



The redesign of manual container moving equipment

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S2617358

21/10/2024

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Abstract

In this research project the redesign of the DHI wheel is presented. The project is executed commissioned by Universal Storage Containers (USC). USC is a storage container manufacturer, selling unique storage boxes: the Z-box. The Z-box is unique as it is transported as a flat package. The package can then be assembled to a complete Z-box on site in around one hour. A large part of the activities of USC is setting up complete container parks for customers all around the world.

DHI storage offered Universal Storage Container their manual storage container moving equipment. This equipment could innovate the building process of USC. However, the product was designed for American containers and therefore are not suitable for the Z-box. The goal of this project is to redesign the DHI wheels to maximize efficiency and financial benefit for the building process of USC.

The goal of the research phase was to analyse all included components and the process. This meant the Z-box, the assembly process, the forklift and the DHI wheels. Additionally, the research aimed to define which aspects define "efficiency" for this product. Concluded was that these aspects are positioning of the Z-boxes, time of use and transportability. Additionally, general performance, production and safety were included as important criteria. All the research concluded in requirements which were distributed among the criteria to substantiate them.

Concluded from the design phase was that to maximize the efficiency and financial benefit, the final design should focus most on production. To increase the efficiency however, the final design therefore includes four changes to its working principle.

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1 Introduction

Introduction

This first chapter serves as an introduction to the project. The chapter introduces the context of the project, the company and its activities. This includes all the involved components and the environment. Additionally, the challenges this project aims to tackle will be laid out concluding with the final goal of this report. After defining the knowledge required to start the design phase, the important stakeholders will be analysed. Finally, the structure of this report is visually presented.

1.1 Context mapping

Universal Storage Containers (USC) is a company manufacturing unique storage containers. In figures 1a to 1c this so-called “Z-box” can be found. The aspects which make the Z-box unique, is the fact that they are foldable making them extremely space efficient in transport and very easy to assemble, benefitting both company and client financially. The folded state in which the containers are transported is shown in figure 1b. Besides this the Z-boxes are insulated making them resistant to weather changes as well as different temperatures. Finally, the Z-box comes in 6 different models varying in compartment amount and size as seen in figure 1c^[1], this also means variation in the number of parts and the total weight of a container. USC not only sells the storage containers, but they also sell complete storage parks to clients all over the world. This includes the complete process of planning, determining the number of containers possible, but also complete transportation, assembly and setup of the containers in the park. Lastly, the company provides useful accessories ranging from solar panels and electricity to locks and visual branding.

Figure 1: the Z-box



Recently, a company called DHI storage introduced to USC a new unique product which could be very beneficial for the assembly process of the Z-boxes. DHI presented the product to USC as they are interested in selling their product to storage box manufacturers. The product is a dolly wheel which can, when four separate wheels are used, completely mechanically lift a storage container. In figures 2a to 2c the DHI wheel is shown. Currently, the assembly processes are carried out with a forklift. These wheels obtain their value by being significantly smaller and therefore easier to transport than a forklift as well as the fact that they can be operated by anyone. These wheels could potentially eliminate the use of a forklift in multiple steps of the assembly process. This increases the efficiency by not being dependent on the forklift as well as the ease of handling. Most importantly, if the heavy machinery can be eliminated to some extent, it could lead to financial benefit.

Figure 2: the DHI wheel



(a): DHI wheel sideview



(b): DHI wheel front-sideview



(c): DHI wheel side-back view

1.2 Main challenge

The largest part of the activities of Universal Storage Containers is the assembly process. Currently, the steps of this process are performed with the help of a forklift of some sort. This forklift and most tools must be acquired by the client, aided by instructions of USC. The forklift is required to be able to lift 4,5 meters high and have an inner distance between the forks of at least 92mm. Besides that, it is also required to have side shift, meaning it can move the forks sideways, to be able to efficiently place the assembled storage boxes in the correct position next to the other boxes. Even though the customers receive complete specifications for the machinery, often it still results in the incorrect machines. This means the assembly process is slowed down significantly by either the assembly team having to wait for correct equipment or them having to figure out a less efficient way to work with the machine. Added to this is the high cost of renting this machinery in the first place, if this could be to some extent eliminated, it would result in a cheaper process.

Since a large part of the USC activities revolves around the assembly and positioning of storage containers, an improvement on this field is very interesting for Universal Storage Containers. Therefore, the company wants the wheels to create as much value as possible for them. For this reason, the main challenge will be to redesign the presented wheels as well as possible, meaning for them to fit as greatly as possible into the USC system. This value is largely generated by replacing or outperforming the heavy machinery as much as possible and therefore saving as much money and time as possible. However, to achieve the replacement of as many activities of the forklift as possible, some redesign is necessary. Currently, the DHI wheels are only designed for the short sides of the containers resulting in the wheels not being able to accurately place every container. Additionally, as the wheels are designed for American containers, they do not fit into the Z-box. This

must be resolved as Jan-Hein Streppel, partial owner of USC stated: “look and feel are essential”. This means the containers should be placed next to each other emitting a professional look towards the customers.

The DHI wheel could replace the forklift to some extent to further innovate the assembly process. The main challenge this research aims to solve is therefore:

“What is the best possible redesign of the DHI wheels to provide the most added value to the building process, while maximizing efficiency and financial benefit?”

1.3 Desired knowledge

In order to answer the main design question a lot more information needs to be obtained. To start with, all the involved components need to be analysed and documented. Then the concerned process of creating a container park should be looked into. This includes every step from transport to assembling a Z-box to positioning them. Important aspects are in which steps a forklift is used and in which of these steps its utilization could be replaced by the new product. Next, a comparison between the DHI wheels and a forklift should be executed. Here the differences between the two will highlight the benefits and downsides of both the current method and the potential new method. The goal of the research is to gather all the needed information and to define what “efficiency” includes.

1.4 Stakeholders

To get a better understanding of which parties are involved with the redesigned process, which parties have an interest and which parties it has an impact on, a stakeholder analysis is performed.

DHI storage

DHI storage is the designer and creator of the dolly wheel product. They are interested in selling the product to the clients of universal storage containers. The redesign is interesting for them as it could result in many potential customers.

Universal Storage Containers

USC is a producer and seller of storage containers and complete storage parks. The company is interested in the new product to make assembly and setup of the storage parks more efficient and make the usage of expensive heavy machinery irrelevant.

The production factory

The factory is responsible for the production of the DHI wheels, in case of changes in the design either this factory has to adapt to the changes, or a new production partner needs to be found.

The transportation company

The transportation partner moves the product from point a to b. in case of design changes this process can either be influenced positively or negatively depending on the final specifications of the product.

USC customers (Salland Storage)

Clients of USC buy storage containers or complete parks. They could be interested in the redesign as financial and, or time-based benefit for Universal Storage Containers could result in financial benefit for clients.

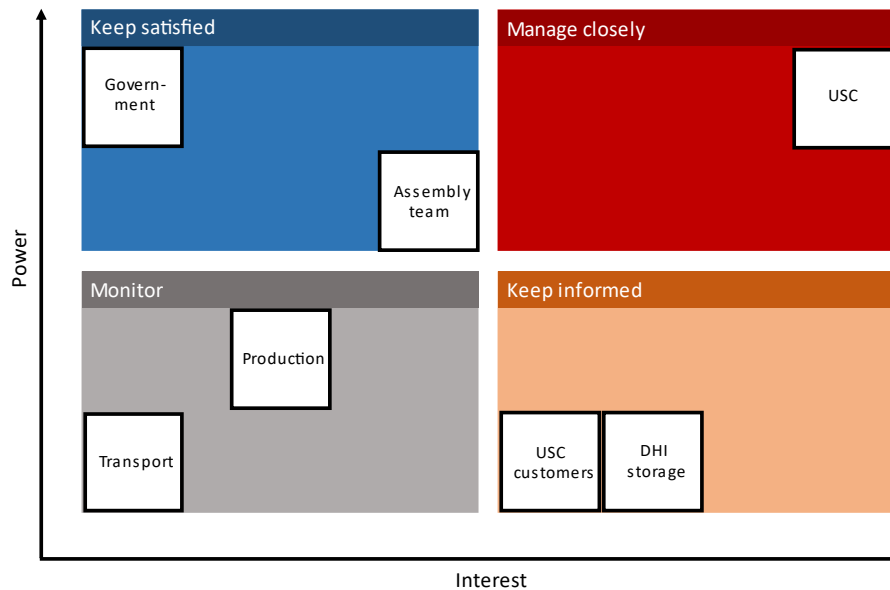
The assembly team

The assembly team is responsible for assembling containers and the complete storage parks and therefore the end user of the product. The team is interested in the wheels as it could potentially make their labour more efficient, faster or less physically demanding. While on the other hand, could also result in the opposite. They are important to consider widening the scope of the value not only to value based on time and money, but also to take a look at the impact it has on human labour.

1.4.1 Stakeholder analysis

In figure 3 below the stakeholder map is shown. The most important actor is Universal Storage Containers, as they are the direct client of this project and desire to use the redesigned product. The other actors are less important, the government must be adhered to, and the assembly team must be taken care of. DHI storage is interested as they could potentially sell more products. The customers of USC are mostly interested in the product as they could purchase the product for own use. Finally, the production and the transportation companies both need to potentially adapt their processes to conform to the new product.

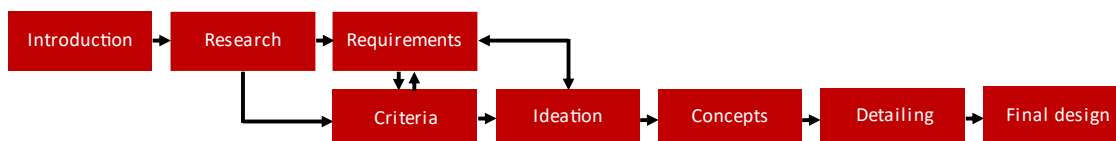
Figure 3: stakeholder map



1.5 Structure of the report

In figure 4 below the structure of the report is visually presented. Each block represents a building block for this report while each column represents a chronological step forward towards the final design. The blocks are connected with arrows which indicate a direct “based on” relation.

Figure 4: structure of the report

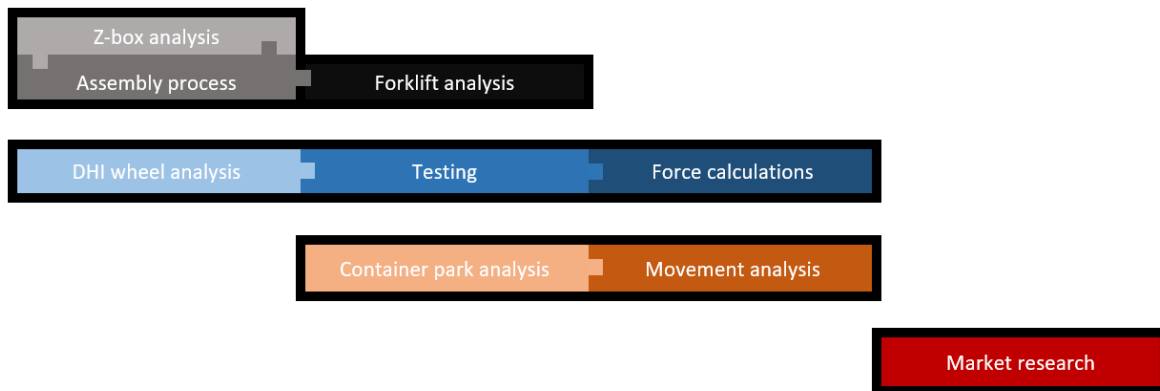


2 Research

Introduction

In figure 5 the layout of the research is presented. The goal of this chapter is to gather all information needed to answer the research question and to determine the most important aspects for a manual container park assembly product such as the DHI wheel. The research will therefore conclude in requirements and six important criteria which will substantiate the design phase.

Figure 5: structure of the research phase



2.1 The Z-box

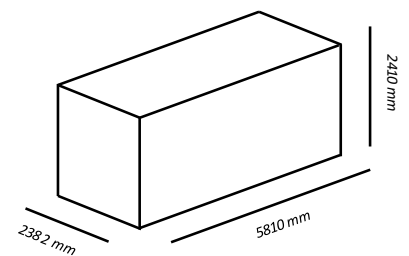
Introduction

In this research the used storage container, the Z-box, will be completely documented. The research will clarify the main features, specifications and the different models Universal Storage Containers produces. Most importantly, the research will focus on the different components the Z-box consists of. The goal is to analyse holes and ridges on the different components by specifications and geometry to find all the possible attachment points for the DHI wheel to the containers and to understand these. By getting insights into geometry and dimensions, requirements can be created, and the design can be adjusted to the storage containers.

2.1.1 General

The cause for the Z-box being award winning, is its unique configuration upon transportation. It is prepared for transportation as a flat package. The Z-box has four main parts, the floor, the long side walls, short side walls and the roof. Additionally, some models of the Z-box have dividing walls for division of the storage space. For the package to be flat in transport the components are pre-assembled. The configuration starts with the floor on the bottom, the short and long side walls are attached to the floor and folded down on top, if required the separating walls are then placed on these and finally the roof is placed atop independently to finish off the package. The different models all have the same outer dimensions being 5810 x 2382 x 2410 mm ($l*w*h$) [2], as illustrated in figure 6. As the different models have a different number of parts the mass differs as well. The mass ranges from 1410 kg to 1850 kg.

Figure 6: Z-box dimensions

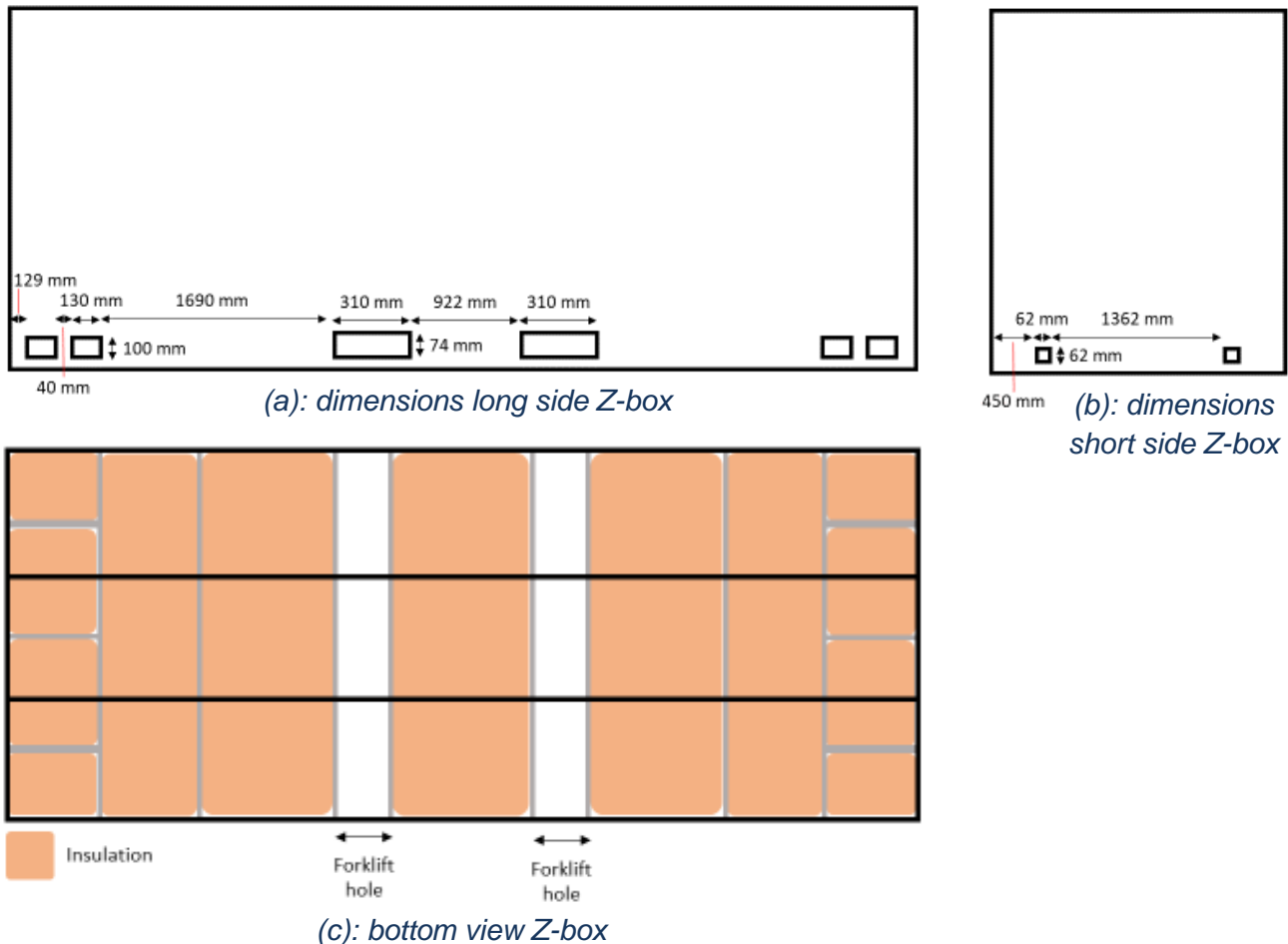


2.1.2 The floor

The first component to take a look at is the floor. All the dimensions are based on internal SolidWorks models, crucial dimensions are checked with a tape measure. The floor has several holes on the long and short side as well as many different beams on its bottom side. Schematic drawings including all the different dimensions of the holes are shown in figures 7a and b. On the long side the largest holes are meant as forklift attachment points and extrude all the way across the width of the container. The smaller sets of holes near the edges are meant for hooks and chains and extend only 664 mm. On the short side the container has two identical holes, these holes are intended for wheels to attach to. The holes are 632 mm deep.

On the bottom of the floor many different beams are located, some for structural strength, other for the holes to exist. All the beams are Q235 carbon steel. In figure 7c the lay-out of the floor is illustrated. The darker set of beams are the lowest and will lie on the ground surface. The lighter set of beams are attached to the surface of the floor part and will not touch the ground surface. Underneath these lower beams lies insulation. This is very soft material and is secured to the bottom of the floor with a 1 mm thick plate making it very vulnerable to any sort of pressure.

Figure 7: Z-box dimensions

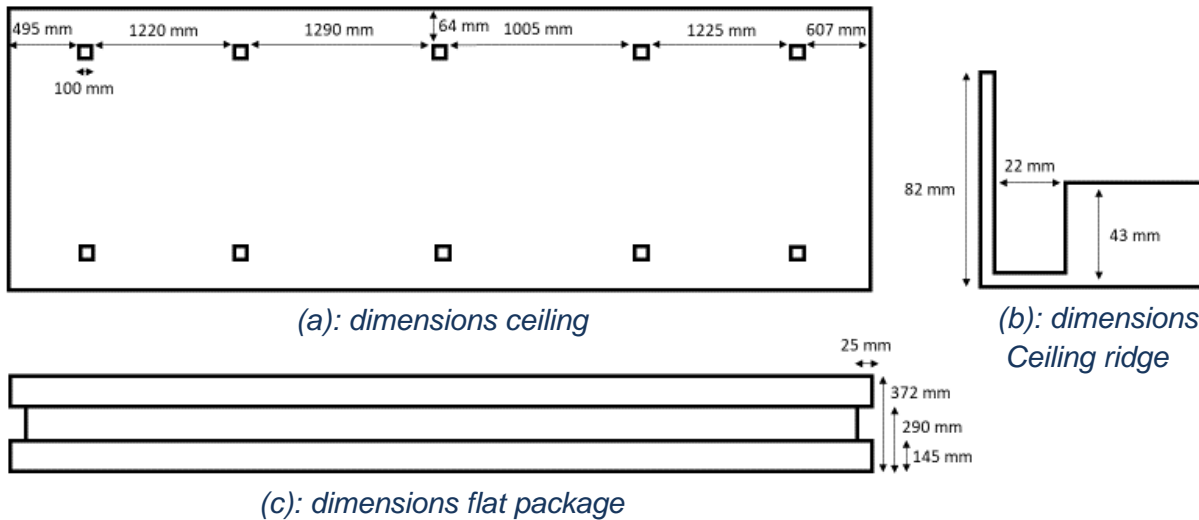


2.1.3 The ceiling

The other part that needs to be moved during the assembly of a container is the roof. The roof is practically a simple plate with a thickness of 43 mm that weighs 350 kg. However, it has some interesting aspects to it. First of all, for the ceiling to fit onto the walls, it needs a slot where the walls fit into. This slot is depicted in figure 8b. Additionally, the ceiling has 5 indentations along each long edge, these holes are illustrated in figure 8a. An important difference between the previously mentioned holes of the floor is that these holes are oriented vertically instead of horizontally.

In figure 8c the flat package on which the ceiling is placed during transport is illustrated. The package has the same dimensions as the assembled containers except for the height.

Figure 8: ceiling dimensions



Conclusions

In conclusion, after diving into all the different important structures and aspects, it becomes clear the redesigned wheel could be designed to be able to utilize many different holes with different dimensions. The specifications of these attachment points range from 62 mm to 310 mm in width. And from 62 mm to 100 mm in height. Additionally, there is the ceiling with vertical holes ranging from around 21 mm to 107 mm in both width and height. It is important for the arm of the wheel to fit securely into the hole to stably move the container. Therefore, it is needed to do further research into the functions the wheels need to carry out, to determine which of these holes the wheels need to be adapted to.

2.2 The assembly process

Introduction

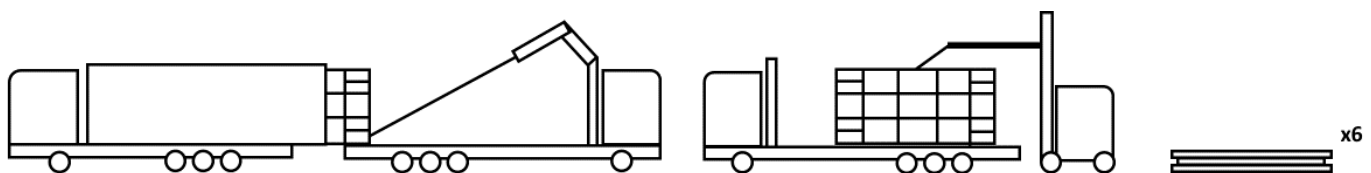
In this research the complete step by step process of assembly of the Z-box will be analysed. This includes the transportation process to the unloading, assembly and positioning of the storage containers. The process is derived from the internal document “building manual” and conversations with experienced member of the assembly team Danny Schmidt. The goal is to get a complete overview and understanding, with emphasis on the usage of the forklift and the advantages and disadvantages of this. The research will gain insights into which parts of the process can be carried out by the new wheels and which steps can be made more efficient, to then translate these into requirements for the final design.

2.2.1 Transportation and unloading

The transport and unloading process is illustrated in figure 9. To get ready for transportation, the folded Z-boxes are placed in a large 40-foot ISO-container. This is done by vertically placing six individual boxes in a rack. These racks are 6 meters long and when loaded weigh close to 11 tons. Two of these racks fit into the ISO-container one placed after the other.

The first rack is then pulled onto a flatbed truck. For the second rack there are multiple options, the easier option is to arrange two flatbed trucks and pull the second rack of Z-boxes onto the second flatbed container. As the second rack is positioned very deep inside the ISO-container, 6 meters, very long chains are required.

Figure 9: unloading process



After the racks are taken from the container, the Z-box packages need to be taken from the racks. This is done by a forklift, required to be able to lift to at least 4.5 meters as the boxes are lifted vertically from the rack on top of the flatbed with lifting straps. An important note is that specifically a forklift is very reliable in unloading the racks, this is because the forklift is very stable, it moves up in a straight motion as well as backwards. Each box package is then placed carefully on the floor ready for assembly.

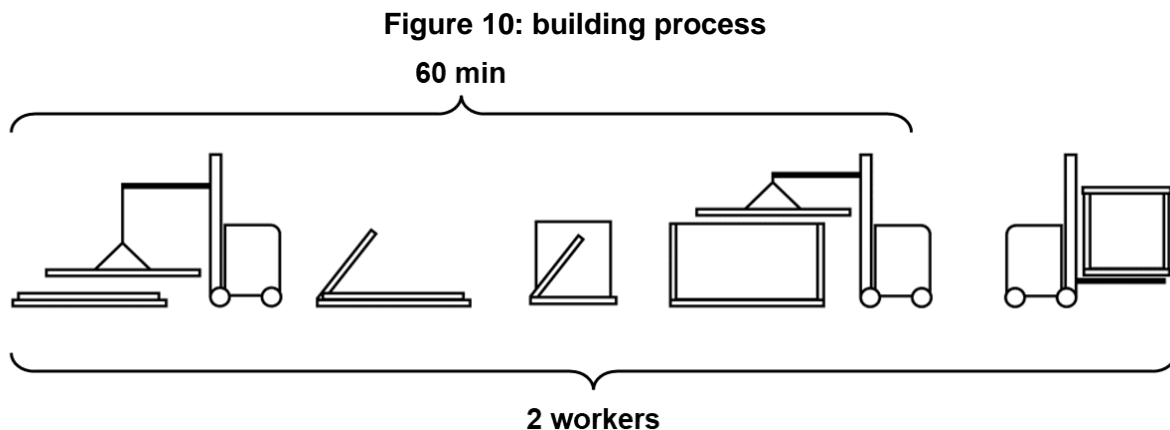
2.2.2 Building and positioning

The building process of the Z-box is presented in figure 10. In total the building process of one of the different Z-box models takes approximately one hour. This process is carried out with two workers and a forklift. To start the building process the roof is taken off the package. The roof weighs around 350kg. The roof is then placed somewhere near the assembly location for a short time.

After the removal of the ceiling, the walls can be folded upwards. This is done using manpower and is achievable with two persons. However, when a long wall has doors such as in model 5, it becomes too heavy and needs to be pulled up with a forklift. After a wall is raised it can be temporarily fixed with a bracket, when an adjacent wall is raised it can be permanently fixed with a corner piece.

After folding up and fixing all the walls, the roof can be placed on top. Again, a forklift is required, the forklift picks up the roof the same way it did before and needs to lift it at least 2.6 meters high. The roof can be gently steered by someone inside the container on a ladder, when the roof is lined up correctly it can be lowered and fixed. The container is now finished and ready to be placed in the correct location.

The forklift can pick up a container easily, however, since it can only do so from the side it results in the forklift being very wide during transportation. If the assembly has to take place in a different location this means entering the location for the park can induce difficulties. After reaching the desired location the container will be put down next to the other already placed containers, here the forklift makes use of the required side shift to accurately place it down. This process continues until all the containers are in place and the park is complete.



Conclusions

Transport and unloading

In conclusion, there are several steps in the process that make use of a forklift and are interesting to look into for the usage of the redesigned wheel. The first step of the assembly process is the loading and preparation for transport. Here the racks are loaded and placed in a large ISO-container. The requirement for the used equipment is to be able to lift the containers at least 4.5 meters. Additionally, the racks including boxes weigh up to 11 tons. This requirement is not realistic to reach for the redesigned wheel, not only do the wheels need to lift the rack, but the rack also has to be pushed or pulled using manpower.

The second step is unloading the container of racks. Here the equipment requires very high lifting. Therefore, there is very little potential for integrating the wheels.

Building and positioning

In the third step, the building and positioning, there is the most potential of integration of the redesign. Here there are many separate steps that require a forklift. Firstly, the roof is taken off the package, here there are not many requirements. The equipment should be able to carry 350 kilograms and have a structure which allows it to pick up the roof carefully and be stable to then drive it a close distance.

The second involvement of a forklift is the pulling up of the heavy side wall with doors, requirements being equipment capable of towing large weight, this again does not lie within the capabilities of the wheels. Next is the placement of the roof, here 2.6 meters of stable lifting is required which is also not realistic for the wheels. The final involvement of the forklift is the moving and positioning of the fully assembled containers. The requirements for the equipment are to be able to lift the container and therefore a mass of 1850 kilograms.

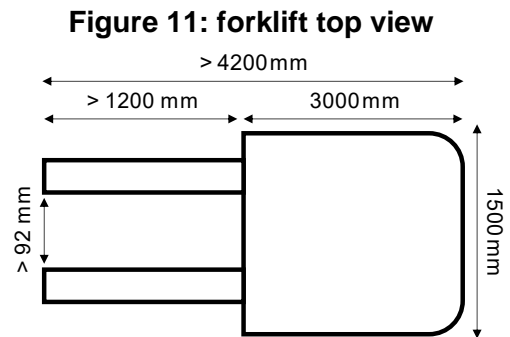
2.3 General forklift analysis

Introduction

As the forklift is currently being used during the assembly process, an overview is needed. As the DHI will take over some tasks of the forklift a comparison needs to be made. The analysis will include average costs, average size and driving speeds. The cost analysis will be used to indicate the maximum production costs of the redesigned wheels. The size analysis will result in an indication of the maximum size of the redesigned wheels. And the speed of the forklift will be used to calculate the time the DHI wheels can save. The forklift currently is required to be able to lift at least 2600 mm, have an inner forklift distance of 92 mm and has to have forks longer than 1200mm. The customers of USC are required to manage the presence of a forklift themselves according to the given specifications. For this reason, the type and specifications of these forklifts vary heavily. This analysis will therefore focus on standard type forklifts.

2.3.1 Sizes

The sizes of a standard forklift are illustrated in figure 11. According to several sources^{[3][4][5][6]} the average length of a standard forklift is 3000mm with a width of 1500mm. Added to that is the forks which need to be larger than 1200mm. the total length of the forklift is therefore larger than 4200mm.



2.3.2 Costs

According to Thijn Hoepman, who recently studied the implications of replacing the forklift with a cardinal mule, Maarten Streppel states renting a forklift costs €400/day. In table 1 all his findings are shown. The redesigned wheels cannot replace the forklift completely. However, it will do so partly.

Table 1: costs assembly process

Case	Amount of containers	Days	Cost of forklift (€)	Tools (€)	Labour cost (€)	Hotel + meal (€)	Total cost (€)
Case 1	42	5	800,00	150,00	4000,00	720,00	5670,00
Case 2	32	4	800,00	150,00	3200,00	540,00	4690,00
Case 3	22	3	800,00	150,00	2400,00	360,00	3710,00
Case 4	12	2	800,00	150,00	1600,00	180,00	2730,00
Case 5	6	1	400,00	150,00	800,00	180,00	1530,00
Case 6	6	1	400,00	150,00	800,00	0,00	1350,00
Case 7	1	1	400,00	150,00	400,00	0,00	950,00

2.3.3 Speeds

Since the forklift drives the containers to its place the speed is an important aspect. The speed of a forklift varies heavily depending on the type of forklift but also the environment, the weather and the surroundings^[7]. There are no defined rules on maximum forklift speeds. However, most forklifts cannot go faster than 20 km/h^[8]. The environment of the container parks contains obstacles such as previously placed containers and placed unassembled containers meaning the forklift has to perform manoeuvres such as tight turns meaning a reduction in speed. These aspects combined result in an assumed velocity of 8 km/h.

Conclusions

By having standard insights into sizes, costs and speeds of a standard forklift several indications for the redesigned wheels can be made. To start with, the transportation configuration, meaning all components of the final solution combined should not exceed the size of a standard forklift. One of the advantages of the DHI wheel is its efficiency in transport. As the redesigned wheel is desired to take over tasks of the forklift, it should outperform it in. All components combined should therefore not exceed 4200x1500mm.

Renting a forklift will cost €400/day if the redesigned wheels could replace the forklift at least for one day it would therefore already save €400. To determine the maximum allowed production costs, the number of days of renting a forklift is set to 10. This results in a maximum price of $€400 * 10 = €4000$.

Finally, concluded is that the average speed of a standard forklift in a USC environment is 8 km/h.

2.4 The DHI wheel

Introduction

In this research the functioning of the current version of the DHI wheel, again presented in figures 2a to 2c, will be studied. It is important to grasp the current advantages and disadvantages. From these can be determined which functions and geometry solutions can remain in the new design and which have to be removed or adjusted in some way. By understanding the product, requirements can be computed by investigating which aspects the current product focuses on.

Figure 2: the DHI wheel



(a): sideview DHI wheel



(b): front-sideview DHI wheel



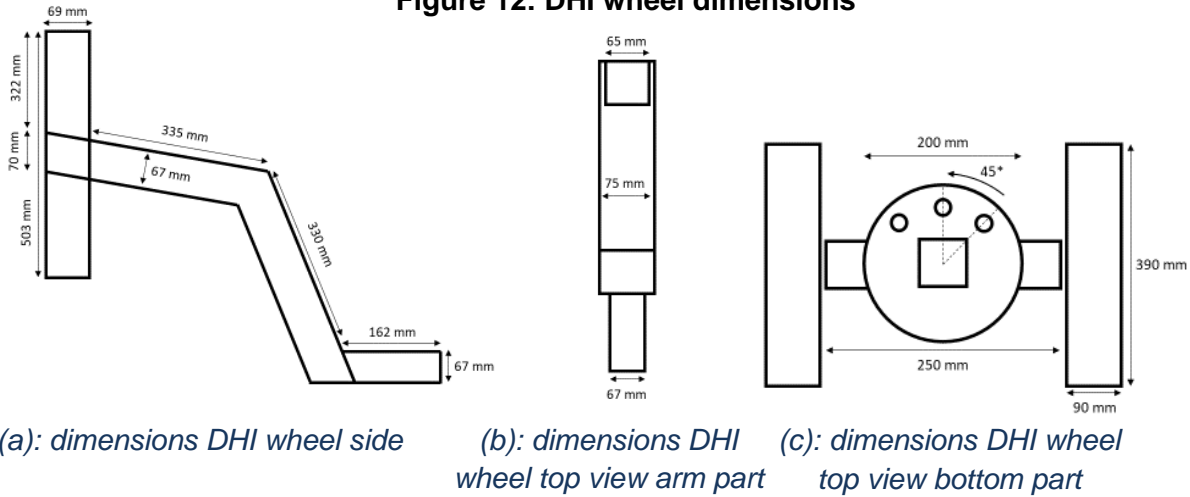
(c): side-back view DHI wheel

2.4.1 Functions and dimensions

The DHI wheel consists of three main components and is completely illustrated with dimensions in figures 12a, 12b and 12c. The first component is a large frame with a zigzag shape, consisting of four beam elements. The second component consists of three main elements, a vertical beam, horizontal circular plate and rotation axis with a radius of. The first and second components are connected by sliding the axis of the first component over that of the second. Inside lies a jacking mechanism, which can be operated by rotating a handle on top of the first component. This jacking system can reach a maximum of 380 mm in height.

The third main component is another identical circular plate with a horizontal beam underneath. Attached to the bottom side are two small blocks next to the edge for the attachment of the wheel axes. To connect components two and three the centre of the third component has a hole for the rotation axis of component two to fall into. This is then secured underneath with a large bolt. Additionally, there are three holes in the circular plate of component three, on the circular plate of the second component there is a pin system with a spring. When this pin falls into one of these holes, the rotation is prevented, and the angle of the wheels can be fixed. The three holes limit the value of the fixed angle to 0, 45 and -45 degrees. All components of the DHI wheel together weigh 46.5 kg. According to NEN 11228-1:2021^[9] table B.1 and B.2, the maximum allowed lifted mass cannot exceed 25 kg for professional male workers between 20 and 45 years old.

Figure 12: DHI wheel dimensions



The DHI wheel functions by inserting its horizontal mouthpiece into a form fit hole in the container. When four wheels are inserted, one on each corner, the container can be raised and pushed as seen in figure 13a^[10]. The four wheels can be placed in a train like configuration as seen in figure 13b^[10] to use a limited amount of space during transport. This configuration takes up around 0,5 by 2,5 meters.

Finally, in figure 13c a structural strength analysis using SolidWorks is shown, the complete report with details of the simulation can be found in appendix C1. According to NEN norm 1494^[11] “all manual operated mechanical jacks defined within the scope of this standard shall be designed to withstand at least 150% of the rated load in all critical modes at ambient temperature without showing permanent deformation of any part.” This means there should be a safety factor of at least 1,5. The maximum stress on the part is 98 N/mm², by assuming the part is made of simple carbon steel, it has a yield strength of 250 N/mm². This means the part currently has a safety factor of $\frac{250}{98} = 2,6$.

Figure 13:



Conclusions

From this research it is concluded that there are many aspects that make the DHI wheel unique and should remain in the redesign. The two most important aspects are the small size of the wheels making transportation of the product very efficient and the fact that it is powered by manpower eliminating the need for skills with machinery. Finally, when looking at the dimensions of the mouthpiece it is concluded that its cross section is too large for the holes on the short side of the containers. This cross section should therefore be reduced to 60x60mm.

2.5 The DHI wheel in practice

Introduction

To further study the functionalities and get real life measurements of the forces on the DHI wheel, several tests were conducted. The tests aim to get more information on the true values of forces and determine which functionalities are flawed and which are not. These flawed functionalities can then be adapted in terms of requirements. The forces will be used to justify or invalidate calculations performed following these practical tests. The tests will include the testing of general functionalities such as lifting the container and the rotation of the container meaning the rotation of the wheels themselves. Furthermore, the required initial and sustained force to move the container and the average walking speed while pushing the container will be measured. The forces and speeds were recorded with exact numbers using several tools. The usability of the functionalities was judged from not functioning to functioning very well and the time consumed while executing the functions.

2.5.1 Environment and equipment

Each test has a specific set-up; however, some parameters remain the same throughout all the tests. First of all, the location of the test, specifically the surface on which the wheels will drive will be a constant. The surface consists of regular road bricks and is slanted slightly parallel to the driving direction, this surface can be seen in figure 14a. To virtually make the floor perfectly horizontal, tests including exact values based on driving are performed in both directions to then use the average value.

The second equal parameter throughout the experiments is the base equipment. The tests are performed on an empty Z-box model 1, this first model weighs 1500 kg and has a centre of gravity precisely in the middle of the container. Each of the tests is conducted using the old design of the DHI wheels with a new mouthpiece of 60x60mm. The final piece of equipment is the measuring tool. The measurements are performed by a crane weighing scale which can be seen in figure 14b. This scale has a hook on the bottom side which can be attached to the container on the eye on a short side. Located on the top side of the scale is another eye which in turn has a rope attached to it, this rope is used to pull on during the tests. A crane weighing scale has a display on its front side where the quantity of force is shown in kilograms.

Figure 14: practical testing



(a): test set-up



(b): crane scale

2.5.2 Tests and results

The first test was measuring the amount of force required to pull a Z-box. This was done with the crane weighing scale and the rope attached to a short side of the container, the container was then pulled until reaching a constant velocity. To record the measurements done by the scale, a person filmed the display of the tool. The test was then repeated in the opposite direction. The average recorded values were:

$F_{initial} = 80 \text{ kg} = 784,40 \text{ N}$ and $F_{sustained} = 35 \text{ kg} = 343,35 \text{ N}$.

Similar to the previous test is the set-up and execution of the next experiment, to determine the force necessary to pass over an obstacle of 20 mm. Again, the container with four wheels attached is pulled by the rope and weighing scale, except now a large plank with a thickness of 20 mm is placed on the ground in the path of the wheels, this can be seen in figure 15a. First a constant velocity was established before passing over the plank. During this test the weighing scale was again filmed for the documentation of the values. The final value was: $F_{obstacle} = 85 \text{ kg} = 833,85 \text{ N}$.

Consecutively, the average constant speed while pushing a Z-box was measured. A distance of 10 meters on the floor was measured out and marked with wooden planks. The container was first pulled from the first mark to second, this took 11,76 seconds. The container was then pulled from mark 2 to mark 1, this took 14,00

seconds. The average time is therefore: $\frac{11,76+14,00}{2} = 12,88 \text{ s}$. The average speed is therefore:

$$\frac{10}{12,88} = 0,78 \text{ m/s} = 2,79 \text{ km/h}.$$

First to last was the testing of the ability of the wheels to rotate a container 360 degrees around its own centre as accurately as possible. The wheels had to be positioned so that the rotation would be possible. However, the gravitational force of the container is so large that the friction of the wheels on the ground surface makes rotating them almost impossible. Therefore, instead, two diagonal wheels were raised while the other two were lowered, this resulted in the lowered wheels to barely be subjected to any force and could therefore be rotated. These wheels were in turn raised while the unrotated wheels were lowered, to then rotate these. This results in a total of 12 different steps looking at only rotating the wheels. When the wheels are correctly positioned the rotation can be done by pushing the container as seen in figure 15b without issue. However, when one or more wheels did not have the correct angle, the container would simply not move.

Figure 15: practical testing



(a): obstacle set-up



(b): rotational pushing

Finally, the ease of putting the container back into its original position was tested. This meant putting the container into a position having a wall next to a short side and another container next to an adjacent long wall. This resembles an average placement of the container which the wheels should be capable of executing. The movements were fairly straight forward. First, the container was pushed in a straight line parallel to the long walls. However, due to the previous movement of rotating the container not being done perfectly, the two containers did not line up exactly parallel. This meant the wheels again needed to be rotated, requiring the same steps as previously were and costing quite some time. The steps of rotating the container 360 degrees and putting it back in its original position together took around 45 minutes.

Conclusions

In conclusion, there are several things that the current version of the product does quite well and can inspire or remain in the redesign. However, there are several aspects which did not perform well during the tests, which require some adjustments.

Advantages

- Small size making the wheels efficient in transport.
- Fixed angle system, which could result in accurate rotations.
- No machinery is required during positioning.

Disadvantages

- Rotation of the wheels is nearly impossible.
- Current angles of the fixation system are not correct.

2.6 The DHI wheel in theory

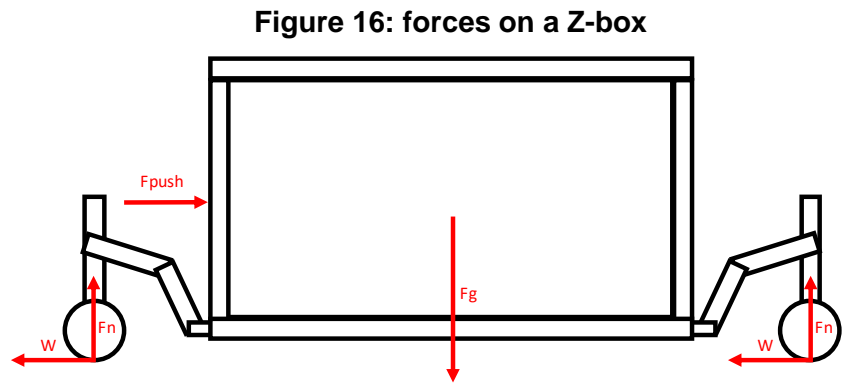
Introduction

Not only does the wheel need to perform well structurally and mechanically, but it also needs to perform well in its tasks as well. Specifically, this chapter takes a theoretical look at the implications of pushing a Z-box with the DHI wheel. This includes the calculations of the amount of force needed to push a container with regards of the surface and the calculations on the amount of force one person is allowed to push. Together with the real-life measurements performed in chapter 2.5.2, this chapter will conclude in a well substantiated determination on the amount of people required to push a Z-box.

2.6.1 Required force calculations

In figure 16 below the forces acting on a Z-box with wheels can be seen. The container is pulled onto the ground by gravity (F_G), which is counteracted by normal forces distributed over the wheels (F_N). The container will be pushed forward by employees of the assembly team (F_{PUSH}), but it is slowed down by the friction of the wheels on the ground (W).

As the container will be moving a dynamic analysis will be done. By Newton's second law the acceleration of an object is equal to the force acting on it divided by its mass. In a dynamic analysis the acceleration is equal to the difference in speed divided by the difference in time. In the figure below the sum of all forces in the vertical direction are equal. However, the pushing force in the horizontal direction and therefore the sum of the vertical forces is variable. To calculate the forces, Newton's second law is set equal to the sum of forces. The complete calculations can be found in appendix B.



For the initial force the container needs to be accelerated from 0 to 0,78 m/s as determined during the practical testing in chapter 2.5.2. This results in a required initial force of 843,97 N.

For the sustained force the container needs to maintain a constant speed meaning an acceleration of 0 m/s². This results in a sustained force of 362,97 N.

2.6.2 Allowed forces

To calculate the maximum allowed forces per person, the norm NEN 11228-2:2007^[12] is used. The norm specifies a method to determine the allowed force by taking into account ergonomics, age, gender and frequency and distance of pushing.

The workers of the USC assembly team are professional males. As the Z-box can be pushed at any height the most ergonomic height, 1,0m is looked at. As the building of the Z-boxes averagely takes one hour they are pushed once per hour. For the initial pushing frequency once per minute is taken. For the maximum travel distance 65 meters, the maximum defined distance, is taken. Tables A.5 and A.6 define the maximum acceptable forces as:

$$F_{initial} = 260 \text{ N} \quad F_{sustained} = 80 \text{ N}$$

Conclusions

After measuring the forces in a practical manner and calculating them theoretically a comparison can be made. In table 2 all the involved forces are laid out as well as the maximum allowed forces. Both the practical findings were measured to be lower than the theoretical findings.

Table 2: force comparison

	<i>F_{initial}</i>	<i>F_{sustained}</i>	<i>F_{obstacle}</i>
Practical findings	784,40 N	343,35 N	833,85 N
Theoretical findings	843,97 N	362,97 N	-
Allowed findings	260,00 N	80,00 N	-

Both the practical and theoretical findings of the initial and sustained forces are more than 3 times larger than the allowed force meaning both values. when it comes to overcoming an obstacle there are no known allowed forces. However, this force will be treated as an initial force as it needs to be overcome once and not continuously. The conclusion is therefore that at least four people are required to push a Z-box.

Additionally, the NEN 11228-1:2021 allows a maximum lifting mass of 25 kilograms. This means that a component of the final solution shall not weigh more than $4 * 25 = 100 \text{ kg}$.

2.7 Container Park analysis

Introduction

In this chapter of the research the first part of the comparison between the forklift and the wheels will be executed. This will be done by analysing previously created container parks sold and set up by USC. This study investigates 22 different parks throughout Europe with areas ranging from 150 to 10284 square meters. The full details of the parks can be found in appendix A. Together these container parks are estimated to have around 1750 containers. The main reason for investigating these parks is to find the added value the wheels could bring. The wheels could either save time or be more manoeuvrable in smaller spaces. In this analysis the focus will lie on looking into the first.

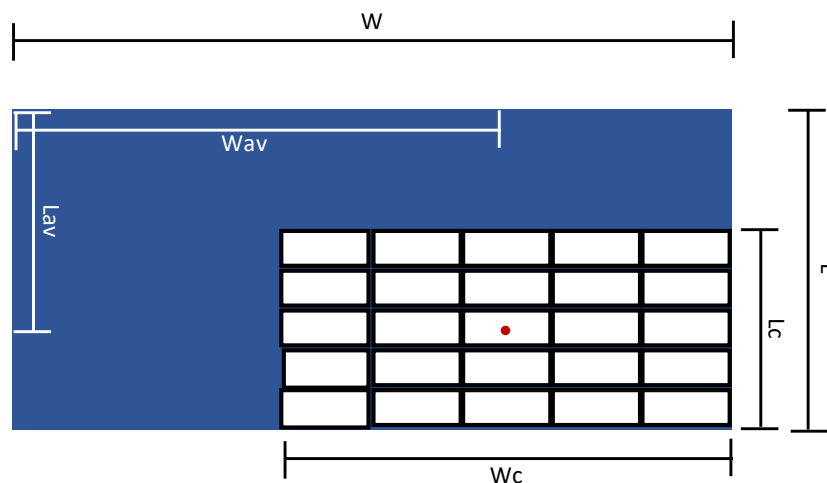
2.7.1 Calculation method

Distance

To find the amount of time the addition of the wheels in the assembly process resulted in, first, the average distance travelled was calculated per park. This was done by adding the length and the width, this value corresponds with the furthest distance one container can travel. However, if one container travels a certain distance, each next container will travel less and less until the last container is placed.

To calculate the furthest total distance, a block of containers with the ratio of the length and the width of the entire park was put into the furthest corner, as can be seen in figure 17 below. In this figure the blue rectangle is the area of the container park, and the white rectangles are the Z-boxes placed. This block of container corresponds to 55 percent of the total area, this number was taken based on the number Universal Storage Container promises to their clients. According to Danny Schmidt from USC they fill around 55 percent of the total area with containers. To calculate the value of W_{av} and L_{av} , the total length and width were subtracted by half of the length and width of the container rectangle, $L_{av} = L - \frac{1}{2}L_c$. To find the average total distance, the following formula was used. $Stot = 2X * (L_{av} + W_{av})$. $Stot$ being the distance travelled and X being the number of containers placed.

Figure 17: distance calculation

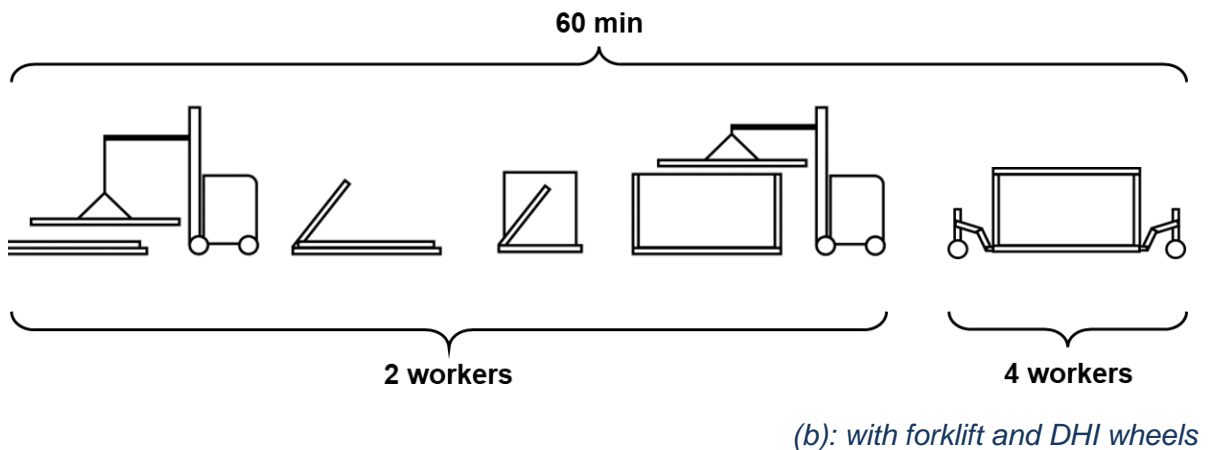
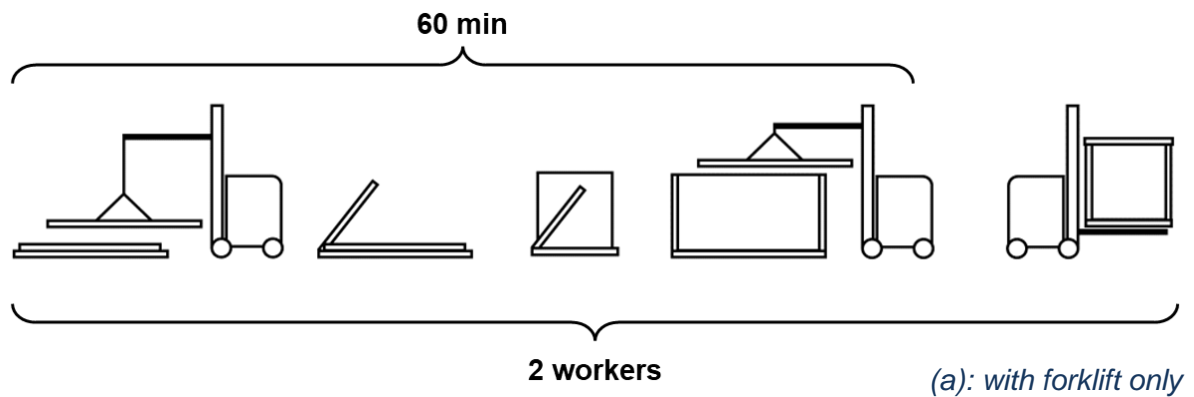


Time

In figures 18a and 18b the difference in steps, time and workers between the two situations can be found. To calculate the total time for a forklift to set up a park is calculated by first adding the building time and the driving time. As determined in chapter 2.3.3, the average driving speed of a forklift is 8 km/h. The driving time, calculated with the distance, is multiplied by the number of containers.

By using the wheels, the driving time of the forklift is eliminated. Since the wheels can be pushed while the forklift is building and the building time is 1 hour, the time it takes to push a container is irrelevant as long as it takes less than an hour. In this case the total time is calculated by multiplying the building time by the number of containers. The last container cannot be pushed while another container is being built and therefore one driving time is added.

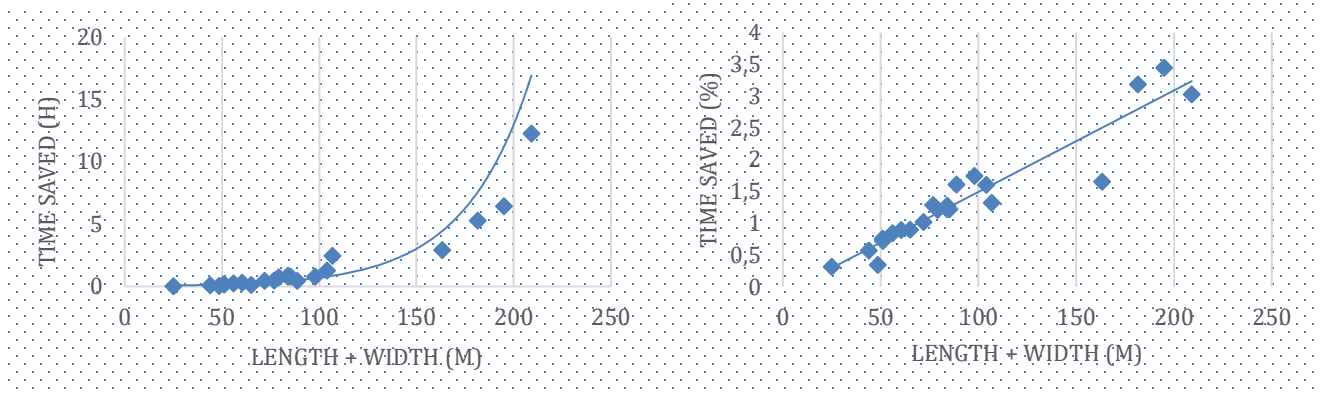
Figure 18: assembly process



2.7.2 Results

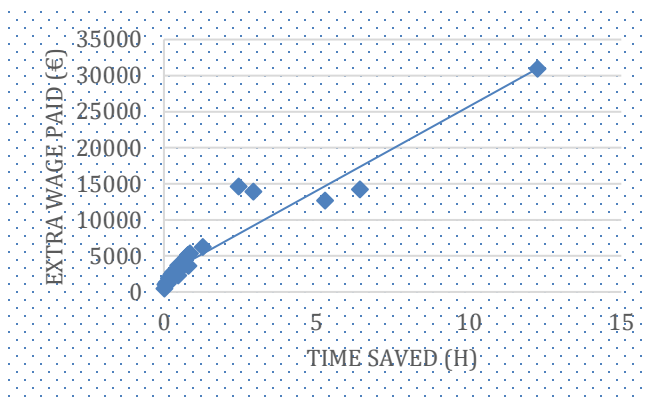
In figure 19a the amount of saved time in hours was calculated and plotted against the length plus width of a container park. It can be seen that the amount of time saved increases when the size of the park increases as well. If used while setting up the largest park, being 10284 square meters, 12,25 hours will be saved. In figure 19b the amount of time saved in percentages is plotted against the size of the park. Here it can be seen that these 12,5 hours comes down to 3% of the total time. In figure 19c the amount of extra costs is plotted against the amount of time saved. These extra costs are based on the extra wage of the four people pushing the container. When again looking at the largest park, it can be seen that saving 12,25 hours will cost €31.000. This means one hour of saved time costs roughly €2500.

Figure 19: result graphs



(a): time saved in hours against distance

(b): percentage of time saved against distance



(c): extra wages paid against time saved

Conclusions

After carrying out this analysis of these 22 container parks it can be concluded that the DHI wheels can indeed reduce the amount of time needed to set up a container park. The larger the park is, the more time the wheels will save. But when looking at the time these wheels save in percentages the maximum time saved is only three percent of the total time. The largest park could be set up in 12,25 hours less than before. This effectively reduces the number of working days from 51 to 49. Additionally, when looking at the amount of money it would cost to make this happen, roughly €2500 per hour, €31.000 in total, it can be concluded that this is far too expensive. The final conclusion of this research therefore is that the wheels do not bring value by saving time. The focus of the value determination should therefore focus on smaller parks with difficult to place containers instead of larger parks with relatively easy to place containers. Further research should therefore be done into the manoeuvrability and movements of the wheels.

2.8 Movement analysis

Introduction

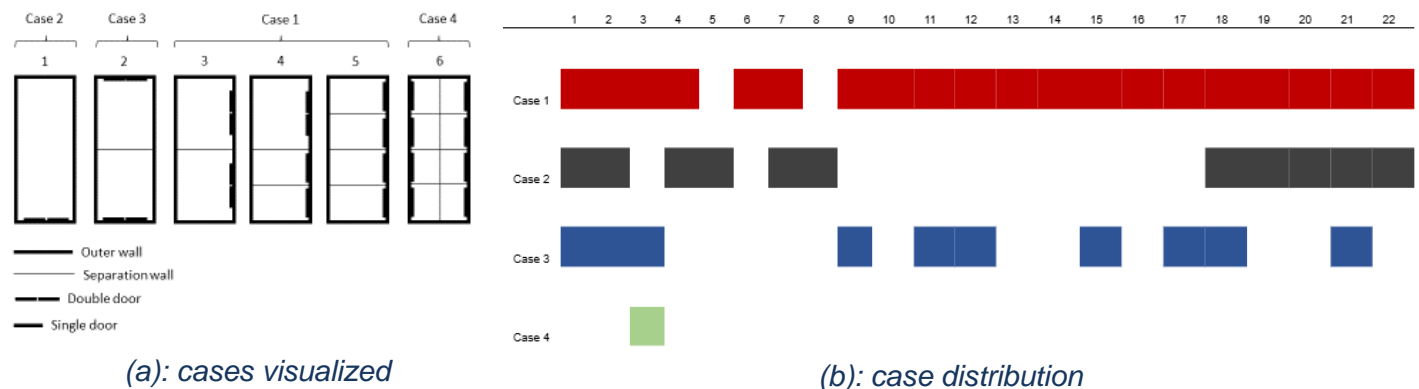
In this research the second part of the comparison between the forklift and the wheels will be executed and will compare the final point of value; the manoeuvrability of the two modes of transport. Value will be created by potentially outperforming the forklift in this area. Therefore, this research first studies the way both methods, the forklift and the wheels, would be used during the setup of generic parks. These generic parks are defined by configurations of containers that occur frequently. This generic case study will conclude in which aspects makes the forklift so efficient and on which aspects the wheels need to be improved. This analysis too is based on the container park analysis found in appendix B.

After looking at the generic cases, more specific cases will be studied. These cases are chosen keeping in mind the final goal, studying the manoeuvrability. This means the most difficult to place container configurations from the previously created container park analysis will be studied. This case study will conclude in the important aspects the wheels will need to properly function and place as many containers as possible.

2.8.1 Generic cases

To study the generic cases, they first need to be defined. In figure 20a the different models of the Z-box, mostly differing on door positions, can be seen. For the purpose of this study these six models can be narrowed down to four different cases. In figure 20b below the distribution of these different cases across the 22 studied parks can be seen.

Figure 20: Z-box model cases



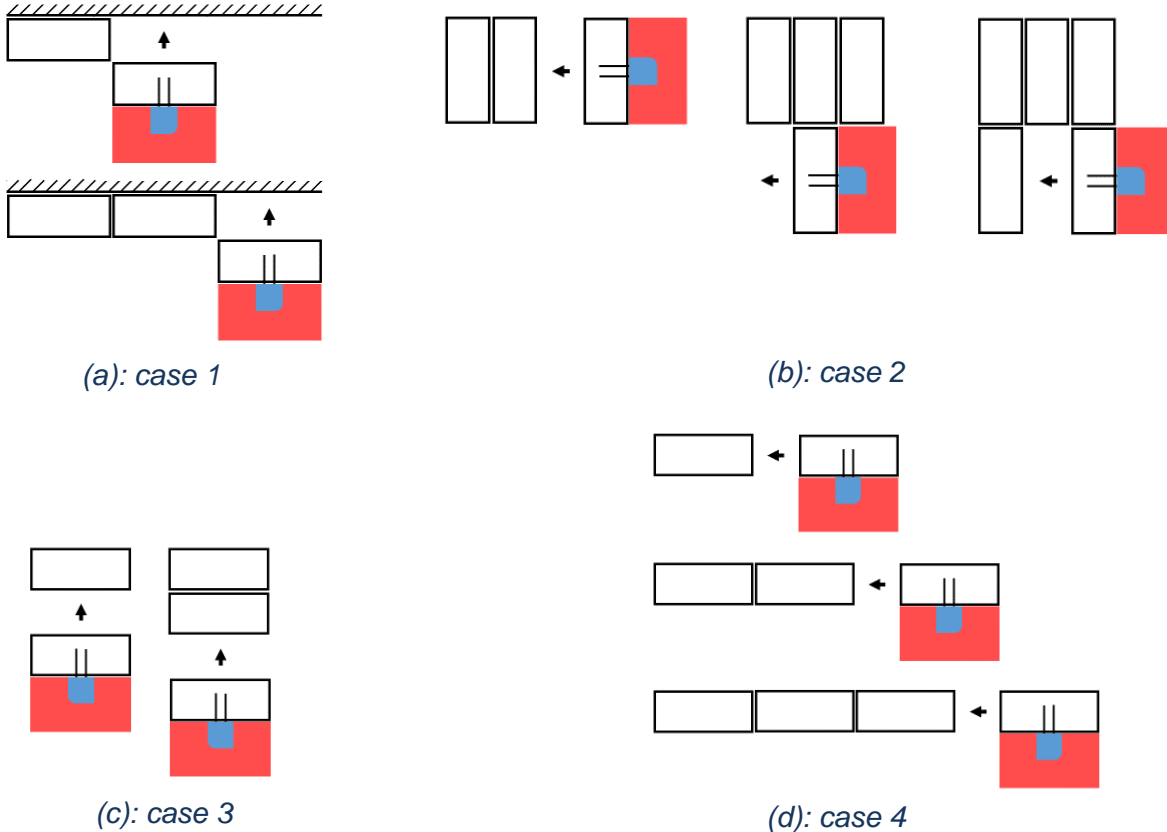
The largest group includes models 3, 4 and 5, these models are different from each other mainly on separation walls. Since the difference is mostly internal these models are effectively the same for this analysis. These containers can have obstacles on both short sides and on one long side. The main configuration this results in is placing a long row of these containers with their short sides touching each other and the long sides to an edge of a container park or touching another long row of the same models, this is seen in 20 out of 22 container parks. All the configurations will be more visually presented in figures 21/22 a to d in the next subchapter.

The next case is model 1, this model can have obstacles on both long sides and one short side. This results in them being placed in long rows touching each other on the long sides, while the short side touches either a wall or another row of these models. These configurations occur in 11 of the 22 parks. Model 2 is similar to model 1, however it cannot be obstructed on either short side. This results in them being placed in long rows touching each other's long side, this occurs in 10 of the 22 parks. Finally, is case 4, since it has doors on both long sides, there can be no obstacle there. This means they can only be placed touching other containers on the short side. This only occurs in 1 of the 22 studied parks.

Forklift

First will be analysed how the forklift, the current method of placement, functions. In the figures 21a to 21d below can be seen how the forklift manages each generic case. The red area represents the area the forklift needs to drive and get the forks out of the containers. In each case the forklift manages without issue. Due to the fact that the forklift requires only one long side to lift and transport a container, case 1 and 4 cannot pose a problem as they cannot be obstructed on a long side. Case 2 and 3 too are no issue for the forklift as there is mostly one long side unblocked for it to lift the containers. However, this is not the case when for example the last container needs to fit next to a wall on one side and next to another container on the other side. This occurs 3 times in the 22 container parks.

Figure 21: forklift case study

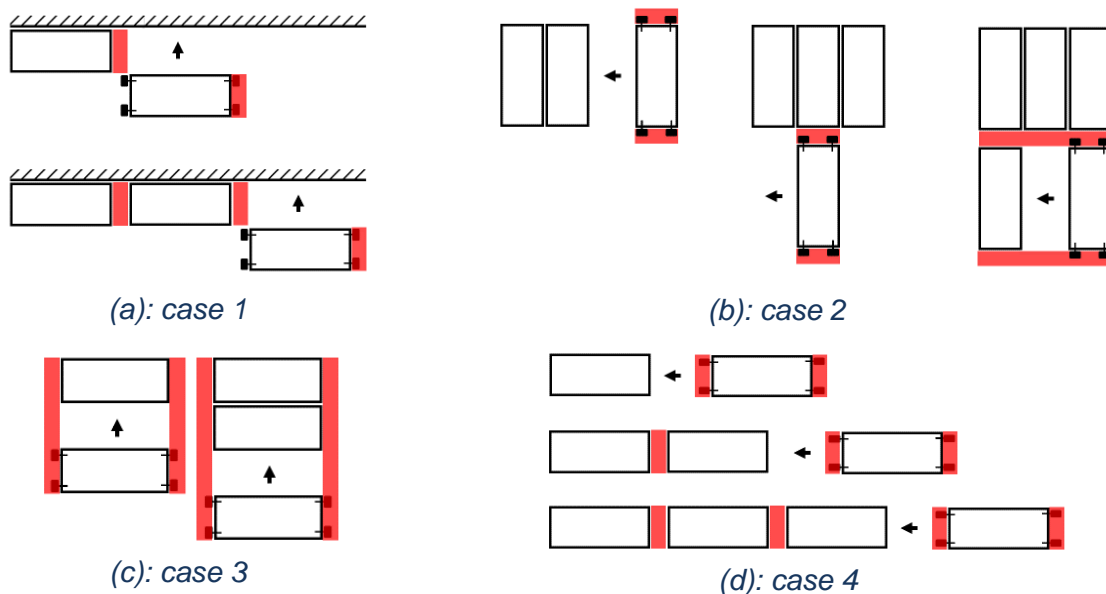


The DHI wheel

To compare how the DHI wheel functions, the same situations are analysed. Below the four figures 22a to 22d these situations can be found. Unlike the forklift, the wheels need to be placed on both the short sides of the containers. This placement causes some issues regarding perfect alignment with the next container. Due to the fact that the wheels need to be taken out of the container in complete, the containers need to be 808 mm apart, this is visualized by the red rectangles. This will result in the needed area being larger for the same number of containers to be placed, or the percentage of containers in an area USC promises their clients currently going down.

When a container needs the extra area on both sides of the container, this container will have a 27,53% increase in area. Where one red area corresponds to 13,76% of the area of a container. Only the third case can be executed without issue since these containers need to be unobstructed on either short side, there are 10 container parks where this is the case. However, as can be seen in figure 15b, there is not a single container park where this is exclusively the case. This means none of the analysed parks could be recreated with the wheels without having to use extra space.

Figure 22: DHI wheel case study



Since the issue of not being able to correctly place the containers arises from the attachment positions of the wheels to the container, these need to be looked into, this will again be done per case. This will be determined on which sides of the container are used. The meaning of using a side in this situation is all the sides which are occupied by attached wheels during transport of the container and all the sides needed to either attach or detach the wheels.

In case 1 the best possible solution is to only use the long side with the doors, since this is the only side which will be unblocked in the end. However, due to the placement procedure most containers will only be blocked on two sides. This does result in the last container needing space on one short side, meaning it will not be possible to place it perfectly next to a wall. The last container needing to align with an obstacle happens with two containers from the 1750 containers across 22 parks.

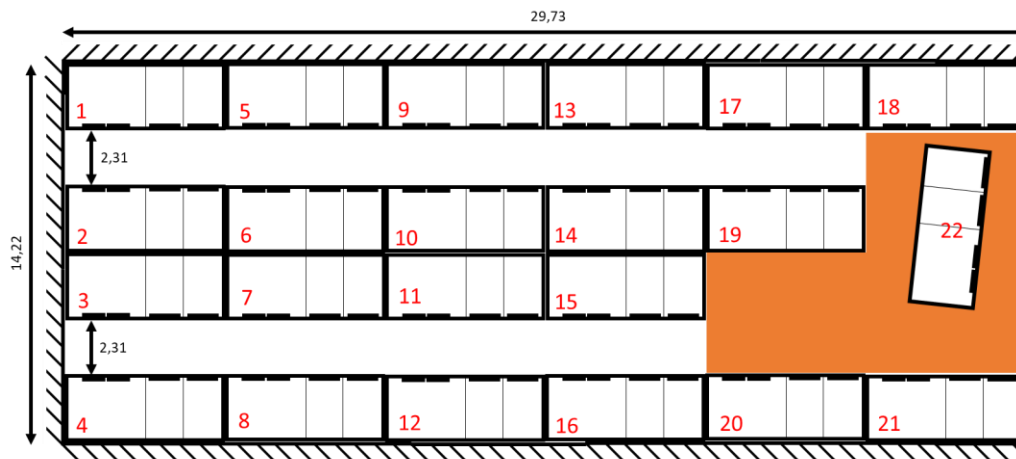
Since Z-box model 1 from case 2 cannot be blocked only on one short side, the optimal way of transporting this container is by using only this short side, as similarly to case 1, all containers during placement are only blocked on two sides except the last container which could be blocked by a wall. This only occurs with 3 out of the 1750 containers. Case 3 and 4 give more flexibility as both cannot be blocked on two opposite sides. The

short side for case 3 and the long side for case 4. This means the wheels can be attached on those two sides for these two cases.

2.8.2 Specific cases

The generic cases focused more on the location of attachment of the wheels. The specific case will focus more on the movements the containers need to be able to make. Again, a comparison will be made between forklift and wheels. The specific case seen in figure 23 is taken from one of the 22 container parks and chosen based on the amount of space available. The red numbers indicate in which order the containers were placed. In this case study the specific container case that was chosen is the container with number 22. This is the last container and makes the manoeuvrability very low, this is the most interesting as the turning radius is one of the parameters this research is focused on.

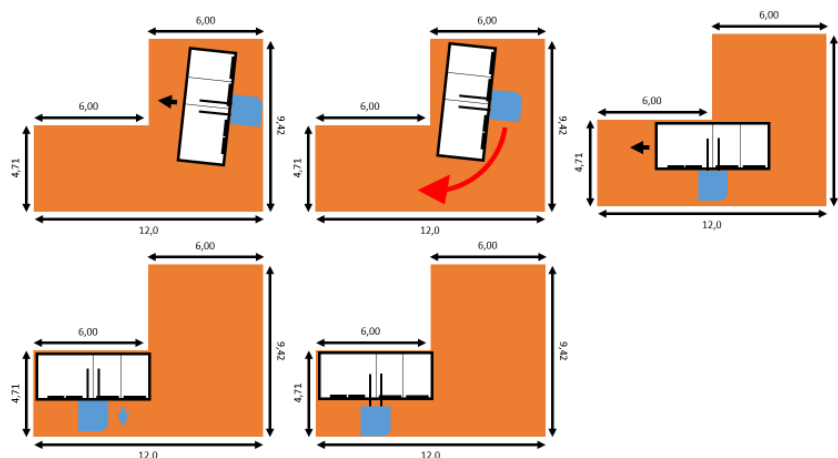
Figure 23: specific case



Forklift

In figure 24 below, the steps taken by a forklift can be seen to move the Z-box from point a to b. In the figure the orange area corresponds with available space in the park as illustrated in figure 18 above. First the forklift slightly moves the container to the wall so that in the second step it can move the container in one motion around the corner, then it moves the container sideways into position taking 4 steps in total. However, when the forklift attempts to move out of the container, it cannot as there is not enough space behind it. The forks alone need to be longer than half of the width of the Z-box to maintain balance. The Z-box has a width of 2,4 meters meaning the forks need to be around 1,5 meters long. Added to that is the space of the vehicle itself measuring around 2,5 to 3 meters depending on the type. This results in a required space behind the forklift of 4,5 meters.

Figure 24: specific case forklift



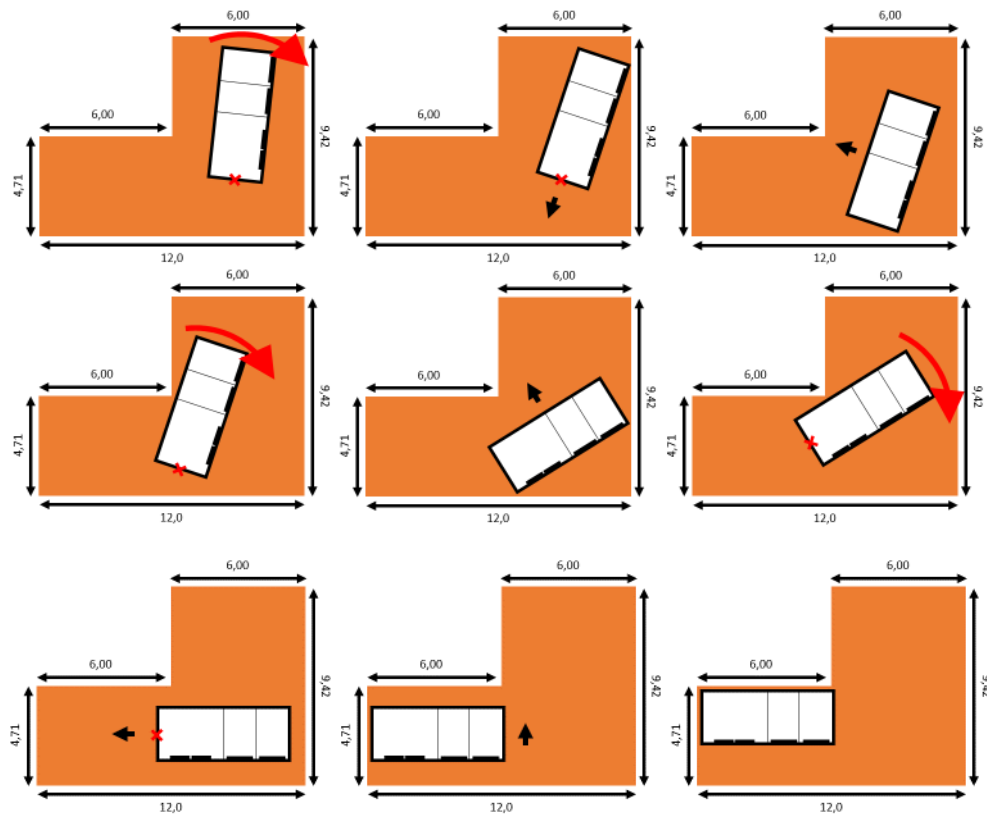
The DHI wheel

To see how the DHI wheels function in this specific case, again the steps taken are illustrated in figures 25a and 25b below. There the starting position and orange area remain the same as with the forklift. As the goal is to determine which movements the wheels need to be able to make to be more efficient than the forklift, the movements are isolated in this case study. This is done by assuming that the wheels are optimally placed, and the red areas seen in the generic case study are eliminated. To further study the movements the DHI wheels are again split into two different situations. One situation where the turning point lies on the short edge of the container, seen as the “worst case scenario”. The second situation the turning point will lie in the middle of the container being the best-case scenario.

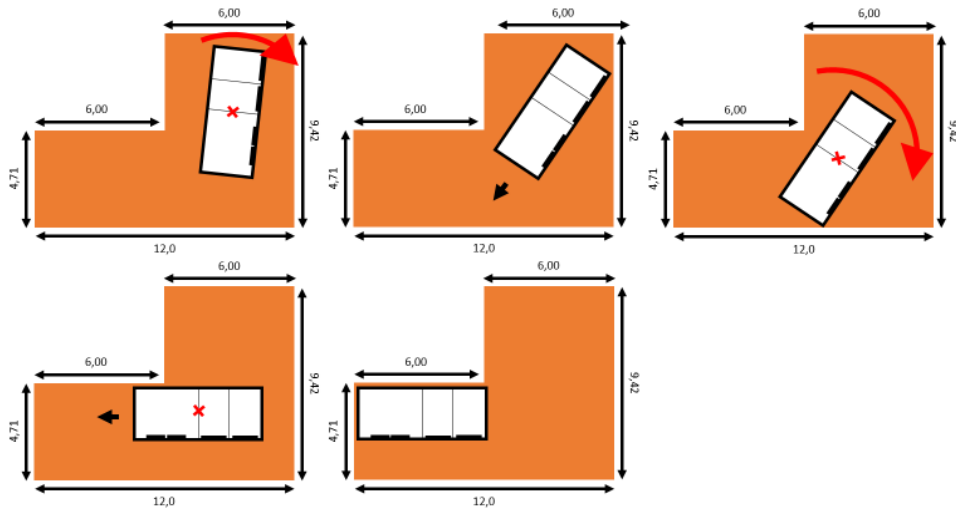
In the figure 20a below, the worst-case scenario step by step process can be seen. The location of the turning point lying on the short edge of the container means a turning radius of $\sqrt{5810^2 + \frac{2382^2}{2}} = 5,9 m$. This radius requires the container to be rotated and then moved upwards three times in a row before resulting in requiring 6 steps before the container is parallel to its final location. To place the container correctly two additional steps are needed.

In figure 20b the process of the best-case scenario can be found. Due to the turning point lying in the middle of the container the radius is reduced to $\sqrt{5810/2^2 + 2382/2^2} = 3,1 m$ Having nearly half the radius cuts the number of steps in half. Instead of needing 3 rotations and 5 translations, this best-case scenario only needs 2 rotations and 2 translations.

Figure 25: specific case DHI wheels



(a): worst-case scenario



(b): best-case scenario

Conclusions

After investigating the differences between the forklift and the wheels when it comes to the placement process of containers in both generic and specific cases, several conclusions can be drawn. The wheels need to be able to attach to different sides than they do now. To make sure the wheels are able to place any regularly occurring container, the wheels should be able to use both only a long side or only a short side. However, when the wheels are able to transport a container using a short and long side simultaneously, it will result in being able to place 5 containers less from the 1750 total investigated containers, this is a 0,29% reduction. When it comes to generic cases this is such a small reduction, it is not necessary to eliminate the possible design direction.

From the specific case study, the required movements can be determined. In both the worst- and best-case scenario, the containers are rotated and translated parallel to both the long and the short sides. From the comparison of the worst- and best-case scenario it can be concluded that the turning radius should be as small as possible. The reduction of the radius by 50% reduced the number of movements by 50%. A movement consists of stopping the movement of the container, rotating all four wheels in the correct direction and then starting the movement of the container again.

Resulting from the testing in chapter 2.5.2, the rotation of the wheels consists of 12 steps, heightening, rotating and lowering the wheels to then repeat this with the other two wheels. In total one movement includes: stopping the container, rotating the wheels and finally pushing again. This comes down to a total of 14 steps per movement. In this case study the number of movements was reduced from 8 to 4, this results in a reduction from 112 sub steps to 56 sub steps. Not only will this result in massive time save but also in human effort both mentally and physically.

In the specific case, to investigate the movements only, the position of the attachment of the wheels and therefore the red areas, were neglected. This also eliminates some important aspects the wheels should be designed for. In the real situation the position of the wheels will influence the manoeuvrability by making the container larger in some directions. This means the product should be as small as possible even when occupying an "allowed" side. In the specific case study, the forklift was incapable of placing the container due to being too large when moving out of the container. The same could occur for the wheels when they end up being too long. In the specific case study, the smallest distance between the containers was 2,31 meters. However, theoretically the containers could be as close to each other as long as the smallest doors could open. The smallest door size is used in model 3, 4 and 5 and is 0,87 meters. Therefore, the effective length of the redesigned product needed to transport the containers and to be attached and detached should be less than 1 meter.

2.9 Market research

Introduction

In this final chapter of research, some inspiration for the design phase is presented. The goal of the market research is to create an overview of already existing products, to get an idea of how other manufacturers solve similar issues. The market research therefore focuses on the important aspects of the redesigned product retrieved in the previously executed research. This research will take a look at products designed for handling shipping containers both manually and mechanically. Furthermore, the research will investigate more specific parts of the product such as wheels and lifting systems as well. Each existing solution will be analysed by determining the weaknesses and strengths especially towards the situation of USC. From these strengths and weaknesses this chapter will conclude in useful solutions relevant for the design phase.

2.9.1 Wheels

As the most important feature of the redesigned product is the fact that they move due to their wheels, it is an important aspect to design. Therefore, it is an important aspect to research as well. For the wheels the most important two aspects are how they are attached to the container and how they can perform the different movements required.

Attachment

In the figures 26a to 26c below, the most important found solutions regarding the attachment of the wheels to the containers can be seen. There is a range of possible ways to attach wheels to containers. It is important to note however, that the containers used in these solutions are often standard shipping containers. These containers differ greatly in their geometry compared to the Z-box, especially in the floor where they are attached to.

Figure 26: wheel attachment market research



(a): container skates

(b): moment force wheel

(c): ContainGo wheel

The first solution found in figure 26a^[13] is a container skate and has a relatively simple working principle. It does not require actual attachment to the container, instead it relies on friction between the surfaces of the container and the product. This allows for easy attachment and detachment. The current version of the product does not solicit the changing of the direction of the wheels. However, it is possible to rotate the entire skate as it is not fixed to the container. Another interesting characteristic of the skate is that it does not require a side of the container to be attached, it does instead utilize only the bottom side. There are many similar products which too utilize the bottom side of the container to keep it from the ground. These products have small abbreviations, such as having a vertical pin to attach to a vertical hole for security instead of relying solely on friction.

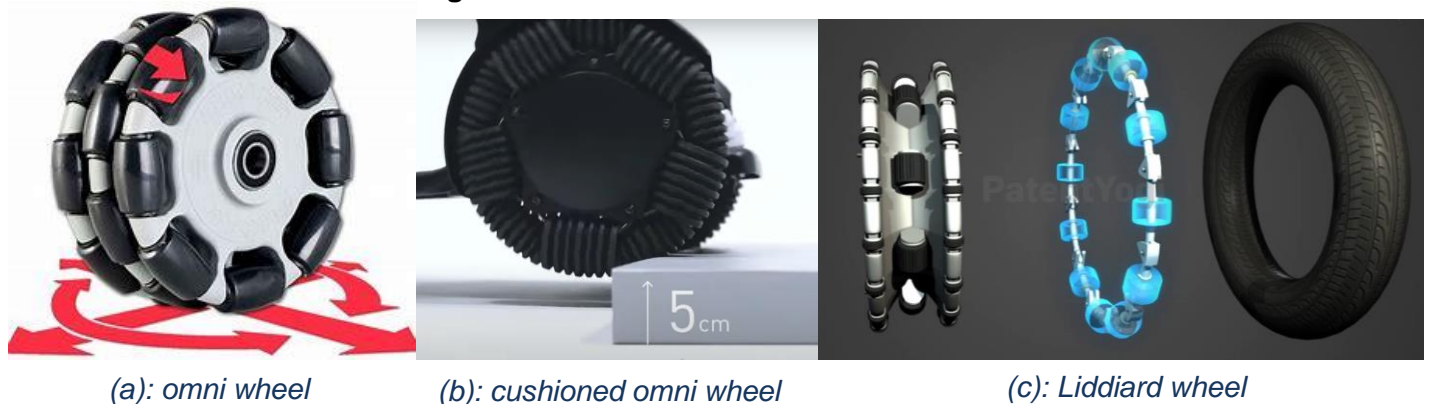
The second unique solution can be found in figure 26b^[14]. This wheel is attached to the side of the container. The horizontal beam goes into an ellipse shaped hole and is then rotated 90 degrees, this way it is locked and cannot come out. As the wheel is attached to the side, the mass of the container will generate a large moment force. To combat this force, the wheel has a vertical beam with a plate attached to it. This plate will make contact with a wall of the container and this way generate its own moment force to obtain equilibrium.

Finally in figure 26c^{[15][16]} the ContainGo wheel is shown. This wheel simply has one horizontal beam inserted into a horizontal hole. The most notable characteristic of this wheel is its simplicity. Due to only having one wheel and one axis and not being rotatable the wheel is very compact. To make the wheel get contact with the floor the opposite side of the container is lifted.

Movement

In the figures 27a to 27c the findings in the research of wheels capable of multiple movements are shown. The wheels generally have the same working principle. By adding a second movement direction perpendicular to the regular movement direction, these wheels can translate in any direction. When four of these wheels are used in a rectangular configuration, any movement can be made^[17]. Not only can they translate in any direction, but the wheels also enable rotation with any radius. This results in the wheels not needing to be rotated. These omni wheels seen in figures 27a^[18] and 27b^{[19][20]} have some deviations, the first option uses three layers of wheels to ensure contact with the ground. The second option has a rubber tire making rougher off-road surfaces less of an obstacle. The last option in figure 27c^[21] shows the Liddiard wheel. These wheels are unique by having one large tire shaped in a ring allowing it to be air inflated.

Figure 27: wheel movement market research



2.9.2 Lifting

The wheels are a crucial aspect of the product. However, if the product cannot lift the container from the ground, the wheels will not be able to function in the first place. This means the lifting too is an essential point to do research for. The investigation of the lifting will consist of two parts. The first part will focus more on mechanical solutions meaning the internal mechanism of many real-life solutions. The second part will illustrate the different applications of these mechanisms in different forms.

Lifting mechanisms

There are four main mechanisms when looking at lifting in the vehicle and construction industry; these four principles are depicted in the figures 28a to 28d on the right. These mechanisms all have a maximum capacity of mass they can carry around the mass of the heaviest Z-box.

The first mechanism is a 3-bag air jack shown in figure 28a^[22]. As the name suggests the jack functions by using air. Uninflated the jack will be at its lowest point, when it is inflated the jack goes upwards. The jack relies on an external air compressor to be inflated.

In figure 28b^[23] a chain hoist is schematically shown. A chain hoist reduces the input load by using a gear train. The first gear is much smaller than the last meaning one input rotation will be only a fraction of the output rotation. By rotating the gears, the chain with the hook can be positioned upwards or downwards.

The screw jack is shown in figure 28c^[24]. The screw jack converts a rotational movement into a translational movement. Setting the angle of the screw thread close to vertical as in figure 23c results in 1 unit of translation requiring many more units of rotational movement.

Finally in figure 28d^[25] a hydraulic pump mechanism can be seen. This mechanism uses hydraulic fluid whose volume will not change depending on the pressure. By pushing down the red lever the yellow fluid from the reservoir is pushed into the main valve. This fluid will then push up the large central pillar where the load is positioned. By making the surface area of the central cylinder larger than that of the lever, the input force is again greatly reduced. The output distance is also reduced however.

Figure 28: lifting mechanisms



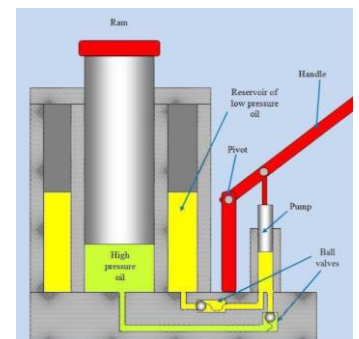
(a): airbag jack



(b): chain hoist



(c): screw jack



(d): hydraulic mechanism

Lifting solutions

In the four figures 29a to 29d the most relevant lifting solutions for similar objects such as containers or vehicles can be found. These solutions are chosen not because of their mechanism but for their unique way of lifting an object.

The first solution is the scissor lift as seen in figure 29a^[26]. The scissor lift features two beams capable of lifting high loads by being moved diagonally when pushed at one end. The scissor lift can even have multiple levels of beams to reach more height. These lifts are often powered by a hydraulic system but could also be functional with mechanical parts only.

The second solution is not a product, but a method of lifting. The unique way of lifting is done by only lifting one side while the other side remains on the ground leaving the container in a diagonal position. While it is diagonally oriented a product can be placed underneath. This could be the wheels required to move the container or as in figure 29b^[27] a balance point. After the balance point is placed the lifted side can be lowered partially and the container will end up in a horizontal position balancing on the balance point and lifting source.

In figure 29c^[28] a pallet jack is illustrated. In practice this piece of equipment is a mechanical forklift. The unique aspect of the pallet jack is the second set of wheels near the tip of the forks. A forklift uses its huge mass to negate the moment force. The pallet jack accomplishes this by having this second set of wheels. These wheels will remain on the ground while the forks are raised.

Finally, the Finkbeiner FHB is shown in figure 29d^[29], this machine is able to efficiently lift passenger cars and transport vans. It is able to do so by having large legs on the floor keeping the equipment in balance. The car is then lifted by heightening the arms in a rotational motion. This motion is powered by a hydraulic system and secured with mechanical solutions.

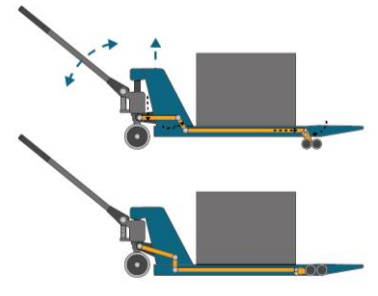
Figure 29: lifting applications



(a): scissor lift



(b): diagonal lifting



(c): pallet jack



(c): Finkbeiner FHB

Conclusions

Wheels

Several interesting conclusions can be drawn from this part of the market analysis. After investigating the attachment of wheels to the container, the most useful conclusion is that the bottom side of the container can be used as well instead of the sides only, this can even be realized by using only friction. When the sides are used however the main focus point of the products is how to counteract the moment force.

Concluded from the unique wheels is that the strength of the three highlighted wheels of not needing to be rotated but allowing any directional movement is considerable. But this freedom comes with a downside as well. Being able to move freely in any direction means that these wheels, when not motorized, can move in an unwanted direction as well. The container requires a large force to be pushed and is distributed over four people. These four people need to work together by exerting the right amount of force in each direction to not cause the container to for example start rotating while pushing. This strength and weakness need to be kept in mind while considering the implementation of the wheels.

lifting

Concluding from the lifting research is that there are many possible variations of lifting a large object. Various solutions for mechanisms are found and when designing can be decided which suits the concept the best. There is many existing lifting equipment available as well. These vary greatly in their solutions for lifting. The main differences are found in the way each product keeps their balance and the sequence of the lifting process. Although there are many solutions available, there are no solutions found on the market for the mechanical lifting and moving of containers, especially on rough terrain.

3 Requirements

Introduction

In this chapter all the requirements found in the research are listed. These requirements are used as the underlying structure in the design phase. As they are concluded from the research it means the designs should follow these findings by conforming to these requirements.

3.1 Requirements

The first requirement comes directly from the design goal as efficiency and financial benefit are the main two goals. Additionally, two general requirements are added

1. The costs of the production of the redesigned product should be as low as possible and shall not exceed €4000.
2. The redesigned product shall not damage the Z-box.
3. The product shall not fail while functioning and shall therefore have a safety factor of at least 1,5.

The next three requirements are based on the Z-box analysis and come from geometry and specifications of the storage container.

4. The redesigned product should be able to mechanically lift at least 1850 kg.
5. The redesigned product shall be capable of attaching to the available geometry of a Z-box when it is on the ground.
6. The wheels of the redesigned product shall be capable of attaching to the Z-box while or after lifting.

The next eight requirements follow from the DHI wheel analysis and testing and are based on the strengths and weaknesses of the old design.

7. Each component of the redesigned product should be as light as possible and should not exceed 100 kilograms.
8. The redesigned product shall not allow any tipping.
9. All components of the redesigned product combined shall be as small as possible. and shall not exceed 4200x1500mm.
10. The redesigned product shall be capable of mechanically lifting a Z-box.
11. The redesigned product shall allow the changing between the desired movements.
12. The redesigned wheels shall have a fixed angle of rotation to ensure accurate rotation of the container.
13. The redesigned wheels shall be able to drive with a speed of at least 0,78 m/s.
14. The process of changing a movement in the positioning process of a Z-box shall have as few steps as possible.

The last five requirements spring from the container park and movement analysis where different existing container parks were compared and analysed based on how they would be assembled. The focus of the requirements is the ability to place as many containers as possible.

15. The redesigned wheel shall be able to make accurate translational movements parallel to the long axis.
16. The redesigned wheel shall be able to make accurate translational movements parallel to the short axis.
17. The wheels shall allow accurate 360 degrees rotational movement with a turning radius no larger than 3,5 m.
18. The space around a Z-box required during attachment, detachment and transportation of a Z-box of the redesigned products shall be no more than 1 meter.

19. The redesigned product shall be able to place a Z-box next to geometry with a maximum distance of 50 mm.

3.2 Filtering the requirements

Based on the research, six aspects most important for the new product were determined. These are: general performance, precision, production, speed, transport and safety. These six aspects are the result of research as well as wishes from USC and the government. The criteria should be reflected by the concepts, and they should include as many criteria as possible. To make these six aspects conform with the previously done research, the requirements concluded from it will be filtered among these criteria. The distribution of the requirements as well as the description of the criteria are shown in table 3 below.

Table 3: filtered requirements

Category	Description	Requirement
General performance	The general performance includes requirements needed for any product to function in the specific environment desired by Universal Storage containers.	<ul style="list-style-type: none"> 2. The redesigned product shall not damage the Z-box. 3. The product shall not fail while functioning. 4. The redesigned product should be able to mechanically lift at least 1850 kg. 5. The wheels of the redesigned product shall be capable of attaching to the Z-box while or after lifting. 6. The redesigned product shall be capable of attaching to the available geometry of a Z-box when it is on the ground. 10. The redesigned product shall be capable of mechanically lifting a Z-box. 11. The redesigned product shall allow the changing between the desired movements. 12. The redesigned wheels shall have a fixed angle of rotation to ensure accurate rotation of the container. 13. The redesigned wheels shall be able to drive with a speed of at least 0,78 m/s. 15. The redesigned wheel shall be able to make accurate translational movements parallel to the long axis. 16. The redesigned wheel shall be able to make accurate translational movements parallel to the short axis.
Positioning	Positioning expresses the ability of placing Z-boxes in their desired position.	<ul style="list-style-type: none"> 17. The wheels shall allow accurate 360 degrees rotational movement with a turning radius no larger than 3,5 m. 18. The space around a Z-box required during attachment, detachment and transportation of a Z-box of the redesigned products shall be no more than 1 meter. 19. The redesigned product shall be able to place a Z-box next to geometry with a maximum distance of 50 mm.
Production	The focus of production lies mostly on the costs of acquiring the products along with some regard to the amount of time it would take.	<ul style="list-style-type: none"> 1. The costs of the production of the redesigned product should be as low as possible and shall not exceed 4200x1500mm.
Speed	The speed is defined as the amount of time it takes to place a container in its place.	<ul style="list-style-type: none"> 14. The process of changing a movement in the positioning process of a Z-box shall have as little steps as possible.
Transport	Transport means how well the redesigned product can be taken to its desired location.	<ul style="list-style-type: none"> 7. each component of the redesigned product should be as light as possible and shall not exceed 100 kilograms. 9. all components of the redesigned product combined shall be as small as possible, and not exceed €4000.
Safety	Safety takes a look at how dangerous the product is during use for anyone involved.	<ul style="list-style-type: none"> 8. The redesigned product shall not allow any tipping.

4 Design phase

Introduction

In this chapter the design phase is presented. The design phase shows the entire process from theoretical rules, the requirements, to the final design. First many ideas will be generated based on the created requirements. Next, the ideas will be filtered into three different concepts. These concepts will be evaluated, and the best will be chosen. This concept will then be worked out completely, ready to be produced.

4.1 Ideation

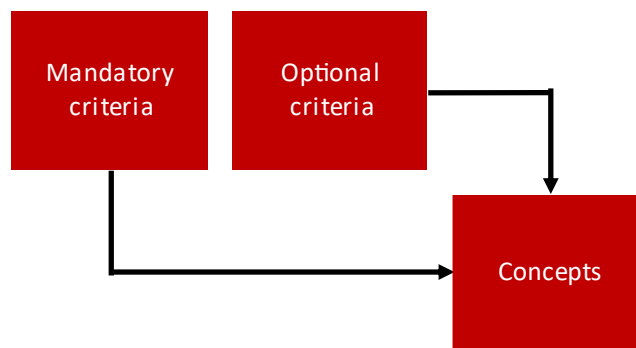
Introduction

In this chapter the ideation will be presented. The ideation includes all the idea generation for the final design and is therefore the start to the design phase. The idea generation will be structured and relevant to the previously executed research phase by being based on the requirements. The goal of the ideation phase is to produce three unique concepts each solving the problem of Universal Storage containers as well as possible in a different way. To fit the problem of USC as well as possible, the concepts should conform to the requirements as well as possible.

To not immediately eliminate many of the possible ideas, the ideation phase starts broad and converges towards the most suitable combination of ideas concluding in the three best concepts. To keep this broad phase structured and not get lost in the many different requirements, the ideation is based on the six criteria.

The general structure is presented in figure 30. Here the time goes from left to right and the arrows represent relations. The idea generation starts with the mandatory criteria, as they are the must have aspects of the design. Then the remaining criteria will be ideated on

Figure 30: ideation structure

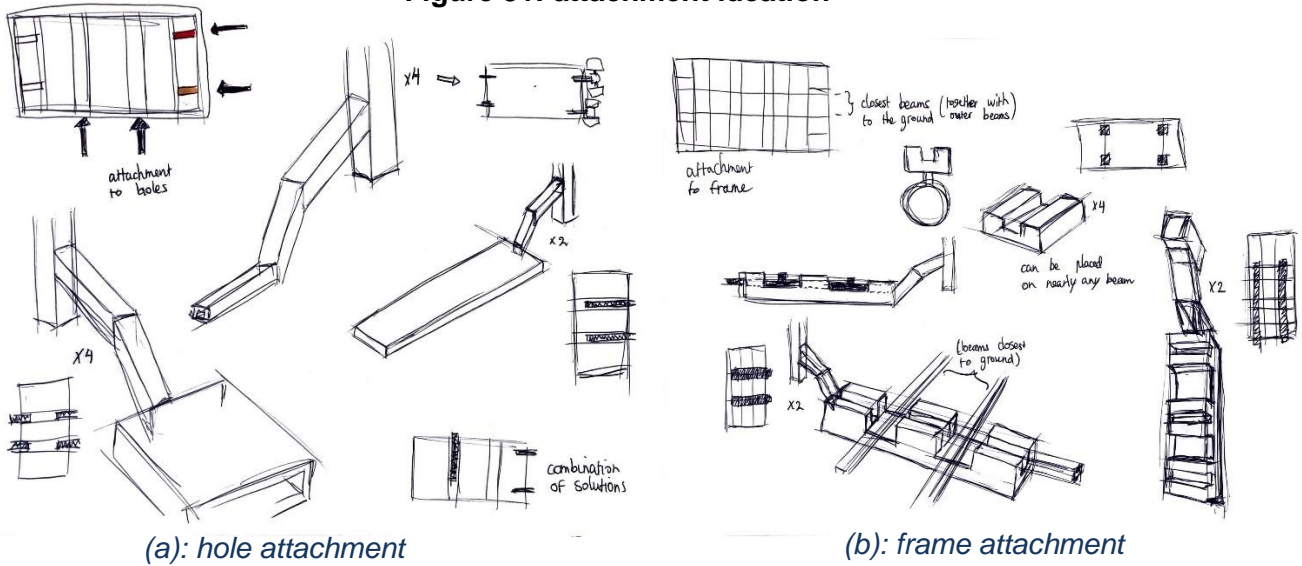


4.1.1 Mandatory aspects: performance and safety ideation

The first step of the ideation process was to ideate on the general performance and safety criteria. These are the first aspects as they are mandatory for any idea. If a concept is not capable of performing the basic functions defined in this criterion, it will not be able to function. The focus of this ideation lies on the requirements established in these criteria and include attachment, rotating the wheels tipping and lifting.

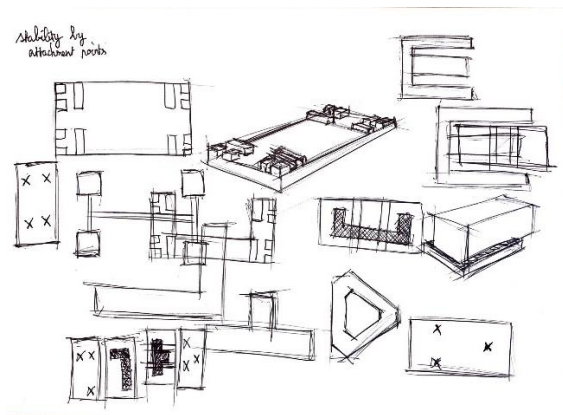
In the two figures 31a and 31b below the attachment ideation can be found. The two possible attachment places are the holes, required when the container is on the ground, and the frame underneath the container, only accessible when the container is lifted. The ideas focus on different shapes and placement of the ideas and dive into the different combinations of these.

Figure 31: attachment ideation



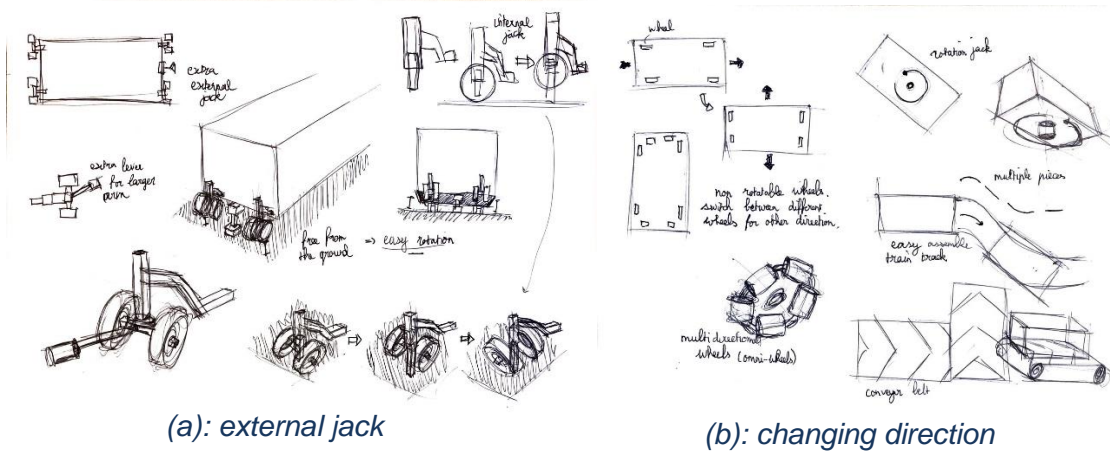
For the stability in figure 32, the ideation focuses mostly on attachment position to prevent tipping. In the figure shapes are sought and the attachment points are marked with x's.

Figure 32: tipping ideation



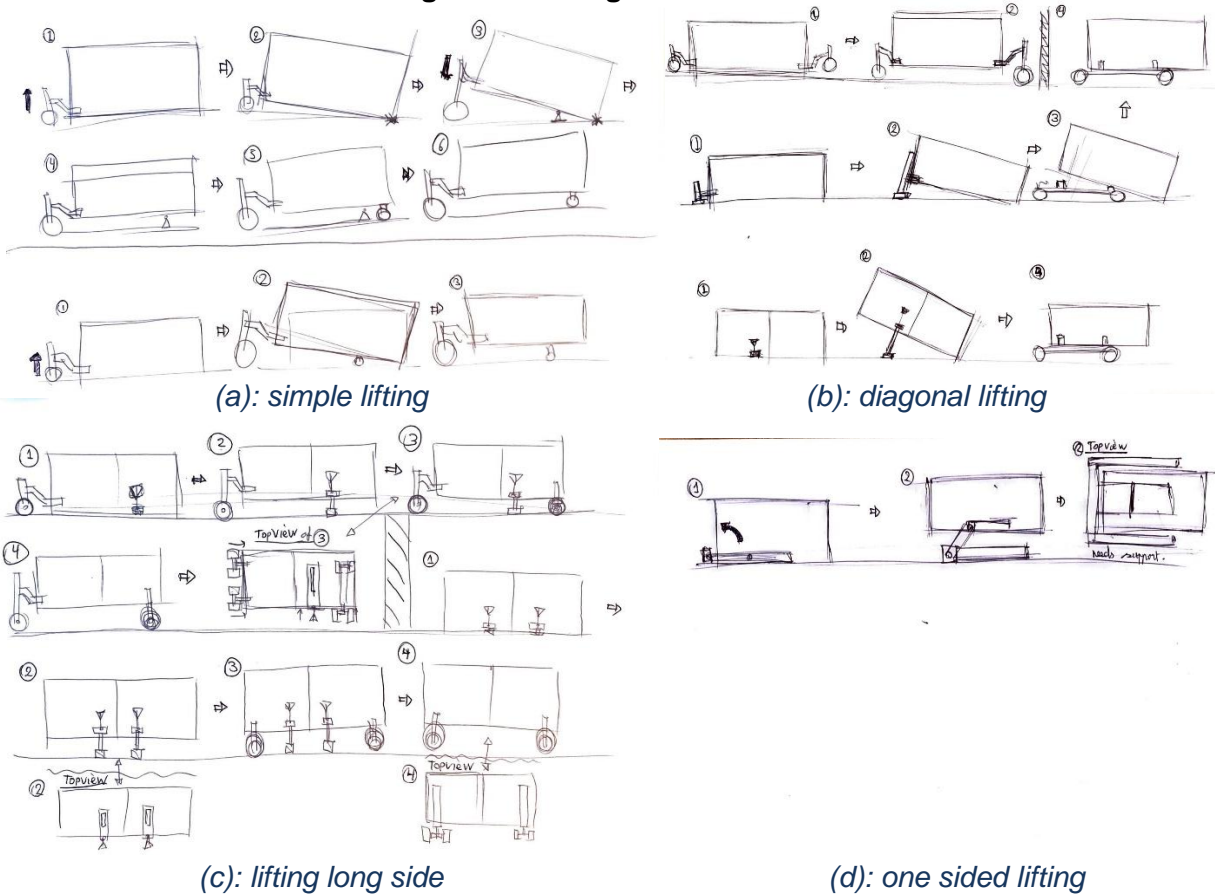
In the two figures below 33a and 33b the ideation for the rotation is presented. The ideation starts with simple ideation on how to rotate the wheels in figure 33a. However, in figure 33b the ideation focusses more on how to change the direction of the container and enable it to make the three required movements.

Figure 33: rotation ideation



In the final four figures 34a to 34d of the first step of ideation the lifting of the containers is ideated on. The goal is to get the container off the ground and onto wheels. The ideation ranges from simple lifting to diagonal lifting to lifting utilizing the different found holes.

Figure 34: lifting ideation

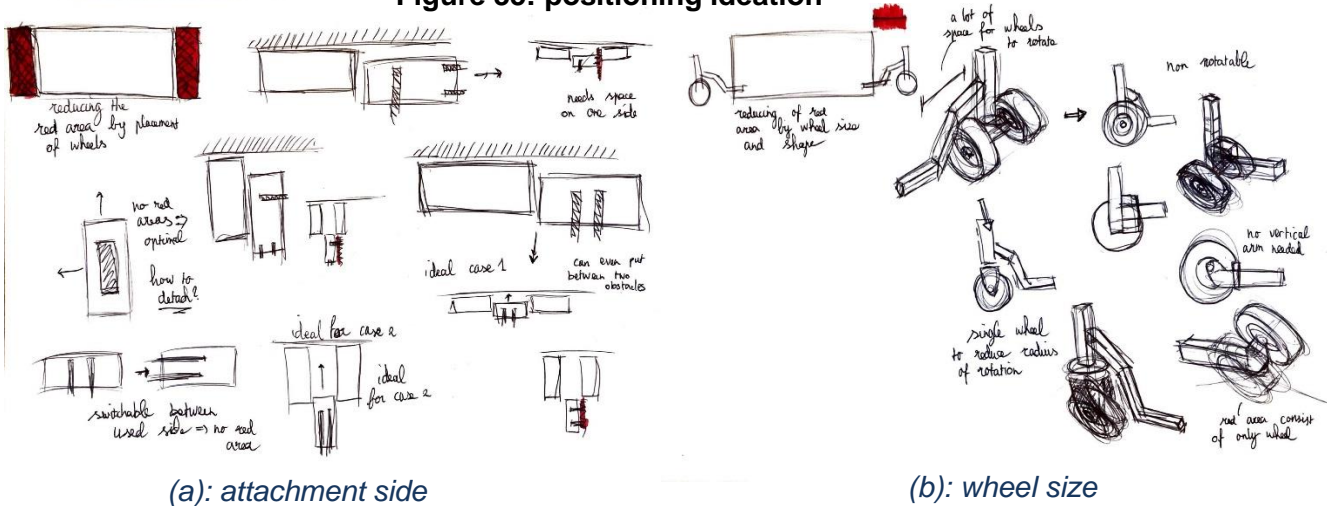


4.1.2 Optional aspects: precision, production, speed and transport ideation

In the second step the remaining aspects are ideated on. These aspects are optional, however, the more and the better an idea integrates these concepts the better it will perform during use.

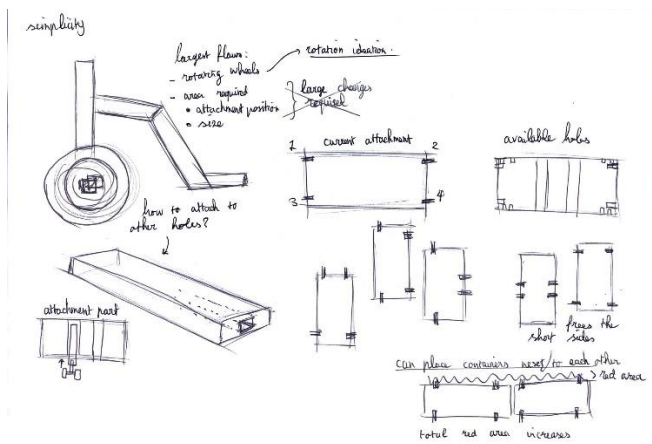
Firstly, the positioning is looked at. In figures 35a and 35b the ideation is illustrated. The positioning mainly focuses on the sides that are used while operation and looks at the different cases of chapter 2.8.1. This often results in ideas utilizing the forklift holes and means the product has a large length. Additionally, some thought is put into not eliminating but reducing the size of the red area around a container.

Figure 35: positioning ideation



For the production the main focus is to minimize costs by making only small adjustments to the existing DHI wheels. Therefore, its largest flaws are investigated. Firstly, the wheels were nearly impossible to rotate. Secondly, due to its attachment positions the wheels cannot align containers of case 1 from chapter 2.8.1. In figure 36 these flaws are ideated on. For the rotation of the wheels the ideation is done in step 1 figure 33 in the rotation of the wheels section. The attachment position is therefore mostly ideated on.

Figure 36: production ideation



To increase the speed of use of the product the rotation must be greatly improved. From chapter 2.5.2 was concluded that the most steps during use are in the rotation of the wheels. Therefore, for this aspect is again referred back to the rotation ideation in step 1 figure 33.

Finally for the transport the focus was on the size of the product. The ideas range from folding the product to detachment into several parts.

4.2 Concepts

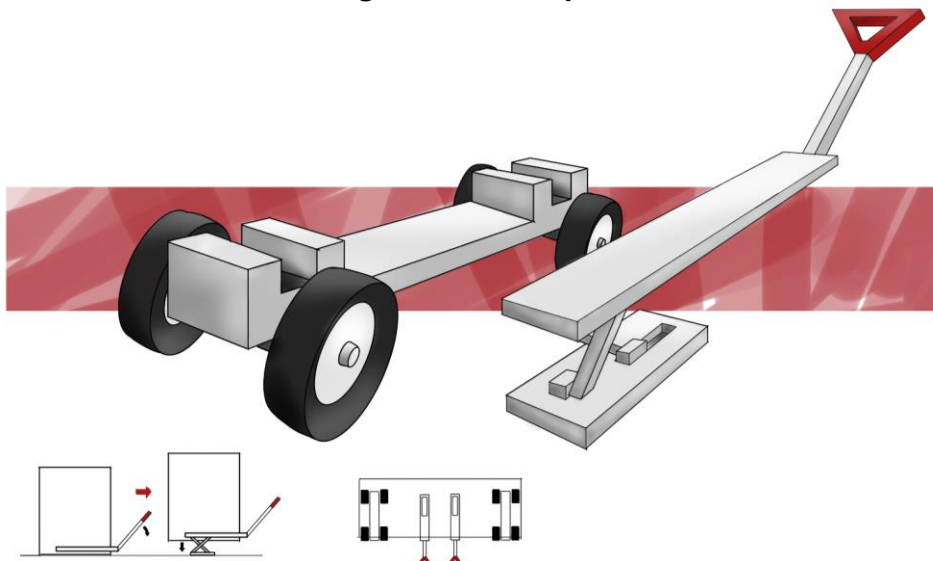
Introduction

In this chapter the concepts flown from the ideation phase will be presented. Each concept has a different focus so that upon evaluation of the three a well substantiated choice can be made as different directions are explored. The ideation is based on the requirements which were separated into six important criteria. From these six criteria each concept is required to include performance and safety as they are crucial to any product. The other four criteria were ideated on and the three best concepts that excelled the most in the criteria remained.

4.2.1 Concept 1

The first concept is illustrated in figure 39 and is a concept focused on performing the tasks as well as possible. This means the concept is capable of placing nearly every container configuration possible. First, two instances of the product on the right in the figure are inserted into the two forklift holes. Then by means of hydraulics a platform is lowered pushing the container upwards, which can be seen in the lower left of figure 28. When this is achieved two instances of the product on the left are placed on the beams of the bottom of the container near the shorter edges, a top view is drawn in the lower centre of figure 28. The jacks are lowered but not removed and the container can be pushed. To change the direction of the wheels, the jacks are lowered so that the pressure is taken off the wheels, these can then be rotated. By using an internal gear train both sets of wheels on one product will be rotated simultaneously, this mechanism can be found in figure 27d. The product on the left is 2 meters in length and 200 mm in width. The product on the right is 2 meters in width as well however to improve stability it is 300 mm in width. The concept should be further developed on its structural strength and both its internal mechanisms, lifting and rotating the wheels.

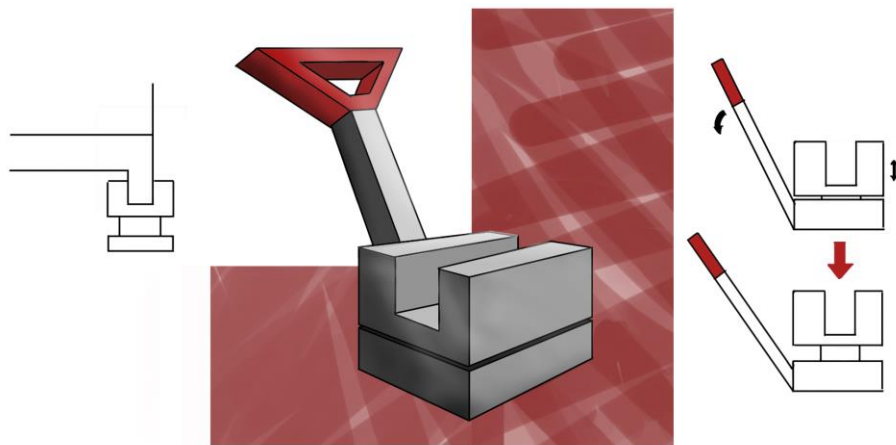
Figure 39: concept 1



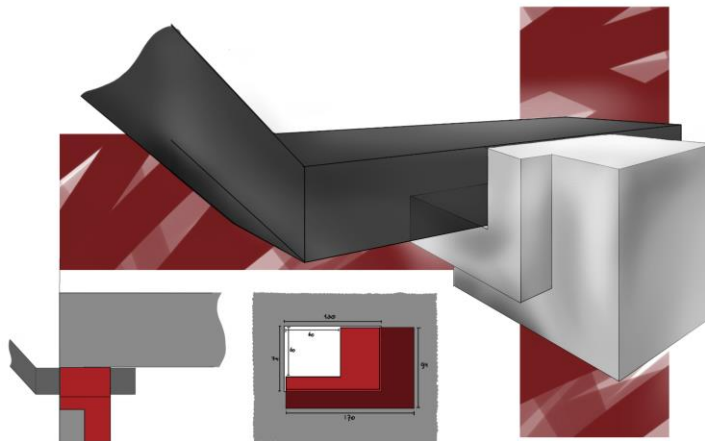
4.2.2 Concept 2

The second concept is focused on the manufacturing process. By making only small changes to the product the manufacturing process will be cheap and fast as the same producer of the original product can be used. The largest flaws in the original design were the inability of rotating the wheels as well as limitation of sides used. By adding a semi-custom jack to the process as drawn in figure 40a, the containers can be lifted and will take the force of the wheels to easily rotate them. To improve how well the concept can accurately place containers, the product seen in figure 40b is added. This product makes the DHI wheel fit into a different hole on the long side of the container by making the hole form fit to its dimensions. Additionally, the product provides support on the bottom and side edge to reduce the moment force. The external jack can be a simple carjack modified to have a mouthpiece fitting the borders of the Z-box. The dimensions of the support block are in figure 40b. This concept should be detailed on the specifications of the jack and the strength and exact size and geometry of the block.

Figure 40: concept 2



(a): external jack

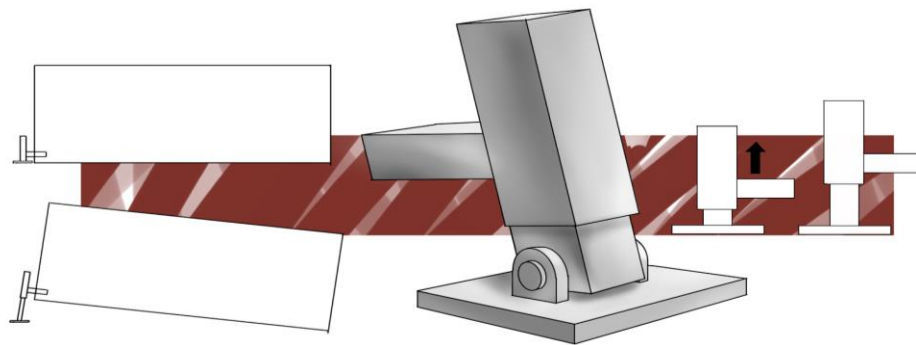


(b): external block

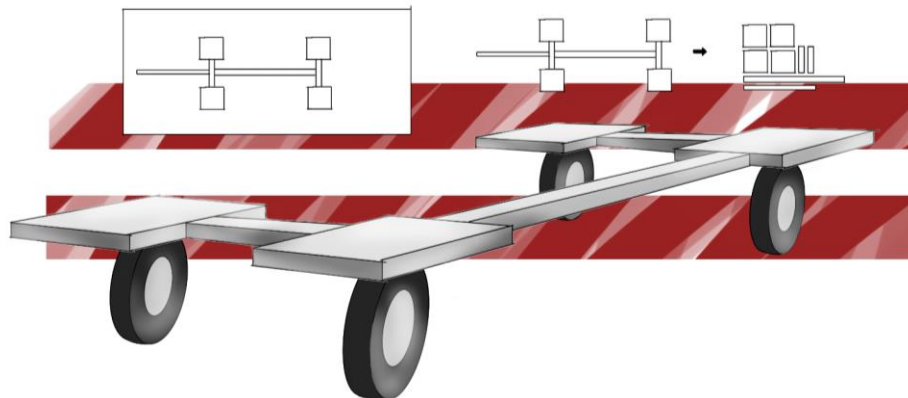
4.2.3 Concept 3

The last solution is focused on the time aspect of the positioning process. By reducing the number of steps required during the placement of a Z-box the amount of time needed can be greatly reduced. To start with, the concept uses only 2 products for lifting by doing so diagonally as illustrated in figure 41a, the product itself is similar to the DHI wheel by having an internal jack system to raise it. The second part of the concept is a carriage shown in figure 41b containing four omni-wheels. These omni-wheels completely eliminate the necessity of rotating the wheels as these omni-wheels are capable of rotations in all directions. This greatly reduces the number of steps during the process as each change in direction needed requires the rotation of the wheels. This carriage can be disassembled easily to reduce the size. This concept requires further research into its strength and into the exact mechanism of the carriage assembly.

Figure 41: concept 3



(a): external jack



(b): wheel platform

4.3 Concept choice

Introduction

In this chapter the final decision between the three described concepts will be made. This concept will then be taken into a detailing phase and completely be worked out. To make an educated decision each concept is evaluated on the important criteria. Each criterion is given a weighting factor and the concepts are then graded on each individual criterion. Each concept will receive a final grade and based on these a concept will be chosen.

4.3.1 Concept evaluation

To make a well substantiated choice, the concepts are first evaluated based on the six established criteria.

Performance

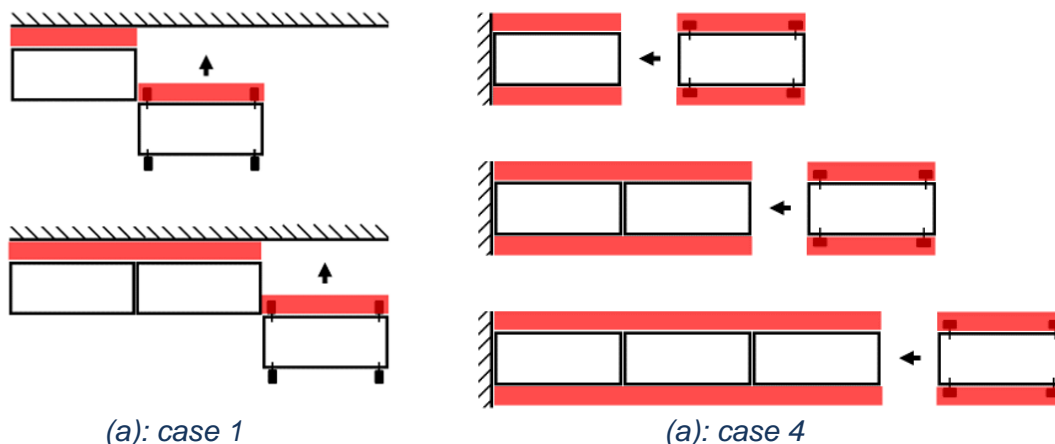
Most of the requirements the performance consists of are equally met by all three concepts. They can all lift a container regarding mass and geometry, they do not damage the containers and can be furtherly designed so that they will not fail. However, when it comes to the required movements which need to accurately be made, concept three performs less. The omni-wheels are capable of making any movement, this could result in the container making movements that are not desired meaning they will not be completely accurate.

Positioning

The first concept is capable of placing nearly every configuration possible. It occupies only one long side during use. This results in the same use case as the forklift which can be found in figures 21a to 21d in chapter 2.8.1. Different from the forklift however the first concept is much shorter meaning it does not run into the issue of not being able to be pulled out.

The second concept performs less well than the first concept. This concept is able to use either two long sides simultaneously or two short sides simultaneously. This means each container will have some extra space depending on which sides the wheels are attached to. The use cases of attaching to the short sides are illustrated in figures 20b and 20c in chapter 2.8.1. The differences of utilizing the long side are only in cases 1 and 4 as illustrated in figures 42a and 42b. In case 1 the containers can now be aligned perfectly when seen from the frontside, this comes however with the cost of requiring a larger red area. In case 4 the DHI wheels now function perfectly.

Figure 42: positioning with new attachment



The third and final concept too performs less when it comes to precision. Due to its unique diagonal lifting method only one short side is required. However, as it is diagonal the unused short side will still result in a red area. This means this concept has the use cases exactly as illustrated in figures 20a to 20d in chapter 2.8.1.

Production

When it comes to production complexity and size are most important. Concept two uses the original wheels with a slightly smaller mouthpiece, four small blocks and two modified car jacks. The size and complexity are very low and will therefore have relatively low production costs. The first and third concepts however have much larger components and each of them has to be created completely. The first concept has the most parts and the most complexity with moving parts and internal mechanisms. The third concept has three components but is smaller in total size. The first concept will therefore be the most expensive followed by the third concept. The second concept has the lowest costs.

Speed

The steps taken in the positioning process are lifting the container, attaching wheels, pushing the container and rotating the wheels. These steps only need to be performed once per container except the rotations. Each time the direction of the container needs to be changed these need to be performed.

Each concept includes lifting, attaching and pushing. The second concept uses four products for lifting meaning two extra steps are performed. Except that this concept combines attaching and lifting while the other two need an extra step to attach a different product. When it comes to rotating the wheels concepts 1 and 2 are very similar. They both lift the container using an external jack and then rotate the wheels. Concept 3 however completely eliminates this step by having all direction wheels. As the direction of the container often needs to be changed during use, concept three saves a considerable number of steps and time.

Transport

The first concept is the largest and therefore the heaviest, meaning it performs the worst in terms of being easily transported. The product is 2 meters long however it can be folded in half. This results in four components of around 1,0 x 1,0 m. The product in the second concept can be configured in a row resulting in a needed area of around 2,5 x 0,53 m. The last concept uses two small lifting jacks and a platform with four wheels which can be disassembled. In total this uses around 1,0 x 1,5 m. This excludes the beams of the platform which need to be taken into consideration as well.

Safety

The first concept is the least safe concept. This mainly comes from the two jacks being near the centre of the Z-box, meaning it is the most prone to tipping. The second concept is the safest, it is not subjected to any tipping and is the concept that needs to be lifted the least out of the three. This means when a part does fail the least number of consequences will occur. The last concept uses diagonal lifting, this could introduce unexpected issues when there is not enough space behind the container. This could result in damage to property, or worse a human. This concept too requires quite high lifting meaning when one of the two jacks fails the container will fall in a very unexpected direction.

Weighting factors

To make a well substantiated concept choice, the multi criteria decision analysis (MCDA) method is used. According to De Montis, Andrea, et al. "Criteria for quality assessment of MCDA methods." *3rd Biennial conference of the European society for ecological economics, Vienna. Citeseer, 2000*^[30]. One MCDA method is to first construct hierarchies, second to define the importance of each criterion and finally to assess the consistency of the concept with these criteria.

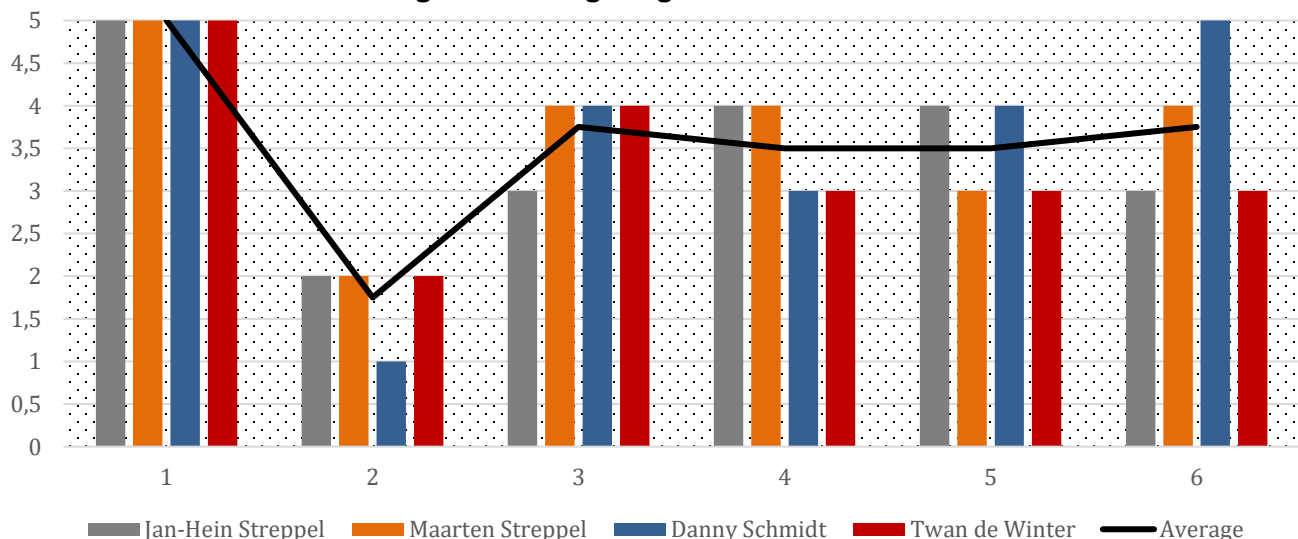
There are six criteria determined to be important for a manual Z-box positioning product. However, not every one of these criteria is as important as the other. Therefore, each criterion is assigned a weighting factor. To make sure these factors are as accurate as possible, multiple parties were consulted. These parties are CEOs of Universal Storage Containers Jan-Hein Streppel and Maarten Streppel as they are important stakeholders and decide on financial matters as well as the direction of the company. Additionally, Danny Schmidt, head of innovation at USC was included. Danny Schmidt has a great deal of experience when it comes to first-hand assembly of container parks. Furthermore, he has guided this project and therefore a good understanding of the factors. Finally, is myself, Twan de Winter as I have carried out this project. Each mentioned name independently filled in the questionnaire below:

From 1 (low) to 5 (high), how important are the following criteria for the redesigned wheel in use?

- 1. The ability to accurately place containers in their desired position*
- 2. Manufacturing time*
- 3. Manufacturing costs*
- 4. Time required to place a container*
- 5. Ease of transporting the product*
- 6. Safety during use*

In figure 43 the diagram with the results can be found per numbered criterion, where the blue line represents the average. There is not much difference in the votes across the different aspects, the largest difference is two points, and this only occurs once. For this reason, the average is the value that is taken for the concept choice.

Figure 43: weighting factors criteria



4.3.2 Concept choice

In table 4 the final scoring is shown. In the left column the requirements are placed and assigned a weighting factor towards their criterion. These criteria then are weighted by the factors from the questionnaire. Each concept is then graded from one to five based on how well it meets the requirements. The average per criterion is taken and then multiplied by its weighting factor. On the last row of the table the final scores can be found.

Table 4: concept choice table

Criteria	Weighting factor	Category	Weighting factor	Concept 1	Concept 2	Concept 3
				Rating (1-5)		
Lifting at least 1850 kg	5	General performance	5	5	5	5
Capable of lifting a Z-box	5		5	5	5	
Capable of attaching to Z-box	5		5	5	5	
Shall not damage a Z-box	5		5	5	5	
Product shall not fail	5		5	5	5	
Product allows accurate translation along x-axis	5		5	5	3	
Product allows accurate translation along y-axis	5		5	5	3	
Product allows changing between directions	5		3	5	5	
The space around a Z-box needed is no more than 1m	3		Positioning	5	5	3
Placing a Z-box next to geometry with max distance of 50mm	5	5		1	3	
Product allows rotation with radius of max 3.5m	3	5		5	5	
Manufacturing costs as little as possible <€4000	5	Production	3,75	1	5	2
Manufacturing time as little as possible	1		1	5	2	
Number of steps during use as low as possible	5	Speed	3,5	3	2	5
Number of steps taking longer than 1 minute as low as possible	5		3	3	5	
Mass of the product shall be as low as possible <100kg	3	Transport	3,5	3	5	4
Size of the product shall be as low as possible <4200x1500mm	5		3	5	4	
The product shall not allow unwanted tipping	5	Safety	3,75	3	5	5
Number of potential hazards is as low as possible	5		3	5	2	
Total score with weighing factors:				83,57	103,11	81,10

Conclusion

In the scoring it can be seen that the second concept scores the highest of the three with a margin of more than 20 points on both alternatives. Although the first concept is more precise and the third concept is faster, the second concept is cheaper, easier to transport and safer during use. In conclusion the second concept is a far more balanced option as it scores averagely on criteria it is not good at and it excels at criteria at which the other two concepts score poorly. Therefore, the second concept is chosen to be worked out further.

4.4 Detailing

Introduction

Now that a concept has been chosen, it needs to be furtherly designed to be ready for production. Therefore, all loose ends will be tied up by specifying the unknowns. Specifically, different jacks will be compared after which the most suitable will be chosen. The strengths of the different components will be simulated and adjusted to make sure they will not fail. The new components will be included in a transportable configuration. The fixed rotation angle of the wheels will be adjusted.

4.4.1 Jack

To make the rotation of the wheels be a much faster process, a jack is added. This jack only needs to raise the container slightly from the ground to remove the pressure from the wheels. The main important aspects that are considered for this jack therefore are: capable of lifting the mass of a Z-box, the stability of the jack, the minimum height of the jack and the price. Car jacks have very similar specifications and are widely available.

In the three figures 44a^[31], 44b^[32] and 44c^[33] below the three most commonly found car jacks are presented. In table 5 below all specifications are presented as well.

Figure 44: car jacks



Table 5: jack comparison

	A	B	C
Price	€119,79	€26,03	€155,99
Load capacity	3000 kg	5000 kg	3000 kg
Size range	125 - 455mm	195 - 380mm	140 - 470mm
Foot size	350 x 595mm	92 - 100mm	250 - 400mm
Lifting method	Pushing lever down	Pushing lever down	Air compressor

Looking at these results, jack A is chosen. The first jack has the lowest minimum height by 70 mm compared to jack B. It has the highest area making it the most stable and does not require an external lifting method such as jack C. This jack is however not the cheapest option but will outperform the less expensive choices.

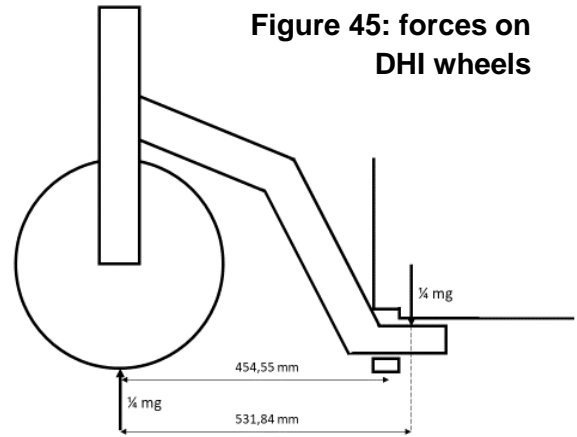
4.4.2 Strength

To make sure all components of the solution will not fail, a strength analysis using SolidWorks will be executed. Especially the block for the wheels to fit on the long of the container must be looked at. Not only should the part not break, but the part should also be designed so that the Z-box will not be damaged either.

In figure 45 on the right the schematic situation of a DHI wheel loaded by a container is drawn. To simplify the mass of the wheel itself is neglected. For the moment force to be in equilibrium however, the bar underneath the hole has to exert a force. This moment and therefore the force are calculated by:

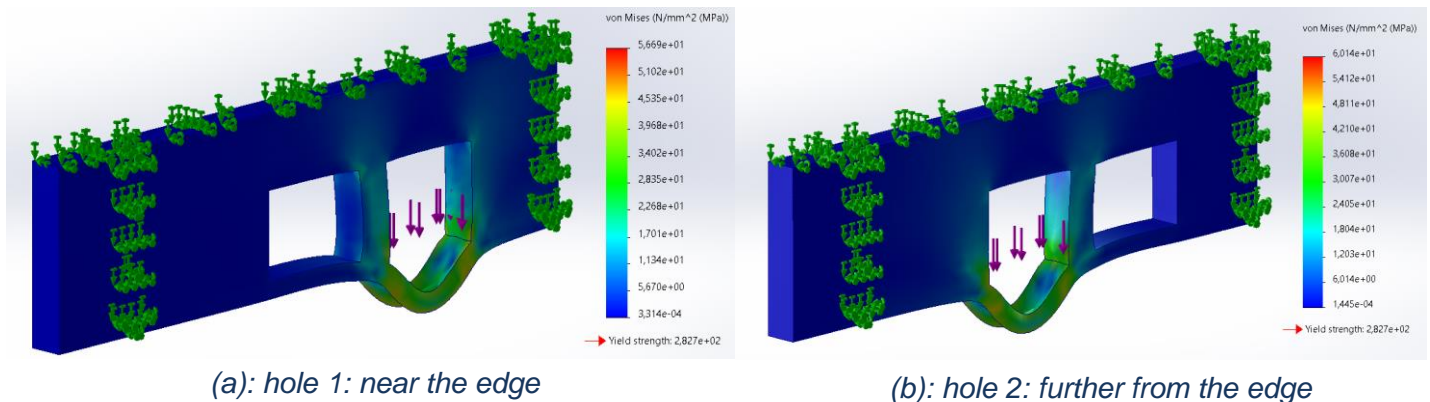
$$M = F * r = \frac{1}{4} mg * 531,84 * 10^{-3} = 2,41 * 10^3 \text{ Nm}$$

$$F = \frac{M}{r} = \frac{2,41 * 10^3}{454,55 * 10^{-3}} = 5,31 * 10^3 \text{ N}$$



In the two figures 46a and 46b below the two options of holes on the long sides are compared. In both situations the bar is subjected to the force calculated above. The full report and details can be found in appendix C2 and C3. This is the situation without the block being part of the solution which would reduce the amount of force the bar is subject to. In the two figures the most important aspect is the amount of von Mises stress. In both cases the highest von Mises stress occurring is more than four times lower than the yield strength of the material. However, in the first situation the highest stress is lower than in the second, ranging up to 57 N/mm². This means a safety factor of $235/57 = 4,1$. The holes used therefore will be those closer to the edge being 130x100mm. Additionally, concluded from this study is that the bar can support the moment force the wheel exerts on it without the help of extra geometry behind or below it.

Figure 46: structural analysis new hole



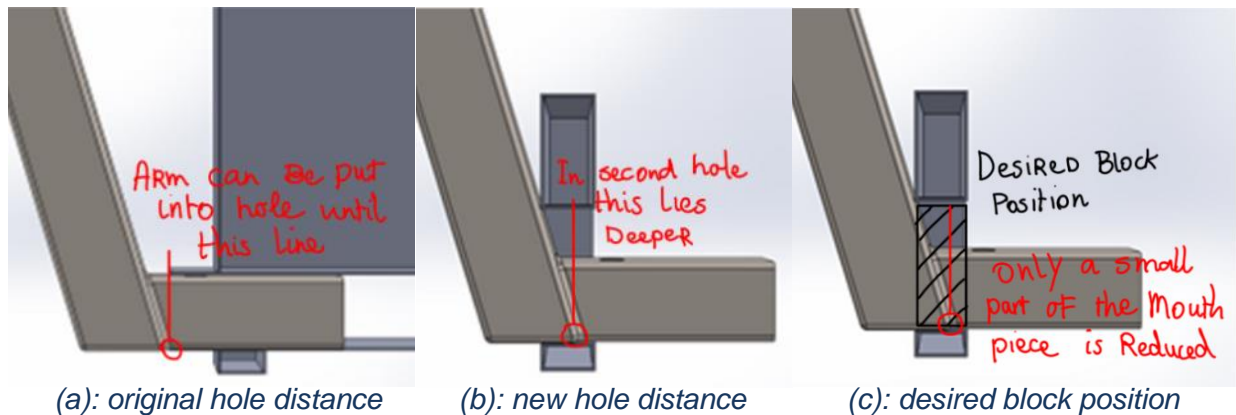
4.4.3 New block

Since the conclusion from the analysis in the previous subchapter is that the block can be simpler, the design of the block geometry should focus less on performance and safety. Instead, it should focus on speed, transport and production.

In the two figures 47a and 47b the current DHI wheel inserted into the two different holes are shown. 47a shows the hole the wheels were designed for and 47b is the hole the block is aimed to fit into. The old block

introduces unnecessary steps as it is detachable and has to be placed when using the larger hole. Additionally, the blocks are separate parts meaning transport will be more difficult. Finally, the block is larger than it has to be resulting in larger material costs.

Figure 47: block detailing



The main difference between the two situations is that the second hole is too large making the diagonal arm falls slightly into the hole as well, which can be seen in figure 47b. Additionally, the first hole extrudes 40mm from the front surface of the container. With these two aspects the block can be attached to the horizontal mouthpiece without greatly reducing its length as seen in figure 47c. The block itself has dimensions of 128x98x40mm. Further analysis is required to determine whether the reduction of the mouthpiece is viable.

Structural analysis

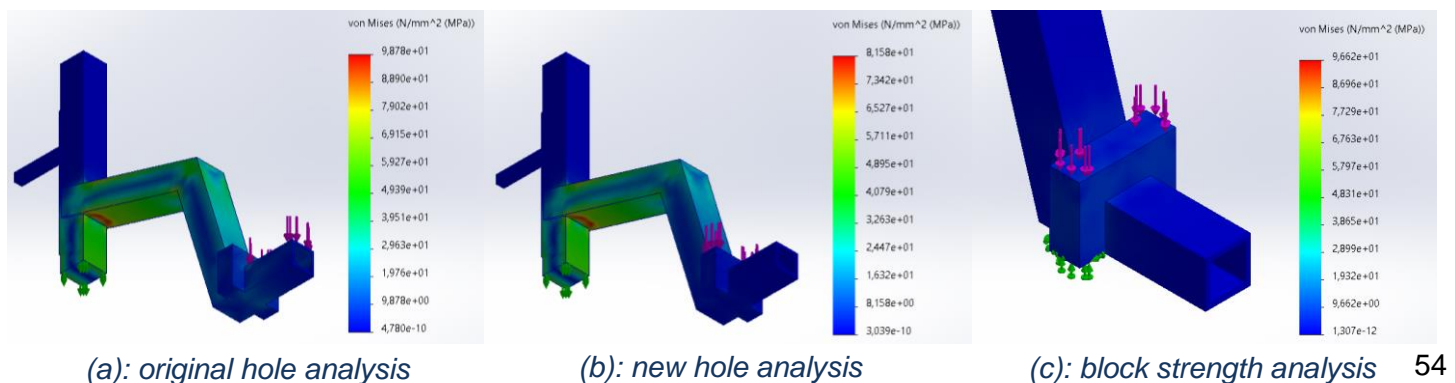
In figures 48a to 48c a structural analysis using SolidWorks is executed on the new design. All the details can be found in appendix C3 to C6 First the original use case, using the holes on the short side, will be analysed. Since the block reduces the mouth pieces length slightly, the stresses on the product will change, this analysis can be found in figure 48a. The maximum stress is increased to 100 N/mm², from 98 N/mm². This reduces the safety factor from 2,6 to 2,5.

In figure 48b the stresses the product is subjected to in the new use case are shown. This is the situation when the wheel is inserted into the holes on the long sides of the Z-box. Here the maximum stresses are 83 N/mm² resulting in a safety factor of 3,0.

Finally, the geometry of the block itself is tested in figure 48c. The maximum stress in the product now reaches a maximum of 33 N/mm² equivalent to a safety factor of 7,6.

After analysing each new stress from the new design, it is concluded that with safety factors from 2,5 to 7,6, the new design is structurally sufficiently strong.

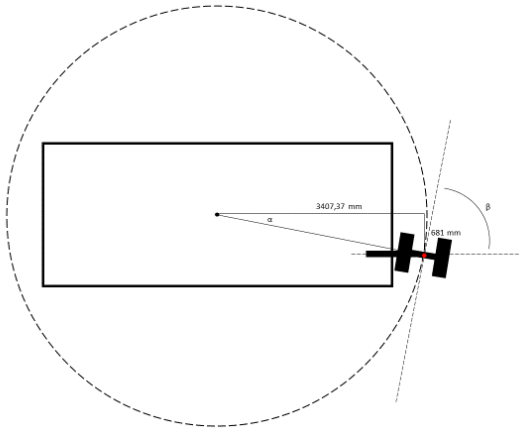
Figure 48: structural analysis new design



4.4.4 Rotation angles

To ensure the smallest possible accurate rotation circle of the container, the wheels need to be positioned in the correct angle. In figure 49 below a schematic is created of the real situation where the rotation path is the dotted circle. By knowing the distances between the rotation point and the centre of the circle the angles can be calculated as follows:

Figure 49: rotation angle



$$\alpha = \tan^{-1}\left(\frac{681}{3407,37}\right) = 11,30^\circ$$
$$\beta = 90 - \alpha = 78,30^\circ$$

The current design has three holes in the lower circular plate and a pin that falls into them on the higher circular plate. Currently these holes are located at 0, 45 and -45 degrees respectively. The 45-degree angles do not serve a real purpose and can therefore only form an obstacle. These holes will be removed and replaced with holes located at 78,70 and -78,70 degrees.

5 Final design

Introduction

In this chapter the final design will be visualized and evaluated. The evaluation will be done by looking at the different criteria and defining and determining how well it performs in each. However, first the complete design will be shown, by visualizing its new and key original features and the functions this enables. In figure 50 the final design can be seen.

Figure 50: final design

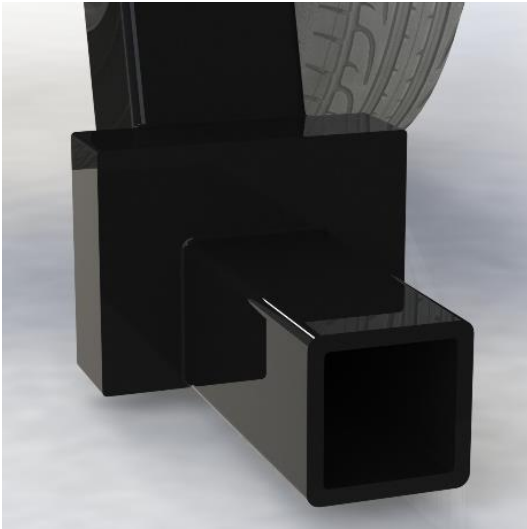


5.1 Functions of the redesigned DHI wheel

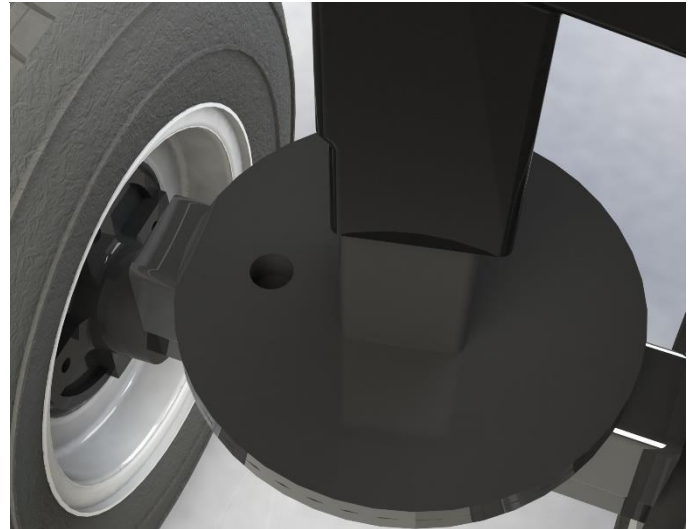
5.1.1 Redesign

In figure 51a and 51b the main changes to the old design can be seen. In figure 65a the new block on the mouthpiece is shown as well as the new cross section of 60x60mm. In figure 65b the fixed angle pin system with the correct angle can be seen. Additionally, an external car jack is added to the process.

Figure 51: new features



(a): mouthpiece

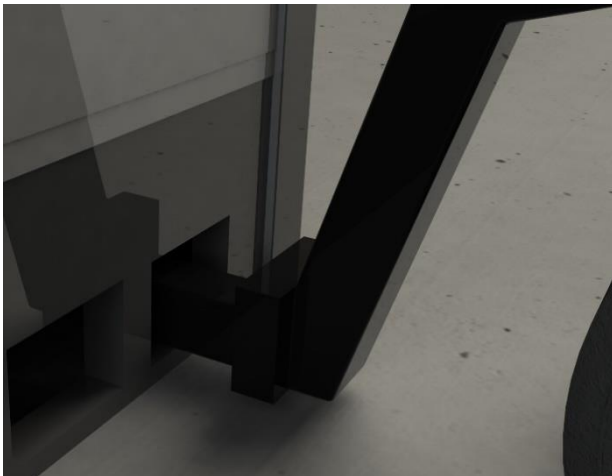


(b): rotational angle

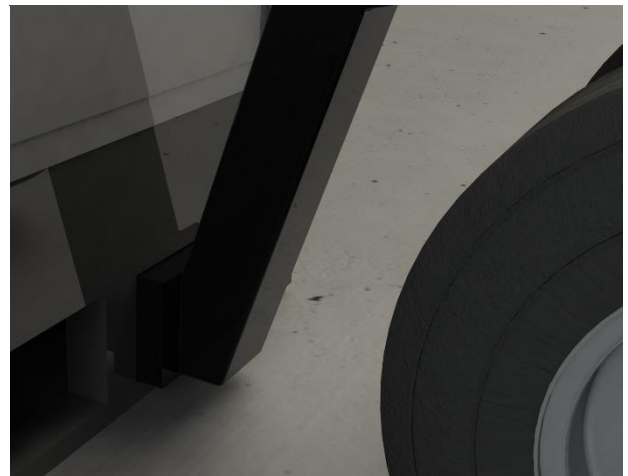
5.1.2 Functions

In figures 52a and 52b the implications of the new block can be seen. The addition of the block enables the product to fit into the holes on the long sides of the Z-box.

Figure 52: new hole attachment



(a): partially inserted



(b): completely inserted

In figure 53a and 53b the original placement of the DHI wheel can be seen. although a block was added to the mouthpiece, the function still remains. The functions of figures 52a, 52b and 53a all enable the wheels to be jacked up by its internal jack system. When this is done the Z-box will be lifted of the ground as seen in figure 53b.

Figure 53: original features



(a): original hole attachment



(b): lifting

After the Z-box is raised from the ground, it can be pushed around by four people. In figure 54a a Z-box model 1 is placed next to another. The new wheel placement allows the Z-box models 3, 4 & 5 to be placed next to one another as seen in figure 54b.

Figure 54: positioning



(a): model 1



(a): models 3,4 & 5



Figure 55: transport configuration

Finally, the redesigned DHI wheel can be configured as in figure 55 to greatly reduce the size during transportation.

5.2 Evaluation of the redesigned DHI wheel

To make sure the final design performs as well as desired, the solution is evaluated with the six criteria as well as the requirements.

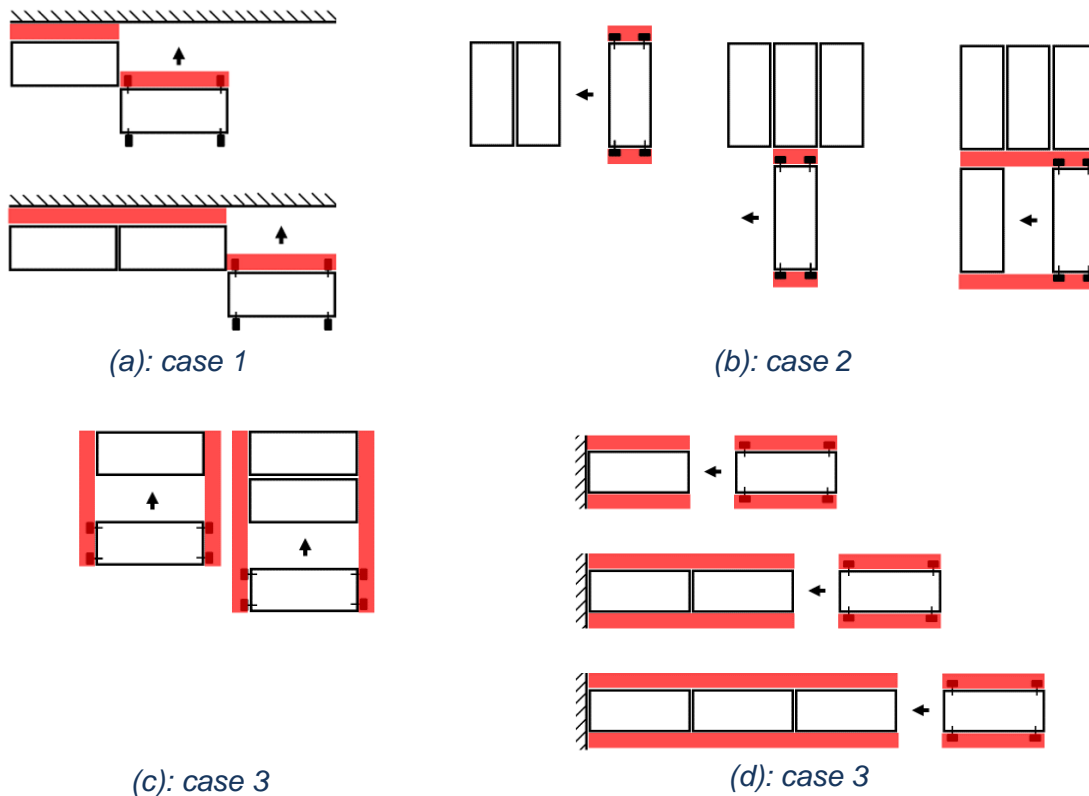
5.1.1 General performance

The redesigned wheels perform perfectly in the first aspect.

5.1.2 Positioning

The performance of the redesigned DHI wheel on positioning is shown in the figures 56a to 56d. Here the four cases seen in chapter 2.8.1 are used. As the wheels can be placed either on the long sides or the short sides, the Z-boxes can be placed aligned with the next Z-box in each of the four situations. However, in the first and the second case the containers cannot be placed with its back touching other geometry. This results in the container requiring extra area to be placed. In the first case this equals: $\frac{0,808*5,810}{5,810*2,382} * 100\% = 33,92\%$. In the second case this equals: $\frac{0,808*2,382}{5,810*2,382} * 100\% = 13,91\%$.

Figure 56: positioning final design



5.1.3 Production

To evaluate the final production costs, the welder of Universal Storage Containers was asked to make an estimation on material and labour costs.

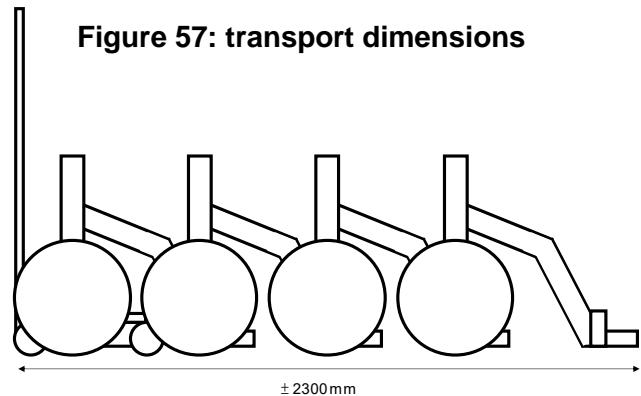
The material price of a steel tube of 128x98 which can be used to produce the four blocks costs €46,83^[34]. Additionally, the welding and drilling of holes will take around 1,5 to 2 hours per wheel. Together this results in an estimated price of €656,83 excluding VAT, meaning €164,21 per wheel. Added to this is the price of the jack being €119,79 and VAT. The total price of the redesigned solution is therefore €914,55.

5.1.4 Speed

The final design requires the following step per movement: stopping the container, placing the jack, jacking up the jack, rotating the wheels and finally pushing the container again. Together this results in 10 total steps.

5.1.5 Transport

In figure 57 the new transportation configuration can be found. This configuration is effectively the same as the old one, except for the addition of the jack. This jack however fits underneath the redesigned DHI wheel, and the dimensions of the configuration do therefore not change. This means the final dimensions are 2300x530x698mm (l*w*h).



5.1.6 Safety

The structure of the final design has safety factors ranging from 2,5 to 7,6 scoring at minimum 1 point higher than required by national norm NEN 1494. Additionally, the final design does not need to be lifted from the floor more than 150mm and the operation of the product does not require vital body parts to be near the edge of the container.

5.1.7 Requirements

In table 6 below the final scores of the final design regarding the requirements can be seen.

Table 6: final design requirement assessment

Criteria	Weighting factor	Category	Weighting factor	Final scores
Lifting at least 1850 kg	5	General performance	5	5
Capable of lifting a Z-box	5			5
Capable of attaching to Z-box	5			5
Shall not damage a Z-box	5			5
Product shall not fail	5			5
Product allows accurate translation along x-axis	5			5
Product allows accurate translation along y-axis	5			5
Product allows changing between directions	5			5
The space around a Z-box needed is no more than 1m	3	Positioning	5	5
Placing a Z-box next to geometry with max distance of 50mm	5			3
Product allows rotation with radius of max 3.5m	3			5
Manufacturing costs as little as possible <€4000	5	Production	3,75	5
Manufacturing time as little as possible	1			5
Number of steps during use as low as possible	5	Speed	3,5	2
Number of steps taking longer than 1 minute as low as possible	5			5
Mass of the product shall be as low as possible <100 kg	3	Transport	3,5	3
Size of the product shall be as low as possible <4200x1500mm	5			5
The product shall not allow unwanted tipping	5	Safety	3,75	5
Number of potential hazards is as low as possible	5			5

6 Conclusions and recommendations

6.1 Conclusion

The final goal of this report was to redesign the DHI in such a way that it increased the efficiency while keeping the financial aspect in mind. Increasing the efficiency was determined to be a balance between general performance, positioning, time taken during use and the ease of transport. After investigating into each of these different design directions was concluded that a complete new design of the DHI wheel was not worth it.

By increasing the precision during positioning of the product it too increased its size resulting in a lesser transportability and safety. Additionally, as the product would need to be completely produced the process would be costly. By trying to reduce the number of steps and therefore the time taken to operate the product, the production, positioning, safety and general performance all were reduced. Therefore, was concluded that a redesign focused on speed too was the incorrect direction.

Instead, the final design focuses on the manufacturing process. By adding an external jack, the rotation of the wheels became possible. And by permanently adding a small block to the mouthpiece the wheels could utilize the long sides of the Z-box and position even models 3, 4 & 5 next to each other. Both these changes were modest and therefore the original wheels purchased by Universal Storage Containers could be adapted.

The final design includes all the mandatory established aspects and requirements. Additionally, it meets most optional requirements. The final design however only reduced the number of steps from 14 to 10 and cannot place a Z-box next to another Z-box with a wall directly behind it, here 808mm extra is required.

In conclusion to answer: *“What is the best possible redesign of the DHI wheels to provide the most added value to the building process, while maximizing efficiency and financial benefit?”*. The final design only includes a few changes compared to the original design. The final design meets all the mandatory requirements while performing averagely on positioning and speed. With this final design the price to efficiency rate is the maximized.

6.2 Recommendations

As mentioned, the final design does not pass all the requirements meaning it is not the perfect product. The first requirement it does not pass completely is placing a Z-box next to geometry with a maximum distance of 50mm. instead it requires one side of the container with a distance of 808mm. Therefore, Universal Storage Containers is recommended to keep this in mind during the design of the layout of a potential storage park. By not placing containers directly next to geometry it enables the assembly team to position the containers using the redesigned wheels.

In chapter 2.6.2 the maximum allowed forces and the amount of people required are calculated. USC is recommended to conform to these values as they guarantee the safety of the workers involved.

To reach structural safety the safety factor should at least be 1,5. The smallest reached safety factor instead was 2,5. This means there is room for further improvements on the final design. The material for example could be changed to a lighter one to reduce the mass or reducing production costs by choosing a less costly material. Furthermore, the structure itself could be looked at. By changes thicknesses and tolerances the product could be reduced in size and mass. However, for these changes further research and development is required.

Appendix

A Container Park analysis

In table A.1 and table A.2 all the information regarding the 22 analysed container parks is shown. These 22 container parks are real customers of Universal Storage containers. Therefore, the names of the parks are not shown due to privacy reasons. The parks were analysed by looking at aerial photos recorded by USC.

Table A.1: container park information 1

	Area(m ²)	Length(m)	Width(m)	Length + width(m)	#Containers	difficult containers	l/w	w/l
1	1664	52	32	84	63,55556	6	1,625	0,615385
2	4212	100,5	81	181,5	160,875	0	1,240741	0,80597
3	887,5	35,5	25	60,5	33,89757	2	1,42	0,704225
4	375	50	15	65	14,32292	0	3,333333	0,3
5	340	8,5	40	48,5	12,98611	0	0,2125	4,705882
6	1196	26	46	72	45,68056	0	0,565217	1,769231
7	780	30	26	56	29,79167	3	1,153846	0,866667
8	1186	48	50	98	45,29861	0	0,96	1,041667
9	4725	90	105	195	180,4688	0	0,857143	1,166667
10	641,25	22,5	28,5	51	24,49219	0	0,789474	1,266667
11	4808	46,8	60	106,8	183,6389	0	0,78	1,282051
12	982,5	40,8	36	76,8	37,52604	3	1,133333	0,882353
13	422,76	14,22	29,73	43,95	16,14708	3	0,478305	2,090717
14	610,791	19,01	32,13	51,14	23,32882	3	0,591659	1,690163
15	2047,5	39	65	104	78,20313	3	0,6	1,666667
16	150	10	15	25	5,729167	1	0,666667	1,5
17	1748	46	38	84	66,76389	2	1,210526	0,826087
18	1566,72	40,8	38,4	79,2	59,84	5	1,0625	0,941176
19	752,76	38,4	50,4	88,8	28,75125	2	0,761905	1,3125
20	4579,2	127,2	36	163,2	174,9	3	3,533333	0,283019
21	1684,8	31,2	54	85,2	64,35	3	0,577778	1,730769
22	10284	80	129,12	209,12	392,7917	0	0,619579	1,614
Sum:					1743,339	39		

Table A.2: container park information 2

	R	a x 0,55	S(m)	T forklift(h)	T wheels(h)	Time saved(h)	Time saved(%)	Wage forklift personnel(€)	Wage wheels personnel(€)	Extra wage(€)
1	1,625	915,2	50,11164	64,35177	63,56808	0,78369	1,217822	2574,071	7628,17	5054,099
2	1,240741	2316,6	132,2448	166,1937	160,9081	5,28566	3,180421	6647,749	19308,97	12661,22
3	1,42	488,125	37,03416	34,21141	33,90683	0,304583	0,890298	1368,456	4068,819	2700,363
4	3,333333	206,25	38,91011	14,46224	14,33264	0,129599	0,89612	578,4897	1719,917	1141,428
5	4,705882	187	14,87107	13,03439	12,98983	0,044562	0,341877	521,3756	1558,779	1037,404
6	1,769231	657,8	42,06349	46,16093	45,69107	0,469855	1,017863	1846,437	5482,929	3636,492
7	1,153846	429	35,07525	30,0529	29,80044	0,252469	0,840081	1202,116	3576,052	2373,936
8	1,041667	652,3	72,43855	46,11895	45,31672	0,802232	1,739484	1844,758	5438,006	3593,248
9	1,166667	2598,75	143,4152	186,9392	180,5046	6,434636	3,4421	7477,57	21660,55	14182,98
10	1,266667	352,6875	31,69287	24,68624	24,50011	0,186134	0,753998	987,4498	2940,013	1952,564
11	1,282051	2644,4	53,78082	186,108	183,6523	2,455617	1,319458	7444,318	22038,28	14593,96
12	1,133333	540,375	53,37171	38,02675	37,53938	0,487364	1,281636	1521,07	4504,726	2983,656
13	2,090717	232,518	24,36308	16,24543	16,15317	0,092257	0,567898	649,8173	1938,381	1288,564
14	1,690163	335,9351	30,22878	23,50512	23,33638	0,168743	0,7179	940,2049	2800,366	1860,161
15	1,666667	1126,125	65,96784	79,49285	78,21962	1,273231	1,601692	3179,714	9386,354	6206,64
16	1,5	82,5	15,16014	5,75088	5,732957	0,017924	0,311669	230,0352	687,9548	457,9196
17	1,210526	961,4	52,42593	67,63893	66,777	0,861933	1,274315	2705,557	8013,239	5307,682
18	1,0625	861,696	49,79138	60,58488	59,85245	0,732431	1,208934	2423,395	7182,294	4758,899
19	1,3125	414,018	67,69559	29,23783	28,76817	0,469659	1,606341	1169,513	3452,181	2282,668
20	3,533333	2518,56	67,43769	177,8487	174,9169	2,931854	1,64851	7113,949	20990,02	13876,07
21	1,730769	926,64	50,06303	65,15539	64,36252	0,792873	1,216896	2606,216	7723,502	5117,286
22	1,614	5656,2	125,1288	405,0791	392,8229	12,25611	3,025609	16203,16	47138,75	30935,59

B Force calculations

Newton's second law:

$$F = ma$$

$$Fx = ma = F_{push} - 4W$$

where: $W = \text{rolling friction}$

B1 Sustained force

The first calculated required pushing force is to maintain a constant speed. A constant speed means the difference in speed is zero meaning there is no acceleration.

$$0 = F_{push} - 4W$$

$$F_{push} = 4W$$

To calculate the required force the friction needs to be calculated. Friction is equal to:

$$W = c * m * g$$

where: $c = \text{friction coefficient}$

The friction coefficient for car tires on gravel or asphalt is 0,02^{[35][36]}

$$F_{push} = 4W = 4 * 0,02 * \frac{1850}{4} * 9,81 = 362,97 \text{ N}$$

B2 Initial force

Next the initial required force is calculated. In this case the container needs to be accelerated from 0 m/s to 0,78 m/s as determined during testing in chapter 2.5.2.

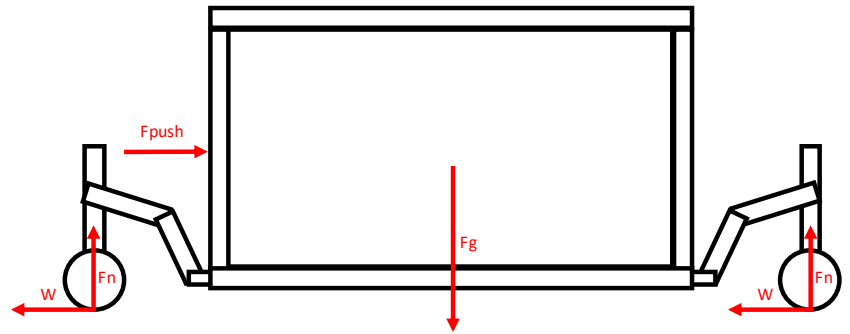
$$a = \frac{\Delta v}{\Delta t} = \frac{0,78 - 0}{3 - 0} = 0,26 \text{ m/s}^2$$

$$ma = F_{push} - 4W$$

$$F_{push} = 4W + ma$$

$$F_{push} = 4 * 0,02 * \frac{1850}{4} * 9,81 + 1850 * 0,26 = 843,97 \text{ N}$$

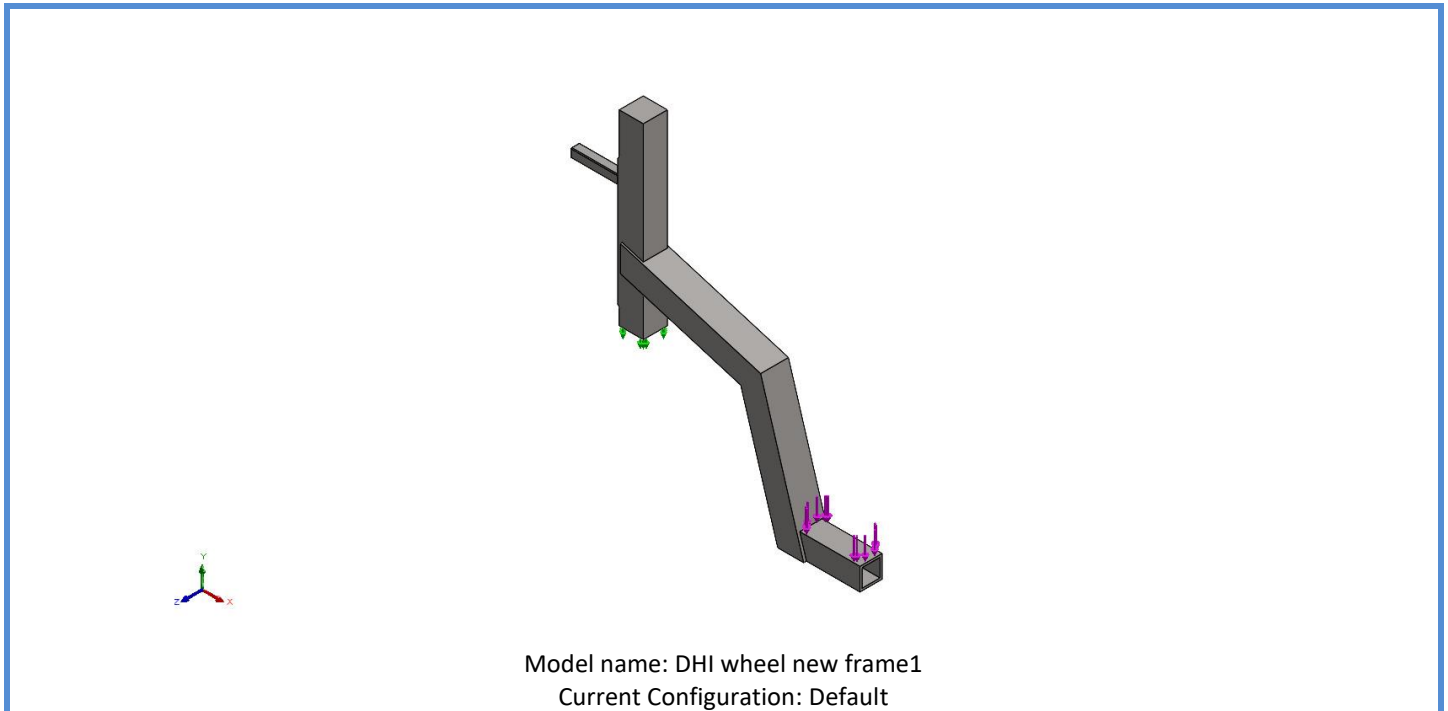
Figure 15: forces on a Z-box



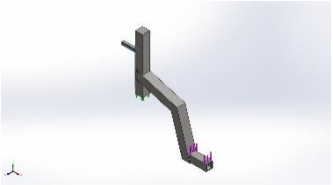
C Simulations

C1 Original DHI wheel report

Model Information



Solid Bodies

Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Boss-Extrude24 	Solid Body	Mass:27,6459 kg Volume:0,00354434 m ³ Density:7.800 kg/m ³ Weight:270,93 N	C:\Users\twand\OneDrive\Do cumenten\Bsc final\DHI wheel new frame1.SLDPRT Oct 21 18:20:49 2024

Study Properties

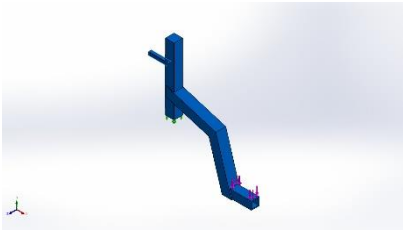
Study name	Static 3
Analysis type	Static
Mesh type	Solid Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Include fluid pressure effects from SOLIDWORKS Flow Simulation	Off
Solver type	Automatic
Inplane Effect:	Off
Soft Spring:	Off

Inertial Relief:	Off
Incompatible bonding options	Automatic
Large displacement	Off
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off
Result folder	SOLIDWORKS document (C:\Users\twand\OneDrive\Documenten\Bsc final)

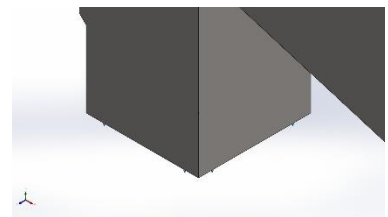
Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/mm ² (MPa)

Material Properties

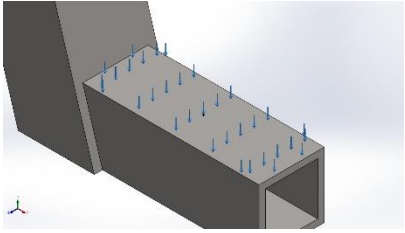
Model Reference	Properties	Components
	Name: Plain Carbon Steel Model type: Linear Elastic Isotropic Default failure criterion: Max von Mises Stress Yield strength: 220,594 N/mm² Tensile strength: 399,826 N/mm² Elastic modulus: 210.000 N/mm² Poisson's ratio: 0,28 Mass density: 7,8 g/cm³ Shear modulus: 79.000 N/mm² Thermal expansion coefficient: 1,3e-05 /Kelvin	SolidBody 1(Boss-Extrude24)(DHI wheel new frame1)
Curve Data:N/A		

Loads and Fixtures

Fixture name	Fixture Image	Fixture Details
Roller/Slider-1		Entities: 1 face(s) Type: Roller/Slider

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	0	4.537,13	0	4.537,13
Reaction Moment(N.m)	0	0	0	0

Load name	Load Image	Load Details
Force-1		Entities: 1 face(s) Type: Apply normal force Value: 4.537,13 N

Mesh information

Mesh type	Solid Mesh
Mesher Used:	Blended curvature-based mesh
Jacobian points for High quality mesh	16 Points
Maximum element size	31,5522 mm
Minimum element size	1,57761 mm
Mesh Quality	High

Mesh information - Details

Total Nodes	29392
Total Elements	15723
Maximum Aspect Ratio	182,41
% of elements with Aspect Ratio < 3	35,9
Percentage of elements with Aspect Ratio > 10	9,08
Percentage of distorted elements	0
Time to complete mesh(hh:mm:ss):	00:00:09
Computer name:	

Resultant Forces

Reaction forces

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	0	4.537,13	0	4.537,13

Reaction Moments

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0

Free body forces

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-0,000505228	-0,00867462	-9,8098e-05	0,00868988

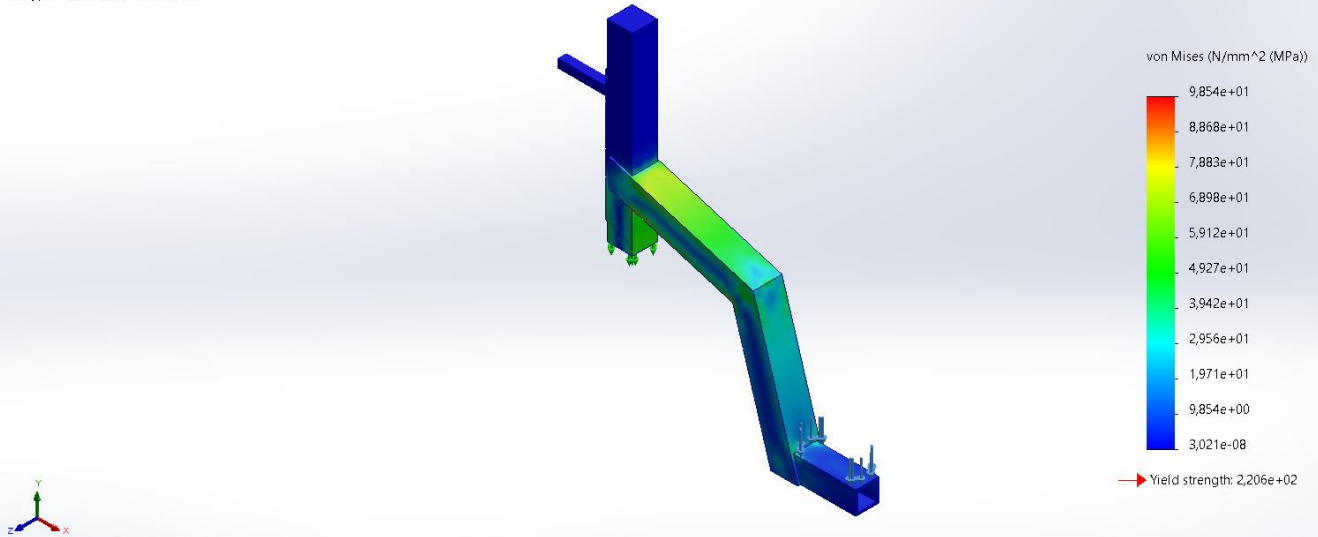
Free body moments

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	1e-33

Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	3,021e-08N/mm ² (MPa) Node: 18390	9,854e+01N/mm ² (MPa) Node: 751

Model name: DHI wheel new frame1
Study name: Static 3(-Default-)
Plot type: Static nodal stress Stress1

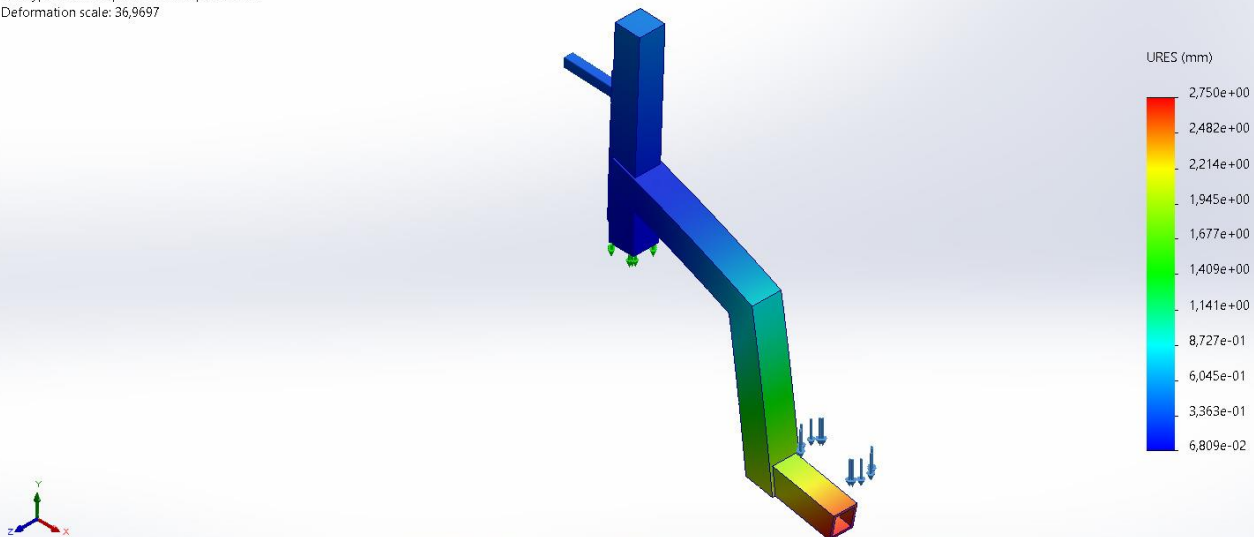


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DHI wheel new frame1-Static 3-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	6,809e-02mm Node: 23	2,750e+00mm Node: 60

Model name: DHI wheel new frame1
Study name: Static 3(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 36,9697

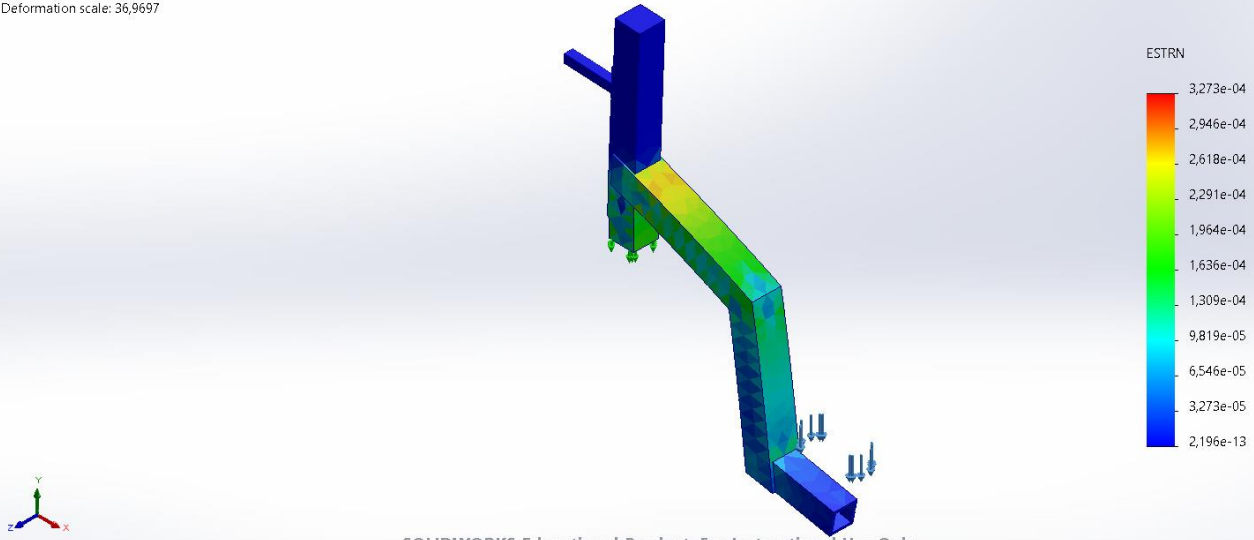


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DHI wheel new frame1-Static 3-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	2,196e-13 Element: 6031	3,273e-04 Element: 6630

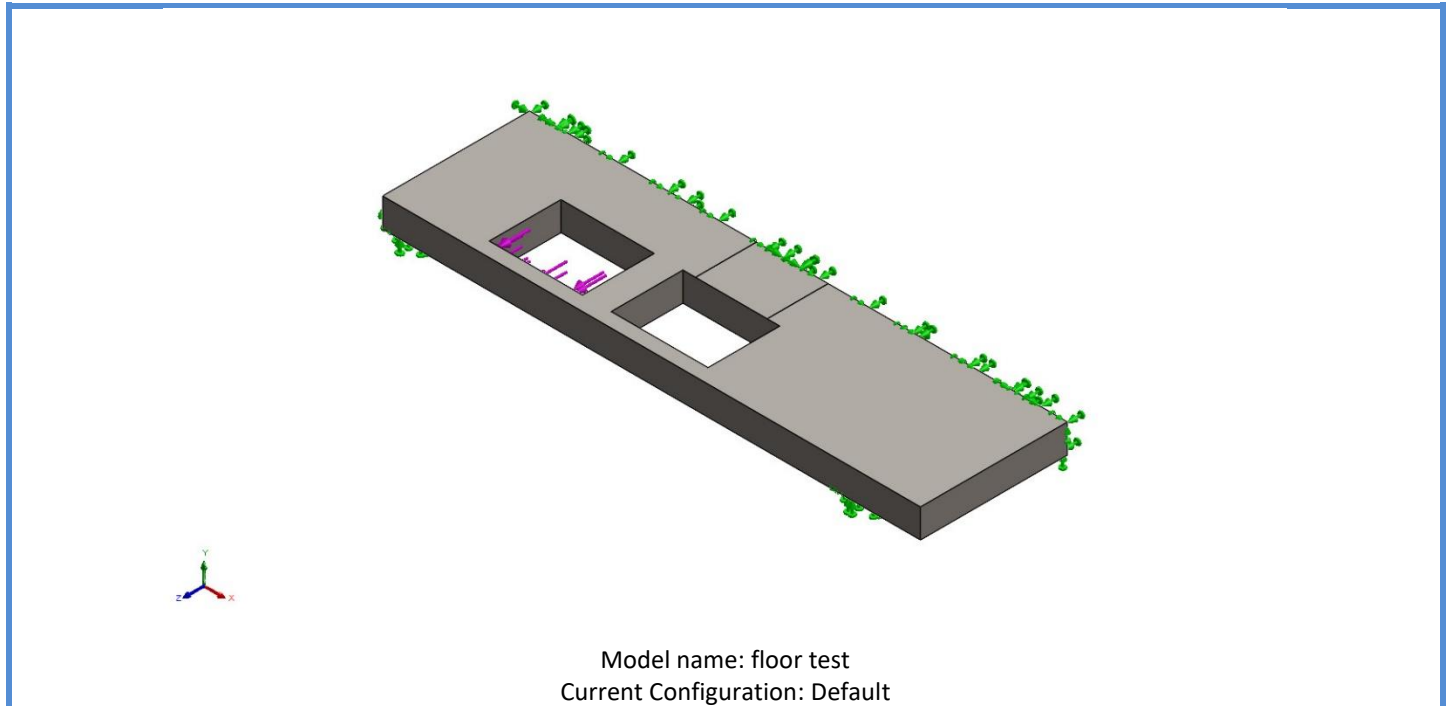
Model name: DHI wheel new frame1
 Study name: Static 3(-Default-)
 Plot type: Static strain Strain1
 Deformation scale: 36,9697



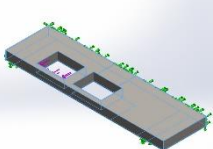
DHI wheel new frame1-Static 3-Strain-Strain1

C2 Z-box support hole 1

Model Information



Solid Bodies

Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Fillet38 	Solid Body	Mass:5,61134 kg Volume:0,000714093 m ³ Density:7.858 kg/m ³ Weight:54,9911 N	C:\Users\twand\OneDrive\Documents\Bsc final\concept2\floor test.SLDPRT Oct 10 15:33:38 2024

Study Properties

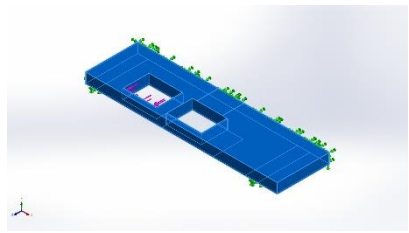
Study name	SimulationXpress_Study
Analysis type	Static
Mesh type	Solid Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Include fluid pressure effects from SOLIDWORKS Flow Simulation	Off
Solver type	Automatic
Inplane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off

Incompatible bonding options	Automatic
Large displacement	Off
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off
Result folder	SOLIDWORKS document (c:\users\twand\onedrive\documenten\bsc final\static test)

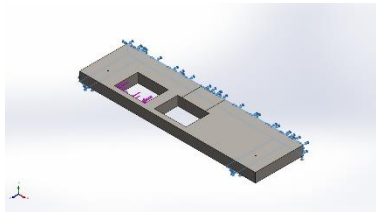
Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/mm ² (MPa)

Material Properties

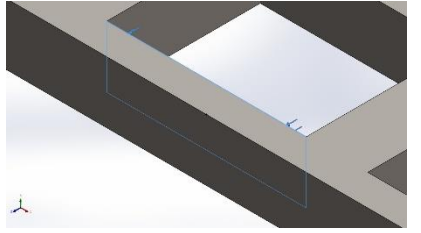
Model Reference	Properties	Components
	Name: 1023 Carbon Steel Sheet (SS) Model type: Linear Elastic Isotropic Default failure criterion: Max von Mises Stress Yield strength: 282,685 N/mm² Tensile strength: 425 N/mm² Elastic modulus: 205.000 N/mm² Poisson's ratio: 0,29 Mass density: 7,858 g/cm³ Shear modulus: 80.000 N/mm² Thermal expansion coefficient: 1,2e-05 /Kelvin	SolidBody 4(Fillet38)(floor test)
Curve Data:N/A		

Loads and Fixtures

Fixture name	Fixture Image	Fixture Details
Fixed-1		Entities: 3 face(s) Type: Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	-9,15527e-05	-4,57764e-05	-5.308,6	5.308,6
Reaction Moment(N.m)	0	0	0	0

Load name	Load Image	Load Details
Force-2		Entities: 1 face(s) Type: Apply normal force Value: 5.308,6 N

Mesh information

Mesh type	Solid Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points for High quality mesh	16 Points
Element Size	16,9 mm
Tolerance	0,844999 mm
Mesh Quality	High

Mesh information - Details

Total Nodes	14735
Total Elements	7387
Maximum Aspect Ratio	34,198
% of elements with Aspect Ratio < 3	0
Percentage of elements with Aspect Ratio > 10	12,7
Percentage of distorted elements	0
Time to complete mesh(hh:mm:ss):	00:00:02
Computer name:	

Resultant Forces

Reaction forces

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-9,15527e-05	-4,57764e-05	-5.308,6	5.308,6

Reaction Moments

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0

Free body forces

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-0,000118885	8,54309e-05	-0,000747681	0,000761878

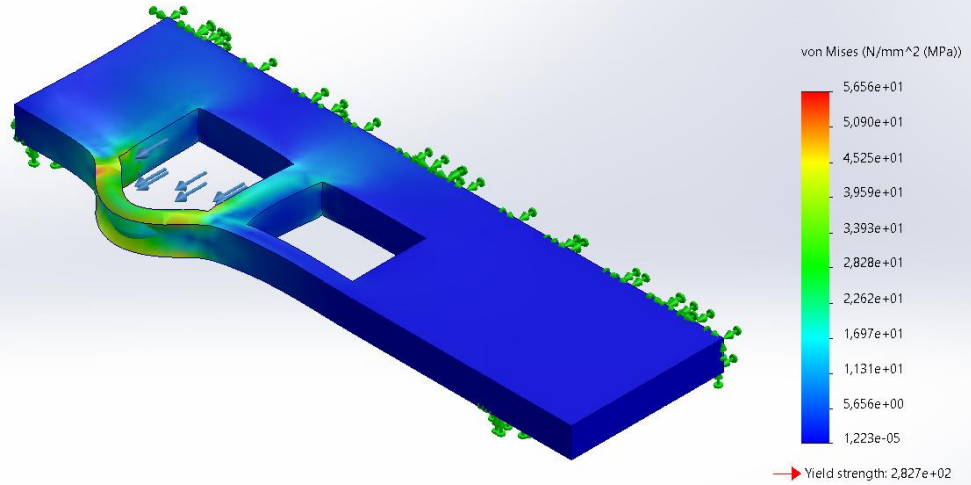
Free body moments

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	1e-33

Study Results

Name	Type	Min	Max
Stress	VON: von Mises Stress	1,223e-05N/mm ² (MPa) Node: 6296	5,656e+01N/mm ² (MPa) Node: 5851

Model name: floor test
 Study name: SimulationXpress_Study(-Default-)
 Plot type: Static nodal stress Stress
 Deformation scale: 1.168,5

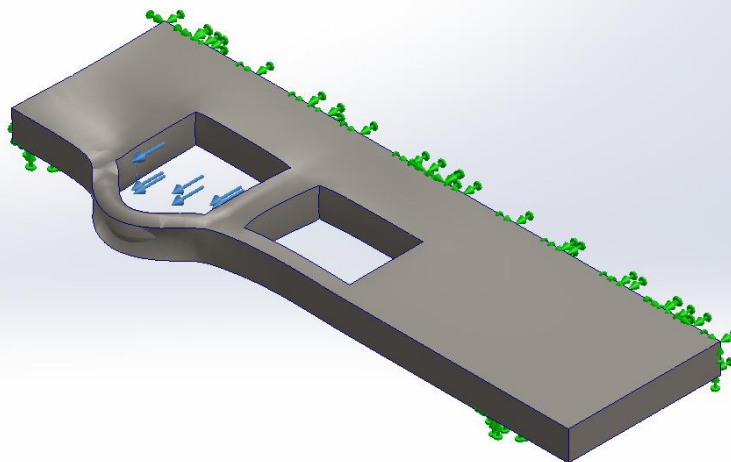


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floor test-SimulationXpress_Study-Stress-Stress

Name	Type
Deformation	Deformed shape

Model name: floor test
 Study name: SimulationXpress_Study(-Default-)
 Plot type: Deformed shape Deformation
 Deformation scale: 1.168,5

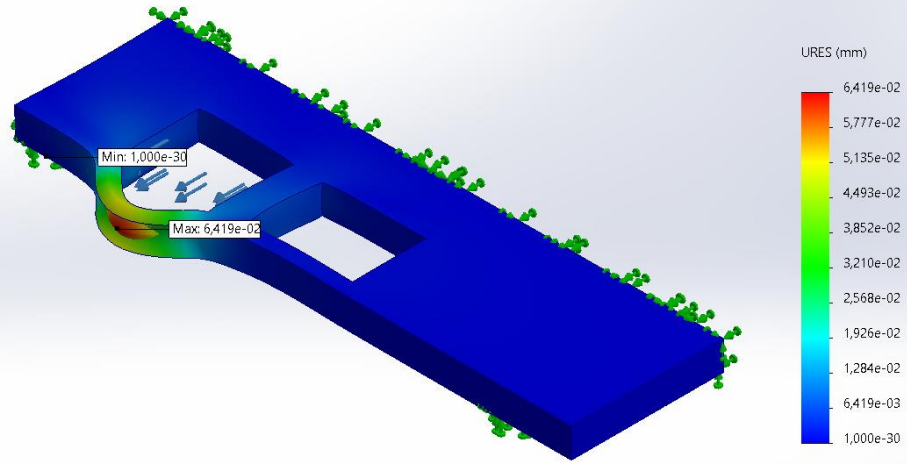


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floor test-SimulationXpress_Study-Displacement-Deformation

Name	Type	Min	Max
Displacement	URES: Resultant Displacement	0,000e+00mm Node: 73	6,419e-02mm Node: 2415

Model name: floor test
 Study name: SimulationXpress_Study(-Default-)
 Plot type: Static displacement Displacement
 Deformation scale: 1.168,5

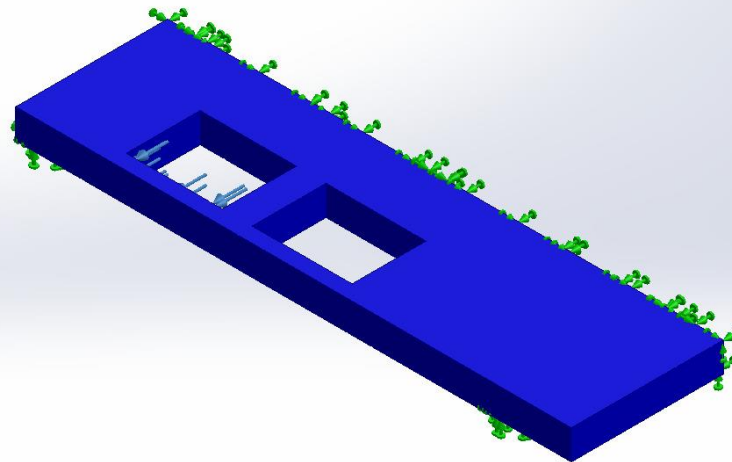


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floor test-SimulationXpress_Study-Displacement-Displacement

Name	Type	Min	Max
Factor of Safety	Max von Mises Stress	4,998e+00 Node: 5851	2,311e+07 Node: 6296

Model name: floor test
 Study name: SimulationXpress_Study(-Default-)
 Plot type: Factor of Safety Factor of Safety
 Criterion: Max von Mises Stress
 Red < FOS = 1 < Blue

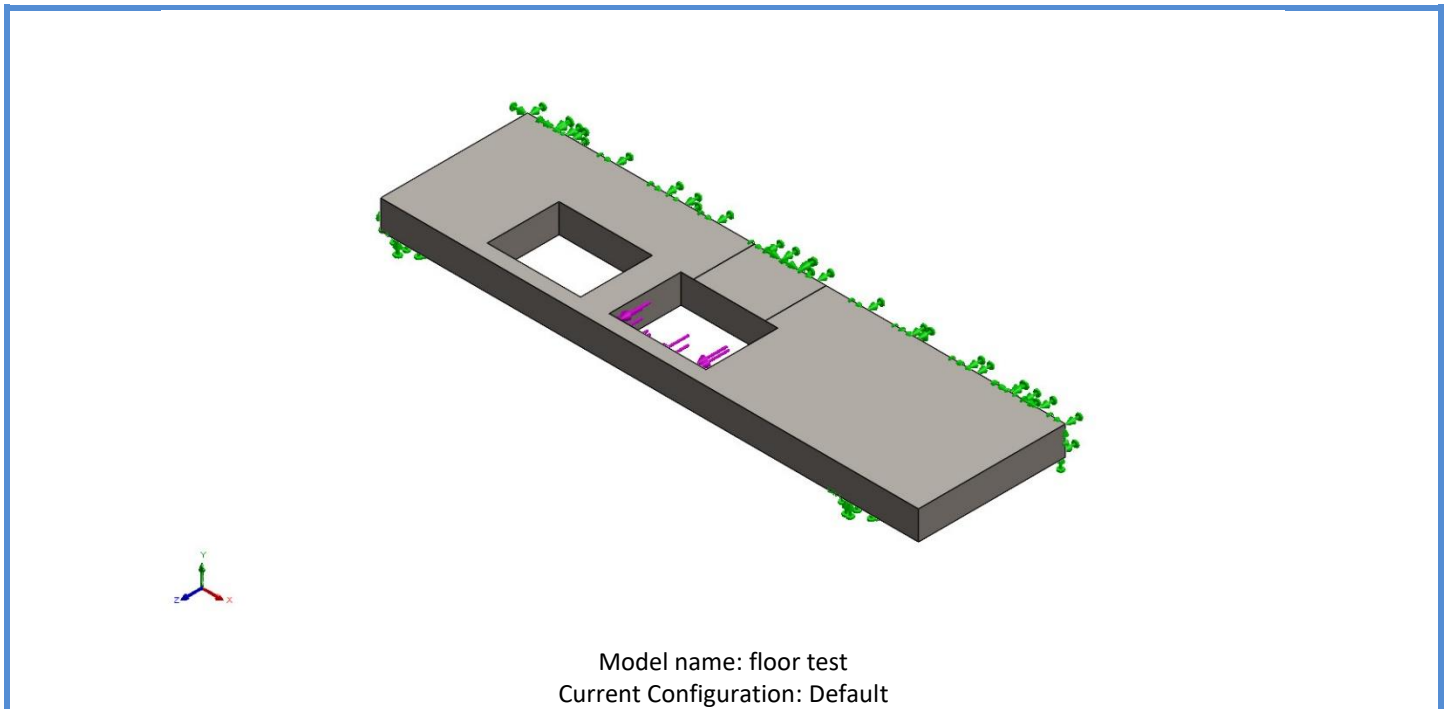


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floor test-SimulationXpress_Study-Factor of Safety-Factor of Safety

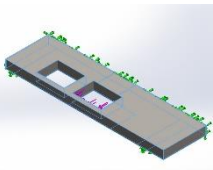
C3 Z-box support hole 2

Model Information



Model name: floor test
Current Configuration: Default

Solid Bodies

Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Fillet38 	Solid Body	Mass:5,61134 kg Volume:0,000714093 m ³ Density:7.858 kg/m ³ Weight:54,9911 N	C:\Users\twand\OneDrive\Documents\Bsc final\concept2\floor test.SLDPRT Oct 10 15:33:38 2024

Study Properties

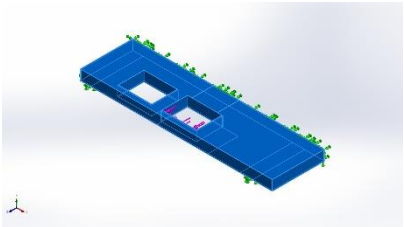
Study name	SimulationXpress_Study
Analysis type	Static
Mesh type	Solid Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Include fluid pressure effects from SOLIDWORKS Flow Simulation	Off
Solver type	Automatic
Inplane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off
Incompatible bonding options	Automatic

Large displacement	Off
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off
Result folder	SOLIDWORKS document (c:\users\twand\onedrive\documenten\bsc final\static test)

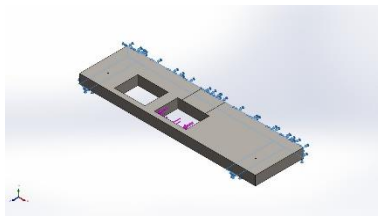
Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/mm ² (MPa)

Material Properties

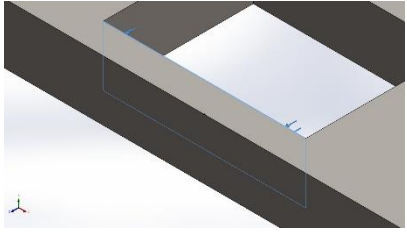
Model Reference	Properties	Components
	Name: 1023 Carbon Steel Sheet (SS) Model type: Linear Elastic Isotropic Default failure criterion: Max von Mises Stress Yield strength: 282,685 N/mm² Tensile strength: 425 N/mm² Elastic modulus: 205.000 N/mm² Poisson's ratio: 0,29 Mass density: 7,858 g/cm³ Shear modulus: 80.000 N/mm² Thermal expansion coefficient: 1,2e-05 /Kelvin	SolidBody 4(Fillet38)(floor test)
Curve Data:N/A		

Loads and Fixtures

Fixture name	Fixture Image	Fixture Details
Fixed-1		Entities: 3 face(s) Type: Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	-9,01222e-05	-2,46763e-05	-5.308,6	5.308,6
Reaction Moment(N.m)	0	0	0	0

Load name	Load Image	Load Details
Force-2		Entities: 1 face(s) Type: Apply normal force Value: 5.308,6 N

Mesh information

Mesh type	Solid Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points for High quality mesh	16 Points
Element Size	16,9 mm
Tolerance	0,844999 mm
Mesh Quality	High

Mesh information - Details

Total Nodes	14735
Total Elements	7387
Maximum Aspect Ratio	34,198
% of elements with Aspect Ratio < 3	0
Percentage of elements with Aspect Ratio > 10	12,7
Percentage of distorted elements	0
Time to complete mesh(hh:mm:ss):	00:00:02
Computer name:	

Resultant Forces

Reaction forces

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-9,01222e-05	-2,46763e-05	-5.308,6	5.308,6

Reaction Moments

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0

Free body forces

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-0,000232089	-3,57544e-05	-0,00212638	0,0021393

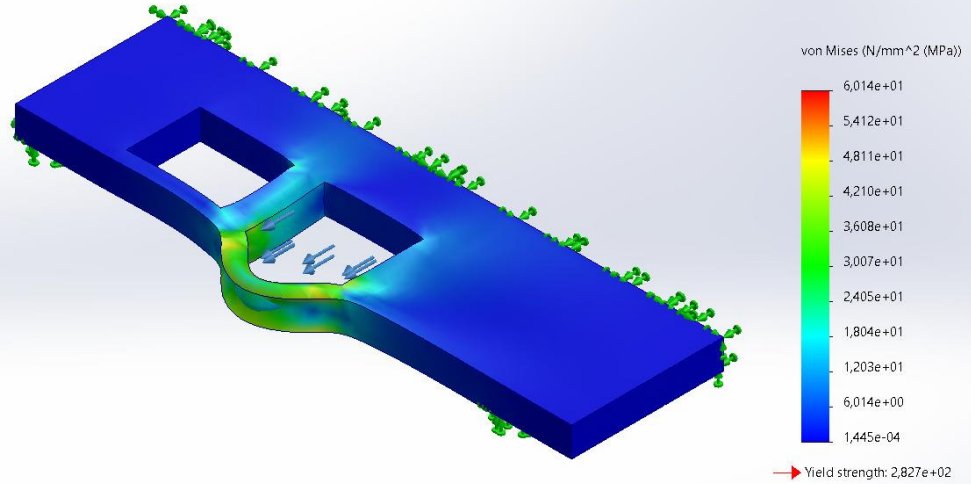
Free body moments

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	1e-33

Study Results

Name	Type	Min	Max
Stress	VON: von Mises Stress	1,445e-04N/mm ² (MPa) Node: 7439	6,014e+01N/mm ² (MPa) Node: 3551

Model name: floor test
 Study name: SimulationXpress_Study(-Default-)
 Plot type: Static nodal stress Stress
 Deformation scale: 1.136,15

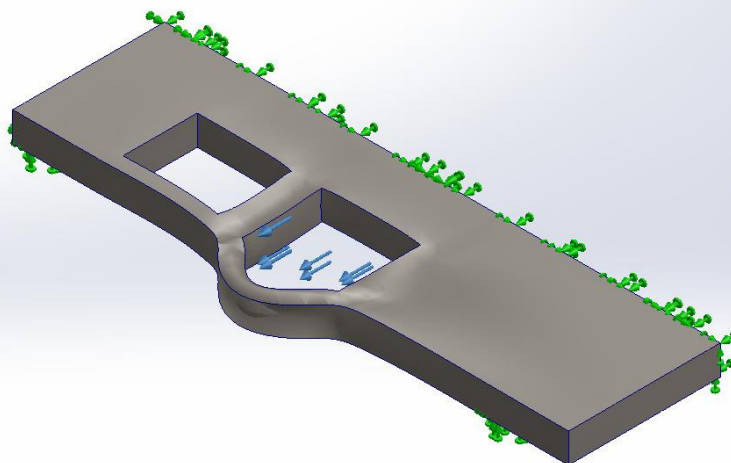


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floor test-SimulationXpress_Study-Stress-Stress

Name	Type
Deformation	Deformed shape

Model name: floor test
 Study name: SimulationXpress_Study(-Default-)
 Plot type: Deformed shape Deformation
 Deformation scale: 1.136,15

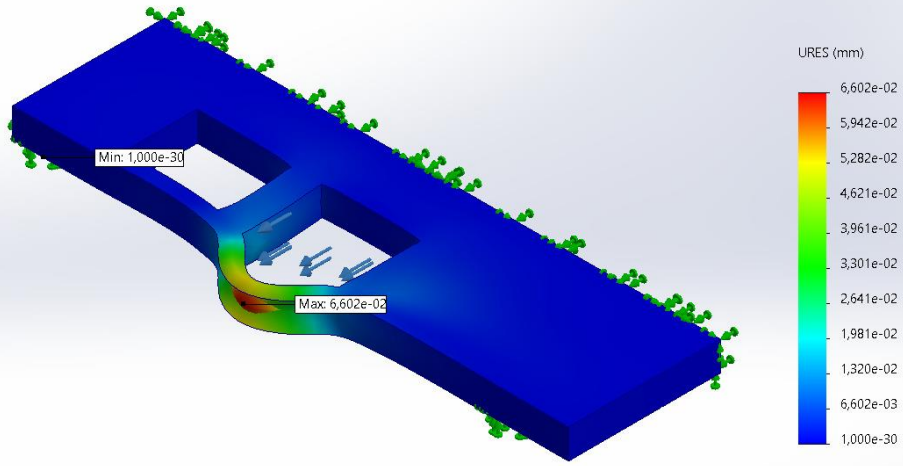


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floor test-SimulationXpress_Study-Displacement-Deformation

Name	Type	Min	Max
Displacement	URES: Resultant Displacement	0,000e+00mm Node: 73	6,602e-02mm Node: 2379

Model name: floor test
 Study name: SimulationXpress_Study(-Default-)
 Plot type: Static displacement Displacement
 Deformation scale: 1.136,15

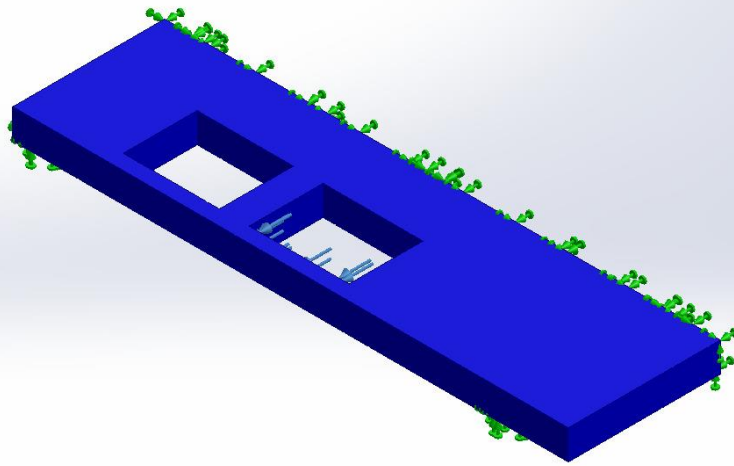


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floor test-SimulationXpress_Study-Displacement-Displacement

Name	Type	Min	Max
Factor of Safety	Max von Mises Stress	4,701e+00 Node: 3551	1,956e+06 Node: 7439

Model name: floor test
 Study name: SimulationXpress_Study(-Default-)
 Plot type: Factor of Safety Factor of Safety
 Criterion : Max von Mises Stress
 Red < FOS = 1 < Blue

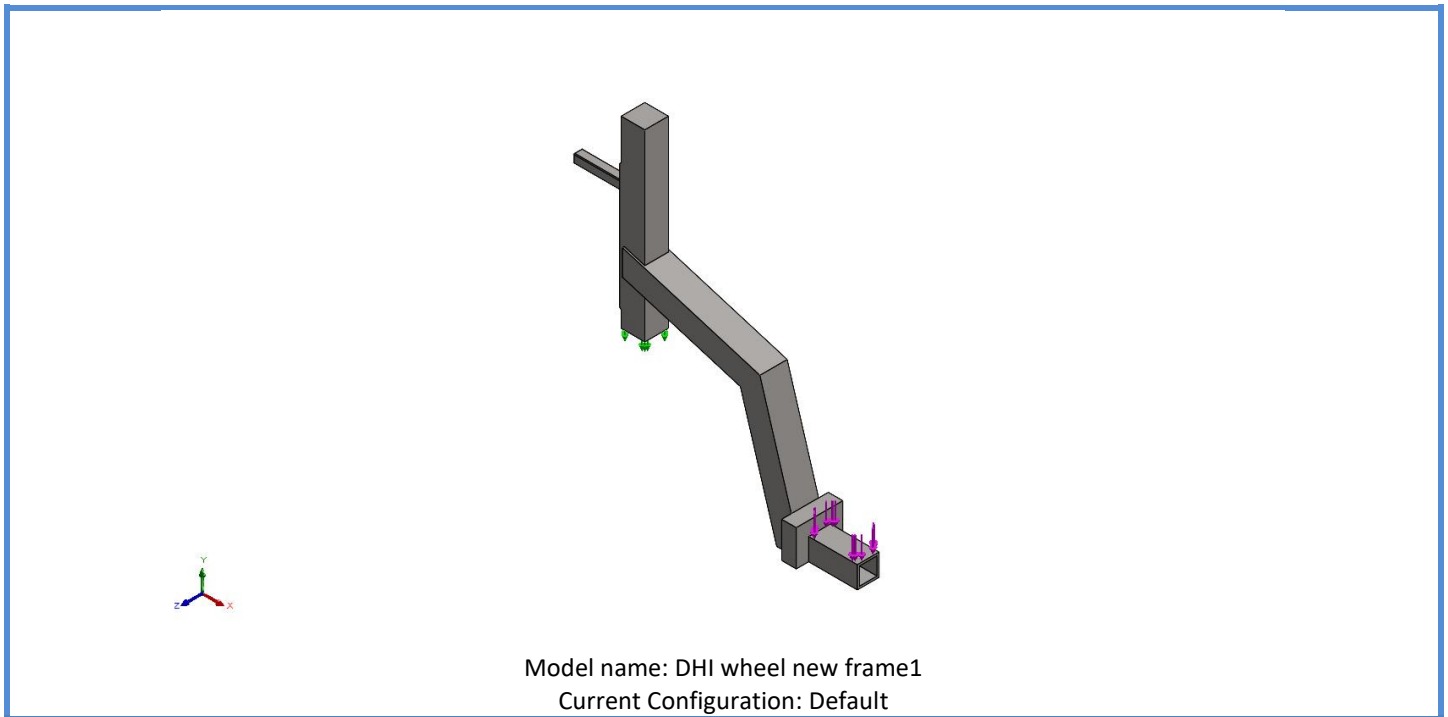


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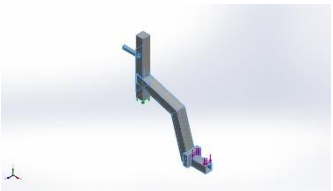
floor test-SimulationXpress_Study-Factor of Safety-Factor of Safety

C4 Original hole final design

Model Information



Solid Bodies

Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Boss-Extrude24 	Solid Body	Mass:28,4474 kg Volume:0,0036471 m ³ Density:7.800 kg/m ³ Weight:278,785 N	C:\Users\twand\OneDrive\Documents\Bsc final\DHI wheel new frame1.SLDPR T Oct 22 15:07:01 2024

Study Properties

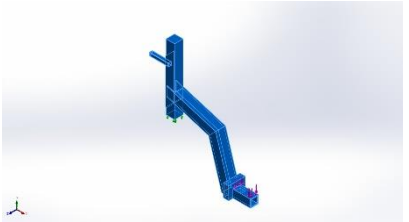
Study name	Static 3
Analysis type	Static
Mesh type	Solid Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Include fluid pressure effects from SOLIDWORKS Flow Simulation	Off
Solver type	Automatic
Inplane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off

Incompatible bonding options	Automatic
Large displacement	On
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off
Result folder	SOLIDWORKS document (C:\Users\twand\OneDrive\Documenten\Bsc final)

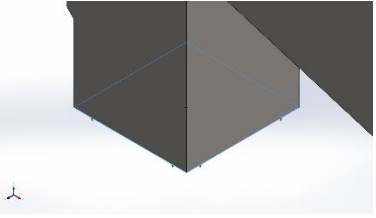
Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/mm ² (MPa)

Material Properties

Model Reference	Properties	Components
	Name: Plain Carbon Steel Model type: Linear Elastic Isotropic Default failure criterion: Max von Mises Stress Yield strength: 220,594 N/mm² Tensile strength: 399,826 N/mm² Elastic modulus: 210.000 N/mm² Poisson's ratio: 0,28 Mass density: 7,8 g/cm³ Shear modulus: 79.000 N/mm² Thermal expansion coefficient: 1,3e-05 /Kelvin	SolidBody 1(Boss-Extrude24)(DHI wheel new frame1)
Curve Data:N/A		

Loads and Fixtures

Fixture name	Fixture Image	Fixture Details		
Roller/Slider-1		Entities: 1 face(s) Type: Roller/Slider		
Resultant Forces				
Components	X	Y	Z	Resultant
Reaction force(N)	0	4.537,12	0	4.537,12
Reaction Moment(N.m)	0	0	0	0

Load name	Load Image	Load Details
Force-1		Entities: 1 face(s) Type: Apply normal force Value: 4.537,13 N

Mesh information

Mesh type	Solid Mesh
Mesher Used:	Blended curvature-based mesh
Jacobian points for High quality mesh	16 Points
Maximum element size	31,5522 mm
Minimum element size	1,57761 mm
Mesh Quality	High

Mesh information - Details

Total Nodes	27929
Total Elements	14563
Maximum Aspect Ratio	177,73
% of elements with Aspect Ratio < 3	34,8
Percentage of elements with Aspect Ratio > 10	10,1
Percentage of distorted elements	0
Time to complete mesh(hh:mm:ss):	00:00:08
Computer name:	

Resultant Forces

Reaction forces

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	0	4.537,12	0	4.537,12

Reaction Moments

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0

Free body forces

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	0	0	0	0

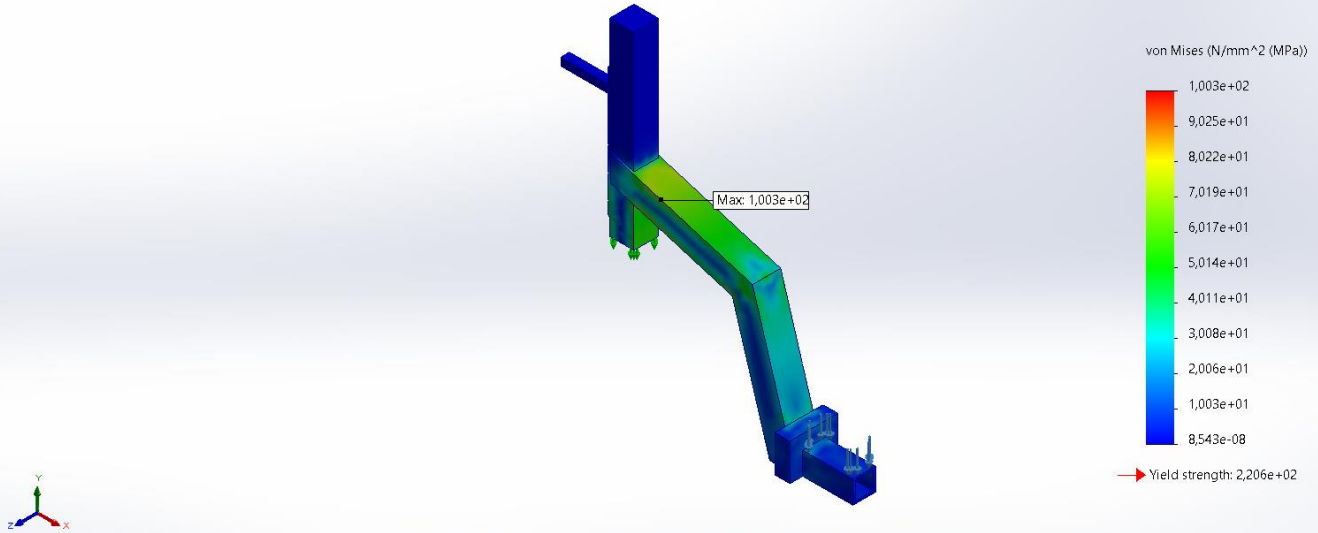
Free body moments

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0

Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	8,543e-08N/mm ² (MPa) Node: 55	1,003e+02N/mm ² (MPa) Node: 827

Model name: DHI wheel new frame1
 Study name: Static 3(-Default-)
 Plot type: Static nodal stress Stress1

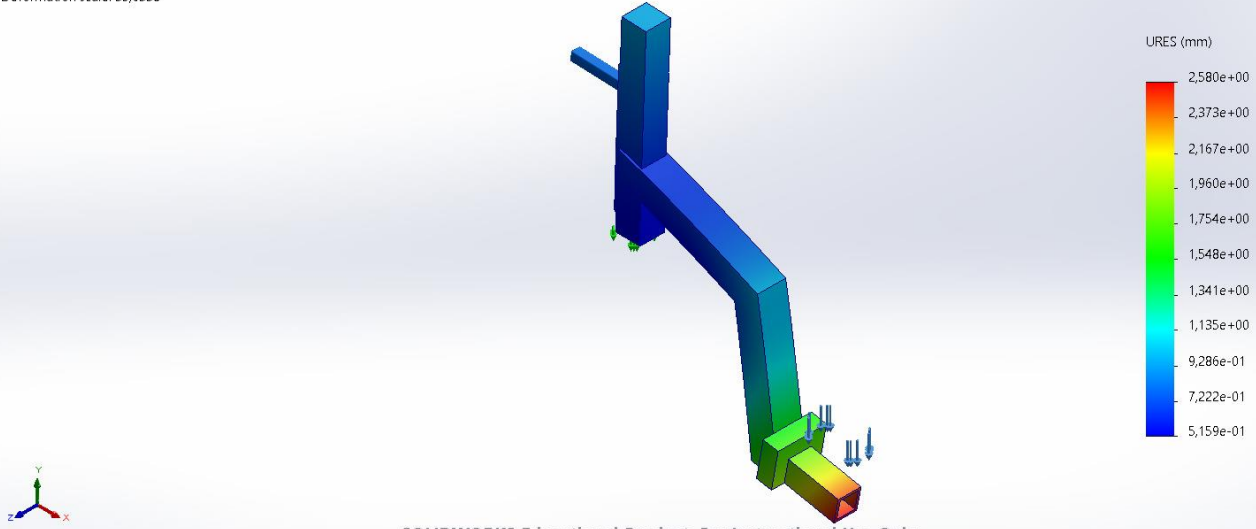


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DHI wheel new frame1-Static 3-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	5,159e-01mm Node: 20425	2,580e+00mm Node: 31

Model name: DHI wheel new frame1
 Study name: Static 3(-Default-)
 Plot type: Static displacement Displacement1
 Deformation scale: 35,6338

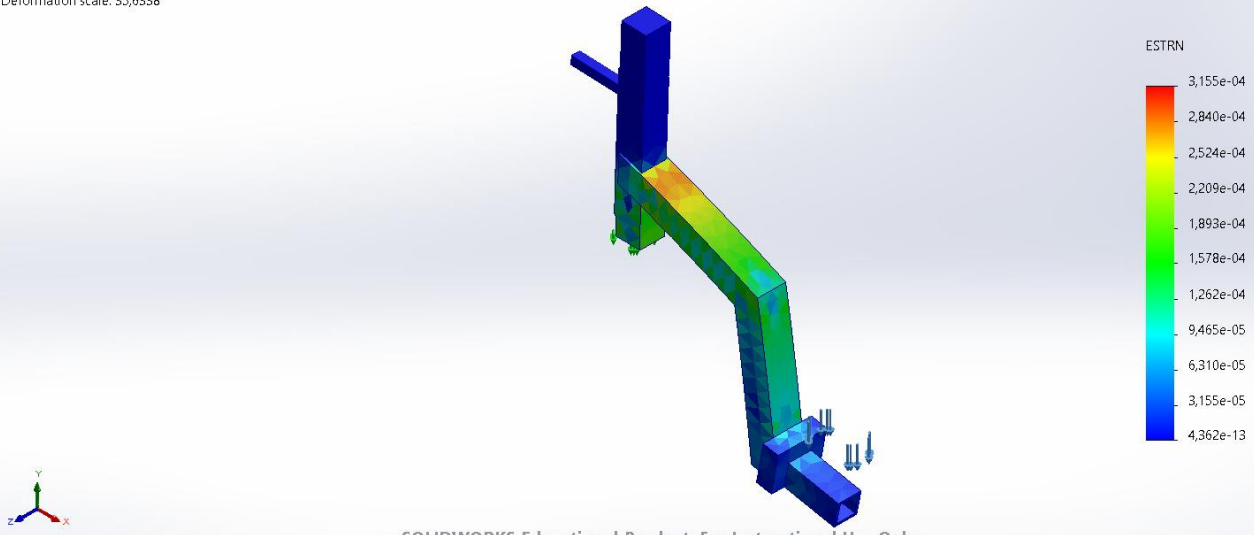


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DHI wheel new frame1-Static 3-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	4,362e-13	3,155e-04

Model name: DHI wheel new frame1
Study name: Static 3(-Default-)
Plot type: Static strain Strain1
Deformation scale: 35,6338

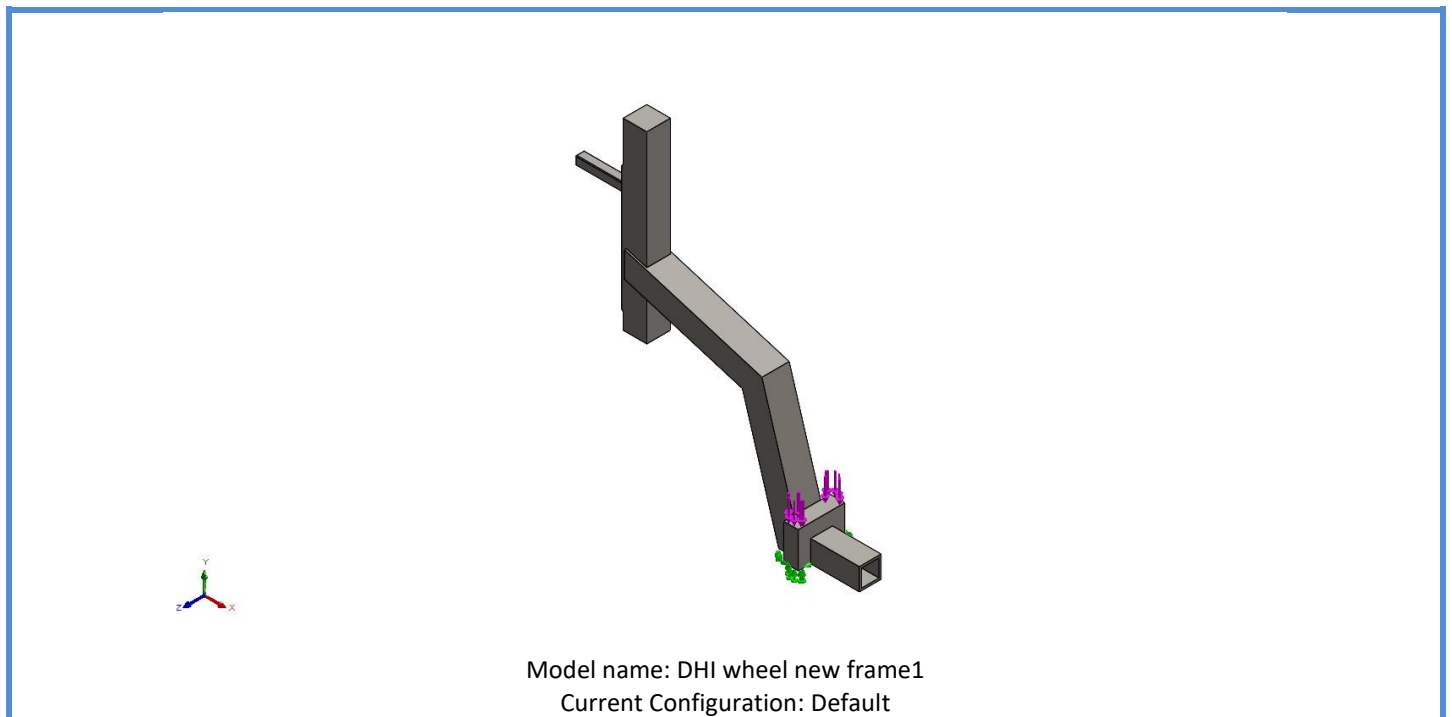


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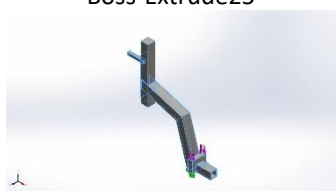
DHI wheel new frame1-Static 3-Strain-Strain1

C5 New hole final design

Model Information



Solid Bodies

Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Boss-Extrude25 	Solid Body	Mass:28,659 kg Volume:0,00364711 m ³ Density:7.858 kg/m ³ Weight:280,858 N	C:\Users\twand\OneDrive\Documents\Bsc final\DHI wheel new frame1.SLDPRT Oct 22 15:18:10 2024

Study Properties


Study name	Static 2
Analysis type	Static
Mesh type	Solid Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Include fluid pressure effects from SOLIDWORKS Flow Simulation	Off
Solver type	Automatic
Inplane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off

Incompatible bonding options	Automatic
Large displacement	On
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off
Result folder	SOLIDWORKS document (C:\Users\twand\OneDrive\Documenten\Bsc final)

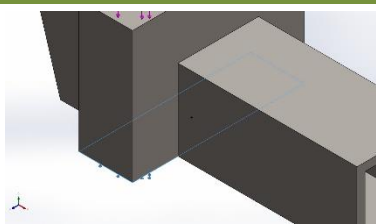
Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/mm ² (MPa)

Material Properties

Model Reference	Properties	Components
	Name: 1023 Carbon Steel Sheet (SS) Model type: Linear Elastic Isotropic Default failure criterion: Max von Mises Stress Yield strength: 282,685 N/mm² Tensile strength: 425 N/mm² Elastic modulus: 205.000 N/mm² Poisson's ratio: 0,29 Mass density: 7,858 g/cm³ Shear modulus: 80.000 N/mm² Thermal expansion coefficient: 1,2e-05 /Kelvin	SolidBody 1(Boss-Extrude25)(DHI wheel new frame1)
Curve Data:N/A		

Loads and Fixtures

Fixture name	Fixture Image	Fixture Details
Fixed-2		Entities: 1 face(s) Type: Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	4,3869e-05	5.308,4	-1,90735e-05	5.308,4
Reaction Moment(N.m)	0	0	0	0

Load name	Load Image	Load Details
Force-1		Entities: 1 face(s) Type: Apply normal force Value: 5.308,4 N

Mesh information

Mesh type	Solid Mesh
Mesher Used:	Blended curvature-based mesh
Jacobian points for High quality mesh	16 Points
Maximum element size	34,5198 mm
Minimum element size	1,72599 mm
Mesh Quality	High

Mesh information - Details

Total Nodes	22737
Total Elements	11298
Maximum Aspect Ratio	36.469
% of elements with Aspect Ratio < 3	33
Percentage of elements with Aspect Ratio > 10	22,3
Percentage of distorted elements	0
Time to complete mesh(hh:mm:ss):	00:00:06
Computer name:	

Resultant Forces

Reaction forces

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	4,3869e-05	5.308,4	-1,90735e-05	5.308,4

Reaction Moments

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0

Free body forces

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	0	0	0	0

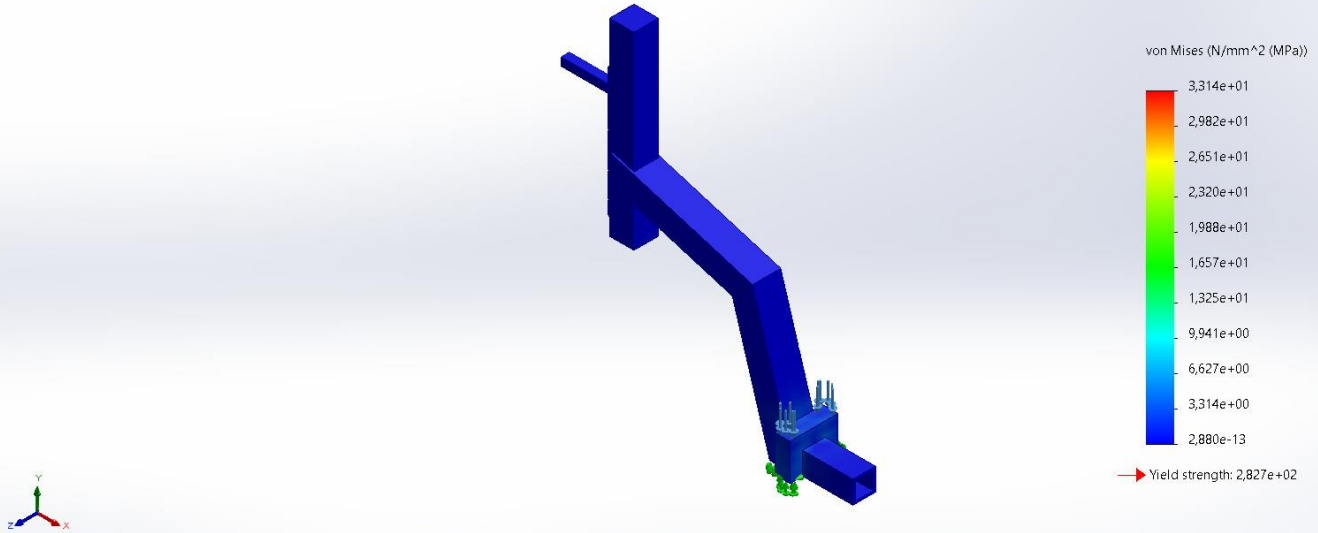
Free body moments

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0

Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	2,880e-13N/mm ² (MPa) Node: 19492	3,314e+01N/mm ² (MPa) Node: 15462

Model name: DHI wheel new frame1
 Study name: Static 2(-Default-)
 Plot type: Static nodal stress Stress1

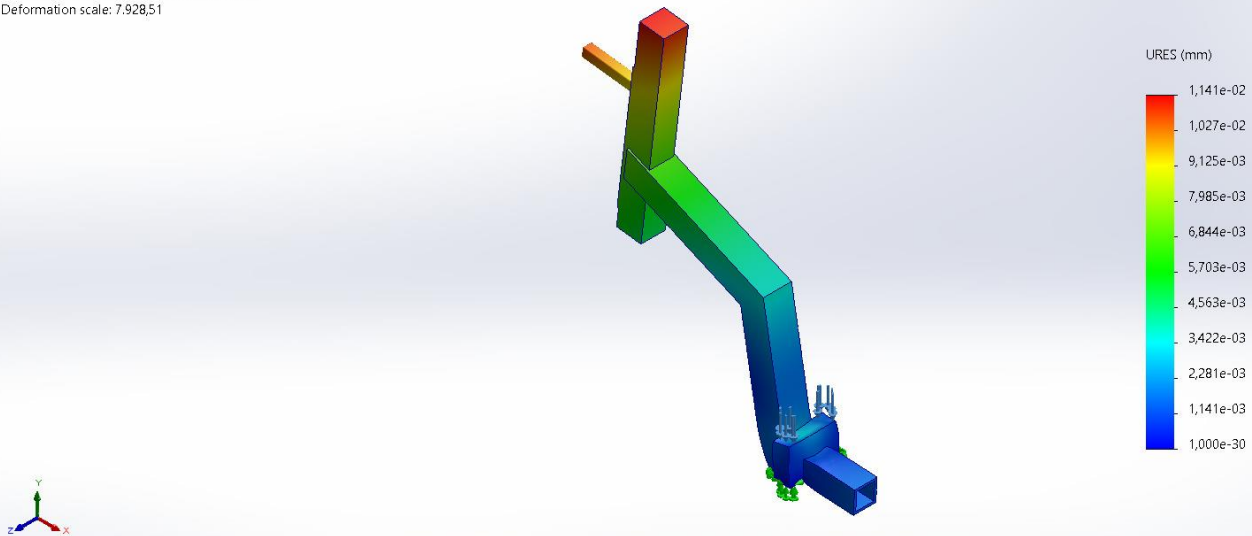


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DHI wheel new frame1-Static 2-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0,000e+00mm Node: 1	1,141e-02mm Node: 57

Model name: DHI wheel new frame1
 Study name: Static 2(-Default-)
 Plot type: Static displacement Displacement1
 Deformation scale: 7.928,51

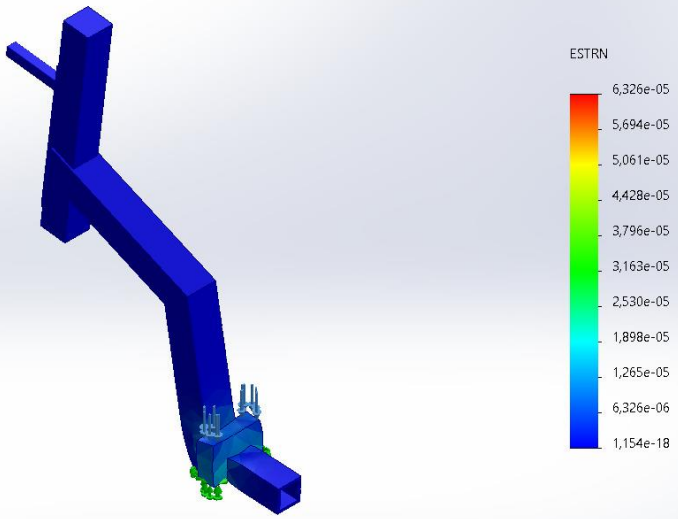


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DHI wheel new frame1-Static 2-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	1,154e-18 Element: 7025	6,326e-05 Element: 4586

Model name: DHI wheel new frame1
 Study name: Static 2(-Default-)
 Plot type: Static strain Strain1
 Deformation scale: 7.928,51

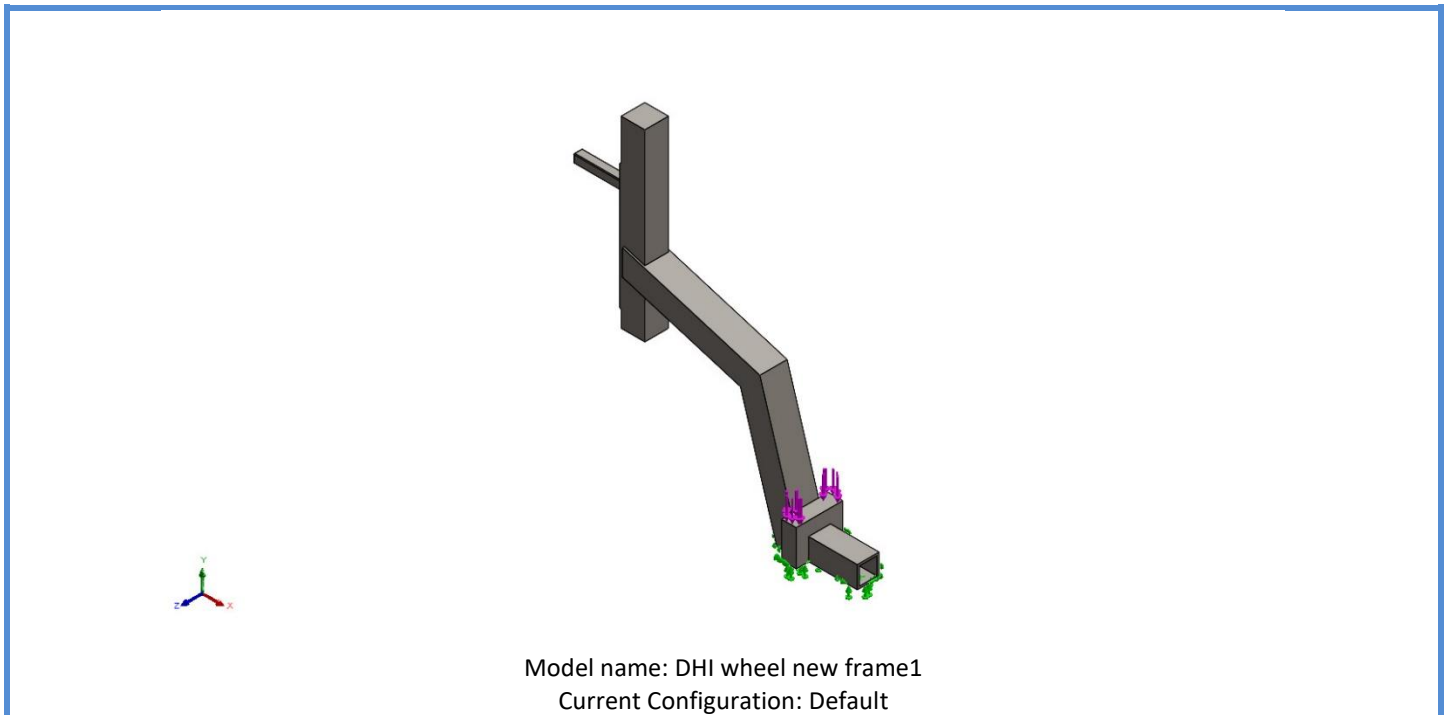


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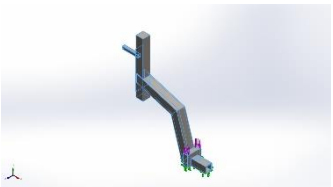
DHI wheel new frame1-Static 2-Strain-Strain1

C6 Block final design

Model Information



Solid Bodies

Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Boss-Extrude24 	Solid Body	Mass:28,6589 kg Volume:0,0036471 m ³ Density:7.858 kg/m ³ Weight:280,858 N	C:\Users\twand\OneDrive\Documents\Bsc final\DHI wheel new frame1.SLDPRT Oct 22 15:07:01 2024

Study Properties

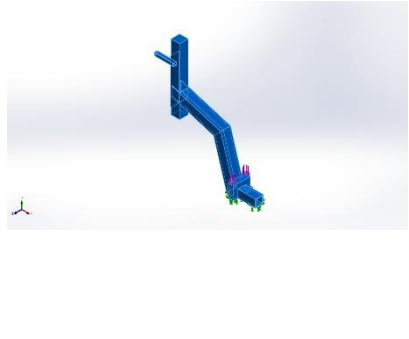
Study name	Static 2
Analysis type	Static
Mesh type	Solid Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Include fluid pressure effects from SOLIDWORKS Flow Simulation	Off
Solver type	Automatic
Inplane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off

Incompatible bonding options	Automatic
Large displacement	On
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off
Result folder	SOLIDWORKS document (C:\Users\twand\OneDrive\Documenten\Bsc final)

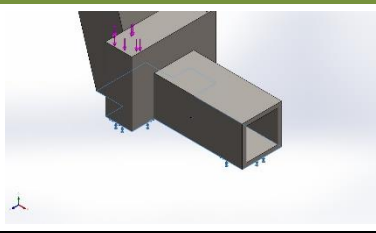
Units

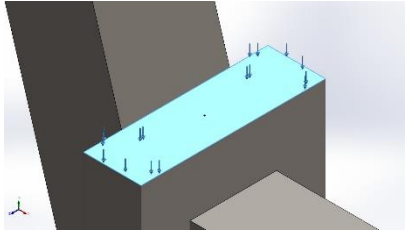
Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/mm ² (MPa)

Material Properties

Model Reference	Properties	Components
	Name: 1023 Carbon Steel Sheet (SS) Model type: Linear Elastic Isotropic Default failure criterion: Max von Mises Stress Yield strength: 282,685 N/mm² Tensile strength: 425 N/mm² Elastic modulus: 205.000 N/mm² Poisson's ratio: 0,29 Mass density: 7,858 g/cm³ Shear modulus: 80.000 N/mm² Thermal expansion coefficient: 1,2e-05 /Kelvin	SolidBody 1(Boss-Extrude24)(DHI wheel new frame1)
Curve Data:N/A		

Loads and Fixtures

Fixture name	Fixture Image	Fixture Details		
Fixed-2		Entities: 1 face(s) Type: Fixed Geometry		
Resultant Forces				
Components	X	Y	Z	Resultant
Reaction force(N)	-1,33514e-05	5.308,4	5,00679e-06	5.308,4
Reaction Moment(N.m)	0	0	0	0

Load name	Load Image	Load Details
Force-1		Entities: 1 face(s) Type: Apply normal force Value: 5.308,4 N

Mesh information

Mesh type	Solid Mesh
Mesher Used:	Blended curvature-based mesh
Jacobian points for High quality mesh	16 Points
Maximum element size	34,5198 mm
Minimum element size	1,72599 mm
Mesh Quality	High

Mesh information - Details

Total Nodes	26581
Total Elements	14211
Maximum Aspect Ratio	197,93
% of elements with Aspect Ratio < 3	32,6
Percentage of elements with Aspect Ratio > 10	14,5
Percentage of distorted elements	0
Time to complete mesh(hh:mm:ss):	00:00:08
Computer name:	

Resultant Forces

Reaction forces

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-1,33514e-05	5.308,4	5,00679e-06	5.308,4

Reaction Moments

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0

Free body forces

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	0	0	0	0

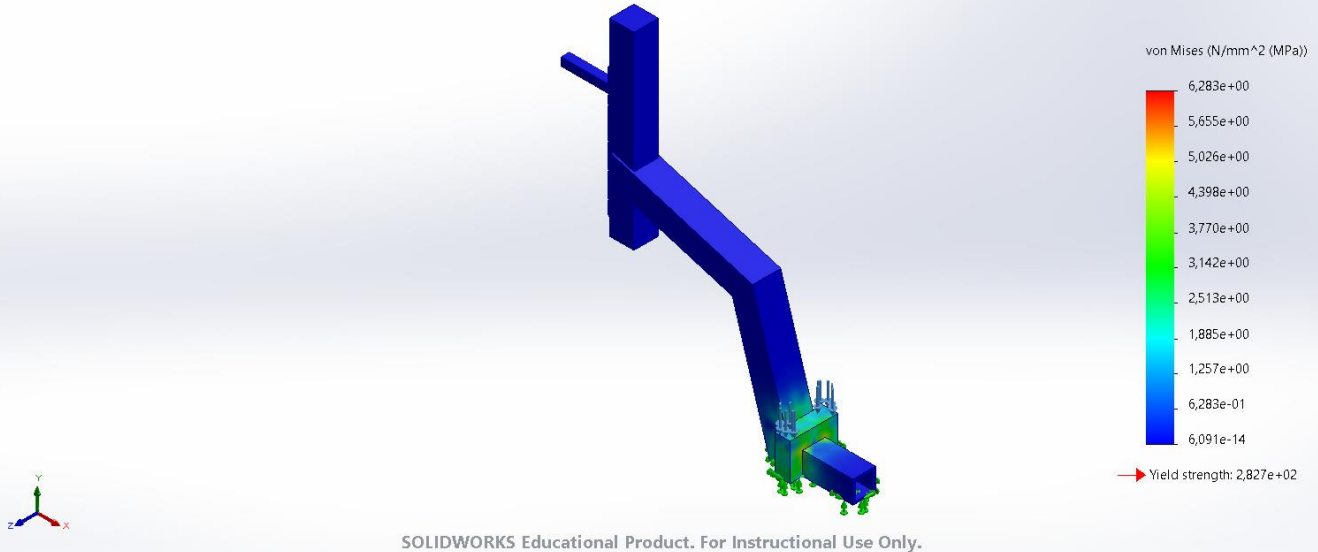
Free body moments

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0

Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	6,091e-14N/mm ² (MPa) Node: 8093	6,283e+00N/mm ² (MPa) Node: 23833

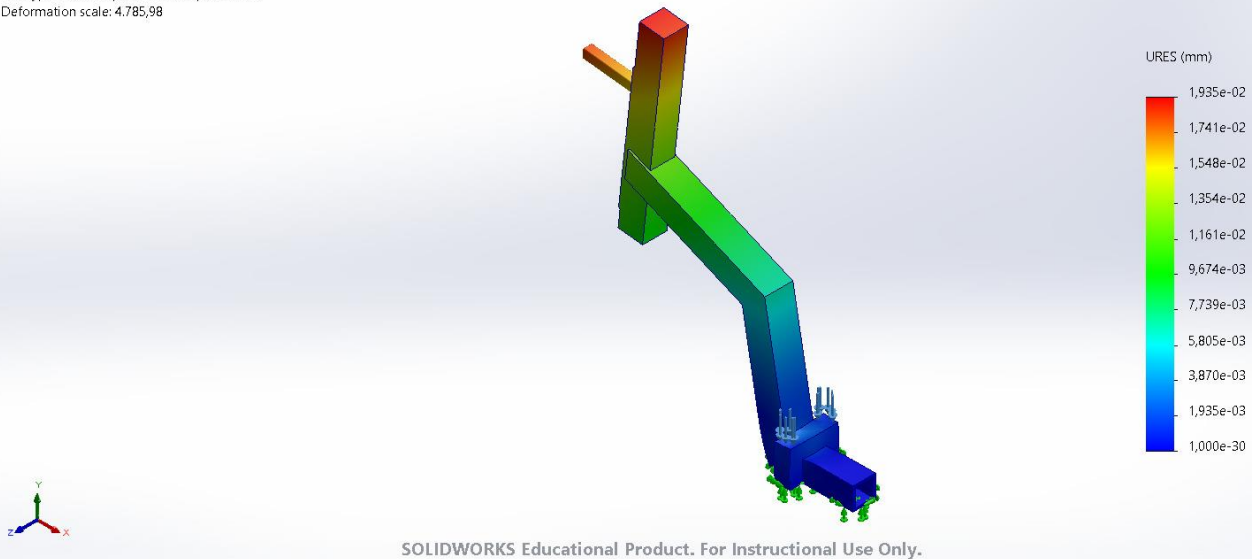
Model name: DHI wheel new frame1
Study name: Static 2(-Default-)
Plot type: Static nodal stress Stress1



DHI wheel new frame1-Static 2-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0,000e+00mm Node: 25	1,935e-02mm Node: 54

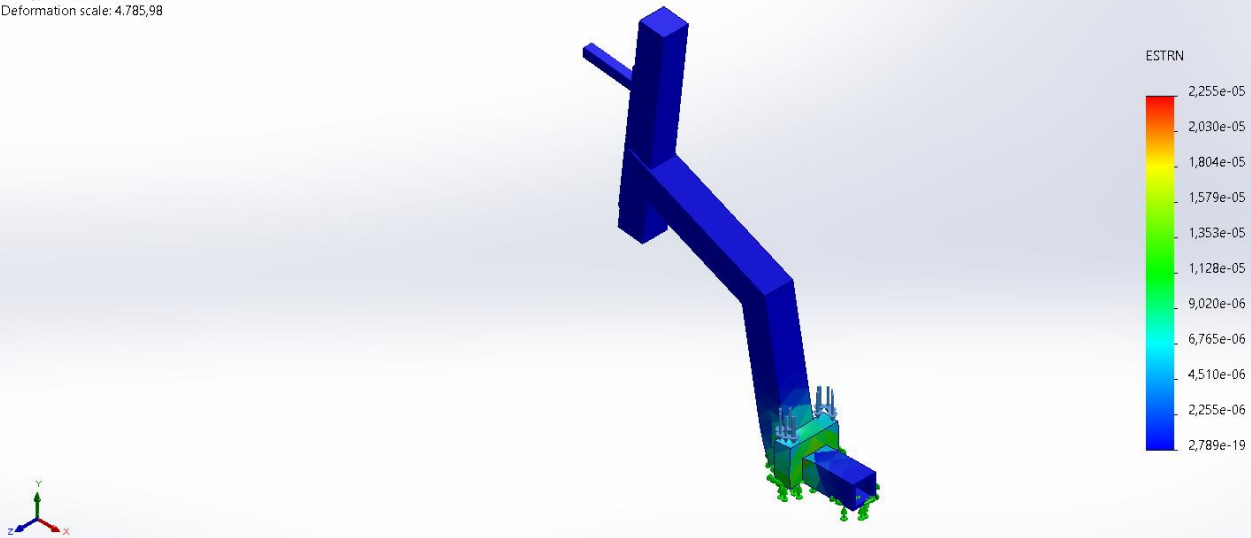
Model name: DHI wheel new frame1
Study name: Static 2(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 4.785,98



DHI wheel new frame1-Static 2-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	2,789e-19 Element: 10325	2,255e-05 Element: 8435

Model name: DHI wheel new frame1
 Study name: Static 2(-Default-)
 Plot type: Static strain Strain1
 Deformation scale: 4.785,98



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DHI wheel new frame1-Static 2-Strain-Strain1

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