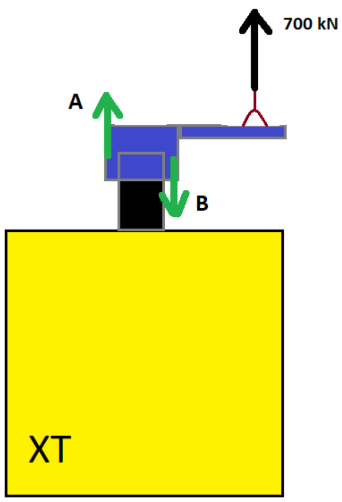


Figure 17: Bottle opener effect

Resolution

Before introducing the three concepts, some calculations are presented to show how large distance from Center Of Gravity (COG) the lifting point could have before maximum tilt at 1.7° is reached.

Note: This calculations covers the tilt that occurs if the tool is 100% correct aligned above COG, seen from a bird-eyes view. An additional angle misalignment in this plane is covered in appendix E -"Angle offset and torque calculations"

In addition to maximum tilt angle, the height parameter needs to be settled, describing the distance from the lifting point down to COG. A study is done to find the height parameter, comparing the parameter at the six assigned projects in SolidWorks (SW).

A smaller distance down to COG will result in a lower resolution/X (see Figure 18a), due to the fixed angle at 1.7°. The lowest value at approximately 2100mm was found at "Ærfugl". A conservative value i set to **2000mm**, taking other project into account, as well as not adding the tool thickness which will increase the distance. Table 8 reflects the study.

Distance from top of spool to COG [mm]						
Client	**Project**	**with CW**	**w/o CW**	**w/o CW FCM**	**w/o CW SCM**	**w/o CW FCM SCM**
Aker BP	Ærfugl 7x5 VXT	2243	2158	2158	2154	2153
Equinor	Troll Phase 3 7x7 VXT	2350	2213	2122	2211	2115
	Aastad Hansen 7x5 HXT	2328	0	0	0	0
Total	Moho (5x2 VXT)	2609	2513	2533	2521	2543
	Kaombo (5x2 VXT)	2623	0	0	0	0
DEA	Dvalin (7x5 HXT)	2378	2287	2266	2283	2259
Reliance	KG-D6 (7x2 HXT)	2529	2449	2463	2459	2475

Table 8: Study regarding distance down to COG. Lowest value is highlighted

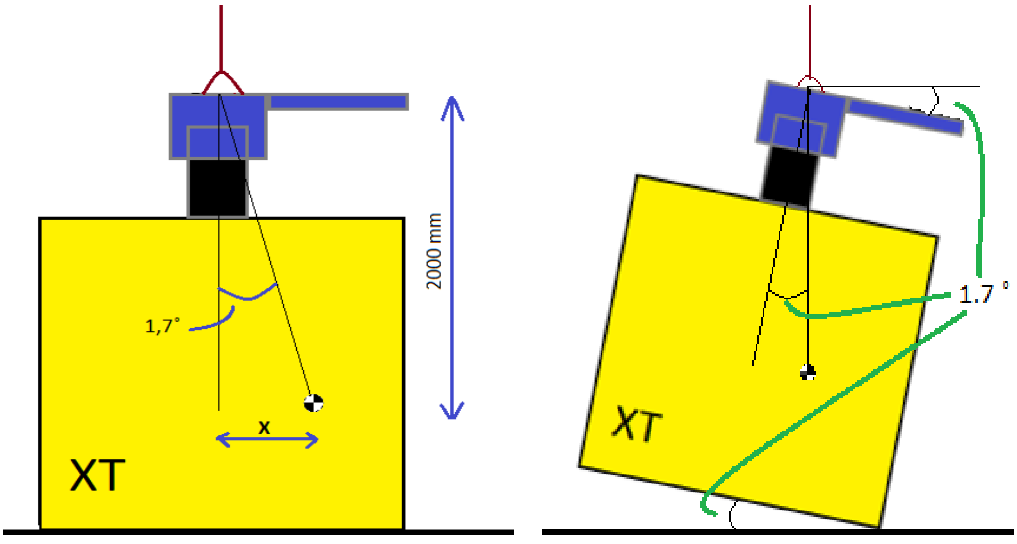
Note: Aastad Hansen and Kaombo has corrupt SolidWorks files and could not be opened without crashing the program. Kaombo and Moho is quite similar, so this is not a crisis

Note: To get a better understanding of the dimensions, the total XT height of the six project from varies from 3800mm to 4500mm

Figures 18a and 18b illustrates the different parameters and how the XT tilts due to a misaligned lifting point by the distance "X". "X" represent the resolution, but note that the parameters are very exaggerated and is only made to illustrate the theory.

Solving the parameter "X":

$$X = 2000mm * \tan 1.7° = 60mm$$



(a) Parameters (b) 1.7°tilt due XT lift

Figure 18: Figures illustrates the tilt that occurs when misplaces the lifting point

The resolution for the off-center concepts is at **60mm**. This dimension removes a lot of uncertainty and enables to create concepts with higher potential.

POTENTIAL CONCEPT NO. 1 - SHARK FIN

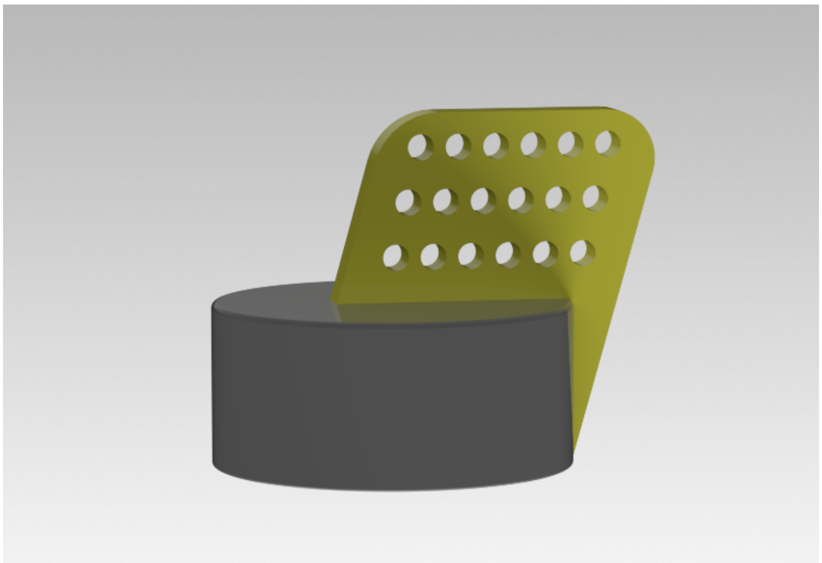


Figure 19: Shark fin off-center lift solution

This concept is based on having several holes in a plate which the shackle connects to. To ensure proper resolution of the holes at 60mm and still ensure enough material between the holes, two additional rows are added. This allows to lift above COG within an acceptable tilt at maximum 1.7°. Note that the solution requires a long shackle or an extender at the top of the shark fin.

The following list reflects the pro's and con's

- Pro's
  - Simple and cheap manufacturing
  - Simple usage
  - Universal
- Con's
  - Resolution may not be high enough
  - Requires a long shackle or an extender to the bottom holes
  - TRT - Inconvenient for the ROV to change the lifting point.

If material thickness between holes are not sufficient during the structural analysis, two alternative solution can be used to increase the distance between the holes. They are presented in appendix B - "Concept Phase".

POTENTIAL CONCEPT NO. 2 - SLIDE

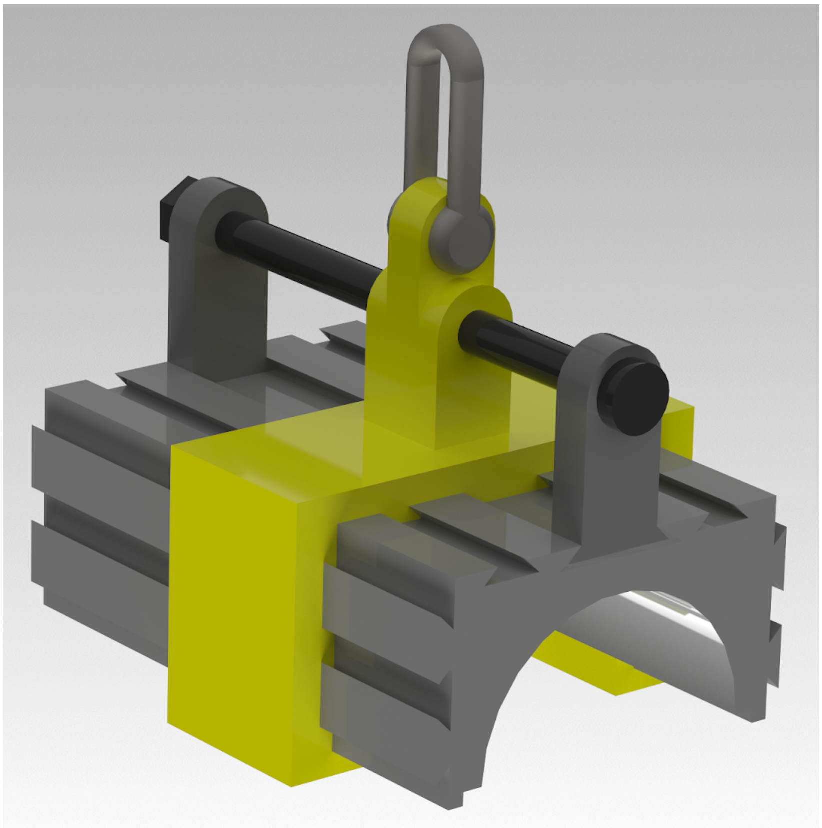


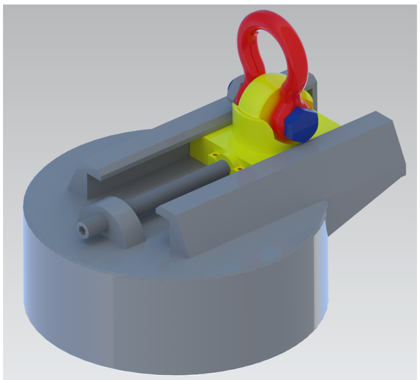
Figure 20: Slide concept with a thread rod

This concept is based on having an adjustable lifting point, moved along with the cap with a screw. The concept has a stepless radius resolution, which allows to find the perfect position above COG.

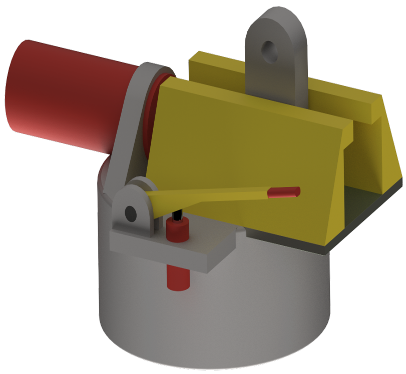
The following list reflects the pro's and con's

- Pro's
    - Stepless radius resolution
    - Simple adjustment
    - Universal
    - TRT - ROV friendly
- Con's
    - Probably heavy
    - Can be hard to distribute the load evenly

Two potential editions of this concept was also made, shown in Figures 21a and 21b.



(a) Overlying support structure



(b) Hydraulic cylinder to adjust the lifting point instead of a screw

Figure 21: Two alternative slide concepts

Potential concept no. 3 - Automatic adjustment - Hydraulic cylinder

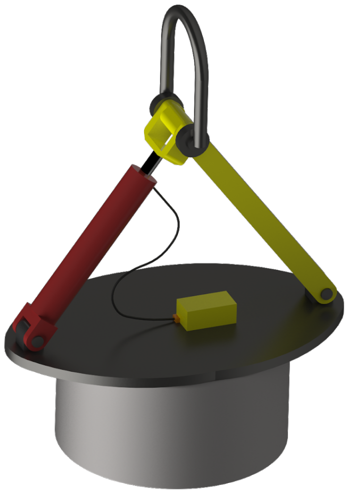


Figure 22: Automatic adjustment concept with a hydraulic cylinder as position regulator

The intention with this concept is to have a solution which enables automatic positioning of the lifting point. The principle of the concept is to use a hydraulic cylinder to position the lifting point above COG.

Both the lifting rod and the cylinder is fixed to the lifting cap (in terms of translation), but free in one rotational DOF. There will be a sensor at each rod to measure the tension ratio between them. If the ratio is not correct, the sensor would tell the throttle valve to open, resulting in an expansion of the cylinder which eventually would create the correct tension ratio between the rods, and thereby the lifting point would be positioned above COG. Option with several hydraulic cylinders is a possibility.

Note: If an automatic solution creates too many challenges, the concept can still be used by bleeding the cylinder manually until correct position is achieved.

- Pro's
  - Automatic positioning above COG
    - No action needed from the operator
  - Stepless resolution
  - Returns to center after lift
  - Does not need any hydraulic pump
  - Universal
- Con's
  - Tall
  - Tool is not fully automatic. There is still a need to rotate the tool into correct angle.
  - Crane needs to follow the shackle as it moves to avoid skidding, introducing another risk and failure mode.
  - The cylinder would probably become too large
  - Needs fail safe mode in case of hydraulics fail–> Complexity

Chosen concept

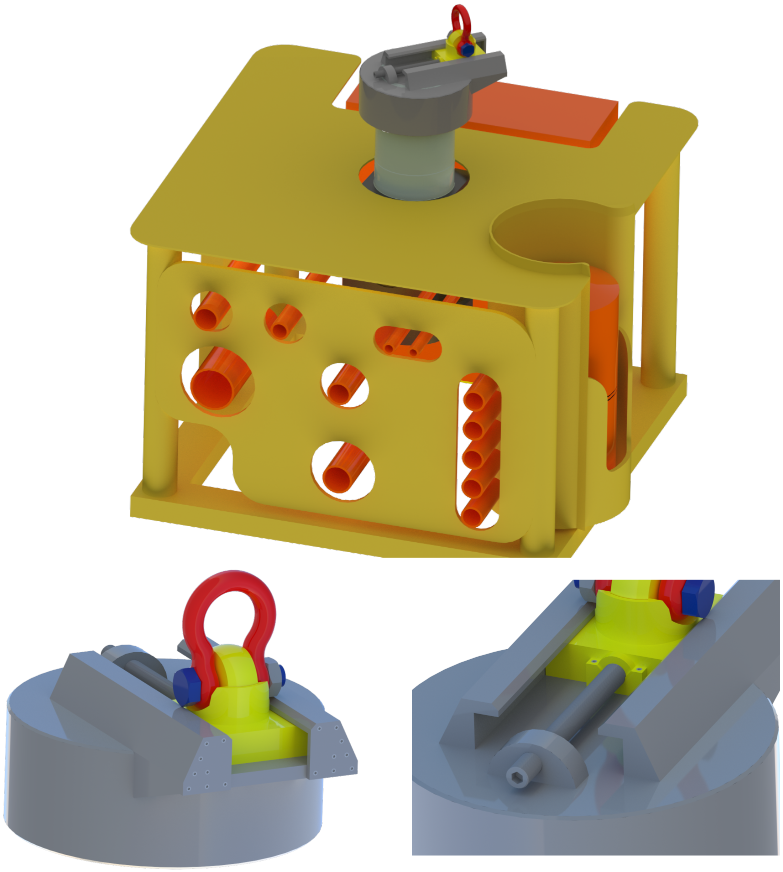


Figure 23: Chosen concept for level lifting

The slide concept with overlying support and screw adjustment became the selected concept for level lifting. The concepts were compared and this concept was concluded to be to one with the highest potential. Basis for the selection is the tools simplicity and few disadvantages.

5.3.3 Concepts for position verification

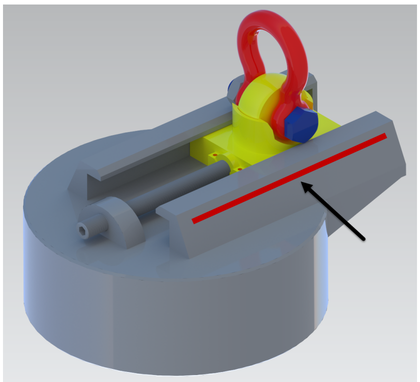
Position verification of the lifting point above COG is necessary to ensure a level lift. The following positions needs to be verified:

- Displacement of lifting lug
- Angle of tool towards COG

The following concepts were made

Displacement of lifting lug

(a) Basic ruler made in steel (Source: http://www.hultafors.no)



(b) Placement of ruler or indication lines

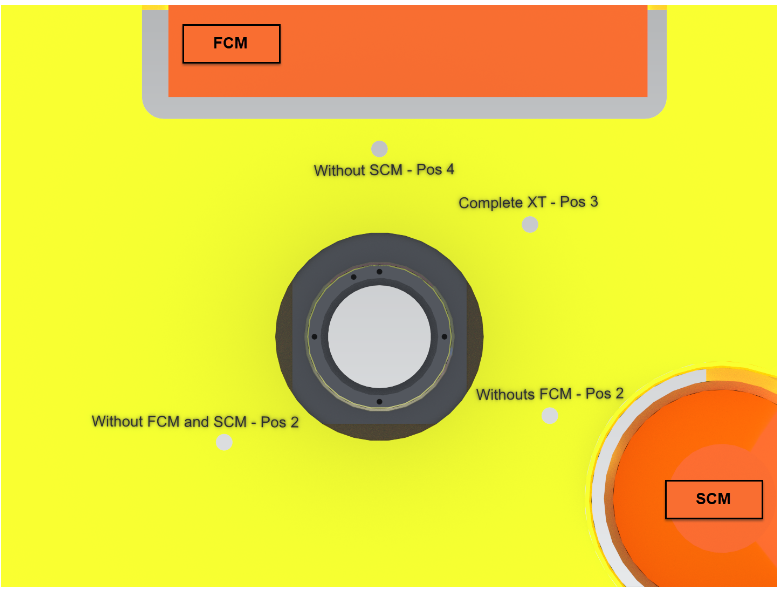
Figure 24: Verification of lifting lug position

The only and chosen concept for this verification is to have ruler or some other length indication along with the overlying support structure, referring to Figure 24. The basis for this selection is the simplicity and inexpensive solution.

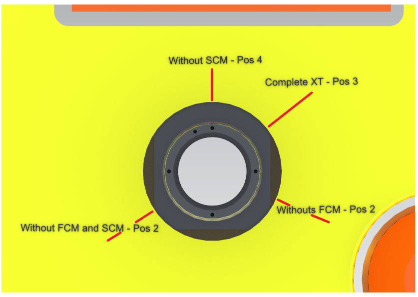
Angle of tool towards COG

In addition to displace the lifting point above COG, the tool needs to be orientated in correct angle towards COG. The design basis requires this to be possible in all four lift configurations. To achieve this, the intention is to exploit the roof at the XT, where the following concepts were made:

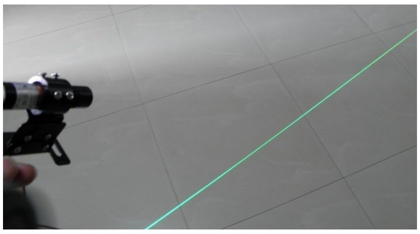
- Holes in the roof, Figure 25a
- Laser, Figure 25b and Figure 25c



(a) Alignment with holes in the XT roof



(b) Alignment using laser



(c) Example laser, to be attached to tool. (Source: https://power4kids.info)

Figure 25: Verification of tool towards COG, bird's-eye view

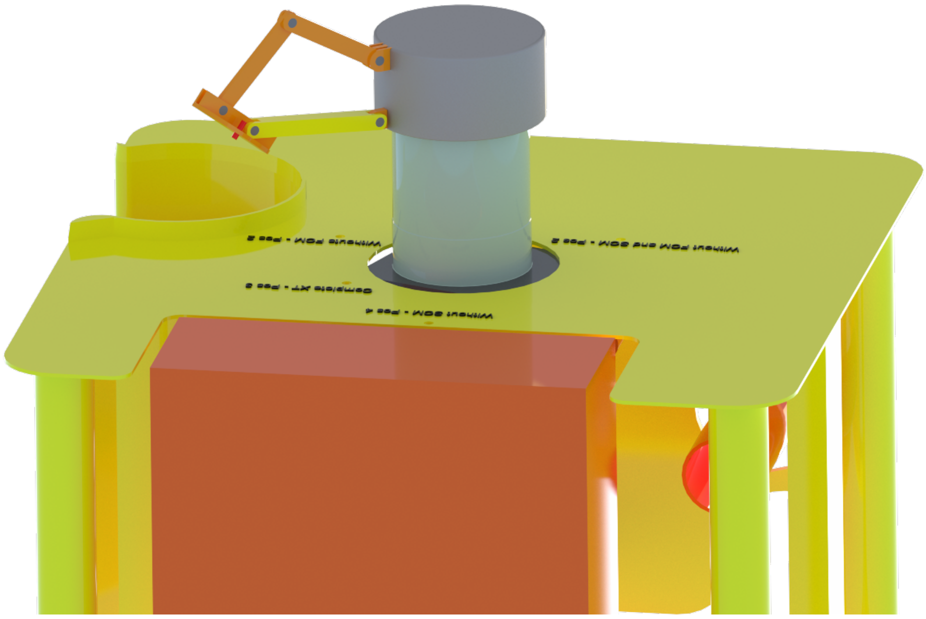
The chosen concept became the one shown in Figure 25a, holes in the roof. The intention of this concept is to have a pin to penetrate the hole. The pin is attached to the tool and enters the applicable hole as the tool is rotated on the spool.

However, the holes need to be made in the correct angle towards COG. The intentions is to use SW to find the theoretically COG. Thereby, after completed XT assembly, the realistic COG can be found by pre-lifts. When the sufficient tilt is achieved, the holes can be drilled by hand.

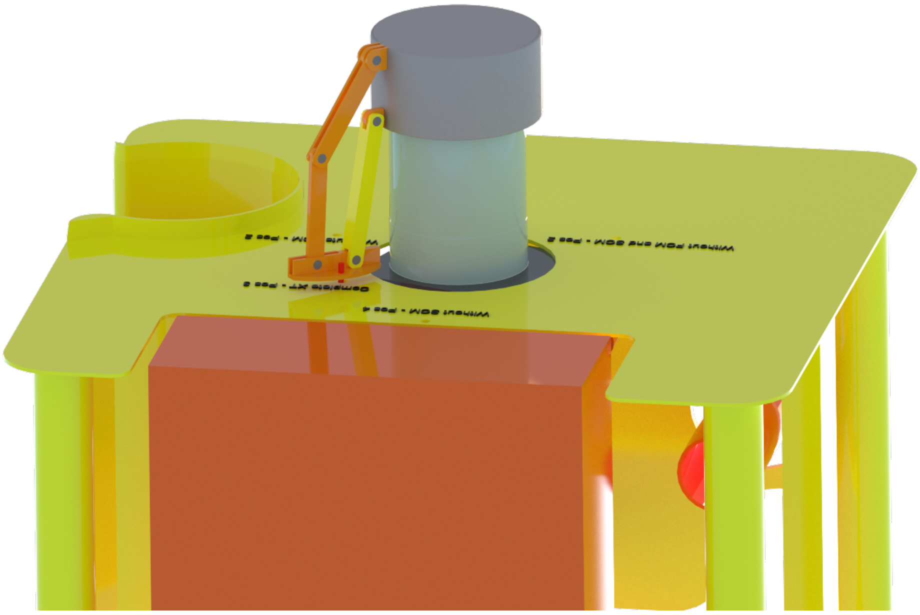
Note: Performing pre-lifts and drilling of the holes in the roof is a risky operation. A complete procedure is made to show how to do this in a safe way, attached as appendix F - "Roof drilling procedure".

Basis for the selection of this concept, is that the holes lower the probability of the tool to be misaligned. There is no possibility of the tool to misaligned, which is possible with the laser.

Some concepts of the pin for were made and Figure 26 shows an example. However, a better solution was figured out during the processes of anti-rotation concepts, which is explained in the next section.



(a) Tool unaligned



(b) Tool aligned

Figure 26: Example of alignment pin concept

5.3.4 Concepts for anti-rotation

This section covers the main work and conclusions taken regarding anti-rotation solutions to the tools. An anti-rotation solution is necessary due to the risk of the lifting point having an offset to COG, as Figure 27 shows. The previous section covered concept to lower the risk of misalignment, however there is still uncertainty. This could for example be in the following situations:

- The holes in the roof is not sufficient located.
- The operator mounts the tool in the wrong hole.
- As the XT goes through the splash-zone during a installation/retrieval offshore, the COG would be displaced.

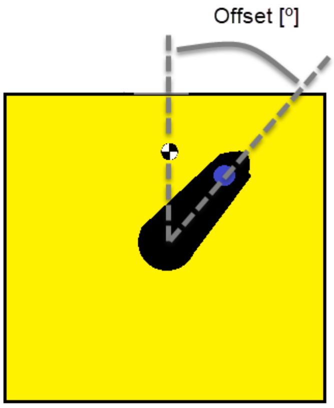


Figure 27: Angle offset

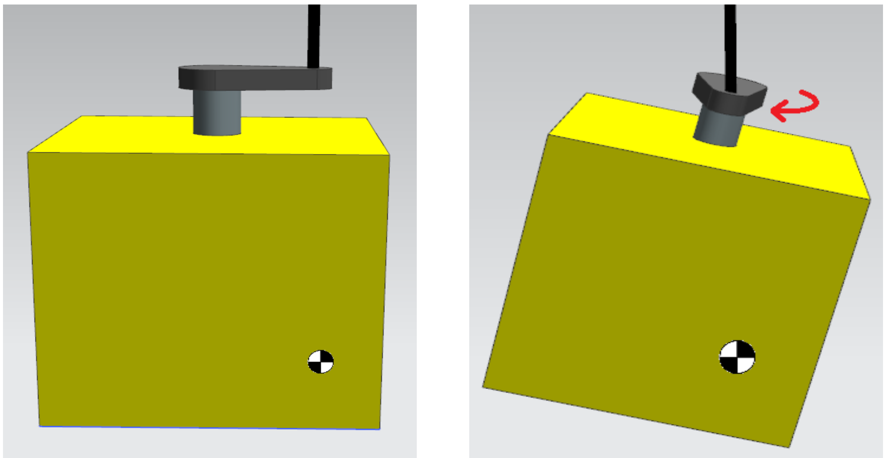


Figure 28: Tilt due to angle misalignment

The tool will experience a rotational force along with the angle offset. The angle offset and tilt that occur is illustrated at overlying figures. A study is done to find the worst case angle offset and the torque that occur at the different offsets. Next page shows a graph and a table of the results. The study is covered in appendix E -"Angle offset and torque calculations".

Worst case		
Angle offset	87	°
Torque generated	85	kNm

Table 9: Worst case angle misalignment

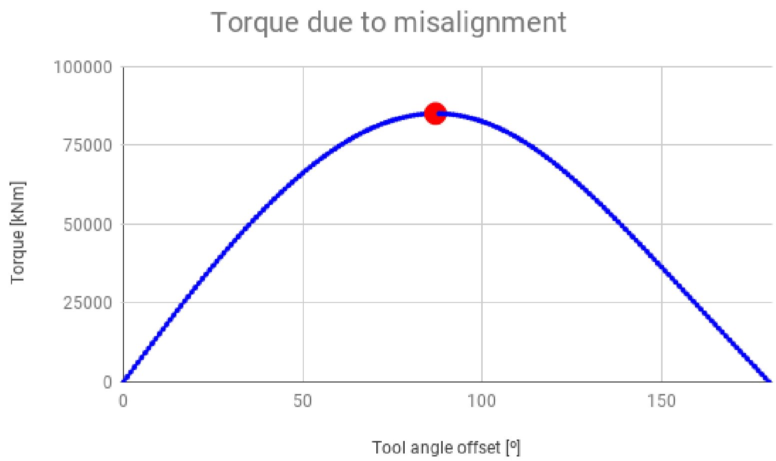


Figure 29: Torque generated along with increased angle offset

A lot of anti-rotation concepts were made throughout the concept phase. The next page shows many of these, as the consecutive page shows and describes the chosen concept. All anti-rotation concepts and details regarding them are covered in appendix B - "Concept Phase".

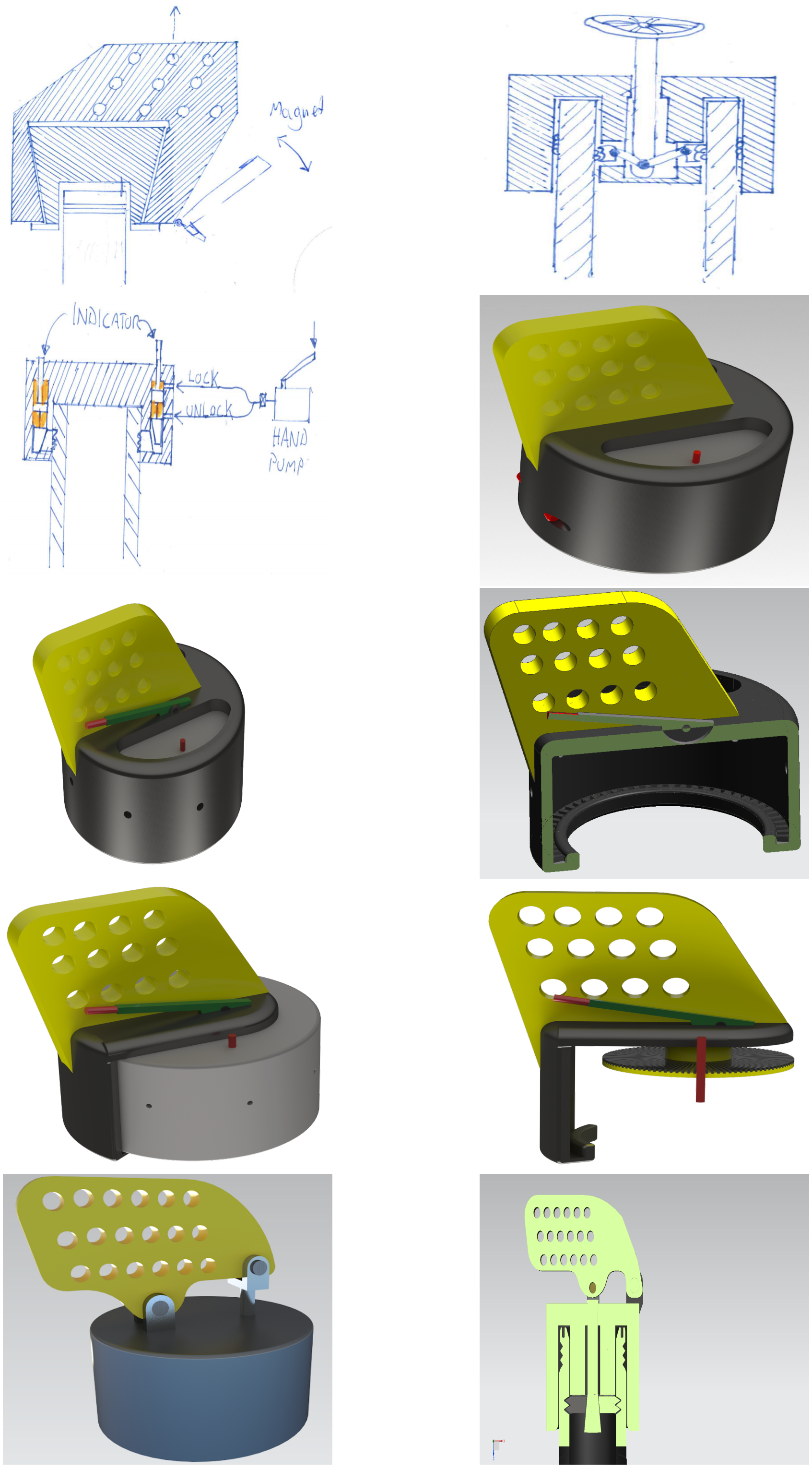


Figure 30: Collection of anti-rotation concepts

Chosen anti-rotation concept

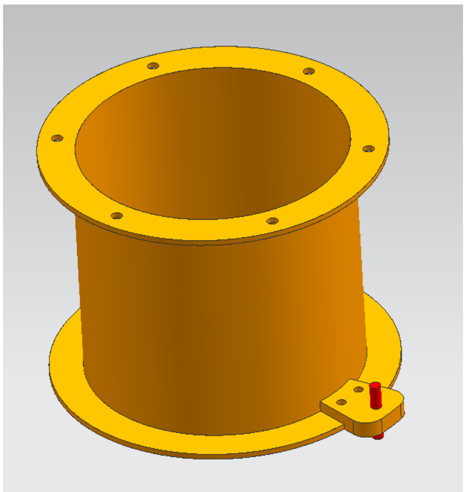


Figure 31: Funnel and locking pin to ensure against rotation, as well as alignment

Figure 31 shows the chosen concept to secure the tool against rotation due to an angle misalignment. The basis of this selection is its low complexity compared to the other concepts, as well as it combines position verification and anti-rotation by the pin, which enters the applicable hole in the roof. The pin should be spring loaded so it could easily enter the hole, as well as collapsing when the tool is parked at the ground.

The concept is basically a funnel assembled to the tools main body. The funnel is then equipped with a replaceable bracket which holds the lock pin. The intention of a replaceable bracket is to have the possibility to use the lock pin at special XT's roof which conflict with the standard bracket dimensions.

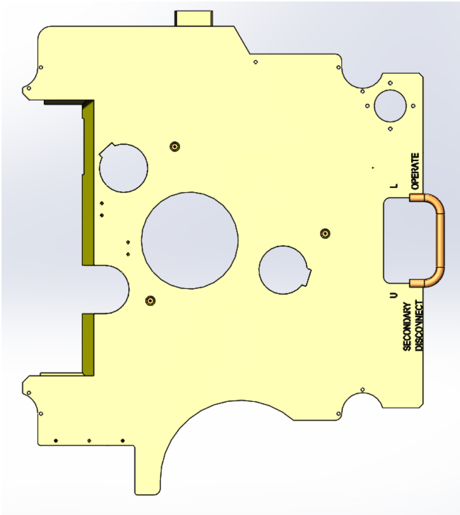
The funnel and bracket dimensions are based on a SW study done at three of the six assigned projects/XT's. The other XT's were excluded from the study as they are VXT's and do not have H4 profiles. The following table and figures reflects the study.

Client	**Project**	**Top spool-Roof**	**Center spool-Roof edge Highest**	**Center spool-Roof edge Lowest**
Equinor	Aasta Hansen	1014mm	550mm	362mm
DEA	Dvalin	1044mm	550mm	362mm
Reliance	KG-D6	1051mm	530mm	350mm
Concluded dimensions		1000mm	500mm	400mm

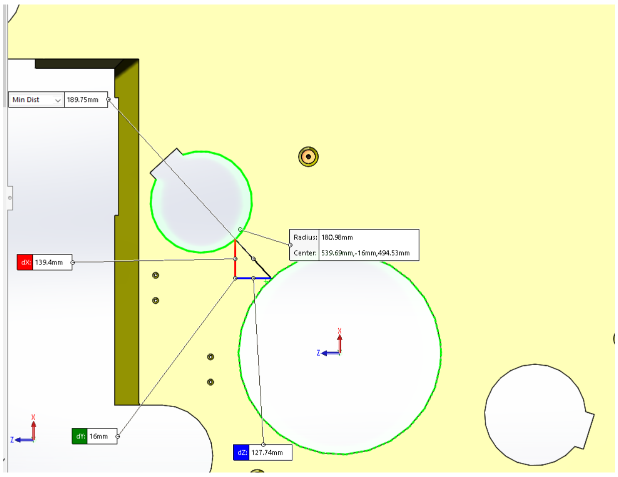
Table 10: Dimension study regarding the funnel

The study conducted in Table 10 helps to find a suitable radius which is always available for roof drilling. The chosen bracket radius is set to 500mm after conversations with Aker Solutions. If the dimension conflict with other XT roofs, the brackets could be replaced.

The "top of spool to roof" dimension is rounded down to ensure that the funnel does not land on the roof. If the tool lands on the roof, it could result in improper locking to the H4 profile. Based on conversations with Aker Solutions, 1000mm will be a sufficient dimension.



(a) Roof at Dvalin HXT



(b) Measuring of highest distance from center spool to roof edge

Figure 32: Lock pin dimension study at Dvalin roof

5.3.5 Final concept for XTHT

By combining the chosen locking element, locking mechanism, concept for level lifting, concept for verification and concept for anti-rotation, the final concept for the XTHT are settled and shown in Figures 33 and 34. This final concept will function as the base in the detail design phase of the XTHT.

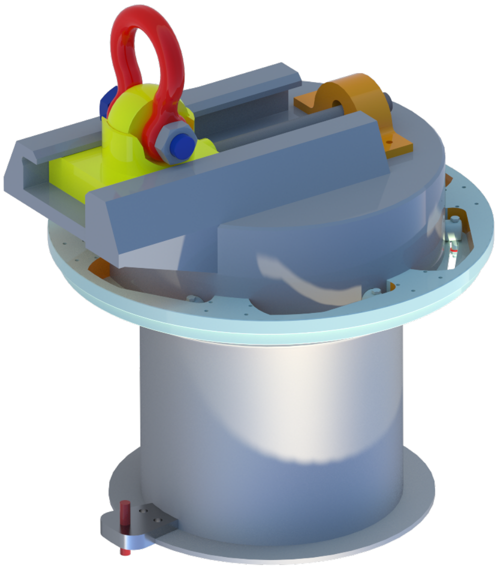


Figure 33: Final concept of the XTHT

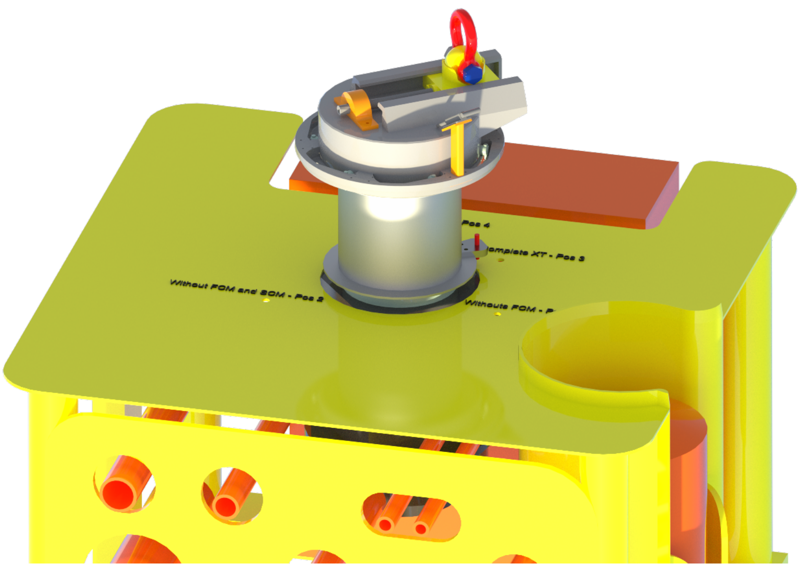


Figure 34: XTHT mounted at simplified XT

5.3.6 Final concept for TRT

The concept of the Tree Running Tool (TRT) is presented in appendix C - "Concept of TRT".

5.4 Detail design of the XTHT

This section of the method chapter covers the detail design phase of the Xmas Tree Handling Tool (XTHT) and corresponds to the "Prepare" phase in the general product development methodology. Detailing and preparing the XTHT for a potential implementation are basically the main work throughout this phase. The final design and detailing of the tool is covered in the next chapter 6 - "Results"

Figure 35: The "Detail design" phase corresponds to the general "Prepare" phase (Source: See reference [5])

Table 11 shows the different parts in the detail design phase and where they are located.

Note: The two last parts were not a requirement from Aker Solutions, but was found necessary during the development

Section	Location	Short description
Final design and intentions	Chapter 6	Describes and shows the result of the XTHT.
Calculation report	Appendix D	The calculation report is created to verify the structural integrity of the XTHT and confirm its 70 tonnes lifting capacity. The calculation phase of the product development has it own objectives and conclusions, and thereby is the calculations presented as a technical report.
Manufacturing drawings	Appendix K	
Product data sheet	Appendix H	A data sheet of the XTHT which lists the tools specifications and describes its basic functionality.
Roof drilling procedure	Appendix F	Describing the approach of how to drill the holes in the roof in a safe way, as well as the hazards and risk when using the tool without a present anti-rotation barrier.
Manufacturing proposal	Appendix G	The students proposal of how the different parts can be manufactured.

Table 11: Detailed design - Overview of content

6 Results

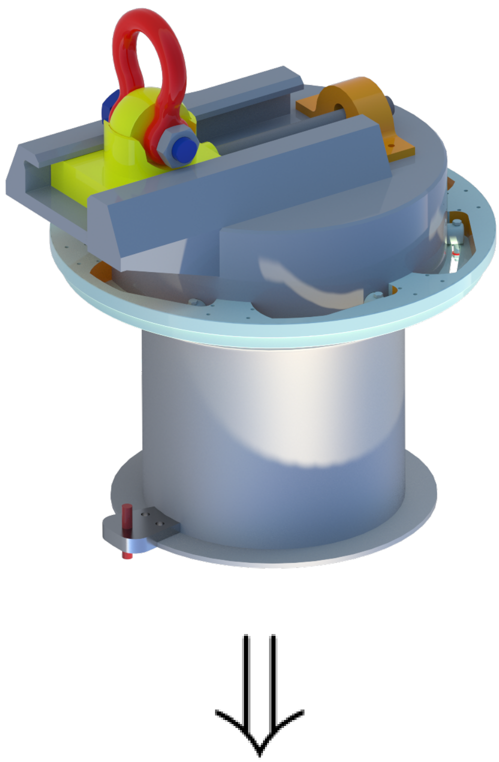
This chapter covers the results for the thesis objectives, which was a detailed design of a XTHT and a concept design of a TRT.

6.1 XTHT - Final design

This section describes and shows the final design of the XTHT. The different intentions and choices taken regarding the design is explained throughout the section. The following list shows the main focus areas during the development, in prioritised order:

- Safety
- Simple interface and easy access for the operator
- Strength and structural integrity
- Manufacturing
- Simple assembly
- Maintainable

The development of the XTHT is based on the chosen concept. A lot of work is done trough the detail design phase, where the concept has been modified in terms of the areas listed above. Trial and error from concept to final design are not documented. Figure 36 shows the transformation.



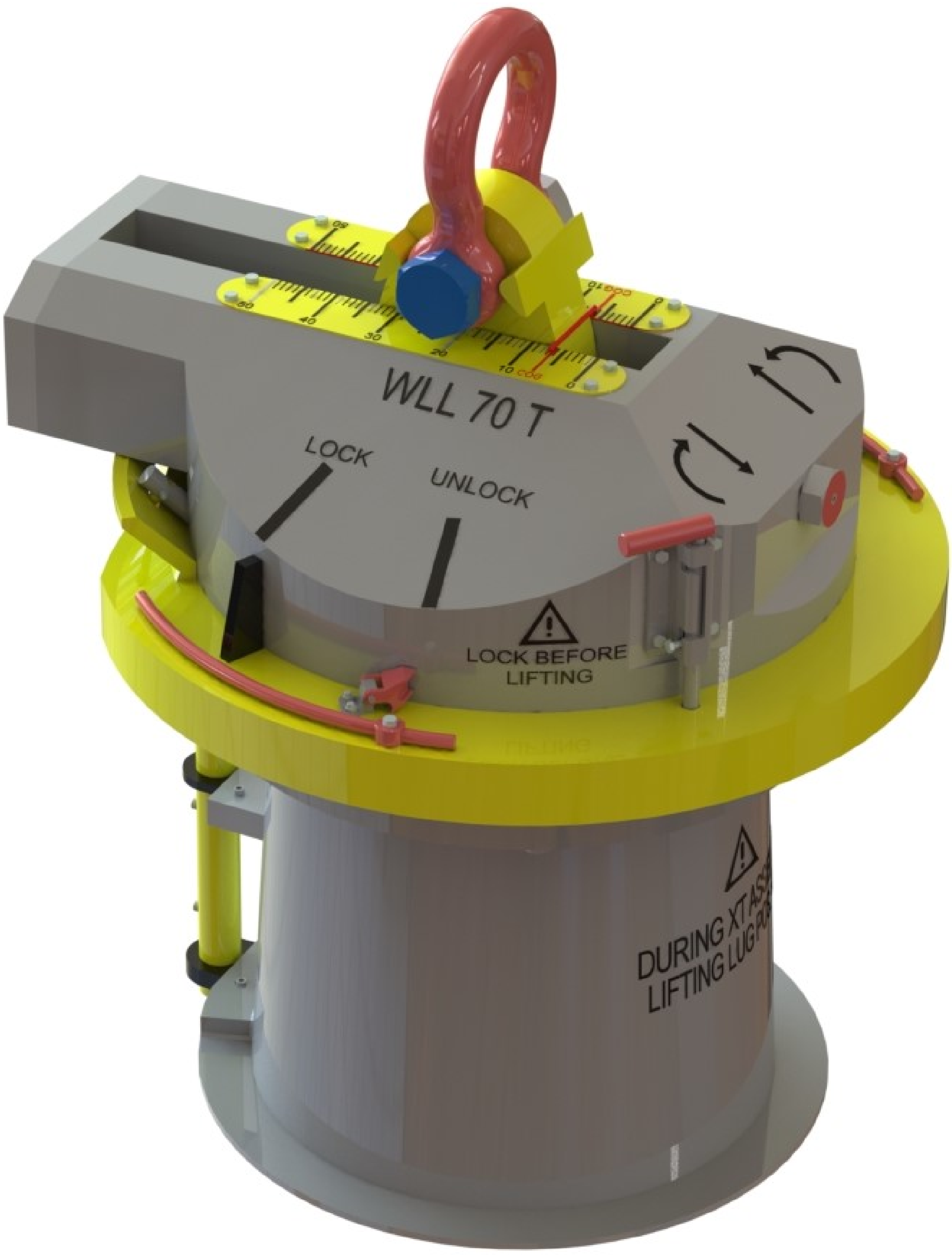


Figure 36: Transformation from concept to final design

6.1.1 Overview

The following figures shows the tool in different angles and section views.

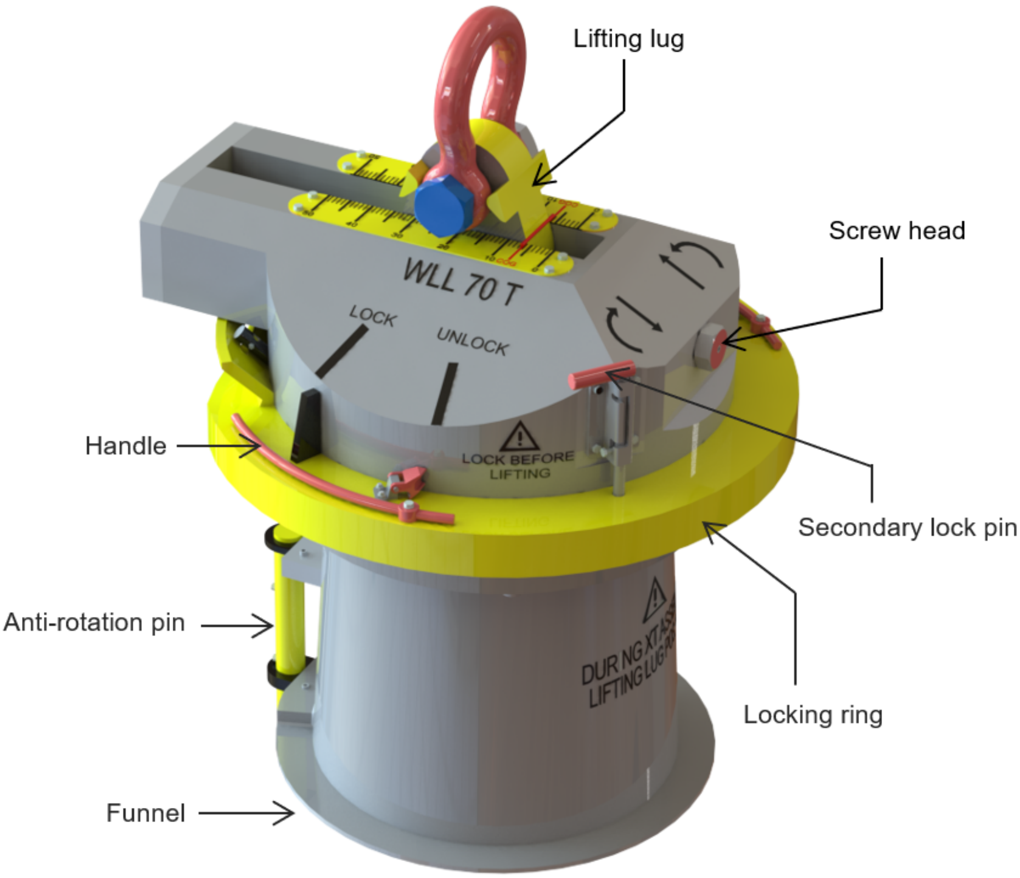
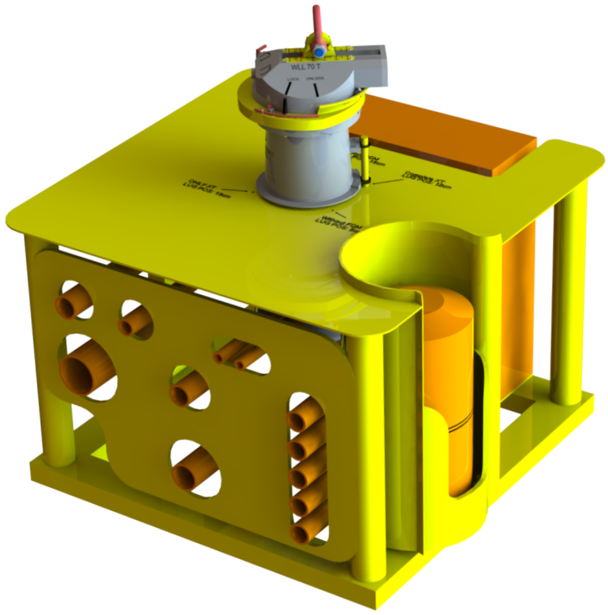
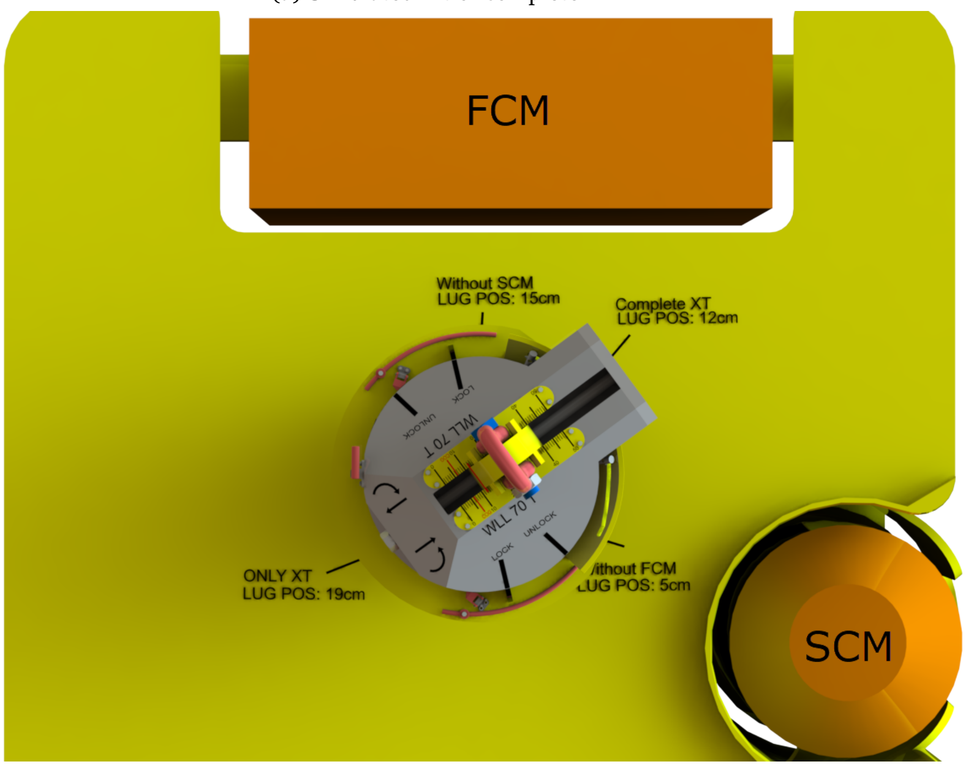


Figure 37: The final design

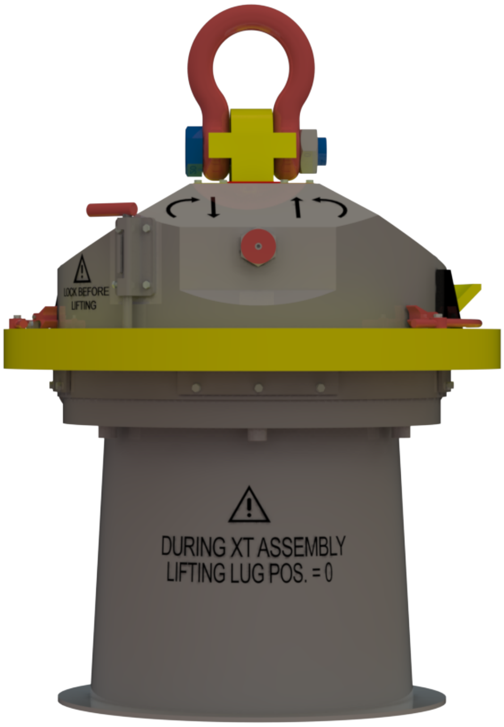


(a) Simulated lift of complete XT



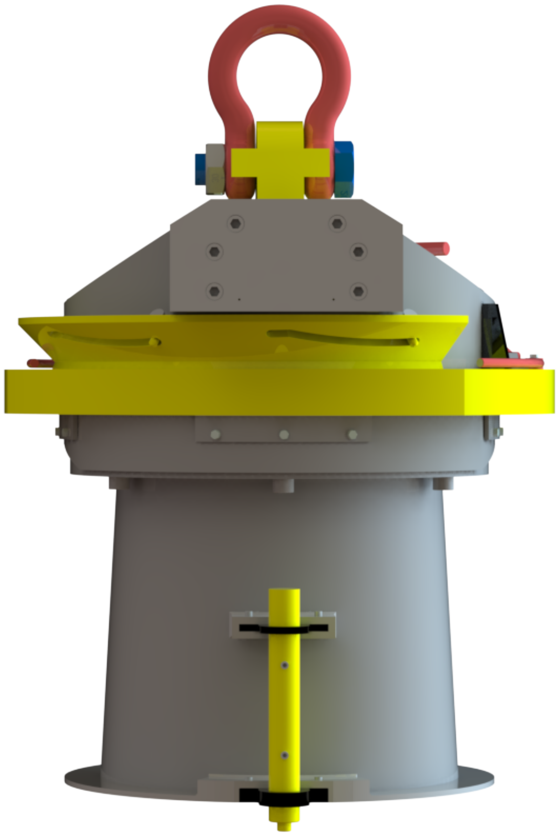
(b) Tool correctly positioned

Figure 38: Lift of complete XT. XT, FCM and SCM are all simplified



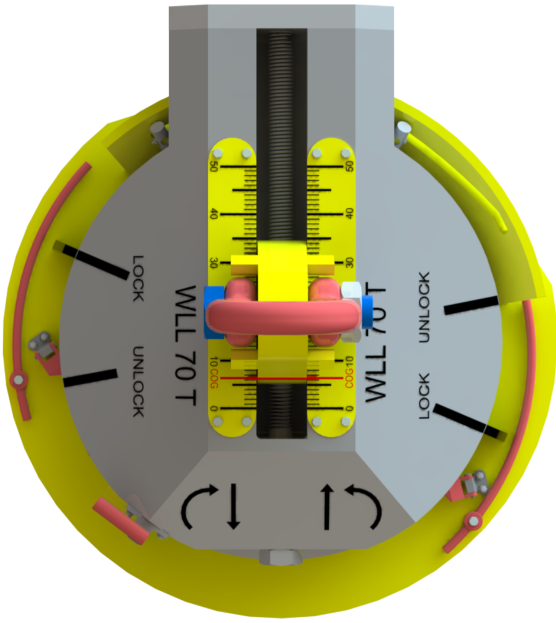
(a) Rare view

(b) First Side view



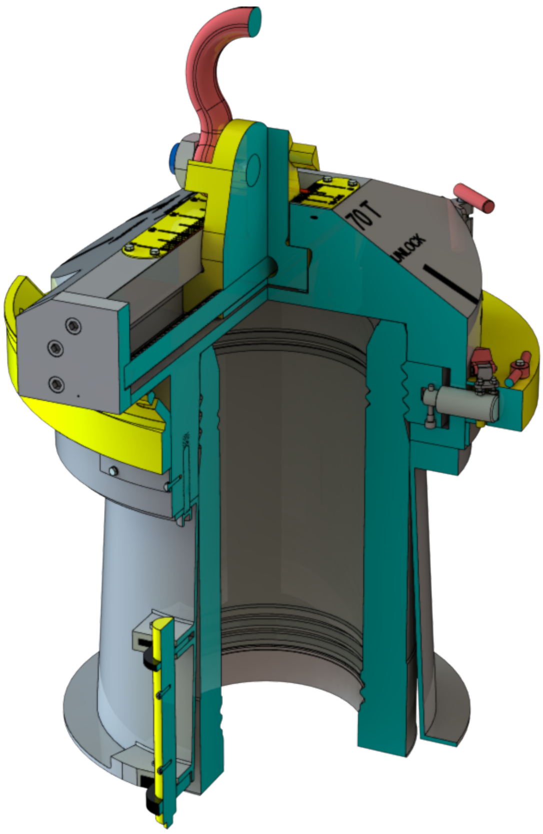
(c) Front view

(d) Secondary side view

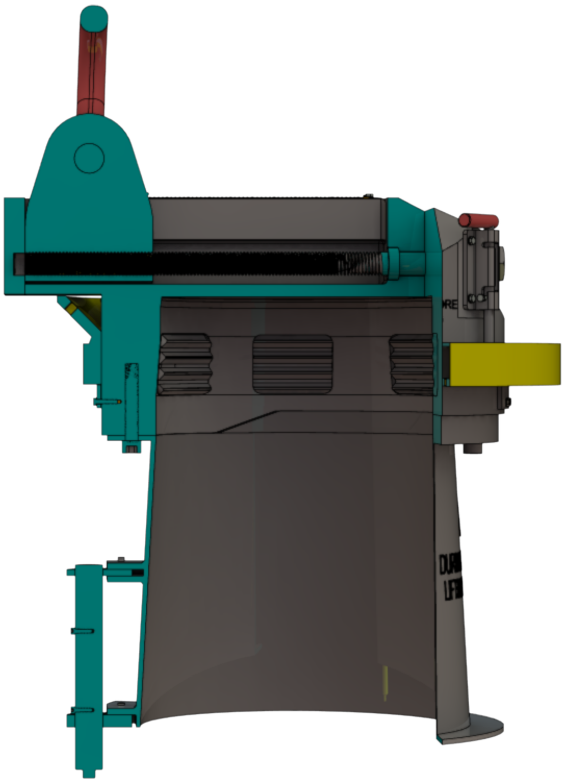


(e) Top view

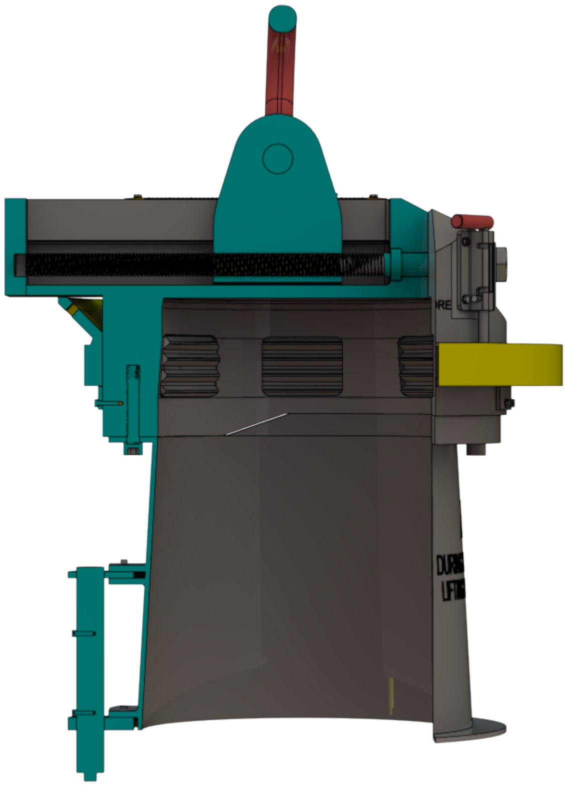
Figure 39: Multiple viewpoints



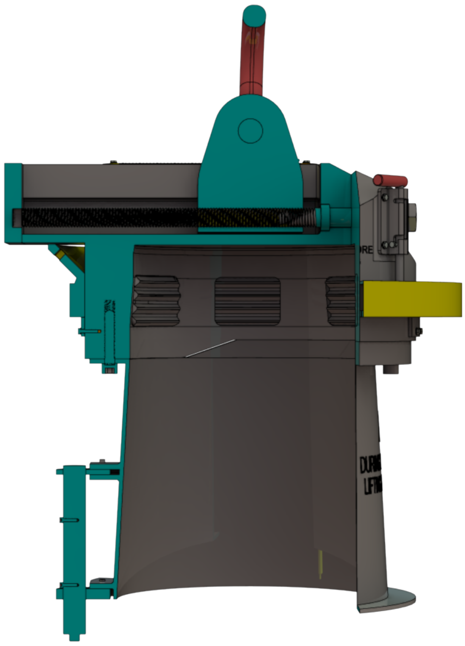
(a) Section view



(b) Section view, off-center lift



(c) Section view, lifting above tools COG



(d) Section view, center lift

Figure 40: Section views

6.1.2 Tool function

The XTHT is a lifting tool which enables multiple lifting positions. As previously described in the report, the intention is to position the lifting point above COG, which will result in a level lift of the XT. The tool is equipped with an anti-rotation pin to prevent the tool from rotating at the spool during a off-center lift and misaligned tool. Figures 41 and 42 illustrate the off-center lifting position and the rotation issue due a misalignment.

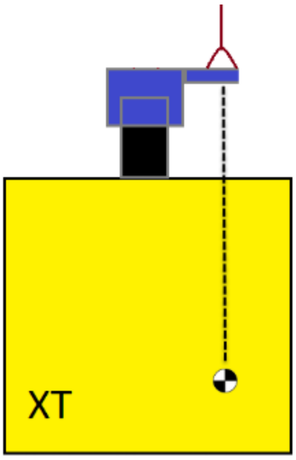
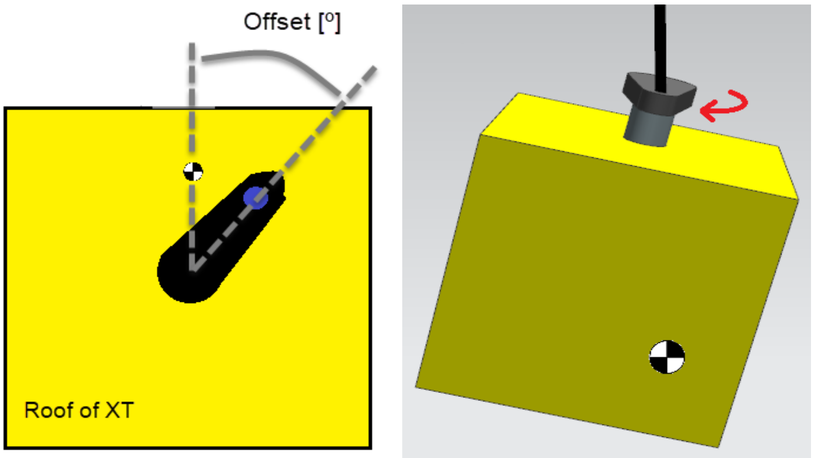


Figure 41: Lifting above COG



(a) Angle misalignment (b) Tilt due to misaligned tool

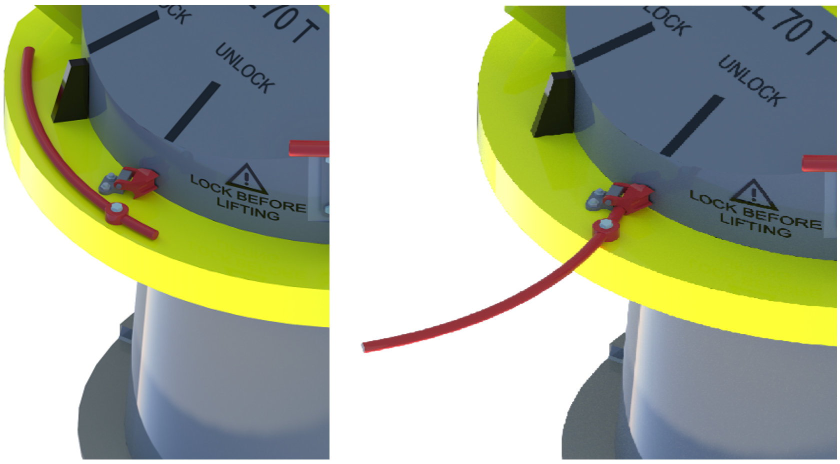
Figure 42: Rotation issue

6.1.3 User interface

A practical and safe user interface must be present at the XTHT. This subsection describes the interfaces which the tool is equipped with. Focus on functionality and the safety for the operators have been given high priority during the design. For example, is all the user interfaces painted with a clearly visible red colour.

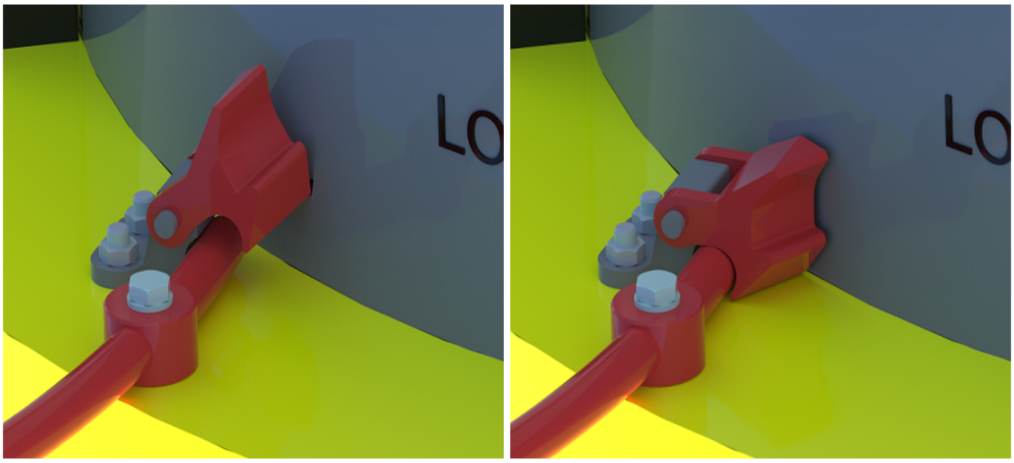
Lock or unlock the tool from the spool

The tool is connected/disconnected to the spool by rotating the yellow locking ring. The operator do this by the handle shown in Figure 43. Indicators verifies locked or unlocked position.



(a) Retracted position (b) Extended position

Figure 43: Locking ring handle



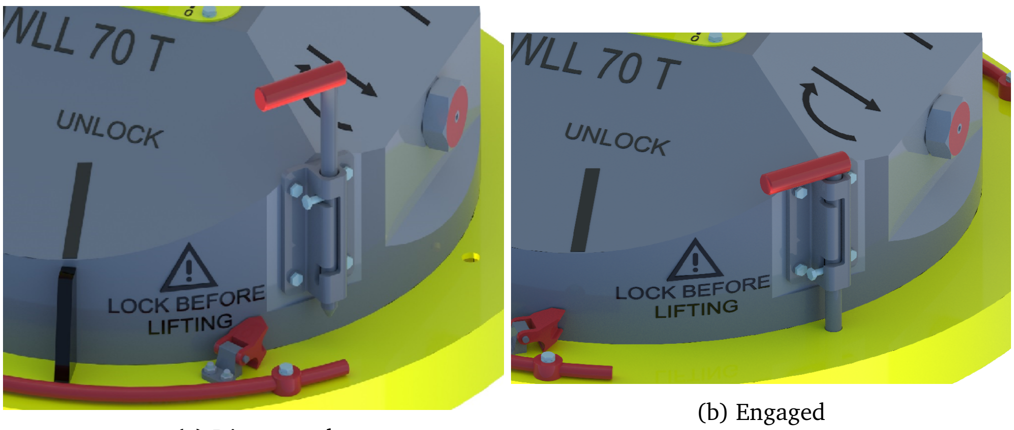
(a) Open (b) Closed

Figure 44: Hinged clamp

Figure 44 shows the hinged clamp which connects to the rear part of the handle. The clamp automatically locks the handle in its extended position, enabling the handle to be used in both directions. The hinged clamps opens when the rear part of the handle push at the conical face of the clamp. Lifting the clamp up will release the handle after usage.

Securing the lock position

The tool its secured in locked position with the secondary lock pin, which penetrates the locking ring. The pin is easily operated and shown in Figure 45.



(a) Disengaged (b) Engaged

Figure 45: Secondary lock pin

6.1.4 Position the lifting lug

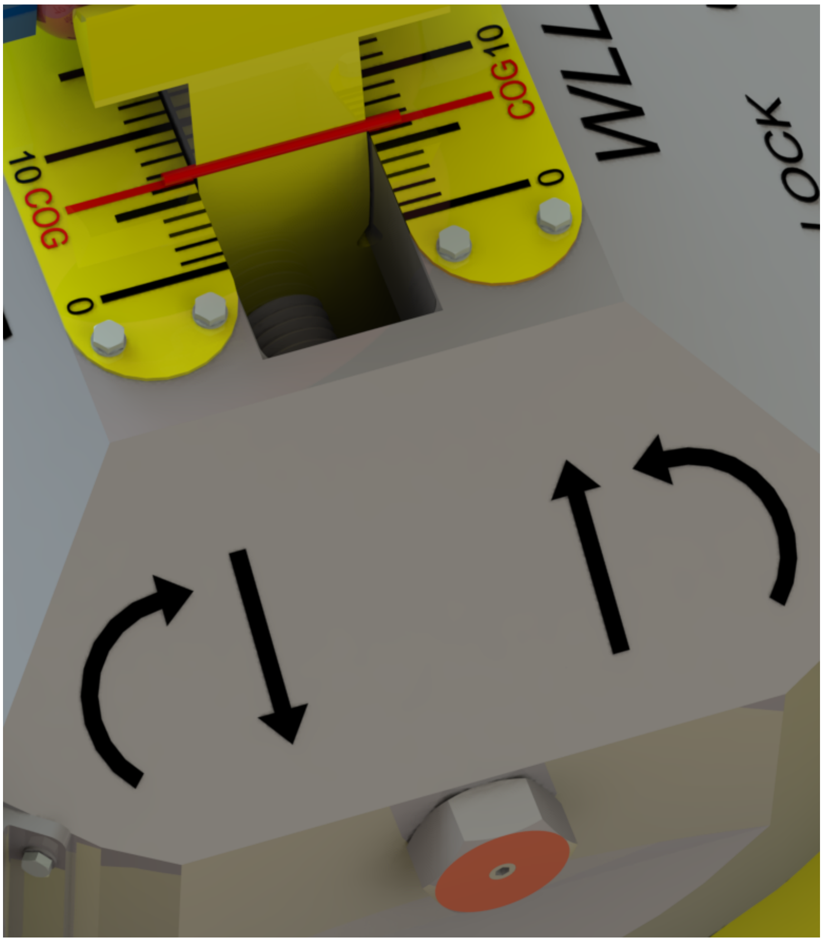
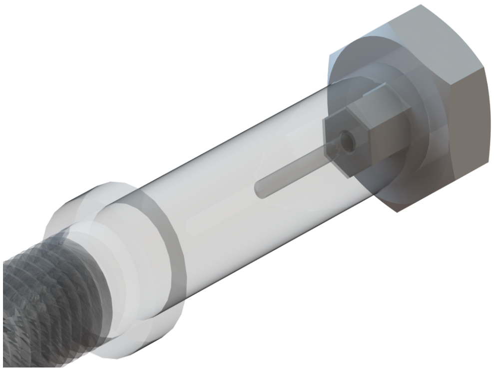


Figure 46: Position the lifting lug, interface

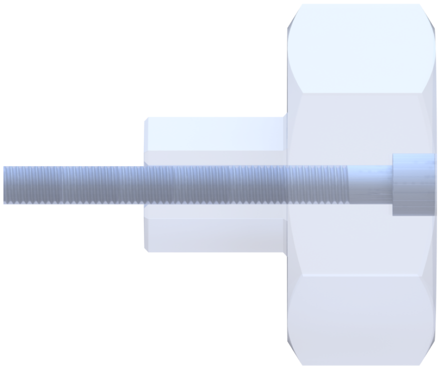
The operator displaces the lifting lug by turning the hex screw head by a ratchet wrench. The ruler verifies the correct lifting lug position, which is painted at the roof. The lifting lug must be settled to "COG" position when only the tool itself is lifted. The arrows painted above the screw head describes the straight line motion of the lifting lug due to rotation of the head screw. All these details in shown in Figure 46

Note: Procedure of painting the positions at the roof is covered in appendix F - "Roof drilling procedure"

Caution: The ratchet wrench shall be safely secured with fall protection equipment when operating the tool at the XT roof.



(a) Hex adapter interface to the screw



(b) Hex adapter securing bolt

Figure 47: Hex adapter

Figure 47 shows the hex screw head and its interface to the screw. The figures shows that the screw head is replaceable and secured to the main screw by a small bolt. The purpose of this design is to could replace only the hex head if it get worn down, instead of the whole main screw. I also enables easy changing of interface.

Shackle

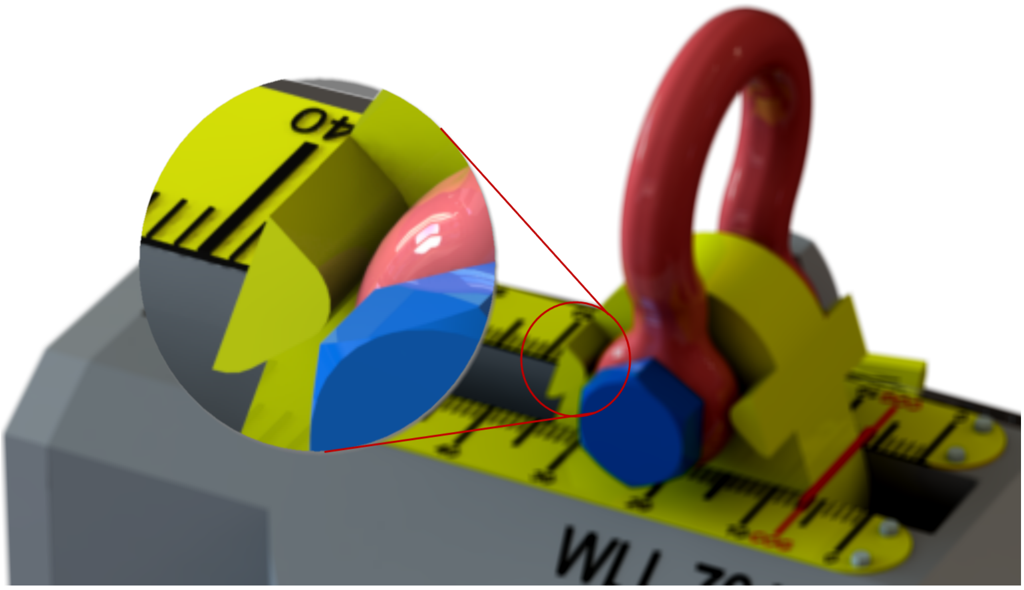


Figure 48: Shackle stopper

The crane hook needs be attached or detached from the shackle during the start and end of the lifting sequence. The operator would then be in contact with the shackle, and to reduce potential crushing hazards and ease the operation, an arrangement at the lifting lug is designed. The arrangement or the "shackle stopper" prevents the shackle to fall down at the main body. Thus, it also prevents unnecessary wear to the ruler and the main body.

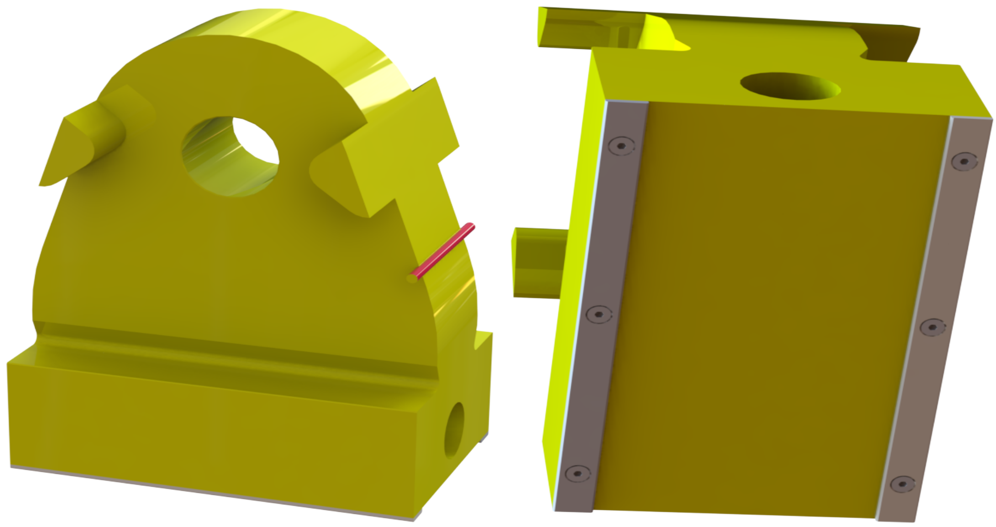
Rotating the tool towards COG

No user interface at the tool is necessary to rotate the tool and penetrate the anti-rotation pin into the applicable hole in the roof. The operator rotates the XTHT when the tool has entered and almost landed at the spool. The operator easily push the XTHT around with some "no-touch" equipment, while the tool rotates in the swivel at the crane hook. When the XTHT has rotated sufficiently, the anti-rotation pin penetrates into the roof hole by itself (gravity).

6.1.5 Design intentions

Lifting lug

The following figure and list describes the different intentions of the lifting lug design:



(a) Overview (b) Nylon rails

Figure 49: Lifting lug

- "Shackle stopper", described in the previous section.
- The lifting lug height is extended to avoid conflict between the crane hook and top of the main body.
- Rails made of nylon is screwed at the bottom of the lifting lug, as shown in Figure 49b. The material properties for nylon is softer and has a general lower friction coefficient [7] [8]. This will result in a lower resistance in the interface which would make the lug easier to displace, as well as the nylon would be worn out and not harm the main body. The holes in the rails are countersunk, which prevent the screws from grinding at the main body.
- Large radii around edges which goes along the load path. This decreased the stress concentration drastically and was necessary to get within the requirement. Referring to appendix D - "Calculation Report" for the calculations and Figure 50 which clearly shows the radii.
- The lifting lug is weight optimized during FE analysis to make it easier to displace.

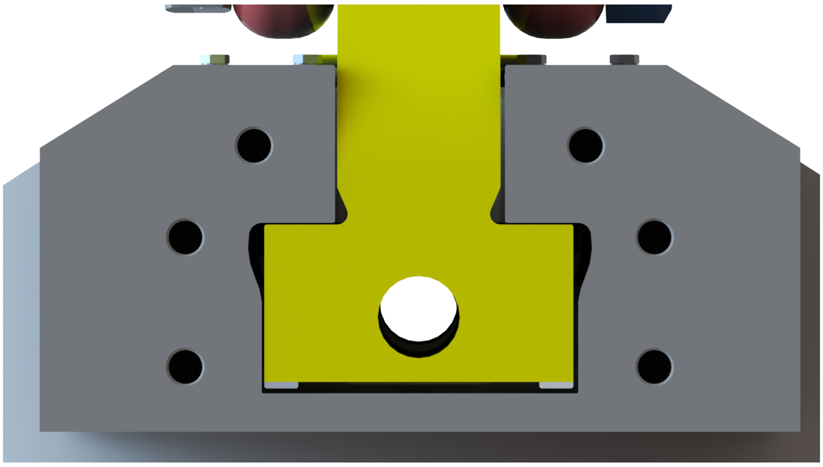


Figure 50: Interface between lifting lug and main body

Main body

Figure 51 and the following list describes the different intentions of the main body design:

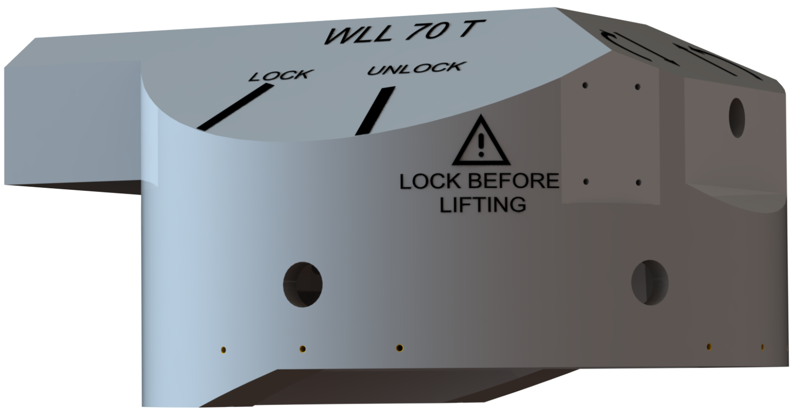


Figure 51: The main body

- Large radii around edges in the lifting lug interface. Same intention as for the lifting lug. See Figure 50.
- The body is designed much more solid on off-center side, were the tilted locking dogs is located. This is necessary due to the large load generated to this area during off-center lifting. See Appendix D - "Calculation report" for further details.
- The design of the body have been regularly considered with Aker Solutions when it comes to machining or if there are other manufacturing possibilities. The manufacturing process leader considered the design as machinable. See Appendix J - "Meeting reports and mails" for some discussions regarding this.
- The design of the main body is mostly cylindrical, and thereby is the risk of the lifting wire to snag at any area of the body considered low .
- Clearly visible text and indicators at both sides of the main body.

Locking dogs

The following figures and list describes the different intentions of the locking dogs design:

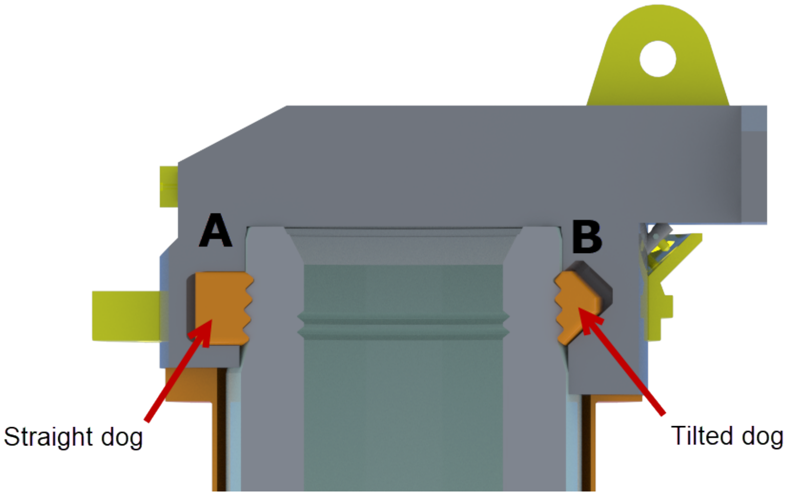


Figure 52: Locking dogs, section view

- General
  There is a total amount of six locking dogs in the XTHT, which are inspired from the locking dogs used at the hydraulic TRT (See appendix A for TRT reference). The intention of this is to use the most solid locking dog Aker Solutions have in their system, due to the high loads generated during off-center lifting. The locking profile is standard due to the H4 profile which the dogs connect to. The H4 profile is an interface used worldwide and further explained in appendix A - "Design basis".
- **Tilted locking dogs**

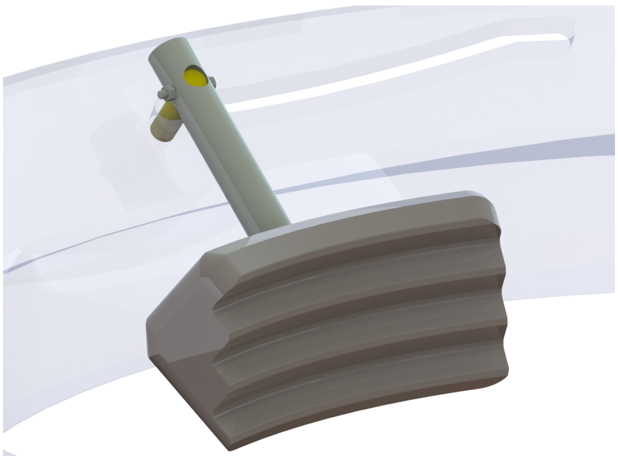


Figure 53: The tilted locking dog and its transparent interface

The tilted locking dog shown in Figure 53 has an angled support face, which interfaces to the housing in the main body. The angled support surface is at 45°, which is equal to the angle in the locking profile of the dog, as well as the H4 profile. This design will result in a straight and complete load transfer through the tilted locking dog, from the H4-profile to the main body. This is due to the equal angles in the different support faces. The lifting load would thereby act in the same direction as the normal forces in the support faces. Hence, the locking ring would not experience any loads. Figure 55b shows the load path through the parts.
Note: This design intention regarding the load transfer is currently used by Aker Solutions.

- **Straight locking dogs**

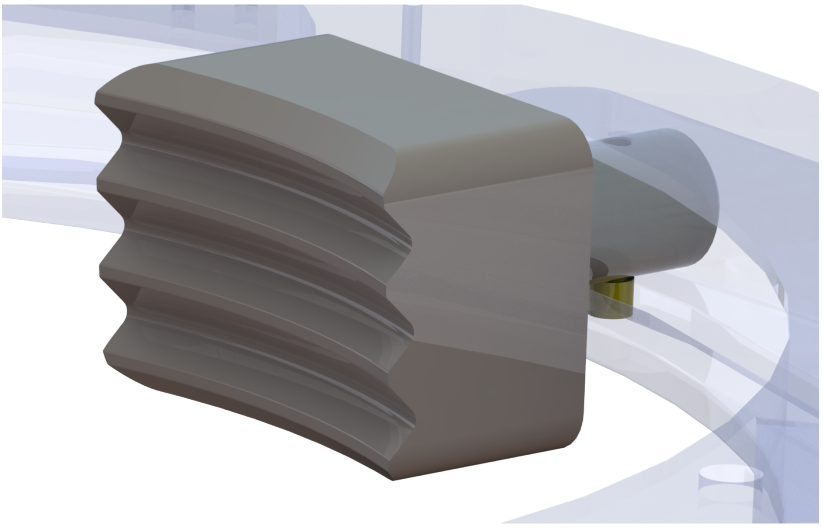
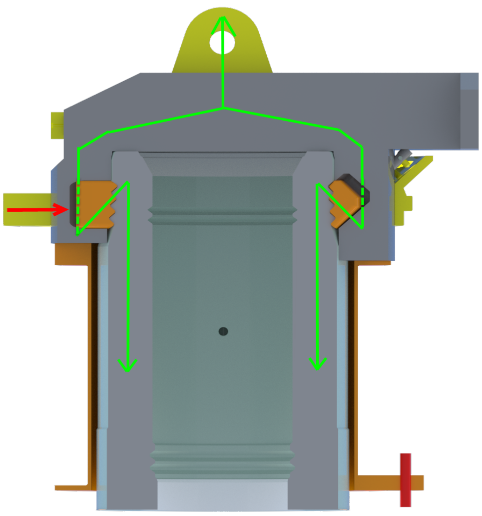
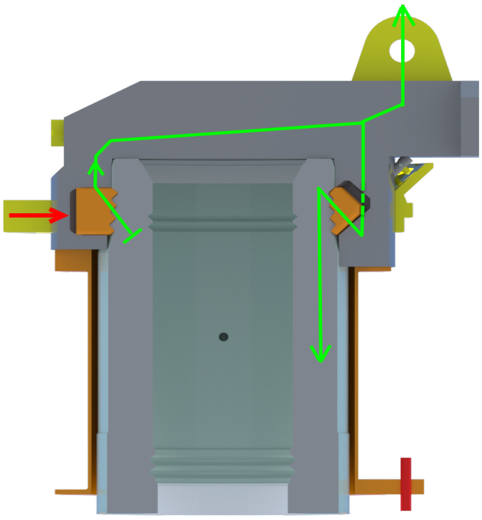


Figure 54: The straight locking dog

The same design intention could not be used for the straight locking dogs, due to the off-center lifting feature of the tool. Referring to Figure 52 for tool side specification, the load path will shift direction at the A-side of the tool, as the lifting lug displaces past the B-side. If the straight locking dog was tilted, the main body would not experience any loads at the A-side during an off-center lift. The locking ring would need to withstand all the loads, as the load path at the A-side has changed its direction (See figure 55b).
Tilting the dogs in the opposite direction would have created the same issue during a center lift (See figure 55a).
Based on this, the locking dogs at this A-side of the tool were design straight, perpendicular at the spool. However, due to the 45°angled surface in the locking profile, a horizontal force will be generated (shown as the red arrow in Figure 55). This load is transferred into the locking ring through the transmission pin. Figure 54 shows the transmission pin (behind the locking dog), while the locking ring is transparent. Appendix D - "Calculation Report" covers the loads in detail.



(a) Load path during center lift



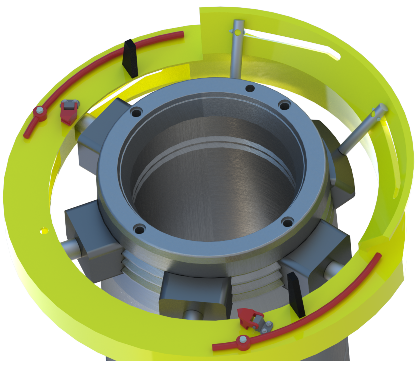
(b) Load path during off-center lift

Figure 55: Load paths

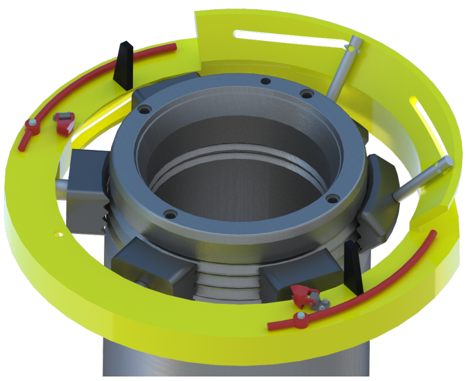
Locking ring

The following list describes the different intentions of the locking ring design:

- The locking ring is inspired by the currently used XTHT and LTRT, and combined into one locking mechanism. The design intends to lock or unlock all the locking dogs at the same time. This is done by having guiding slots in the ring which the transmission pin follows. Figures 56 and 57 shows the locking sequence.
- The locking ring has greater thickness at the area of were the transmission pin is located when the tool is locked. The additional thickness is necessary due the horizontal force generated in the straight locking dogs. The locking ring area where the tilted locking dogs are located does not experience any load and is thereby not designed with additional thickness.

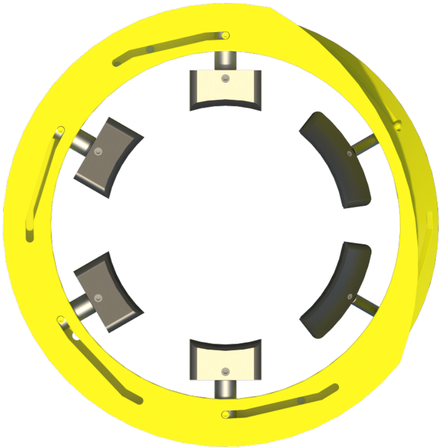


(a) Locked

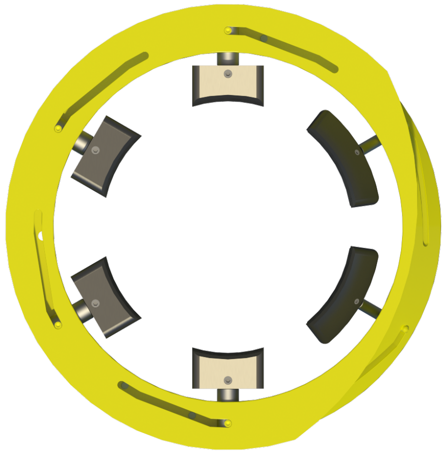


(b) Unlocked

Figure 56: Locking sequence to the H4 profile



(a) Locked



(b) Unlocked

Figure 57: Locking sequence

Funnel

The following list describes the different intentions of the funnel design:

- The lower part of the tool is designed as a funnel, instead of a pipe. The intention of this is to create some guiding properties to the tool as it enters the spool. The funnel could not have any larger angle, due to the placement of the anti-rotation pin (see dimension study in section 5.3.4). The angle and guide properties are visible in Figure 40a
- The funnel also function as base when the tool is parked on the ground.
- Base for anti-rotation pin.

Support brackets

Figure 58 and the following list describes the different intentions of the support brackets:

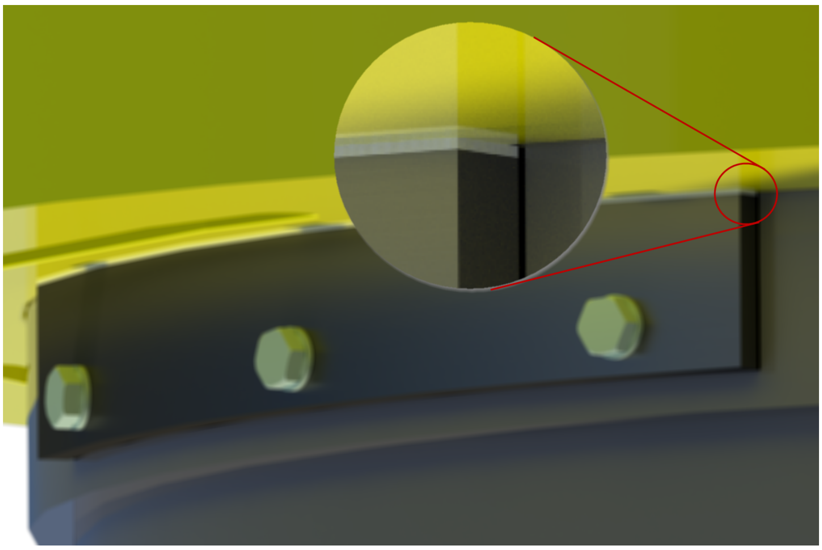
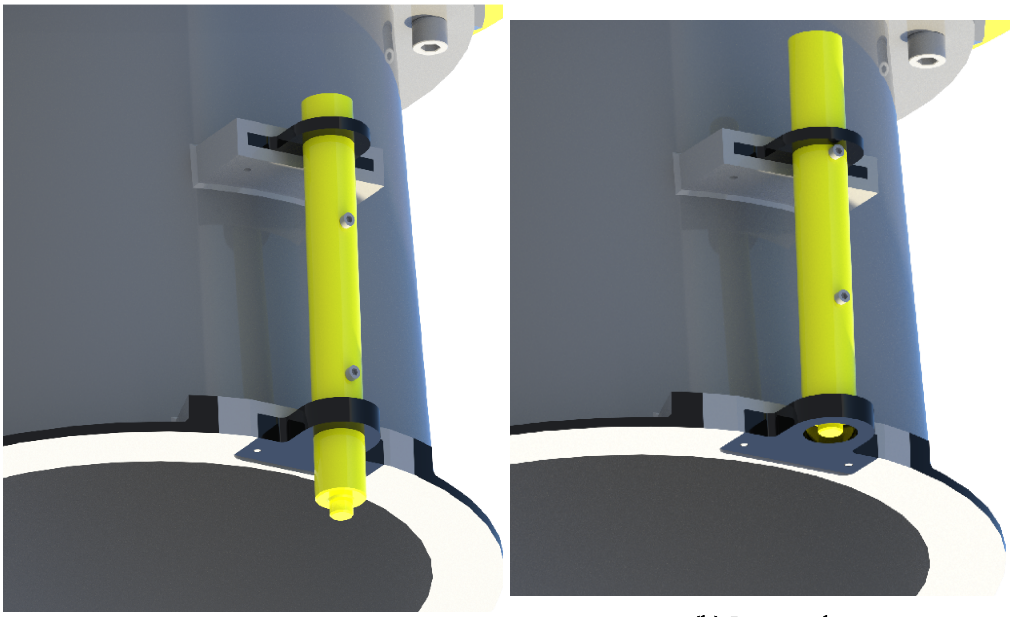


Figure 58: One of the locking ring support brackets with nylon layer.

- The support brackets support the locking ring, preventing it from falling down.
- Replaceable.
- The brackets is equipped with nylon material. The locking ring is approximately 200kg, and the nylon material will reduce the resistance due its low friction coefficient [8]. In addition with the handle, the locking ring would probably require a low torque to be operated.
  The locking ring will recede as a result of material removal. And since the nylon would be worn down over time, it is important to have the material thickness under control. A thin layer of nylon enables this, compared to a bracket which only consist of pure nylon. Inspection and monitoring of the nylon will be easier with a thin layer of nylon at the bracket.

Anti-rotation pin and brackets

Figure 59 and the following list describes the different intentions of the anti-rotation pin and brackets design:



(a) Extended

(b) Retracted

Figure 59: The two possible positions of the anti-rotation pin.

- The anti-rotation pin function as a position indicator and as the name implies, to prevent the tool from rotating on the spool. The risk of the tool to rotate occurs due to a misaligned tool in an off-center lifting position. The importance and calculations regarding this issue is covered in detail in appendix D - "Calculation Report".
- The anti-rotation pin works with the gravity and thereby there is no need for the operator to control the pin. The pin would also ascend as the tool hits the floor. The two bolts at the anti-rotation pin prevent it from falling out of the brackets.
- The anti-rotation pin is equipped with two replaceable brackets, as Figure 59 shows. These are replaceable with the purpose of having the possibility to change them into extended or decreased brackets, in case some XT roofs conflicts with the

present anti-rotation pin radius. A study was done in section 5.3.4 to find an appropriate radius.

- The brackets are attached to the funnel by two screws at each bracket, where the hole diameters are enlarged. In this way, the screws would not experience any shear stress due to an angle misalignment of the tool. The result would be a complete load transfer through the bracket housings. See appendix D - "Calculation Report" and appendix G - "Manufacturing proposal" for reference.
- The distance from top of the spool to the roof varies from project to project. A study regarding this is covered in section 5.3.4, where the maximum distance was measured to 1051mm. The funnel and anti-rotation pin is designed with the following dimensions:
  - Distance from landing shoulder to bottom of funnel: 1000mm
  - Stroke length of anti-rotation pin: 120 mm

  Note: The tip of the anti-rotation pin is 20mm long and it is completely retracted when the tool is parked. Due to the need for complete penetration of the roof holes, the maximum distance from the bottom of funnel to the roof is at 100mm.

End cap

The following figures and list describes the different intentions of the end cap design:

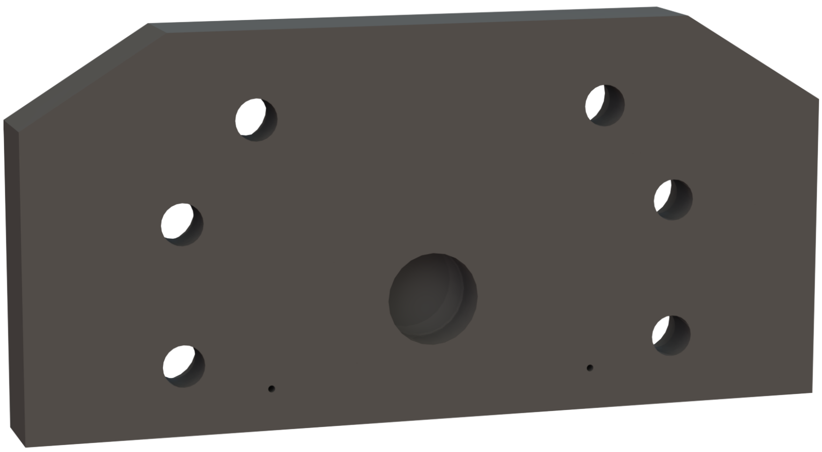


Figure 60: The end cap

- Two drain holes are drilled through the end cap to prevent trapped water. One hole in each corner. See Figure 61
- The end cap design enables easy assembly and maintenance of the lifting lug and screw.
- The diameter of the hole which support the main screw, shown in Figure 60, is enlarged. The intention of this is to prevent the main screw from experiencing bending stress. In this way, the screw will only experience axial load due to a tilted lift of the XT, which would be transferred into the endcap. The main body interface in the opposite end of the screw is design with the same intentions.

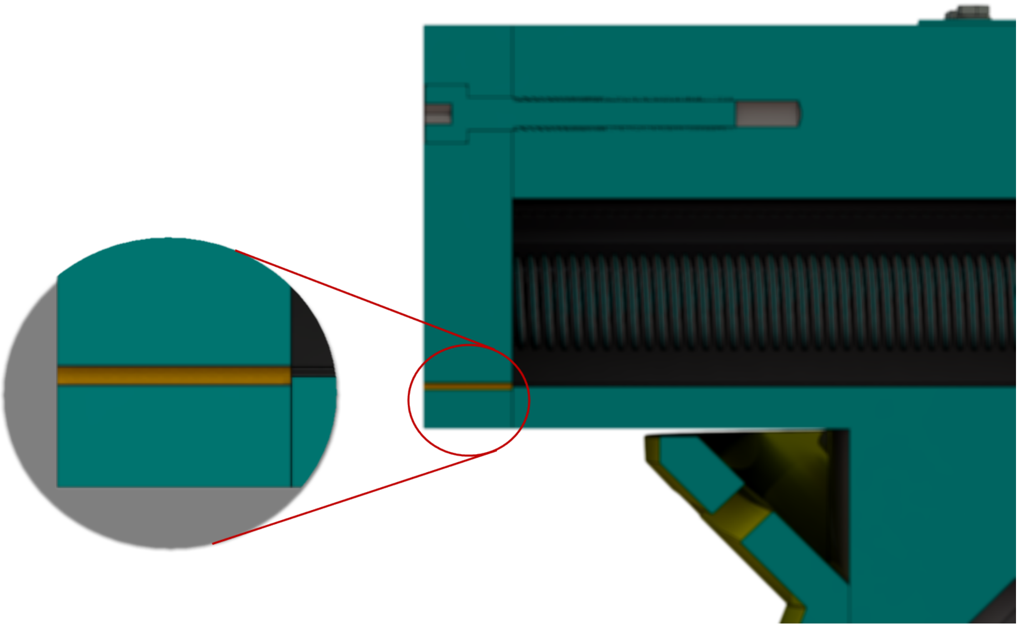


Figure 61: One of the drain holes

6.2 TRT - Final design

Figure 62 shows the final design and result of the TRT. The different design intentions and more figures are covered in appendix C - "Concept of TRT".

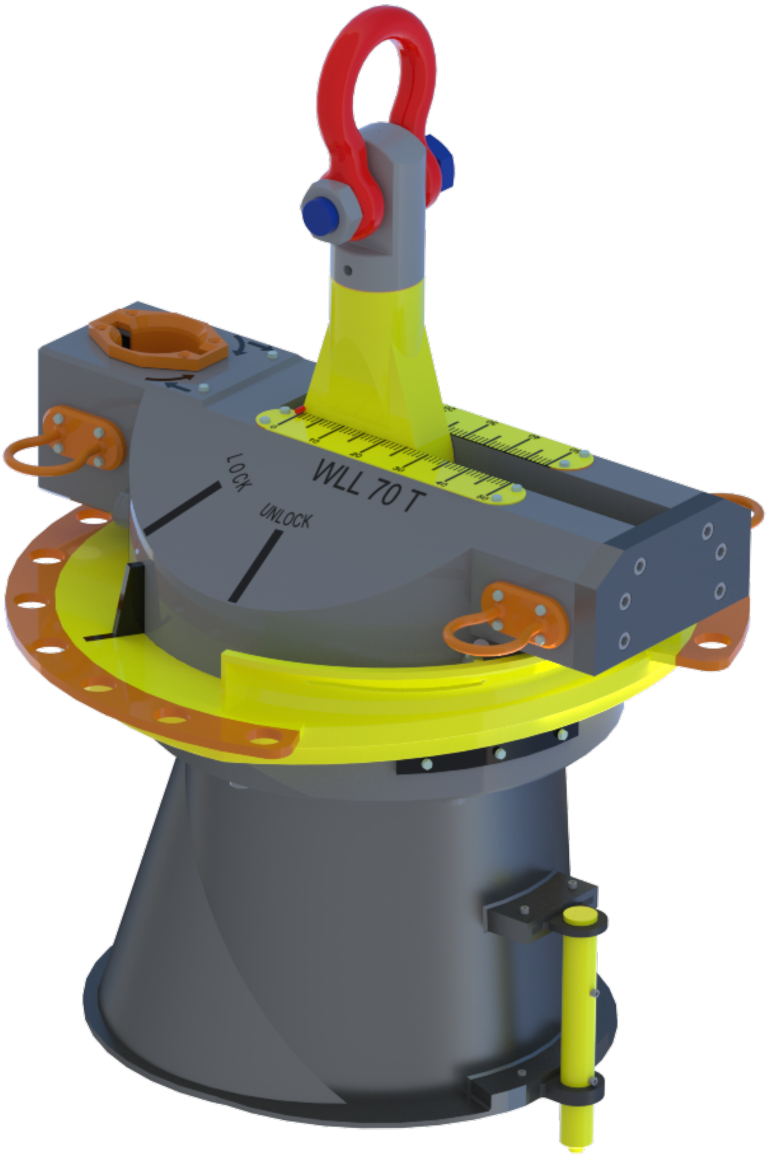


Figure 62: TRT final design and result

7 Discussion

This chapter discuss the results and work done throughout the thesis period. It also includes potential improvements of the tool, as well as further work which is considered as necessary before a possible implementation.

The product development of both the XTHT and the TRT is based on the product development methodology and include the three first phases: "To see", "To create" and "Prepare". The work regarding the TRT is carried out in the first two phases, where the final TRT concept is inspired by the XTHT and equipped with ROV interfaces. The concept is considered to be good basement for the possible "Prepare phase" for this tool.

The XTHT is considered to be a safe and user friendly lifting tool. The design basis evaluates all lifting scenarios of the tool, and detects all known limitations and possible failures that could occur. This makes the tool compatible to perform in a safe manner in every intended lifting operation. In addition to that, the tool is equipped with simple user interfaces to avoid confusion and increase safety during use. On the other hand, the students does not possess high knowledge in offshore related operations, and situations which could restrict the XTHT's functionality can have been overlooked during creation of the design basis.

The weight of the XTHT is at 2343 kg, which is less than half the weight restriction at 5000kg. Today's XTHT has a weight of 780kg [9]. The business case shows that the tool weight is way below a typical CW, which means the total lifting load has decreased. This could for example lead to easier operation offshore and longer operational weather windows.

The structural integrity of the tool and its 70 tonnes lifting capacity is confirmed through the calculation report. However, these calculation needs to be verified by competent personnel.

The main objective of this thesis was to develop a XTHT which could compensate for a potential CW removal. In the end, the final result is considered to be a great solution which fulfills the objective. The additional TRT concept is also considered to be a good base for further work.

However, the tool has the possibility to be improved, which is reflected in the next section. The consecutive section also list work which is considered as necessary before an implementation.

7.1 Potential improvements

- To lower the risk of the tool to be positioned in the wrong verification hole at the roof, the holes could be drilled at different radius. However, than the anti-rotation pin at the tool must be modified to enable multiple radius configurations.
- The cantilever beam at the main body could be improved when it comes to snagging. The underside could be added with some curved geometry made out of PVC material (or similar material) to easy guide the wire away from this area.

- To ease the assembly of the tool, make threaded holes for eye bolts at the main body and at the locking ring.
- If desired, a set screw could be implemented at one of the anti-rotation pin brackets to prevent the pin from falling down during tool lift and getting in the way.
- Secondary lock to anti-rotation pin.
- At new XT's, the MVB could be modified with an anti-rotation interface, instead of using the roof and the anti-rotation pin. For example could a fixed annulus with teethes be attached to the spool and the roof would only be used as position verification.
  - *Note: The students was recommended in start of the thesis period to not modify the MVB. Therefore, the XT roof is exploited as an anti-rotation barrier for the current solution. However, the advantage of using the roof is that it enables easy modifications to existing XT.'s*
- Look at the possibility to use low friction coating instead of nylon to make the lug and locking ring even easier to operate.
- For even easier user interface, use a "Easy-Loc V2, Shackle bolt securement system", from Crosby [10]. See reference.
- While performing the roof drilling procedure, a camera which is attached to the XTHT could film a level to verify the horizontal alignment. With livestream, there is no need for the operator to physically place a level to the XT. Such an implementation would increase the safety in a already risky operation. See appendix F - "Roof drilling procedure".

7.2 Further work

- Verify the calculations and reproduce FEA nr.6. See appendix D for details.
- Verify the design basis
- FEA of the XT framework, where the torque generated during a misaligned tool is simulated. It is expected that this would not be a problem due to the solid structure of the framework, and that the anti-rotation pin would be the weak link.
- Conduct a tolerance study between the main body and the locking ring at side where the tilted locking dogs are located. The straight locking dogs act on and push the locking ring at the opposite side, and thereby would the support face of the locking ring sustain equilibrium. The tolerances here are important as it affects the engagement of the locking dogs.
- Make assembly procedure
- Verify the manufacturing drawings. Control the tolerances and optimize for machining if desired/needed.
- Implement a verification for proper landing at the spool.
  Some suggestions:
  - Pep hole in the main body to physically see and verify proper landing of the tool.
  - Paint a red verification line at the spool, which the funnel will conceal when the tool has landed.

7.3 The students review

We have experienced the thesis project as precise, interesting, challenging, fun, and most of all acquired high learning outcome at many aspects in this diverse thesis.

The follow-up and guidance provided by the supervisors at both Aker Solutions and NTNU have been exceptional. Aker Solutions has in general been a professional and helpful business partner. As an example we got our own computer with fully access to their system, which were time efficient compared to communicate and share files externally.

We feel that we have increased our knowledge within product development, as this thesis included all the first three and most important phases when it comes to engineering work.

Regarding the concept phase, we realized that the most time efficient approach was to extend the phase. Removing as much uncertainty as possible and find a concept with high potential became a high priority, instead of choosing a concept which could have required a lot of extra work and time to develop. Therefore, the plan would have been created differently if the students could start over again, where more time would have been given to the concept phase.

The most challenging work in the thesis was the anti-rotation issue. However, our solutions is concluded to be a reliable, backward compatible, safe and user friendly anti-rotation interface for XT, XTHT and TRT, supported by thorough calculations and studies.

Overall, the students are satisfied with the entire thesis period and hope Aker Solutions can benefit their project.

8 Conclusion

The thesis concludes that it is possible to perform a level lift of a XT due to a CW removal, in both a safe and user friendly manner.

This is achieved by the use of the XTHT developed in this thesis. By position the tool towards COG and displace the movable lifting lug above COG, a level lift can be performed. The tool secures against rotation with the anti-rotation pin which penetrates the roof.

The tool is designed with safety as highest priority and has proven its 70 tonnes lifting capacity through calculations. The design provides easy user interface and intends to enable simple manufacturing, maintenance and assembling. However, these aspects of the tool need to be verified by professionals.

The concept of the TRT is mostly based on the XTHT. The functionality and design intentions are the same, but the TRT concept is equipped with the required interfaces.

Both the XTHT and TRT are concluded to be a good bases for further development.

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Appendix

The following table shows the attached appendices. They are attached in the same order as they are listed in the table.

Appendix	Name
A	Design basis
B	Concept phase
C	Concept of TRT
D	Calculation report
E	Angle offset and torque calculations
F	Roof drilling procedure
G	Manufacturing proposal
H	Product data sheet
I	Plan and log
J	Meeting reports and mails
K	Manufacturing drawings

Table 12: Appendix overview

A video user manual is made, describing the simple steps of how to use the XTHT in a complete XT configuration. The video could be found in the attached USB stick or at the followng link: https://youtu.be/Arxt_RrENos