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Design of UV-Bio Configuration of the NMBU Agricultural Robot

Design av UV-Bio konfigurasjon av landbruksroboten Thorvald

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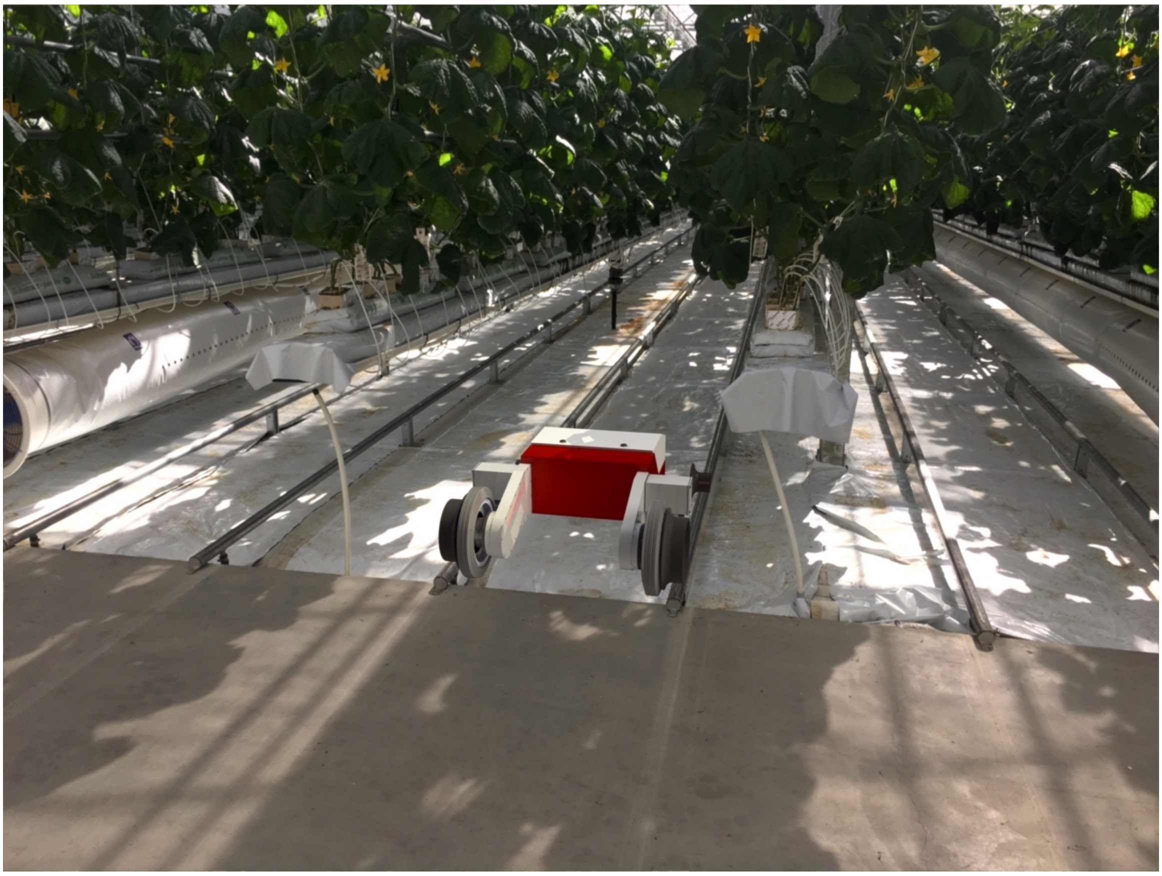
Mechanical Engineering, Process and Product Development



PREFACE

This project concludes my master of science degree at the Norwegian University of Life Sciences. It feels strange to be at the end of an education that has been my life-long dream. My childhood hero, Gyro Gearloose (Petter Smart) from the Donald Duck series, inspired me to disassemble broken devices and try to fix them. And just like Gyro, "fixing things" would only make matters worse. From there on, my curiosity and interest for technology and machines only increased.

I had a concept development course that introduced me to the Thorvald group at the end of the fourth year. Lars Grimstad, former NMBU student, co-creator of Thorvald and now working on his Ph.D. at NMBU, would always be skeptical about my designs and push me to think outside the box. This was at the same time challenging and a rewarding experience. So rewarding that I soon realized I had to write my master's thesis for the Thorvald project.

This semester has been a mix of frustration over realizing how little I actually know, excitement when my knowledge gets put to use, and late nights doing something I love. This robot is just a small step in the direction of a greenhouse research platform for Thorvald, and hopefully it will be the future of horticultural robots.

I would like to thank the good people at STRYVO Oslo and Blickle Norge for delivering splendid parts at a discounted price. I would like to thank my fellow master student, Kristine Skattum, for great teamwork. I would like to thank Marius Austad and Øystein Sund for taking their time to discuss concepts. I would also like to thank my friends and family for always being there for me. At last I would like to thank my supervisor Pål J. From for letting me be a part of this magnificent team and Lars Grimstad for his invaluable guidance.

Ås the 15.05.2017

Remy Nazir Bård Zakaria

ABSTRACT

This master's thesis is a part of an ongoing development project of the agricultural robot Thorvald at NMBU. Kristian Guren, a gardener cultivating cucumbers south of Moss, contacted the Thorvald project in need of an autonomous robot for a project he established called UV-Bio. The goal of the project is to see how utility insects and pests are affected by UVB light when used to fight mildew. Tests will be conducted in a greenhouse owned by the gardener. The main challenge when developing a prototype robot for the greenhouse is to adapt it to a rail system that goes in between the cucumber rows.

Since Thorvald is a modular concept, the goal of this thesis will be to design and build a prototype utilizing predominantly standard Thorvald modules to meet the gardener's demands. The thesis is based on modules that were designed as part of previous master's theses and the first step is to get acquainted with said modules. Then, with the possibilities of the modules in mind a prototype will be designed to meet the gardener's demands

One of the standard configurations have three wheels and is called Trikevald. It is sensible to start by assessing to what degree it can be used. Time was seemingly wasted as a consequence of a visit at the nursery revealing that the strategy had to be entirely changed. The shortcomings of Trikevald were assessed and the recommendations made a foundation when generating prototype concepts from scratch.

The resulting design is a four wheeled prototype that is superior to Trikevald in all operational aspects of a greenhouse robot. Most importantly, mass produced standard Thorvald components are part of the design making it a competitive concept in terms of price in the greenhouse robot market. It might also replace a slim Thorvald version in polytunnels in the future.

The future work on this configuration will be to actually build the prototype, then complete all calculations and optimize the design with respect to loads.

SAMMENDRAG

Denne masteroppgaven er en del av et kontinuerlig utviklingsprosjekt av landbruksroboten Thorvald ved NMBU. Kristian Guren, en gartner som dyrker agurker sør for Moss, kontaktet Thorvald gruppen i søken etter en autonom robot til et prosjekt han opprettet kalt UV-Bio. Målet med dette prosjektet er å observere hvordan nyttedyr og skadedyr påvirkes av UVB-lys når det brukes til å bekjempe meldugg. Testene vil bli gjennomført i et drivhus eid av gartneren. Hovedutfordringen når det gjelder å utvikle en prototype for dette drivhuset, er å tilpasse den til et skinnesystem som går inn mellom agurkradene.

Siden Thorvald er et modulært konsept, vil målet med denne oppgaven være å designe og bygge en prototype hovedsakelig ved bruk av standard Thorvald-moduler for å møte gartnerens krav. Avhandlingen er basert på moduler som ble utformet som en del av tidligere masteroppgaver, og det første trinnet blir dermed å bli kjent med standardmodulene. Med tanke på modulenes muligheter, vil en prototype bli designet for å møte gartnerens krav.

En av standardkonfigurasjonene til landbruksroboten har tre hjul og kalles Trikevald. Det er fornuftig å begynne med å vurdere i hvilken grad den kan brukes siden den er smal og kan passe mellom skinnene. Et besøk ved gartneriet gjorde det klart at tiden brukt på Trikevald var bortkastet og strategien måtte endres. Trikevalds feil og mangler ble vurdert og skapte et grunnlag for utvikling av nye konsepter.

Det resulterende designet er en firehjuls prototype som med tanke på de operative aspektene av en drivhusrobot er overlegen over Trikevald. Masseproduserte standard Thorvald-komponenter er en del av designet, noe som gjør det til et konkurransedyktig konsept når det gjelder pris i drivhusrobotmarkedet. Det kan også erstatte en slank Thorvald-versjon i polytunneler i fremtiden.

Arbeidet fremover vil innebære å ferdigstille prototypen for så å gjøre ferdig utregningene og optimalisere designet med tanke på last.

TABLE OF CONTENTS

ABBREVIATIONS

Abbreviation	Meaning
CG	Centre of Gravity
CAD	Computer-Aided Design
CNC	Computer Numerical Control
FEM	Finite Element Method
FWS	Front Wheel Steering
IPD	Integrated Product Development
POM	PolyOxyMethylene
PDS	Product Design Specification
RWD	Rear Wheel Drive
RC	Rotational Centre
SF	Safety Factor
SSD	Soil Structure Degradation
SW	Solid Works

CHAPTER 1
INTRODUCTION

This chapter introduces the reader to the background of this thesis, which involves relevant projects, companies and the product design specification.

1.1 THE THORVALD PROJECT

In 2014, a team of four students from NMBU studied the operation of conventional agriculture. They learned that increased demand in agriculture is directly proportional with the size increase of machinery. Agricultural machinery is extremely heavy causing serious compression of the that is unfavourable to growth. According to McGarry, "Soil structure degradation (SSD), often called soil compaction, is regarded as the most serious form of land degradation caused by conventional agriculture" [1]. The tendency in today's agriculture is to solve the problem by increasing surface contact area of tires, but the results vary as shown in Figure 1-1 (b). *LandbrugsAvisen* claims that 90% of the energy consumed in earth treatment is used to restore SSD [2]. Realizing the industry was heading in the wrong direction, the team saw a potential in transforming agriculture and make it more sustainable. Their contribution was to develop a small and lightweight agricultural robot with low SSD impact, which they named Thorvald, pictured in Figure 1-1 (a).

(a) A rendered picture of the first Thorvald prototype.

(b) Tractor ruining soil despite using counter-SSD measures.

Figure 1-1: Salvation versus destruction. Image: NMBU/Pinterest

During spring of 2015, a new team of students explored possibilities for achievement of an autonomous agricultural robot. A tool for weed control was developed[3]. Autonomous liming of fields and its feasibility was assessed[4]. The battery management of Thorvald was improved[5]. However, last year was when real improvements took place, Marius Austad and Øystein Sund took the game to the next level by focusing heavily on the modularity of Thorvald, calling it Thorvald II [6, 7]. Ease of testing the same robot on different platforms were the results of this improvement.

There are now three standard modules making up Thorvald. As pictured in Figure 1-2, the aluminum tube chassis, the nacelle containing batteries and the wheel module. These can be assembled in different configurations with ease. This and Kristine Skattum's thesis revolves around increasing the arsenal of configurations that are possible with the current standard modules. Strengthening the foundation of Thorvald's concept is important.

Figure 1-2: The current possible configurations of Thorvald II lined up. Observe the recurring modules. Image: Halvard Grimstad

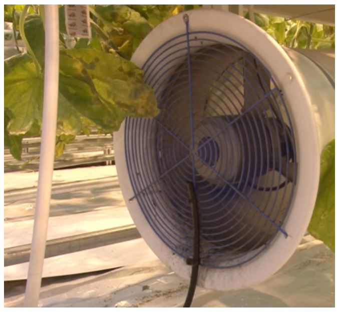
The Thorvald project has evolved from being a mere student project into a potentially commercial product. Numerous enterprises, gardeners and farmers showed their interest when Thorvald appeared at SIMA International Business Show Paris-Nord Villepinte 2017; an international agricultural exhibition with roughly 250 000 attendants.

Figure 1-3: A size comparison of Thorvald II and a Hollander tractor at SIMA Paris. Size matters.

1.2 Guren Gartneri, UV-Bær and UV BIO

Kristian Guren runs a nursery, Guren gartneri AS, just south of Moss[8]. He cultivates small plants, flowers and cucumbers from roughly 10000 cucumber plants in the nursery. These greenhouses contain state of the art technologies to regulate temperature Figure 1-4 *(a)*, air flow and humidity Figure 1-4 *(b)*, and nutrients Figure 1-4 *(c)*. Producing a fresh product is achieved through use of mites and only minimal amounts of pesticides to fight pests Figure 1-4 *(d)*.

(a) *Valves as part of the heat regulator of the greenhouse.*



(b) *Air flow and humidity regulating fanned system.*

(c) *Automatic irrigation with nutrient water coming out of the tube.*

(d) *Mites used to fight pests bought in small sawdust filled bags and fastened to the cucumber plants.*

Figure 1-4: Modern greenhouse operation at the Guren nursery. Image: ndla

Mildew, in Figure 1-5 (a), is a pest responsible for spoiling large amounts of produce the last few years[9]. Simen Andreas Myhrene is a strawberry producer in Sylling. Sustaining great losses he established UV-Bær in collaboration with NMBU and Bioforsk in 2015[10]. The project investigates use of UVB-light as a practical method for eliminating mildew and grey mould fungus. The Thorvald project conducted, as seen in Figure 1-5 *(b)*, numerous tests on strawberries in polytunnels last season and has resumed testing this April. In hearing about this project, the gardener, Kristian Guren wondered if he could use this technology, and how UVB-light would affect beneficial insects used in cucumber production. In 2016 he established UV Bio, a project with intent to observe how UVB light affects pests and beneficial insects [11].

(a) *Mildew on a strawberry.*

(b) *Thorvald II radiating strawberries with UVB light.*

Figure 1-5: UV-Bær related pictures from sylling. Image: Erling Fløistad/NMBU

A modified automatic pesticide sprayer, in Figure 1-6 *(b)*, is currently what conducts tests at the greenhouse[12]. The gardener needs to be present during the process to oversee and manually move the machine between rows. Moreover, the machines lowest speed setting is still too high for optimal UVB exposure and produce sub-optimal results. To prevent skin damage from the UVB light on workers, tests are done at night. NMBU, being a collaborator, has agreed to deliver a robot. This robot has not been designed yet, but would activate at night-time and autonomously manoeuvre itself to the rails in between rows.

(a) UVB light-rack created by Guren to conduct testes with a pesticide sprayer.

(b) The automatic pesticide sprayer. The sprayer unit, at the right of the picture, is removed in favour of the light rack in (a).

Figure 1-6 Pieces of the modified automatic pesticide sprayer at the Guren nursery.

Dr. A. Suthaparan, a renowned scientist researching UV-light and its effect on plants, is part of the UV-Bær and UV Bio project [13]. His responsibilities include calculating optimal UV exposure to cucumbers and designing the light-rack. Moreover, he will provide necessary data for design.

1.3 UMOE Bioenergy

In January 2017 the students working on Thorvald went on a field trip to Brazil. In Presidente Prudente, which is a city in the state of São Paulo, the group encountered Knut Arne Karlsen who is the CEO of UMOE Bioenergy; He is running an enterprise producing bioethanol from sugar-cane plants. Karlsen gave a guided tour in which he showed all the plants in different stages of growth at the farm. Furthermore, he described challenges in these stages; they faced floods, weeds and invasions of different kinds of insects. To reduce losses, different strands of sugar cane are mixed.

They have different strengths and weaknesses and only 18% of each strand is allowed. However, pests must be observed and dealt with quickly to obstruct spread.

According to Karlsen, deploying a series of autonomous robots would be advantageous to sugar cane operations. At first, autonomous operation would involve survey. Ultimately the tasks would include precise farming operations in the fields. Guren's challenges are similar to Karlsen's, and this robot could theoretically be operational on multiple platforms of production. Currently, a team of Brazilian postgraduates are in charge of designing such a robot.

Figure 1-7 Knut, in yellow,explaining the metric boundaries of a cane robot in Brazil. Image: Marius Austad

1.4 Competing Concepts

This thesis will merely assess agricultural robots within the field of horticulture. Competing concepts within general agriculture has already been assessed in Lars Grimstad's Marius Austad's theses[6, 14]. There is currently a great deal of research on greenhouse robotics. The search words "autonomous greenhouse robot" yields 12.400 results in google scholar. Only two of the many concepts will be mentioned.

A similar modular autonomous robot concept was created by Spanish engineers at the University of Almeria in 2012[15]. The robot is showed in Figure 1-8. It does, on the other hand, not possess the ability to use greenhouse rail systems.

(a) Without any tools attached. *(b) With a 400L pesticide sprayer*

Figure 1-8 University of Almeria modular robot in tomato greenhouse[15].

Priva International is an enterprise developing technologies for horticulture. Priva has developed a robot, which is called Kompano, capable of autonomously deleafing tomato plants[16]. They claim that this innovation is necessary due to a continuously increased cost of manual labour and that a motivated workforce is harder to come by. It can run on greenhouse rails, as seen in Figure 1-9.

(a) Prototype conducting tests by cutting leaves in a tomato greenhouse.

(b) The final design available from June. 2017.

Figure 1-9 Priva Kompano prototype and final product[16].

The Kompano has been commercialized and Priva claim that each unit can maintain 0.75 to 1 hectares. As of the information provided on the website, modularity and other tools are not mentioned. This may, however, be under development as harvest of cucumbers is mentioned as a future project.

1.5 Product Design Specification

During the design of this robot, both the Thorvald project and Kristian Guren have spesific demands. Important design properties will be explained, quantified and metric boundaries will be set.

1.5.1 Operational Aspects of a Greenhouse Robot

Before specifying the table of characteristics, essential requirements are presented.

Thorvald modules

As mentioned, the fundamental of Thorvalds concept is modularity. Proving that the same modules can be used for a whole new platform will strengthen the foundation. A third generation of Thorvald is currently under development where the goal is to produce roughly 10000 robots within the next three years. Therefore, making the most of standard modules will reduce cost due to mass production. Moreover, less parts are designed from scratch facilitating design.

Greenhouse rail system

At Kristian Gurens nursery, there is a rail system between the cucumber rows shown in Figure 1-10. The rail system consists of two 55mm tubes with an 80cm space in between. The space will vary with different greenhouses and an adjustable width on the wheels is therefore advantageous to increase the customer group. Where the rails start there is a step that descends 20cm from the concrete floor. Drive on both concrete and rail is therefore an essential criterion.

Tool mount

Since the robot does not have Integrated tools, it is necessary to have a tool Mount rack. In this case it serves as an area to attach the light rack, but there needs to be space for other accessories that will be developed in the future.

Figure 1-10 Area of action inside the greenhouse. This section is dedicated to the UV-Bio project for research.

1.5.2 Important Product Properties

This section lists criterions and functional properties derived from the operational aspects of a greenhouse robot.

Table 1-1 Overview of indispensable properties.

Absolute properties		
No.	Property	Need/Comment
1	Modular	Pursuit of concept.
2	Rail/concrete drive	Unobstructed drive in nursery surroundings.
3	Mount	Ability to attach tools.

The importance factor in Table 1-2 emphasizes how desirable the feature is as well as simplifying a quantitative comparison in chapter 6. The scale ranges from 1-4, where 4 is most important.

Table 1-2 Overview of product properties including importance factor

Important properties			
No.	Property	Need/Comment	Imp
4	Battery capacity	Should complete one process cycle without charging the batteries.	4
5	Total cost	Competitive price	2
6	Electronics access	Numerous tests will require easy physical access to the inside of the electronics hub.	3
7	Adjustable width	Wheel width to match rail gap ranging from 40-80cm.	4
8	Stability	With a tall tool the robot is required to be heavy with a low CG.	3
9	Waterproof	High air moisture leads to dripping from the ceiling. IP 55 should suffice[17].	1
10	Economy of space	How well the metric boundaries are taken advantage of.	2
11	Manufacturing	Production complexity and time use for prototype development.	3

1.5.3 Metric Boundary Specifications

Based on the interview with the gardener and section 1.5.1, maximum outer dimensions of the robot are specified inTable 1-3 and showed in Figure 1-11. The body in the picture is the boundary.

Table 1-3 Metric boundary of robot illustrated in Figure 1-11.

Parameter	Max	Unit
Height 1 (Robot)	500	mm
Height 2 (Total)	2500	mm
Width 1 (Robot)	950	mm
Width 2 (Tool)	600	mm
Length (Robot)	1200	mm

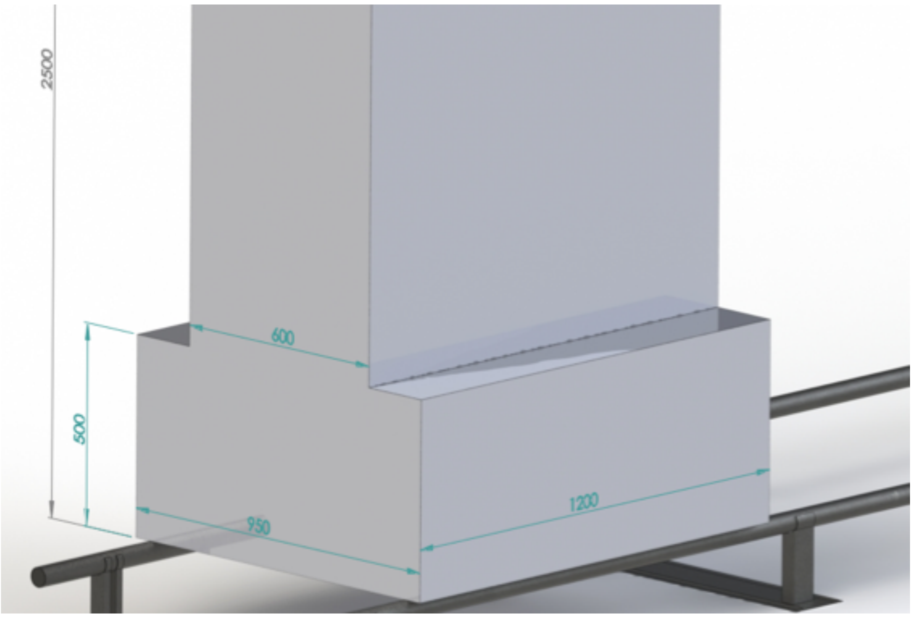


Figure 1-11 Illustration of the metric boundary specifications in millimetres.

CHAPTER 2 PROJECT PLAN

This chapter presents the work plan for this thesis. The goal of the thesis is divided into partial objectives. Limitations are defined at the end of the chapter.

2.1 Scope of Thesis

The prospect of this thesis is to design and assemble a robot prototype capable of driving autonomously on both rails and concrete. Maintaining the concept of modularity is essential when expanding the number of Thorvald configurations.

Specific requirements given by Kristian Guren and the Thorvald project must be met and the prototype must be designed and produced within a time limit of four months. In order to reduce costs Thorvald modules will be primarily used. However, there are many requirements to keep track of during the design process.

Early stages of design will involve assessing if the standard configurations and modules meet the requirements. A three-wheeled configuration, called Trikevald, is a natural place to start. If Trikevald is not satisfactory, the configuration will undergo customization or replacement. Smart solutions, production cost and feasibility will be determining factors of the production method. The finished product will facilitate future modifications, have electrical components that are accessed with ease and a short assembly time.

July 1, 2017 is the deadline for delivering a functioning robot. May 15, 2017 is the deadline of the master's thesis. Therefore, this thesis will assess the design, assembly technique and as much of the finished product as possible leading up to May 15.

2.2 Goal of the Thesis

Design and build a functioning prototype robot for the UV Bio project to conducts tests; using as many Thorvald standard modules as possible.

2.3 Objectives

The following objectives must be completed in order to complete the goal of the thesis:

- Review earlier master theses from the Thorvald project
- Generate realistic product design specifications
- Develop concepts and CAD models
- Simplify design and production method
- Find suitable materials and components
- Complete the report and present current conclusion
- Build the robot

2.4 Milestones

Table 2-1 Milestone plan. The darker shade has most focus.

Short term goals	Week																	
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
PDS																		
Early prototype test																		
Concept generation																		
CAD-modeling																		
Screening of concepts																		
Optimization																		
Production																		
Report																		

The main objective of this thesis is clear and time is of the essence. A considerable amount of time is dedicated to CAD-modelling and optimization of production and design.

2.5 Limitations

- Selection of materials will not be evaluated in depth. The selected materials will merely be described and compared
- Fatigue will not be evaluated
- Economic and ecologic aspect will not be evaluated
- The production method is optimized to fit the time constraint and authors ability to independently built prototype
- Thorvald project and Kristian Guren requirements interfere

CHAPTER 3
METHODOLOGY

This chapter presents the formulas and tools used to develop a product that fits the product design specification.

3.1 Terminology, Symbols and Physical Constants

Table 3-1 List of terminology.

Term	Description
Horticulture	The practice of garden cultivation and management
Monocoque	A self-carrying chassis constructed as a shell.
Teething trouble	Difficulties or problems that arise during the initial build of a prototype

Table 3-2 List of symbols.

Symbol	Description	SI-Unit
$\boldsymbol{A}$	Maximum vehicle cross section	m^2
$\boldsymbol{\alpha}$	Angle of upgrade or downgrade	°
$\boldsymbol{C_d}$	Coefficient of drag	-
$\boldsymbol{C_{rr}}$	Coefficient of rolling resistance	-
$\boldsymbol{F}$	Force	N
$\boldsymbol{F_f}$	Friction resistance	N
$\boldsymbol{F_L}$	Aerodynamic drag	N
$\boldsymbol{F_{Ro}}$	Rollin resistance	N
$\boldsymbol{F_{St}}$	Climbing resistance	N
$\boldsymbol{F_W}$	Tractive resistance	N
$\boldsymbol{\mu}$	Coefficient of friction	-
$\boldsymbol{N}$	Normal force	N
$\boldsymbol{\omega}$	Rotational speed	s^{-1}
$\boldsymbol{P}$	Power	W
$\boldsymbol{r}$	Radial distance to torque inducing force	m
$\boldsymbol{\rho}$	Density	kg/m^3
$\boldsymbol{\tau}$	Torque	Nm
$\boldsymbol{v}$	Road speed	m/s

Table 3-3 List of physical constants.

Symbol	Description	Magnitude		Unit
C_{rr}	Between a truck tire and dry concrete	0.008	[18]	-
C_{rr}	Between a polymer and steel	0.057	[19]	-
μ	Dynamic between Delrin and steel	0.2	[20]	-
μ	Dynamic between rubber and steel	0.6	[21]	-
g	Gravitational force (for simplicity)	10.0		m/s^2

3.2 Formulas

Table 3-4 List of formulas.

Relation	Formula	Index
Power	$P = F \cdot v$	(3.1)
Total driving resistance	$F_W = F_{Ro} + F_L + F_{St}$	(3.2)
Rolling resistance	$F_{Ro} = C_{rr} \cdot N$	(3.3)
Aerodynamic drag	$F_L = \frac{C_d \cdot A \cdot \rho \cdot v^2}{2}$	(3.4)
Climbing resistance	$F_{St} = \mathrm{Sin}(\alpha) \cdot N$	(3.5)
Friction force	$F_f = \mu \cdot N$	(3.6)
Torque	$\tau = \frac{P}{\omega} = F \cdot r$	(3.7)

3.3 Integrated Product Development

IPD is a method that looks at development in a much broader sense than just the functionality of a product[22]. Every step of the development process has to be effective or “lean”. There are four pillars, development, production, economy and ecology. In developing a complete and sustainable product it is important to optimize all four aspects. However, this thesis will not assess the last two pillars.

Pugh’s Method.

Pugh’s method, also called decision-matrix-method[23]. Making choices in design is a complicated process with many factors and influences. By making a PDS one can list important characteristics of the product and score them. The concept with the highest score is best suited for the product. Subjective opinions can somewhat be neglected when using this method.

3.4 Quality Assurance

- Calculations will be performed on a spreadsheet to eliminate uncertainty from rough rounding
- Assumptions will either be based on relevant literature or statements from experts
- Sources of error in FEM-analysis results will be discussed. Computer Tools

Table 3-5 Computer tools.

Program	Use
MS Word 2016	Writing
MS Excel 2016	Data processing
SolidWorks 2016/2017	CAD
ANSYS Workbench 17	FEM-analysis

3.5 Development process

The design of this robot follows a simple design process derived from IPD. What is important to mention is that this thesis starts by testing a prototype. A short and streamlined cycle will increase the chances of finishing the robot in time. After the specifications are determined a cyclic design process will start. The process showed in Figure 3-1 is designed to adapt to the outcome of chapter 0, early prototype testing.

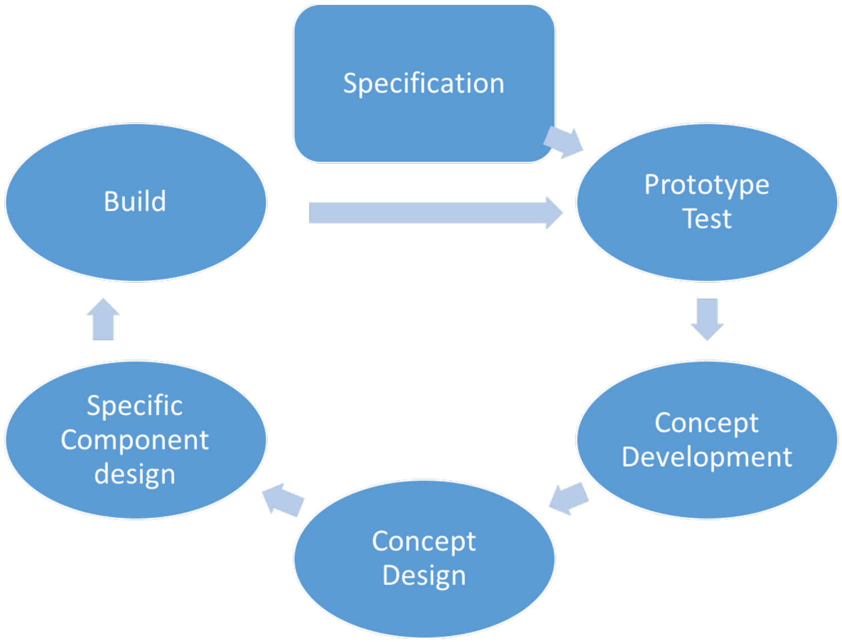


Figure 3-1 Design development process chart. Clockwise.

CHAPTER 4 THEORY AND TECHONOGY REVIEW

This chapter will introduce the reader to relevant knowledge and technology used in this thesis.

4.1 UV-Bio

Today, utility insects are the most used method of fighting pests in nurseries. It is less polluting than its counterpart, chemical pesticides. The insects used, mainly mites and wasps, have no effect on fungi. At the laboratory, Dr. Sutaparan's research concludes that a combination of UVB, which has an optimal wavelength of 280nm, and dark red lighy works best when fighting mildew [24]. The practical use of this technology is being developed using Thorvald.

While a commercial product is developed, it is crucial to observe how UVB affects the utility insects. Research shows that UVB exposed microorganisms perish after a certain amount of UV-radiation. Eggs are most sensitive to this radiation, but regenerate when exposed to white light; a reparation mechanism not yet fully understood[25, 26]. UVB exposed insects will try to hide from the light source, but green light will attract them[27]. However, the relevant insects in the greenhouse has not been tested at the low doses that is used on fungi. Moreover, how the specific wavelengths used to fight mildew affect the utility insects and pests present in the nurseries remain to be tested.

The desired outcome is that the UVB light eliminates pests without affecting the utility insects. That would lead to a completely pesticide-free nursery operation.

4.2 Calculations

4.2.1 Coefficients of Rolling and Friction

Finding coefficients that represent this special situation is problematic. First, galvanized steel, or zinc, has to be tested with the exact polymer that is used, and manufacturers datasheets do not cover all materials. There are 5 different types of POM alone, all with minimal differences. Second, the friction coefficient between rubber and concrete varies with a great deal of factors other than dry/wet surfaces. It is likely that a layer of dust is stuck to the rubber reducing the coefficient of friction.

4.2.2 Total Driving Resistance

When $\boldsymbol{F_w}$ is calculated, aerodynamic resistance is neglected because of the relatively low speeds. Bosch Automotive Handbook dictated that all speeds lower than 40km/h are low speeds with respect to aerodynamic friction [28]. Also, the greenhouse floor is level and will in theory have negligible climbs, but as a safety measure a 1% climb will be added.

4.3 Standard Modules and Configurations

As previously stated, Thorvald consists of three main modules. The wheel module, the nacelle and the aluminium tube chassis. These modules and their possibilities will be reviewed in this section.

4.3.1 Wheel Module

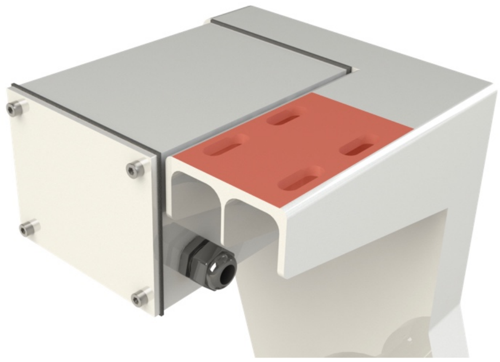
This modules purpose is to propel the robot. As shown in Figure 4-1 it consists of two parts, the tower Figure 4-1*(a)* and the propulsion foot Figure 4-1*(b)*. The tower houses the motor controller and the steering system of the wheel. Both steering and propulsion motor is connected to the motor controller. The propulsion foot contains a motor, transmission system and wheel.

(a) Rendered picture of the tower.

(b) Rendered picture of the propulsion foot

Figure 4-1 The wheel module components separated.

The possibilities of this module are vast. Normal Thorvald has four-wheel independent steer and drive. By removing or changing components different kinds of steering can be implemented. With the axle, on top of the propulsion wheel in Figure 4-1*(b)*, and tower removed, there are two possible connection methods. Figure 4-2 displays that the propulsion wheel can either be connected through the bracket that connects the rotational axle to the propulsion wheel Figure 4-2*(a)*, or directly to the propulsion wheel Figure 4-2 *(b)*.



(a) Mounting possibility on bracket.

(b) Mounting possibility directly on the propulsion foot.

Figure 4-2 Illustration of the possibilities when mounting the propulsion wheel. The mounting area is marked in red.

4.3.2 NACELLE

This modules purpose is to hold the batteries and computers. It is a watertight container with lids on either side for electronics access. As showed in Figure 4-3 the nacelle connects to the aluminum chassis with the clamps on top. The holes on the sides do not carry any loads.

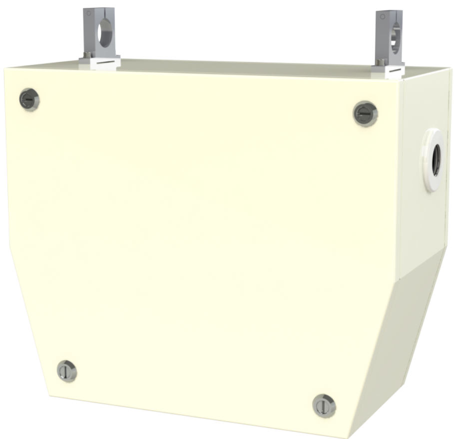


Figure 4-3 A rendered picture of the nacelle.

The possibilities with this module are rather narrow. Its sole purpose is to contain essential electrical components, but it can be mounted upside-down.

4.3.3 Aluminum Tube Chassis

The chassis provides a rigid and robust structural framework. The end pieces are specially designed to mount nacelles and wheel modules. Sensor rack and tools are adapted to be clamped on the tubes, which also serve as a ground to the electrical system.

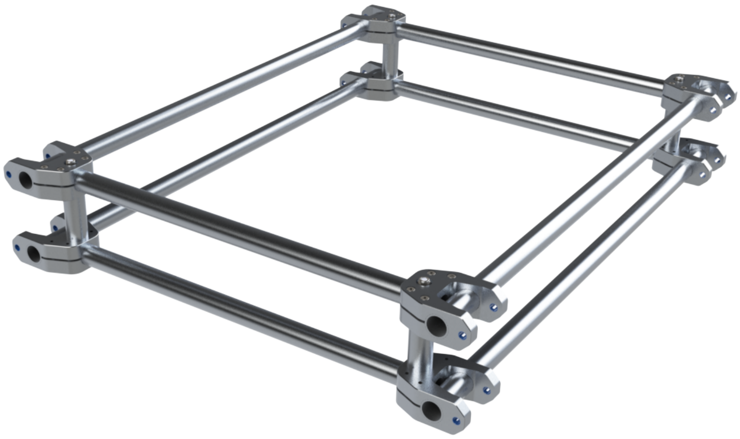
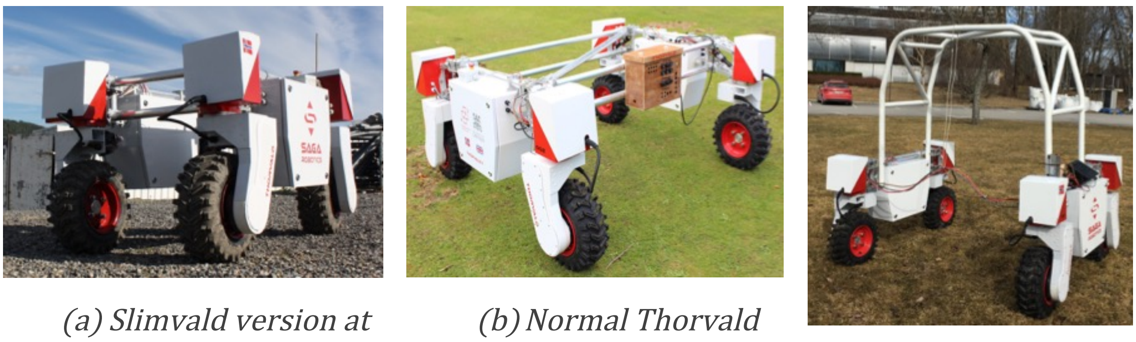


Figure 4-4 Rendered picture of the aluminum tube chassis.

The chassis can be adjusted to whatever measurement the situation requires. Also, anything can be clamped onto it if there is space.

4.3.4 Configurations

When Marius Austad and Øystein Sund developed Thorvald II they created an arrangement of what was thought to be the possible configurations at the time. It is possible to select a Thorvald for almost any platform with the same modules. With two nacelles and four wheel modules the Thorvald project has been able to test a slim version, fit for strawberry polytunnels, a wide version, where a plough was tested, and a tall version, used for phenotyping, of the standard configurations.



(a) Slimvald version at sylling, ready for UVB light tests.

(b) Normal Thorvald version with sensor box in Lincoln.

(c) Thora assembly test at NMBU

Figure 4-5 Different Thorvald configurations that have been built. From the slimmest on the left, to the broadest on the right. Picture: Lars Grimstad/Lars Grimstad/Kristine Skattum

A three wheeled robot, called Trikevald, was made for narrow spaces where even the slim version of Thorvald would not fit. The summer of 2016, the group was curious to test how effectively they could change the configurations. During that time Trikevald was assembled and its picture taken.

Figure 4-6 Assembled Trikevald during test day in the summer of 2016. Image: Erling Bjurbeck

CHAPTER 5
EARLY PROTOTYPE EVALUATION

In this chapter, the three wheeled configuration will be assessed against the PDS. Then, a recommendation for the further progress of this thesis will ensue.

5.1 INTRODUCTION

The metric boundary specifications of chapter 1.5.3 dictate that the three wheeler will fit. On the other hand, it remains to see how well the configuration will perform in an environment that requires rail drive.

Figure 5-1 Rendered picture of the first generation Trikevald. Image: Lars Grimstad

5.2 DESIGN AND PRODUCTION OF DOUBLE WHEEL MODULE

The characteristic double wheel module of the three wheeler was only a simple CAD model used for the line-up with no blueprint for production. Available materials at the NMBU workshop was used to design the module in SW and then build a functioning module showed at the end of the previous chapter in Figure 4-6. This design was improved upon after the prototype revealed shortcomings with the mount, stability and aesthetic look. Figure 5-1 and Figure 5-2 are very similar, but the most important difference is that the rear wheels are pointing toward the nacelle instead of away. This difference is better pictured when compared to Figure 4-6.

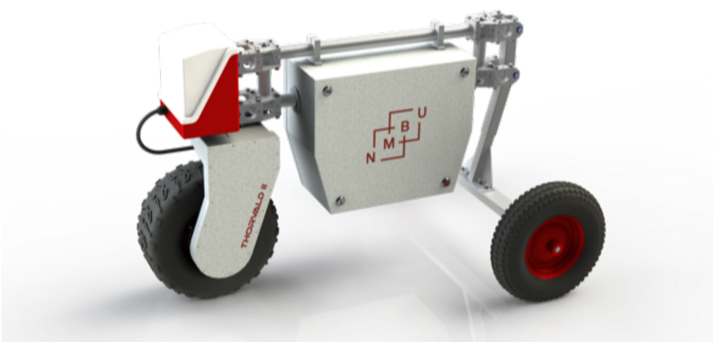


Figure 5-2 Rendered picture of the final version of the Trikevald in the summer of 2016. Image:Halvard Grimstad

5.3 Discussion of early results

The absolute- and important properties derived from the operational aspects will be assessed when discussing the early results. Since there are no concepts to compare the properties with, a score will be given and discussed.

Table 5-1 Reiteration of Table 1-1.

Absolute properties		
No.	Property	Need/Comment
1	Modular	Pursuit of concept.
2	Rail/concrete drive	Unobstructed drive in nursery surroundings.
3	Mount	Ability to attach tools.

The three wheeler is a standard configuration requiring little to no effort building. Moreover, as explained in 4.3, the currently developed tools are adapted to be clamped on the aluminum tube chassis. However, it will face a challenge when driving down the step showed in Figure 5-3. First, because of the tall light rack, the robot may fall over when driving down the step. Furthermore, shock damage will be sustained adding on to potential fatigue failure. Secondly, the ground is covered in a slippery plastic, thus complicating the programming of the steering. Finally, the original Thorvald can climb stairs because trust from the rear wheels produces a normal force between the front wheels and a vertical surface enabling it to climb. Trikevald does not currently possess a system generating thrust other than a single wheel module. Also, a large enough wheel to climb the 20cm gap will not fit.

Figure 5-3 Step down from concrete floor is steep and provides no climb assistance. Also, the white plastic sheets seen between the rails are loose and slippery.

Table 5-2 Reiteration of Table 1-2. The scores are bad, neutral and good.

Important properties		
No.	Property	Performance
4	Battery capacity	Good
5	Total cost	Good
6	Electronics access	Good
7	Adjustable width	Neutral
8	Stability	Bad
9	Waterproof	Good
10	Economy of space	Bad
11	Manufacturing	Good

The design of Thorvald has constantly been improved the last four years. Therefore, it is sensible to assume that the properties linked to Thorvald II are good. These are: battery capacity, total cost, electronics access, waterproof and manufacturing.

The original Thorvald configurations were, however, not designed to run in a greenhouse resulting in bad stability and economy of space. With only three contact points to the ground and the CG in the front, between the transmission and the batteries, low stability ensues. The trikevald is also slim and do not exploit the metric boundaries sufficiently.

5.4 Recommendation

After a visit to the greenhouse discussing the design with Guren, it dawned that Trikevald had many aspects that needed to be modified. Modifying the design would be time-exhausting and not possible within the scope of the thesis. It is more sensible to design a new prototype configuration that fits, rather than completely redesigning an existing module. The current inability to use the rail system, an absolute requirement, is a deal-breaker.

Important points when designing a new prototype:

- Make better use of the lower space
- Lower the CG
- Increase from three to four contact points for a better stability
- Use a manner of steering that allows rail and concrete propulsion with the use of only two motors

CHAPTER 6 CONCEPT GENERATION AND SELECTION

In this chapter, conceptual design proposals are generated from function analysis. Then, in chronological order, the concepts will be screened using Pugh's method and determined.

6.1 FUNCTION ANALYSIS

For an effective concept development phase in the development process, the primary functions will be determined in turn. Figure 6-1 shows the sequence of the concept development and selection process.

Figure 6-1 Concept development process chart.

Below, primary functions and characteristics of a cucumber robot are presented.

Table 6-1 Primary functions.

Primary function	Comment
1. Steering	There are various ways of steering. Differential steering, front wheel steering with rear wheel drive and skid steering will be accounted for in this situation. Optimal steering will be robust as well as simplistic.
2. Propulsion wheel	The wheel accounts for propulsion on both concrete and greenhouse rails. The steering will determine what kind of propulsion wheel this configuration calls for.
3. Chassis	The chassis is the main unit where everything is installed through easily accessible mounting points. It should be strong, rigid, configurable and match the criterions.

6.2 Development of Selection Matrix

The selection matrix is based on Table 1-2 in Section 1.5.2. The criterions will however be selected to suit the different functions. If changed, the criterion will be bold, and if added it will in addition not have a number from the original table.

Table 6-2 Overview of criterion used in selection matrix.

No.	Criterion	Need/Comment	Imp
		Steering	
5	**Production Cost**	Price of all components.	2
7	Adjustable width	Wheel width to match rail gap ranging from 40-80cm.	4
8	Stability	To prevent the robot from tip over when the 3m tall light rack is installed.	3
	Manoeuvrability	To what degree the design makes for an unreliable steering.	1
10	Economy of space	How well the metric boundaries are taken advantage of.	2
11	Manufacturing	Production complexity and time use.	3
		Propulsion wheel	
5	**Production cost**	Price of all components.	2
	Manoeuvrability	To what degree the design makes for an unreliable steering.	1
10	Economy of space	How well the metric boundaries are taken advantage of.	2
	Strength	To what degree the design enfeebles remaining structures.	4
11	Manufacturing	Production complexity and time use.	4
		Chassis	
4	Battery capacity	Should complete one process cycle without charging the batteries.	4
5	**Production cost**	Price of all components.	2
6	Electronics access	How difficult access to the electronics hub is.	3
7	Adjustable width	Wheel width to match rail gap ranging from 40-80cm.	4
9	waterproof	High air moisture leads to dripping from the ceiling. IP 55 should suffice[17].	1

10	Economy of space	How well the metric boundaries are taken advantage of.	2
11	Manufacturing	Production complexity and time use.	4

Production cost reflects the price of the concept rather than the robot as a whole. Manoeuvrability compares the steering of the prototype both on concrete and the rail system. The strength criterion of the rim compares the rotational moments created in the propulsion foot by the rim.

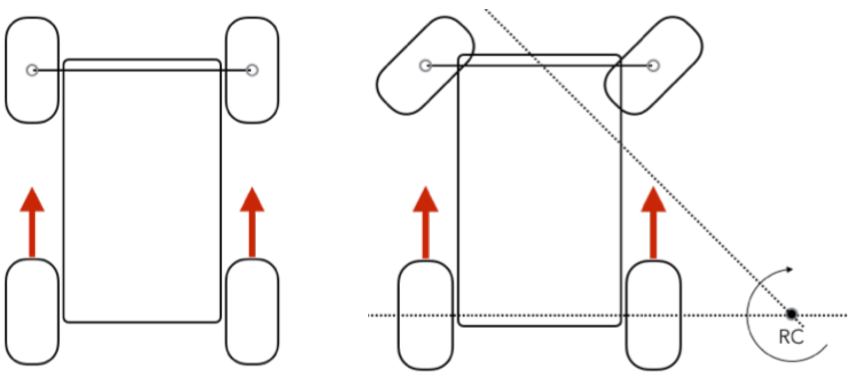
In the screening process the concepts will compete with regard to the specified criterions. The ranking system is simple; the weakest concept within a criterion receives 0 points, the next 1 point, and so on until the last concept has received points. If two competing concepts are equally weighed, they recieve the same score. The product of the points and importance will sum up. The concept receiving the highest total is then seen as the best concept.

6.3 Function Alternatives of Steering

As drawn from the early prototype recommendations, the robot should have four wheels for balance and a simple drive solution. There are three typically known steering methods when it comes to the use of two actuators. Front wheel steering with rear wheel drive, differential steering and skid steering. The strengths and weaknesses are compared to another with consideration to the robot's functionality.

Concept 1	**FWS RWD.**
Summary	This way of propelling a machine is popular among car manufacturers. It is a reliable and efficient way of steering a vehicle at high speeds.

Illustration



(a) Propulsion. (b*) Steering with rotation centre.*

Figure 6-2 Illustration of FWS RWD.

Strengths

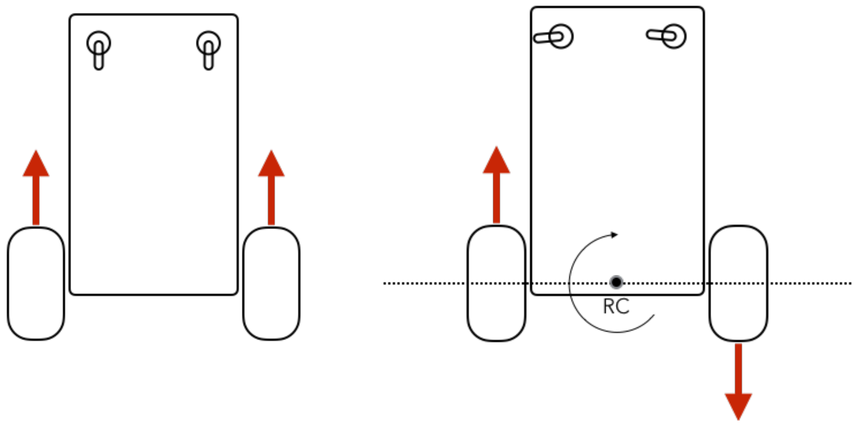
- Mechanical simplicity and strength

Weaknesses

- Thorvald does not implement this kind of steering, so a new steering mechanism has to be developed
- Largest turn radius of the three
- Complicated front wheel adjustable wheel spacing mechanism
- Complicated to design and make

Concept 2	**Differential steering.**
Summary	This way of propelling a machine is popular among actuated wheel chair and different kinds of robot manufacturers. It is a precise, cheap and effective way of steering slow vehicles.

Illustration



(a) Propulsion. *(b) Steering with rotational centre.*

Figure 6-3 Illustration of differential steering.

Strengths

- Tight turns can be made, as the rotational centre is at the intersection between the axle and the robot's bisector
- Simple width adjustment
- Easiest concept to improve on as Lars Grimstad has already made the code for Thorvald differential steering
- Only 2 rotating parts (except for caster wheels)
- The thorvald wheel modules can be used without using too much space

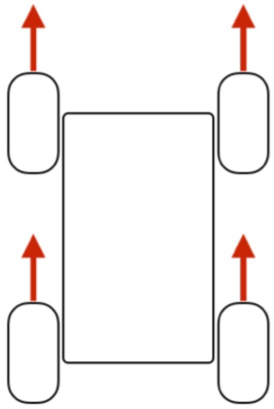
Weaknesses

- Poor stability on the caster wheels as they are loose.

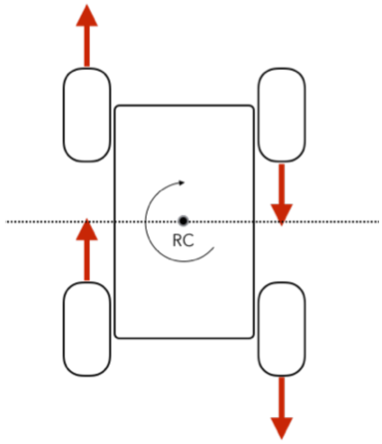
Concept 3	**Skid steering.**

Summary	This way of steering is popular among heavy machinery manufacturers. It gives the vehicle high moment with all-wheel drive, usually at low to medium speeds.

Illustration



(a) Propulsion.



(b) Steering with rotational centre.

Figure 6-4 Illustration of skid steering.

Strengths

- Tightest turn radii of the three, as the rotational center is at the centre of the robot
- Simple width adjustment

Weaknesses

- Medium cost, a belt system has to be developed for two actuators. Using four actuators is perhaps easier, but higher in cost.
- A new wheel system has to be developed
- Higher rolling friction when turning

6.4 Selection of Steering

Table 6-3 Screening of steering.

Criterion	Imp	Concept 1	Concept 2	Concept 3
Production Cost	2	1	2	0
Adjustable width	4	0	1	1
Stability	3	1	0	1
Manoeuvrability	1	0	1	2
Space use	2	0	0	0
Manufacturing	3	0	2	1

TOTAL	**5**	**15**	**12**

Differential steering will be used. The weighed sums of Table 6-3 shows that this is a close call. This is also the simplest and cheapest build with regard to the given conditions. With this steering the standard wheel modules can be used and a propulsion system will be designed to fit onto the transmission shown in Figure 6-5.

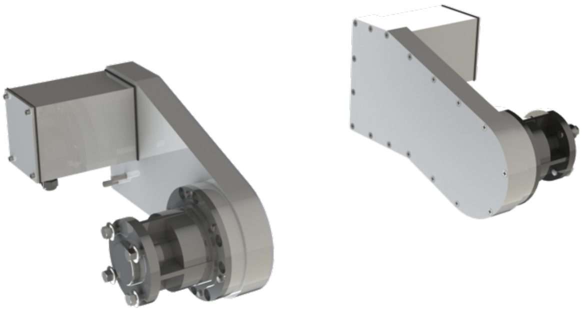


Figure 6-5 Standard wheel modules laying in a horizontal position.

6.5 Design Alternatives of Propulsion Wheel

The kind of wheel mounted on the transmission will be analysed in this section. Finding a wheel able to navigate on both concrete and the greenhouse rail system and fit the transmission was beyond the scope of this thesis. The closest discovery was for train and metro rails. Sticking to a few important constraints was key to developing concepts within a short timeframe. The rim had to have a minimum internal diameter of 140mm to make space for the transmission. Also the outer diameter should be larger than 270mm to keep the floor from scratching the wheel module. The transmission proved to be the dimensioning factor. An important factor is torsional moment on the wheel module, this is illustrated in Figure 6-6.

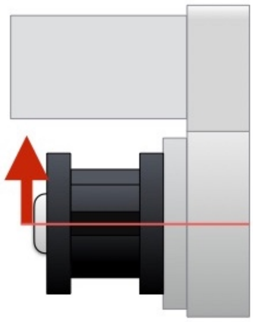


Figure 6-6 Illustration of wheel module seen from the front. The force arrow is red; the light red line is the distance creating moment.

There are two currently evident solutions, either fasten a rail-wheel outside the standard wheel, or create a completely new rail- and normal-wheel solution. The strengths and weaknesses are compared to another with consideration to the prototypes's functionality.

Concept 1	**Separate rail-wheel.**
Summary	This is a relatively simple build, where a circular profile is welded on to a plate. This is fastened to a turned polymer rail wheel. The build is simple in theory, but complex to manually build.

Illustration

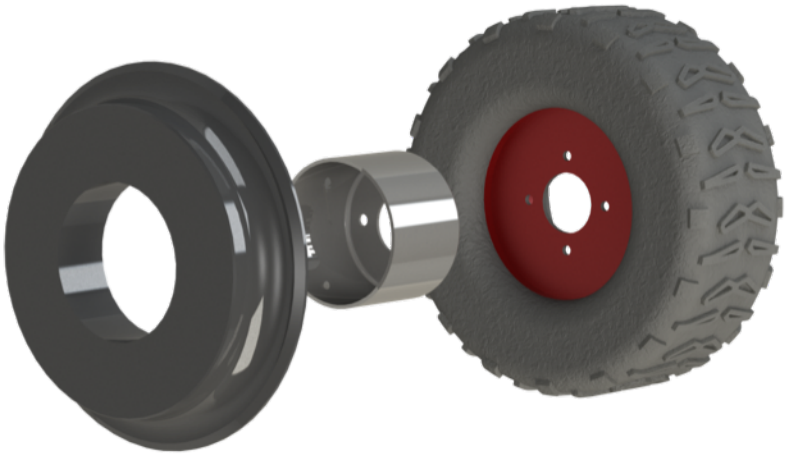


Figure 6-7 Exploded view of rail wheel outside the normal wheel. The two parts to the left has to be made manually as described in the summary.

Strengths

- Low cost of materials

Weaknesses

- Complicated manual labour
- Low economy of space
- Highest torsional moment on wheel module

Concept 2	**New complete rail-wheel.**
Summary	This build consists of a solid rubber tyre that is clamped onto a custom rim with a modified version of the steel rim that came with the tyre. The rim is too complicated to manually create. Therefore, it would be ordered from a company using CNC lathes to create it in polymer.

Illustration

Figure 6-8 Exploded view of new rail wheel design. This picture illustrates that there are more components compared to the previous concept, but only the rim unit to the left must be made. The steel rim to the right comes with the rubber tyre.

Strengths

- Slim area of contact with concrete for good manoeuvrability
- Low difficulty of production if machined
- Small outer radius to reduce height of robot and CG

Weaknesses

- High production cost of rim
- High number of bolts and nuts

6.6 Selection of Propulsion Wheel

Exploded view of the components was used to show the number of parts in the concept description. The real shape is illustrated below in a side by side comparison.

(a) Concept 1

(b) Concept 2

Figure 6-9: Comparison of the two rail-wheel concepts. Concept 1 is greater in size.

Table 6-4 Screening of propulsion wheel.

Criterion	Imp	Concept 1	Concept 2
Production cost	2	1	0
Manoeuvrability	1	0	1
Economy of space	2	0	1
Strength	4	0	1
Manufacturing	4	0	1
TOTAL		**2**	**11**

A new designed wheel will be used. Table 6-4 shows that concept 2 is the obvious choice. This is the simplest, but most expensive build. Parts will be outsourced and ordered for a low assembly time. This is shown in Figure 6-10 and is the foundation for designing the chassis.

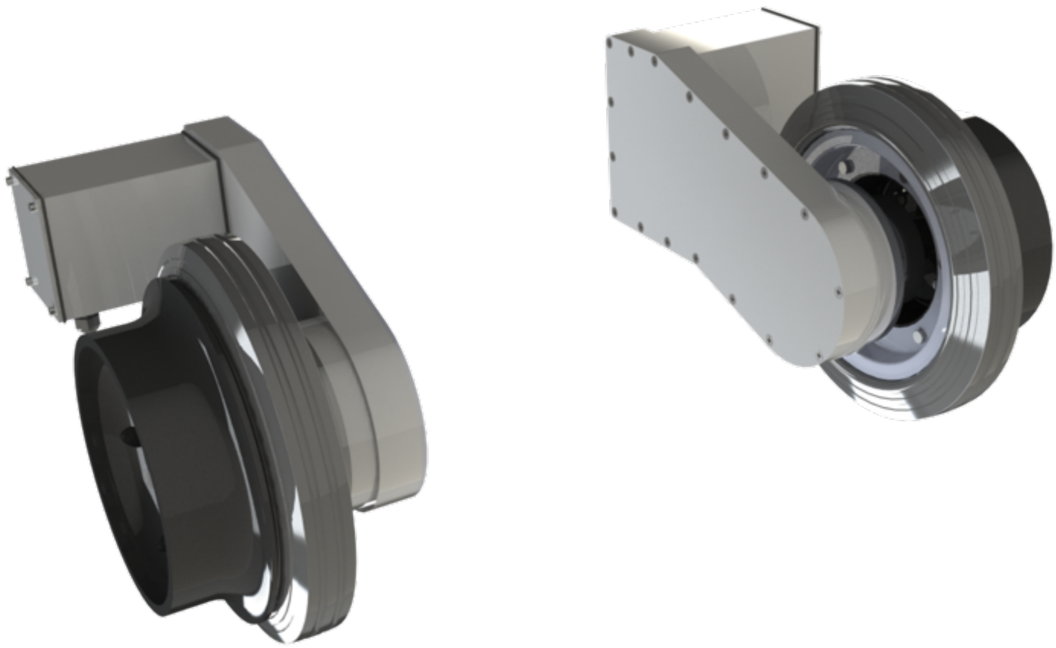


Figure 6-10 Rendered picture of wheel modules with rail-wheels.

6.7 Design Alternatives of Chassis

In this section, the design alternatives of the chassis are presented. Different degrees of standard component integration are showed in the different concepts. Strengths and weaknesses are compared to another with consideration to the robot's functionality.

Concept 1

Summary This concept has all the standard modules included, except for the wheel tower. It is the longest, at rougly 1,2 meters in length. Having the nacelle module flipped upside down leaves the aluminium tubes underneath, rendering them unusable for mounting purposes.

Illustration

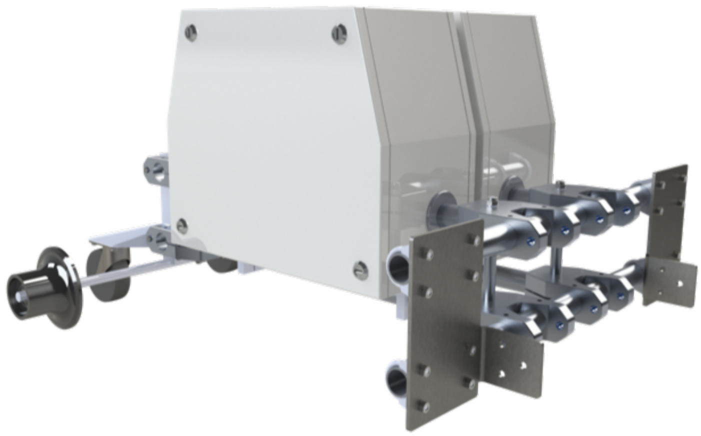


Figure 6-11 Rendered picture of the first concept. The rear has caster wheels and rail wheels and the front has a mounting mechanism for the wheels.

Strengths

- Only the mount of the wheel module has to be built
- Assembly is similar to Thorvald's characteristic look
- Same battery capacity as Thorvald
- Watertight nacelle designed for field work

Weaknesses

- The nacelles obstruct the tools and mount areas
- The length reduces the manoeuvrability
- Highest cost because of production of many unnecessary components for this application
- Shear force on the bolts mounting the wheel module to the chassis will deteriorate the structure, because movement will have the steel bolts slowly dig into the aluminium

Concept 2

Summary In this concept the nacelles have been swapped out. The result, a robot with a good mounting spot that lacks the ability to alter wheel width. It can, however, be manufactured with different widths at the expence of battery capacity.

Illustration

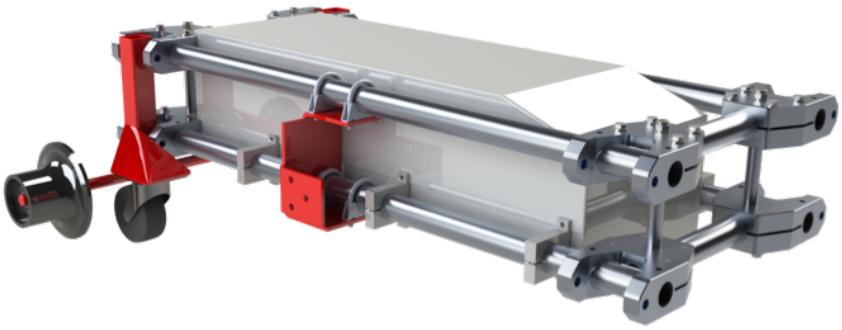


Figure 6-12 Rendered picture of the second concept. The rear has the same composition of caster and rail wheel as the first concept. In this one, however, the wheel module mount is located on the sides of the chassis.

Strengths

- Good mount area for tools on the chassis
- Relatively simple build using standard parts

Weaknesses

- Wheel width is not adjustable; the width depends on the size of the electronics box
- Shear force on the bolts mounting the wheel module to the chassis will deteriorate the structure, because movement will have the steel bolts slowly dig into the aluminium
- Wheel width dependent battery capacity

Concept 3

Properties In this concept, the aluminium tube chassis has been removed as well. The remaining chassis acts like a monocoque.

Illustration

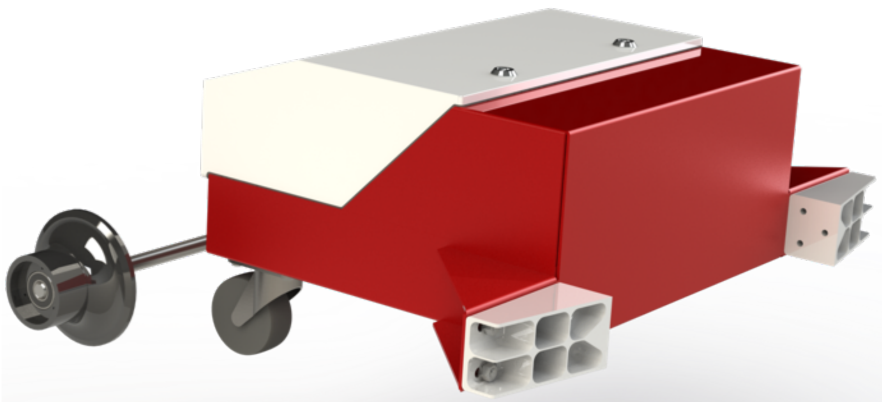


Figure 6-13 Concept 3. The brackets that connect the wheel module to the chassis is a standard component.

Strengths

- Low material cost
- Good electronics accessibility even when a tool is mounted
- Friction connection between wheel module and brackets as the bots pinch the two faces together
- The wheel module lays against the chassis when weight is applied

Weaknesses

- Limited space in chassis
- Requires more manual construction than the previous alternatives.

Concept 4

Properties All the standard Thorvald component has been removed to create this simplistic concept. Many new parts will be time consuming and expensive to develop. On the other hand, the motors, motor controllers and transmissions will become cheaper, as the current once are over dimensioned.

Illustration

Figure 6-14 Concept 4. This design has no standard modules.

Strengths

- Best economy of space
- Good mounting platform
- Large space in the chassis

Weaknesses
- Time consuming development
- Expensive to buy all new parts in low quantities

6.8 Selection of Chassis

Table 6-5 Screening of chassis designs.

Criterion	Imp	Concept 1	Concept 2	Concept 3	Concept 4
Battery capacity	**4**	1	0	0	2
Production Cost	**2**	0	1	3	2
Electronics access	**3**	3	0	2	1
Adjustable width	**4**	1	0	2	3
Watertight	**1**	2	0	1	0
Space use	**2**	0	1	2	3
Difficulty	**4**	3	1	2	0
TOTAL		**31**	**8**	**33**	**33**

The score is very close between concept 1, 2 and 3.

Concept 1 will be omitted due to its size, cost, economy of space and manoeuvrability issues. Moreover, the width adjustment is limited and do not have the same possibilities as concept 3 and 4. Concept 4 will not be feasible due to the time constraint and frame work of the thesis. No standard components lead to an expensive build that will not strengthen the Thorvald concept. Concept 3 is selected. Many points were lost on battery, but the space is sufficiently big to fit the required amount of batteries.

As the recommendations from the early prototype tests provided the foundation for the concept development the final concept is superior to Trikevald. Concept 3 is also easier to build within the time frame.

CHAPTER 7
STRUCTURAL ANALYSIS

In this chapter the chassis and wheel module will undergo a FEM-analysis in ANSYS. For the chassis, material thickness will be determined. Because of the unusual orientation of the propulsion foot, the stress and deformation will be evaluated.

7.1 Static Forces

The gross vehicle weight load is incidental set to 200kg. This presumed load will just lay the ground for calculations and then a better estimation. Acting forces will be showed in Figure 7-1 and the corresponding magnitude in Table 7-1. The reaction forces have been calculated and are showed in a shear and moment diagram in appendix D.

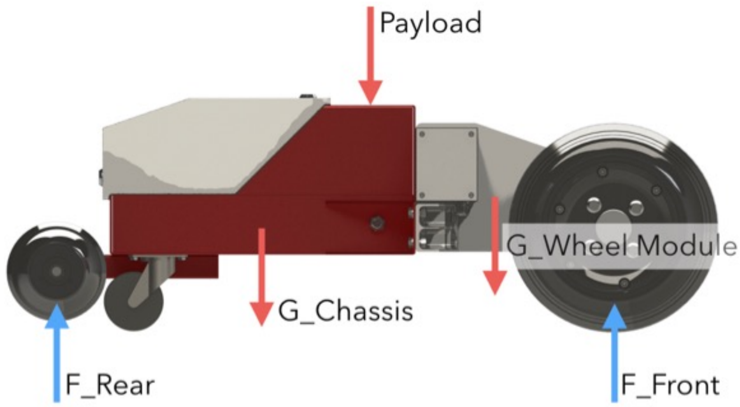


Figure 7-1 Static forces illustrated with location.

Table 7-1 Magnitude of static forces.

Force	Force type	Magnitude(N)
F_Rear	Normal	868
F_Front	Normal	1132
G_Chassis	Gravitational	500
G_Wheel Module	Gravitational	400
Payload	Gravitational	1100

7.2 Material Choice

There is less room for mistakes in the load bearing structure. Steel is easy to weld compared to aluminium and will be the main component of the chassis. Hot rolled steel plates from Stena Stål will be used [29]. Marius Austad has informed that standard components are machined from 6061-T6 aluminum. The lid will be aluminum as well, but the material data is irrelevant, as it carries no loads.

Table 7-2 Relevant material data.

Material	Type	Yield strength(MPa)	Tensile strength(MPa)	
Steel	S235J	235	360-510	[30]
Aluminum	6061-T6	276	310	[31]

7.3 FEM Optimization of Steel Chassis

To paint an approximate picture of how the forces, a workspace is set up in ANSYS. The wall thickness will be screened against a few criterions. When a thin walled structure such as this one is built, buckling is an important mechanism to look at. Only the thinnest plate will be tested for buckling, since the moment of resistance increases exponentially with wall thickness.

Table 7-3 Criterions of the chassis.

Criterion	Need/comment	Imp
Deformation	Little deformation counters eventual fatigue cracks	4
Stress	The SF needs to be at least 2	3
Weight	High weight is preferable for a stable structure.	2
Manufacturing	Convenience of production	4

As seen in Figure 7-2, A moment is added to the F_rear force. This is becaus it has been moved laterally, and any force moved in such a manner will generate a moment. That moment is the product of the distance moved and magnitude of the force.

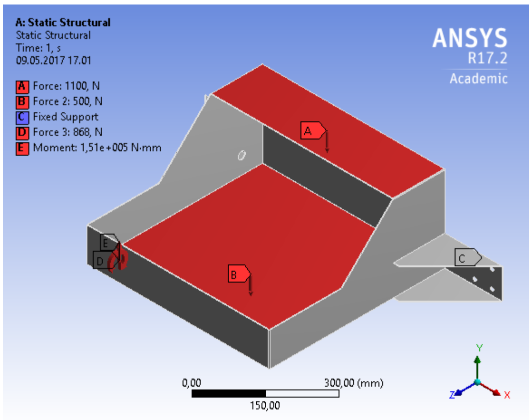
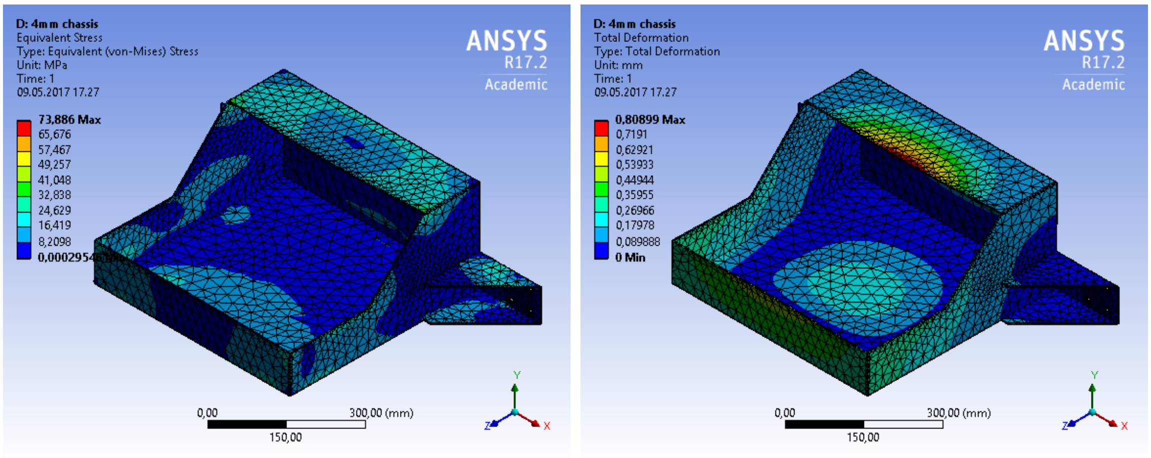


Figure 7-2 Ansys setup. Forces and moments are in red, and supports in purple. The program does not display all faces of action making the setup look unsymmetrical.

However, the symmetric results in the following section will reveal that everything was set up correctly.

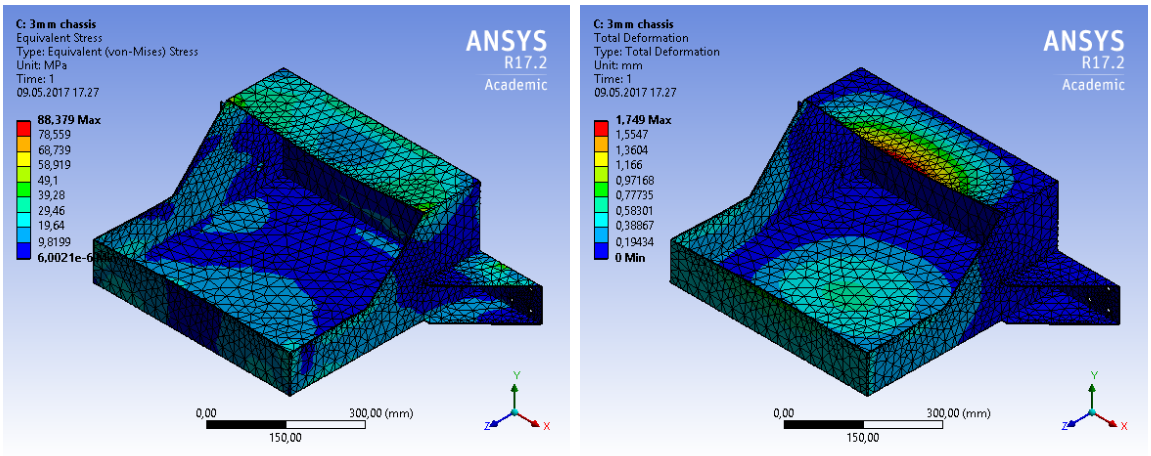
7.3.1 Analysis Results

The deformation amplification factor is the same for all three thicknesses(x10). Therefore, note that the relative deformation between the structures is significant. Also, stress will be higher than reality. When a face is given an attribute, sharp corners will lead to stress concentration factors in the simulation that will not occur in reality. Moreover, when welded and worked on, the edges will be rounded, and not sharp.



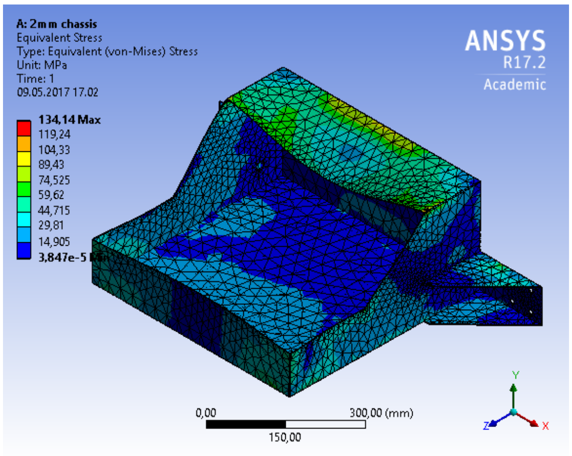
(a) Von Mises Stress in MPa *(b) Deformation in mm*

Figure 7-3 Stress and deformation of a 4mm thick chassis.

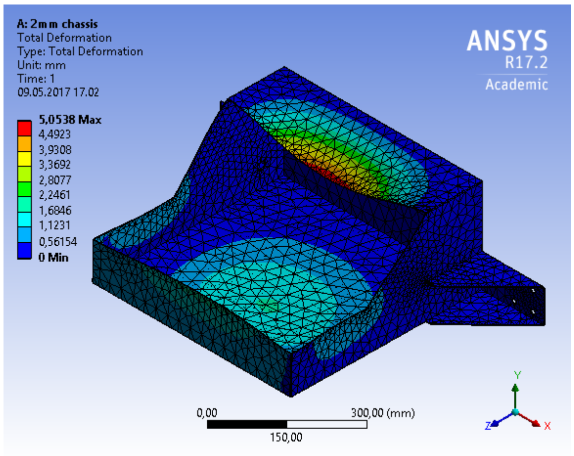


(b) Von Mises Stress in MPa *(c) Deformation in mm*

Figure 7-4 Stress and deformation of a 3mm thick chassis.



(c) Von Mises Stress in MPa



(d) Deformation in mm

Figure 7-5 Stress and deformation of a 2mm thick chassis.

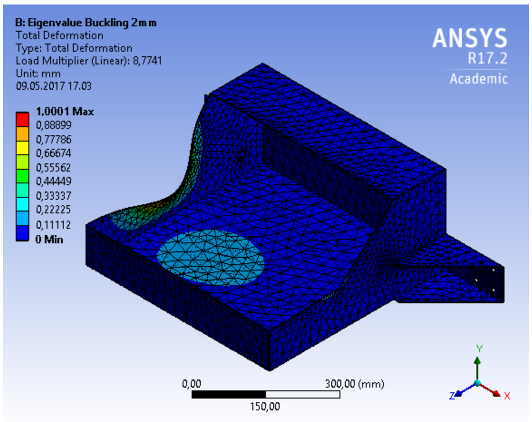


Figure 7-6 Buckling of the 2mm steel chassis will occur at a load multiplication of an 8.8 factor. Buckling is therefore neglected.

7.3.2 Selection of Thickness

Table 7-4 Screening of sheet metal thickness.

Criterion	Imp	4mm		3mm		2mm	
Deformation	4	*0.8mm*	2	*1.7mm*	1	*5.1mm*	0
Stress	3	*73.8MPa*	1	*88.3MPa*	1	*134.1MPa*	0
Weight	3	*24kg*	2	*18kg*	1	*12kg*	0
Manufacturing	4		0		2		1
TOTAL		17		18		4	

All thicknesses that has a lower stress than half of the yield stress stand as equals. Thinner plates produce cleaner cuts when CNC-plasma cutting and smaller bend radii. There are also alternative, more effective, ways to stiffen structures other than a thickness increase. For example, a rib to support the most deformed areas of the component. The 3mm sheet is selected.

7.4 FEM Analysis of Propulsion Foot

The static forces are inserted and the propulsion foot and set up like the chassis.

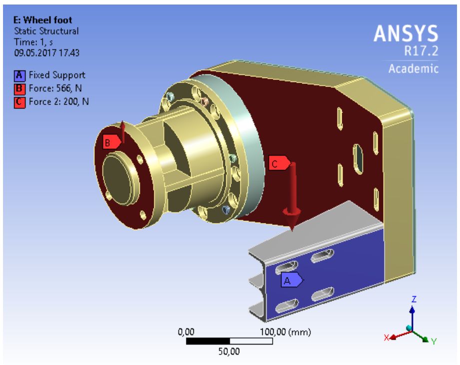
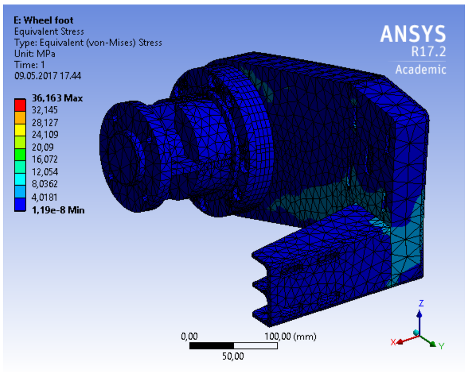
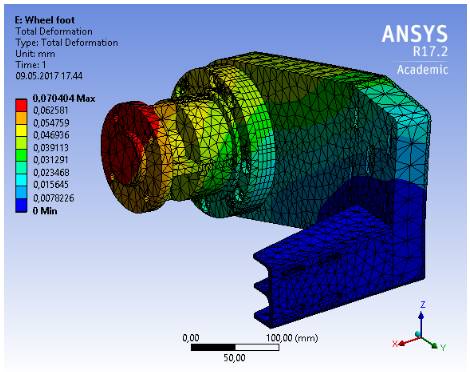


Figure 7-7 Setup of propulsion foot. Force 2 is the weight of the whole propulsion foot.



(d) Von Mises Stress in MPa



(e) Deformation in mm

Figure 7-8 Stress and deformation of propulsion foot.

Stresses that occur in the propulsion foot are relatively low compared to the material data. Also, due to the same flaw in the program the stresses are abnormally high. From Figure 7-8 these stresses do not occur in the supports, but in connection areas of the assembly. Deformation is negligible.

7.5 Surface Treatment

Carbon steel oxidize readily. Especially when exposed to the high temperatures of plasma cutting, water and fat from fingers. Assembling, priming and painting the surface as soon as possible after work has started is therefore essential to prevent rust. Using isopropanol to clean the surface prior to painting improves the results.

CHAPTER 8 COMPONENT SELECTION

This chapter will explain the calculations and selection of batteries, motors and motor controllers. All calculations are from appendix C.

8.1 Introduction

The robot will be moving down the lanes with a speed of roughly 0.03m/s for the UVB light to optimally expose the mildew. Dr. Suthaparan explains that this speed is highly uncertain and that UVB light radiation dosage has to be measured in order to calculate a precise speed. When changing lanes, the speed will increase to approximately 0.1m/s. The speed will be low in the autonomous testing stages. When the programming is complete the speeds will be increased to somewhere between 0.2 and 0.3m/s. Eight lanes of 70 metres are traversed before the unit goes back to the charge area. There should be enough batteries to provide the required amount of energy.

8.2 Resistance and Reaction forces

From the static forces in section 7.1 rolling resistances are calculated. Acting forces will be showed in Figure 8-1 and corresponding magnitude in Table 8-1. Friction forces if the rear wheels were to lock will also be shown.

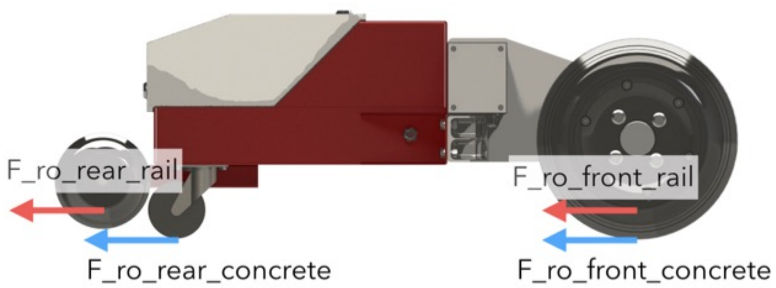


Figure 8-1 Rolling resistance of the robot. The red forces are on the rail, and blue forces on concrete.

Table 8-1 Magnitude of rolling resistance. Locked wheel friction force is highlighted in blue.

Force	Force type	Magnitude (N)
F_ro_front_rail	Rolling resistance	64.5
F_ro_rear_rail	Rolling resistance	49.5
F_ro_front_concrete	Rolling resistance	9.1
F_ro_rear_concrete	Rolling resistance	6,9
F_f_rear_rail	Friction	217
F_f_rear_concrete	Friction	521

8.3 Energy requirement

From the datasheet of the batteries the Thorvald project currently use, each battery has a capacity of 1.67Mj [32]. Therefore, six old or two new batteries will be needed to provide the necessary energy of 9.02Mj. Calculations shows that over 99% of energy is used by the lambs.

8.4 Motors

Thorvald has two different motors from 3Men. BL830 for steering and BL840 for propulsion[33]. Calculating the power required by each motor will help choosing one.

Table 8-2 Comparison of 3Men BL840 and BL830.

Model no.	Speed (rpm)	Power (watt)	Torque (Nm)	Torque Peak	Current (ampere)	Current Peak	Voltage. (Volt)
BL830	3000	350	1.10	2.16	16.0	32.0	48[1]
BL840	3000	500	1.57	3.13	12.8	25.6	48

If the robot was to climb the edge from still, it would require 1.24Nm of torque. However, the robot will always be moving when climbing the edge. Moreover, 2.48Nm would occur if the robot would pivot with locked caster wheels on the concrete. The friction number is as mentioned in section 4.2.2 too high. BL830 is suficcient, but BL840 is selected so that the wheel module can be put on a Torvald if required.

[1] This motor is originally a 24 Volt motor, but it was ordered with custom windings to operate on a 48 Volt power grid.

CHAPTER 9
ASSEMBLY AND PRODUCTION OF THE SELECTED DESIGN

This chapter will explain the assembly, production and possibilities of the selected design.

9.1 Assembly of Johannes

The selected design consists three main units, chassis, modified propulsion foot and rail wheel. In addition, the caster wheels are added to complete a functioning robot. All units are assembled through the use of bolts and nuts as seen in Figure 9-1. On the red top plate of the chassis mounting of tools is possible.

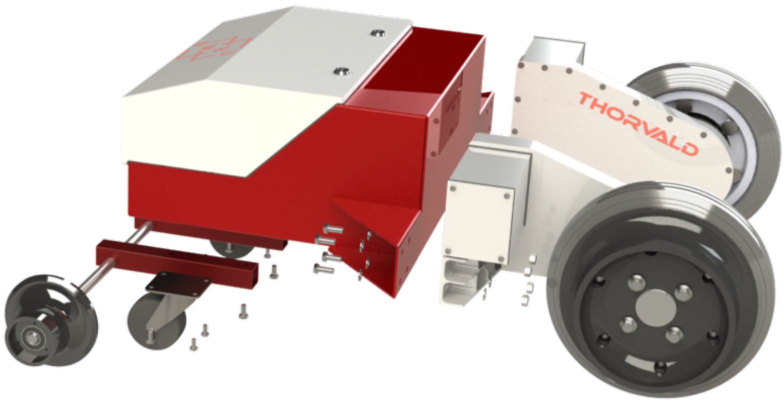


Figure 9-1 Exploded view of the main units, castor and rail wheels.

9.1.1 Chassis

The chassis contains all of electronic equipment and is simultaneously the supporting structure. The front face on the right in Figure 9-2, is where the wheel module is added as shown in Figure 9-1. Since it is flat, an opportunity to adjust the width of the wheels is presented.

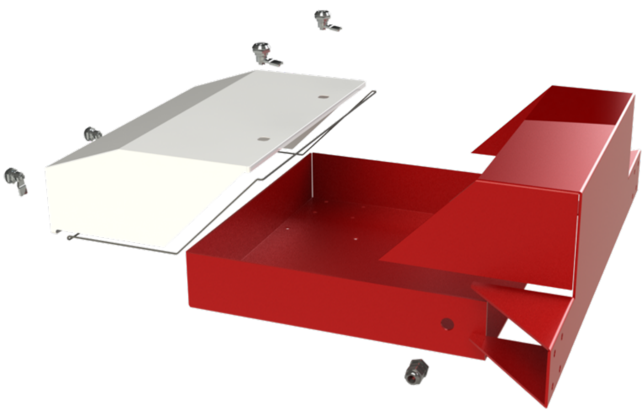


Figure 9-2 Exploded view of the chassis.

9.1.2 Rail Wheel

The rail wheel is designed in such a way that it is possible to have the rail wheels both on the outside and inside of the bracket. When the wheel adjustment is too narrow, the caster wheels will collide with the rail and has to be moved. This solution gives the user freedom of width adjustment in the rear as well. As seen in Figure 9-3, square profiles are used t connect the rod to the chassis. The rod is fastened by set screws.

(a) The set screws seen as tiny black dots underneath the profiles.

(b) Rail wheel from the gardener.

Figure 9-3 Rail wheel assembly.

9.1.3 Modified Propulsion Foot

On the left of Figure 9-4 is the standard propulsion foot module. On the right of the same picture is the custom wheel.

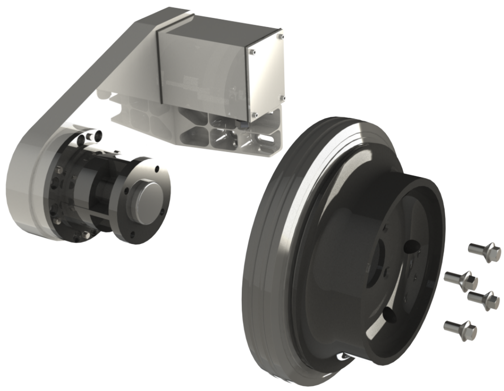


Figure 9-4 Exploded view of propulsion foot.

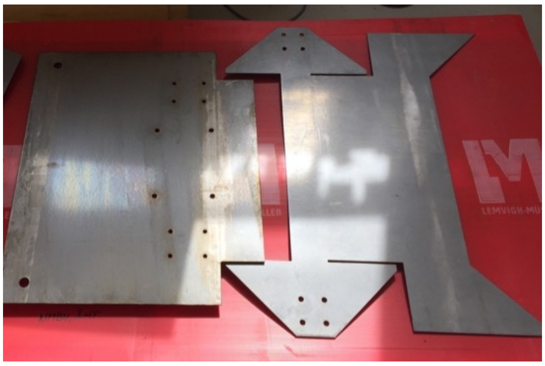
9.2 Production

When evaluating production method, accessibility, feasibility and cost was important factors. Using easily accessible materials and manual production methods that lets the robot be built within time. Ås high school has a CNC plasma cutter available for the throvald project to use. The NMBU workshop has professionals to help build. Utilizing the available resources is subsequently sensible.

9.2.1 Chassis and Lid

Plates will be cut in the plasma cutter and bent at NMBU, welding will then be used as a joining method. A sheet thickness of 3mm is not too thick to bend and not too thin to weld.

(a) Pål Holm making sure everything works out.



(b) Steel chassis parts ready for bend and weld.

Figure 9-5 Pål Holm from Ås vgs. is assisting with the plasma cutter.

9.2.2 Custom Rim

Wheel catalogues from various wheel manufacturers where scoured through in search of a fitting wheel. Blickle is a wheel manufacturer that has all kinds of different wheels for industrial applications. A solid rubber tyre from the assortiment was found. The advantage of a tyre without air, is that it can have a larger inner radius and a long life span. On the other hand, it is heavy, but this is an advantage in this case.

The greenhouse rail wheel part of the rim is designed similarly as the rail wheels provided by the gardener. To select the right plastic, VINK AS, a plastic manufacturer, recieved the drawings and plans with requirements. They advised the use of POM-C for this purpose. STRYVO AS is in charge of machining the part using a 5-aksis CNC-lathe.

(a) Tyre and steel rim mounted on the back of the custom rim.

(b) Blickle V350/25-80R wheels used. The tyre and one steel rim will be used.

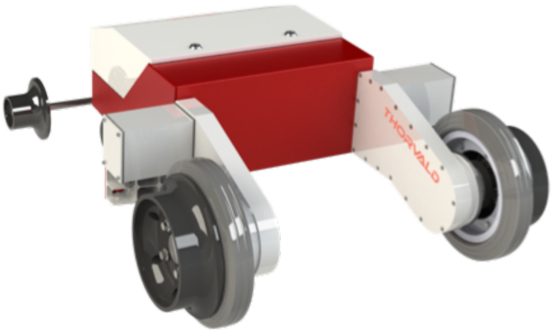
(c) A better view of the custom rim.

(d) Custom rim mounted on the transmission.

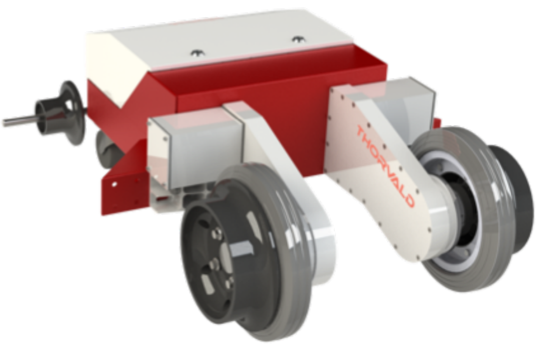
Figure 9-6 fastened wheel on rim and the weel used.

9.3 Possibilities

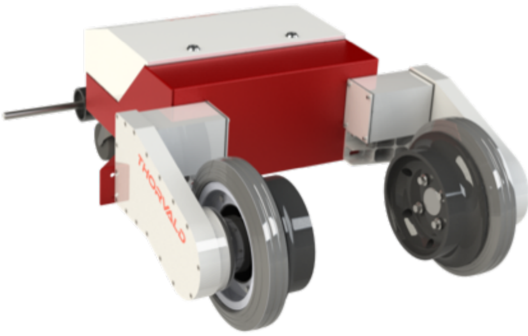
An important aspect when designing this robot was wheel width adjustment. This feature lets the robot be of use on all rail systems. With the mount space on top this robot is with the right setup ultimately capable of any process.



(a) 80cm configuration



(b) 50cm configuration



(c) 40cm configuration with inverted wheel modules

Figure 9-7 Width adjustment possibilities.

CHAPTER 10
DISCUSSION

This chapter will discuss the development process, final design and prospects.

10.1 Review of Development Process

Since this thesis builds on previous work on the Thorvald project; a lot of time was spent investigating and getting to know the core of the project. Studying the earlier Thorvald related theses lead to an understanding of how the design evolved over the years. Since this is the fourth year of Thorvald there are many mistakes to learn from.

The initial objective was to both design the prototype and then program the steering. A lot of time was spent learning robot operating system(ROS). After the Nursery visit, it became clear that a four wheeled robot had to be created from scratch. This task proved to be much harder and time consuming than anticipated as there were interfering requirements from the gardener and the Thorvald project. In the end there was no time left to program. It was a miscalculation to spend so much time on Trikevald prior to the nursery visit.

A greenhouse operating robot, called Johannes, has been designed and added to the Thorvald family. The prototype is a result of decisions aiming for the ultimate solutions within the framework of this thesis. Computer aided design and technical drawings are created and early sent to manufacturers to start the building process quickly. Unfortunately, the robot was not built within the deadline of this thesis. All components except the standard modules have been received and are ready for processing and assembly.

10.2 Review of Progress

The recommendations from the early prototype evaluation were followed. Main components are dimensioned to fit the metric requirements and specifications. Modularity has been preserved by the use of a monocoque where tools and wheels can be mounted. Furthermore, the standard propulsion wheel is included in the design. Most importantly, with the use of a specially designed wheel, propelling can occur on both concrete and the greenhouse rail system. The new design is also superior to the original prototype in terms of production cost because plate processing is a low cost manufacturing method. There is, nevertheless, room for improvement on this design as well. How well this design performs in reality remains to be seen when the prototype is built. Teething troubles are expected, but the Thorvald team has experience building robots and any teething trouble should be handled swiftly.

The tool mount is small, and tools for Thorvald have been adapted to be clamped on the alumium tubes. This disadvantage leaves three choices; either make a more fitting tool rack, or redesign the tools to fit more platforms or make special tools for this configuration. Currently the last alternative is under development, as the cucumber light rack is different than the strawberry light rack.

The components of the wheel module are over dimensioned and unnecessarily expensive for this robot. This is, however, not important, because the standard modules of the Thorvald-series are expected to become much cheaper onward as a consequence of production improvements and volume increases. Moreover, the wheel modules can be removed and put on a field qualified Thorvald; where the only modification would be a change of wheel sets.

The finite element method simulations reveal that the payload could probably be increased by at least 50%. However, welds lead to fatigue failure. Therefore, the magnitude of shocks loads and corresponding cycles has to be recorded and analysed prior to calculations of a new payload with respect to fatigue.

When it comes to a sugar cane bot, this design fits the metric requirements of 70 cm in width with minor adjustments. Differential steering is not advised, as heavy rain and mud will cause the robot to drag the caster wheels. But, as mentioned the team of Brazilian postgraduates are developing a prototype that they have already started building.

10.3 Market potential

With an adjustable width, the robot can be used on all greenhouse rail systems available. The Netherlands use a 42.5cm width[12]. If UV-Bær and UV-Bio yield favourable results and the technology is commercialized, capitalism will ensure that the conventional horticulture operation will change. Because, less destruction of crops, less use of pesticides and a simpler operation will increase horticulture sustainability and yield more revenue.

Priva has already commercialized an autonomous horticultural robot with plans to expand the number of automated solutions. The Johannes prototype is a moving platform with the potential to mount any tool. The demand for horticultural robots is rising, and the Thorvald project now has potential foothold on this platform as well.

CHAPTER 11 CONCLUSION

This chapter will discuss to what degree the objectives were completed and how well the final design of the prototype compares to the design specifications.

11.1 Objective and Resulting Design Evaluation

A completion date was not specified in the goal of the thesis, but the deadline given by the UB-Bio project is on the 1. July. Therefore, the main objective will at this rate successfully be completed.

This development has resulted in the design of an autonomous greenhouse robot prototype with the following attributes:

- Use of standard Thorvald components result in competitive pricing on a potentially mass produced unit.
- The ability to use run on both greenhouse rails and concrete as well as adjusting the width of the wheels gives this prototype the possibility to be used regardless of the greenhouse configuration.
- The prototype is not optimal for use on sugar-cane farms.
- In addition to meet the gardeners demand, there is a real market potential in horticultural robots.

11.2 Further work

As mentioned, there is still a lot of work left to be done. Components are still to arrive and be assembled. With regard to future development of a commercial product:

- Production methods should be reviewed and improved.
- The potential of chassis concept 4 in Figure 6-14, should be assessed.
- Material choices reviewed and shapes optimized. Topography optimization is an interesting method to optimize shapes.
- Improve the mount plate as it is currently small.
- Calculate the correct payload with a safety factor of 2.
- The use of this prototype in strawberry tunnels should be assessed.

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APPENDICES

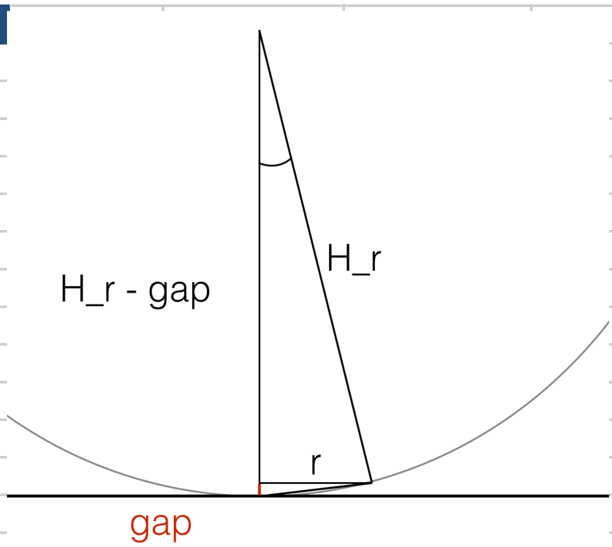
A. LIST OF TABLES

B. LIST OF FIGURES

All figures that are not named, are taken or created by the author of this thesis.

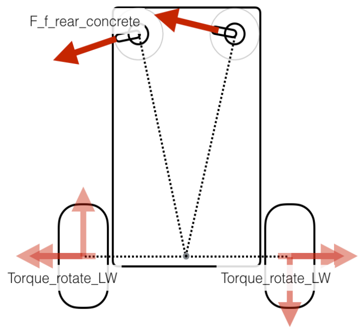
C. WORKSHEET

Constants	Magnitude	Unit	
Row length	70,00	m	
Number of rows	8,00	-	
Concrete length	50,00	m	
Speed 1	0,03	m/s	
Speed 2	0,10	m/s	
Power per light	120,00	W	
Number of lights	4,00	-	
C_rr1	0,01	-	
C_d	0,06	-	
C_fric_pom_steel	0,25		
C_fric_rub_concrete	0,60		
Lighted path length	560,00	m	
incline	1,00	%	
Transmission	41,00	-	
Rotational speed	2,39	s^-1	
Calculated constants	**Magnitude**	**Unit**	**Function**
Time on rails	18666,67	s	l*v
N_front	1132,00	N	m*g
N_rear	868,00	N	m*g
F_ro_front_rail	64,52	N	(3.3)
F_ro_rear_rail	49,48	N	(3.3)
F_ro_front_concrete	9,06	N	(3.3)
F_ro_rear_concrete	6,94	N	(3.3)
F_f_rear_rail	217,00	N	(3.6)
F_f_rear_concrete	520,80	N	(3.6)
F_st	20,00	N	(3.5)
Significant Values	**Magnitude**	**Unit**	**Function**
F_tot_energy	114,00	N	Fr_ro_rail
F_tot_work	301,52	N	F_f+st
Energy requirement			
Energy lamps	8,96	Mj	Light*Time
Energy movement	0,06	Mj	(3.1)
Energy	9,02	Mj	(3.1)
Locked rear wheels			
P_lock_rail+F_st	9,05	W	(3.1)
P_lock_concrete+F_st	52,99	W	(3.1)
The torques on motors after transmission			
Torque_climb_motor	1,24	Nm	(3.7)
Torque_rotate_LW	2,48	Nm	(3.7)

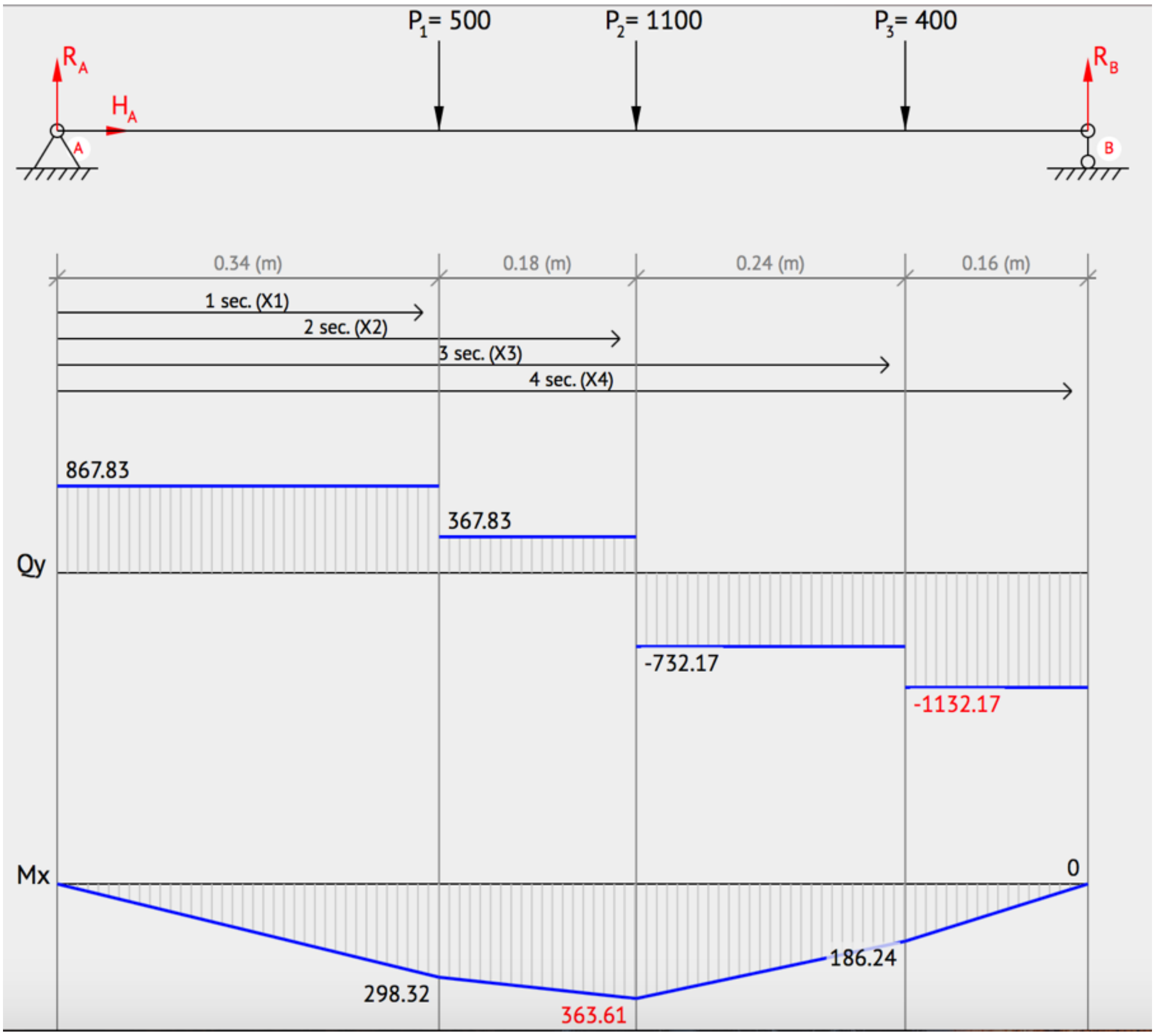


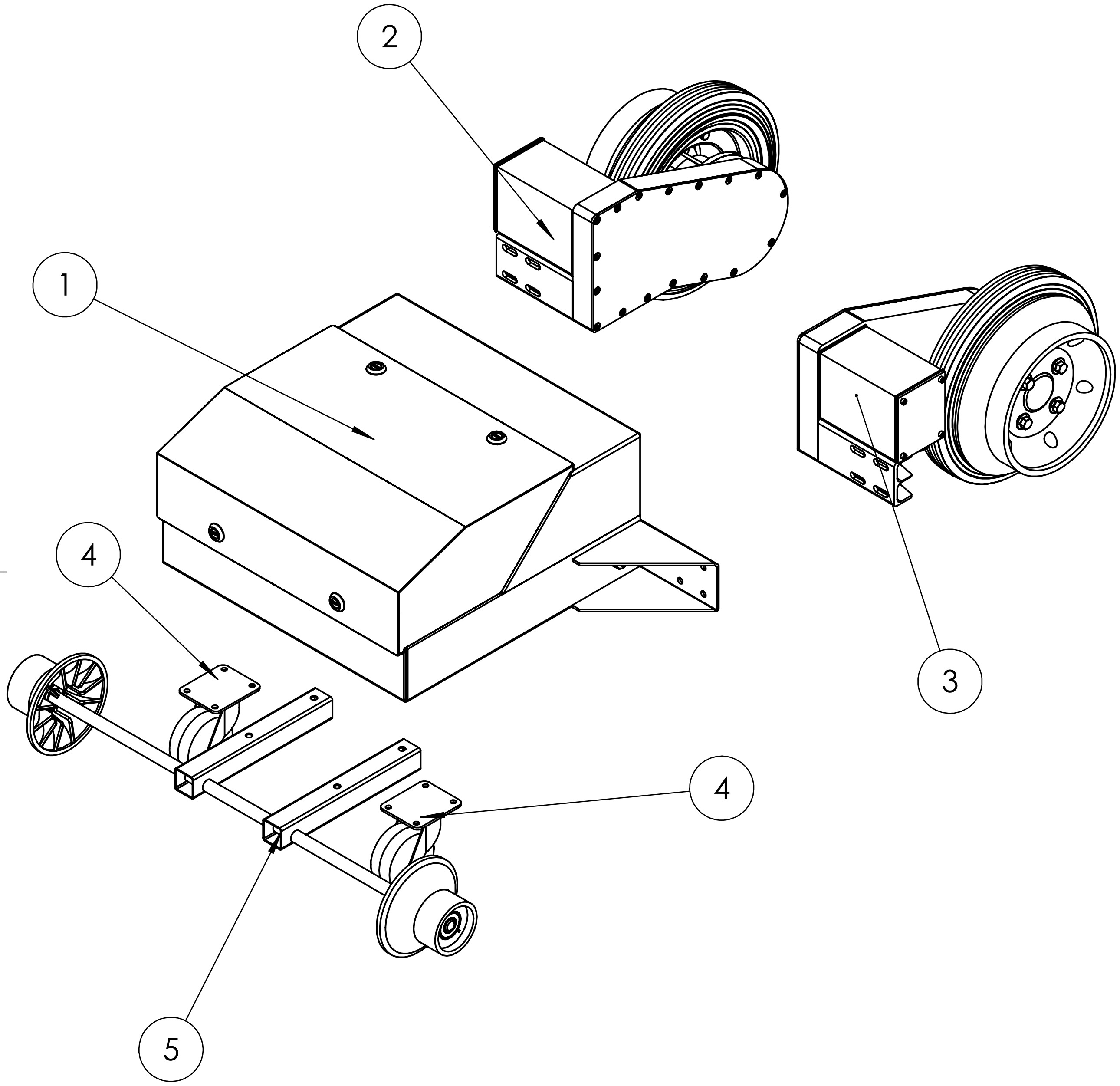
Hr	175,00	mm
gap	5,00	mm
r	41,53	mm
Torque_climb	47,02	Nm

Torque required to turn with locked rear wheels



D. SHEAR AND MOMENT DIAGRAM





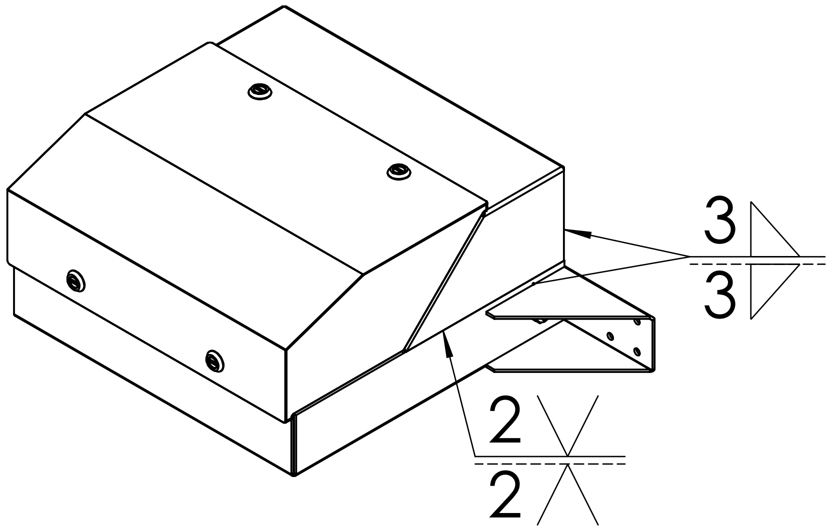
ITEM NO.	PART NUMBER	QTY.
1	Chassis & Lid	1
2	Propulsion Unit	1
3	Mirror Propulsion Unit	1
4	Jula art: 322051	2
5	Rail Wheel Assembly	1

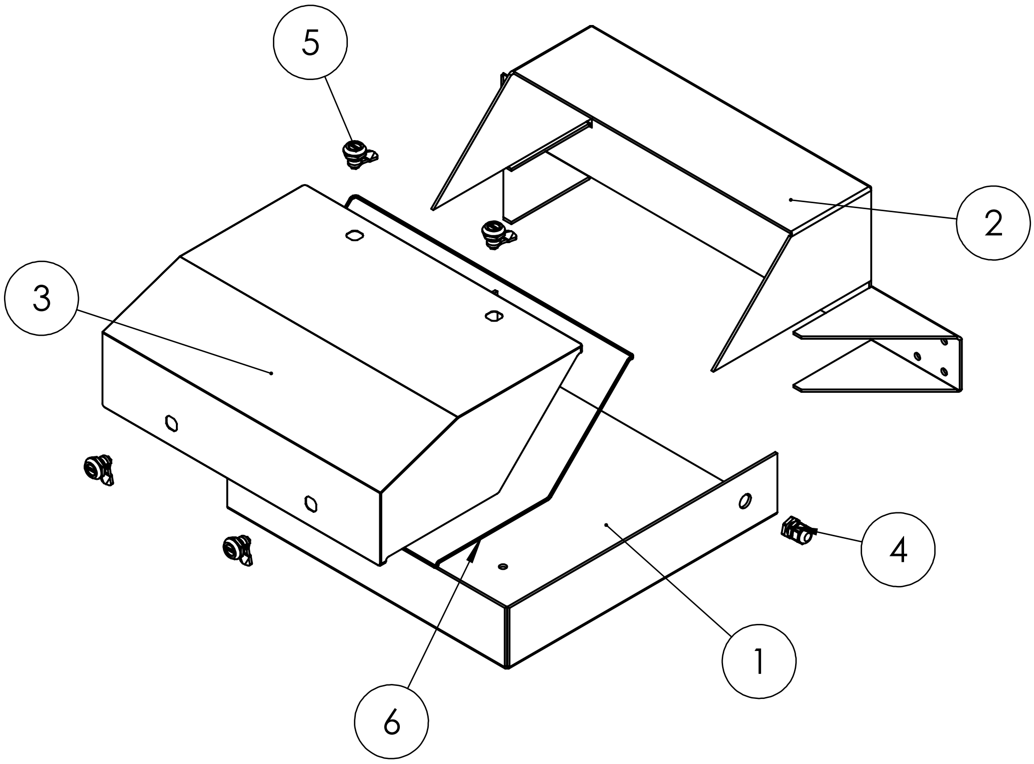
Title:
Cucumber robot V3

A4

SCALE:1:20

SHEET 1 OF 1





ITEM NO.	PART NUMBER	QTY.
1	Steel Base pt.1	1
2	Steel Base pt.2	1
3	Aluminum Lid	1
4	Twist Lock	2
5	Alu836712V5	4
6	Rubber Packing	1

Title:

Chassis & Lid

A4

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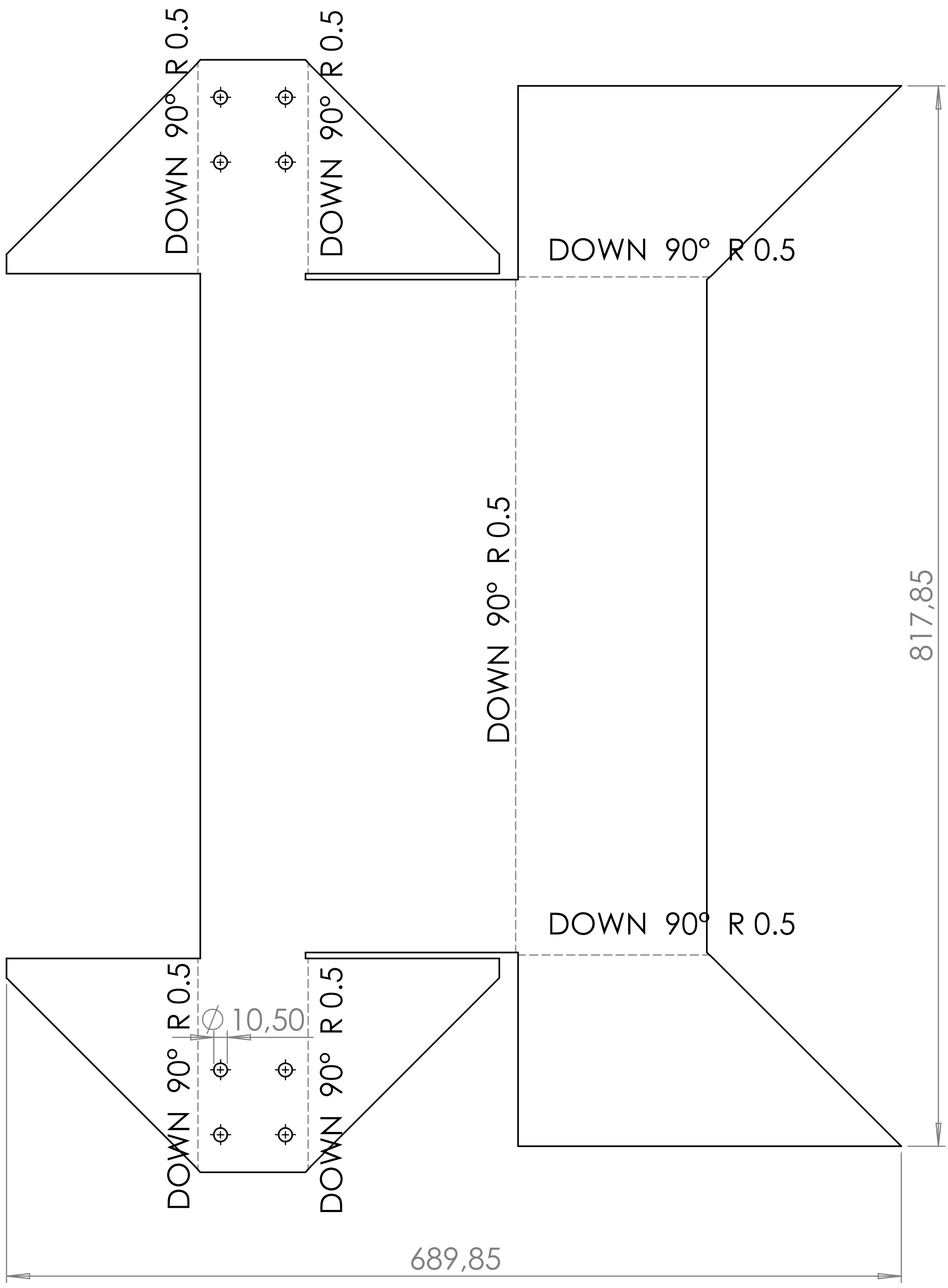
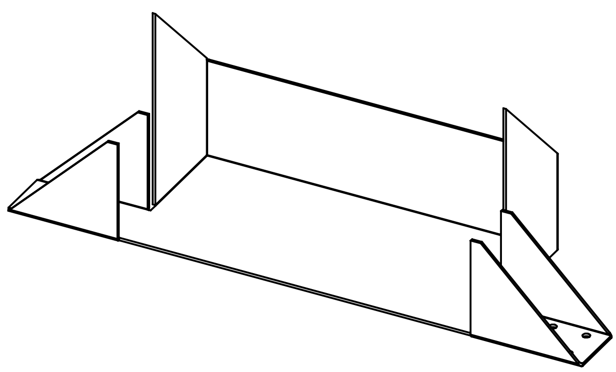
SHEET 1 OF 1



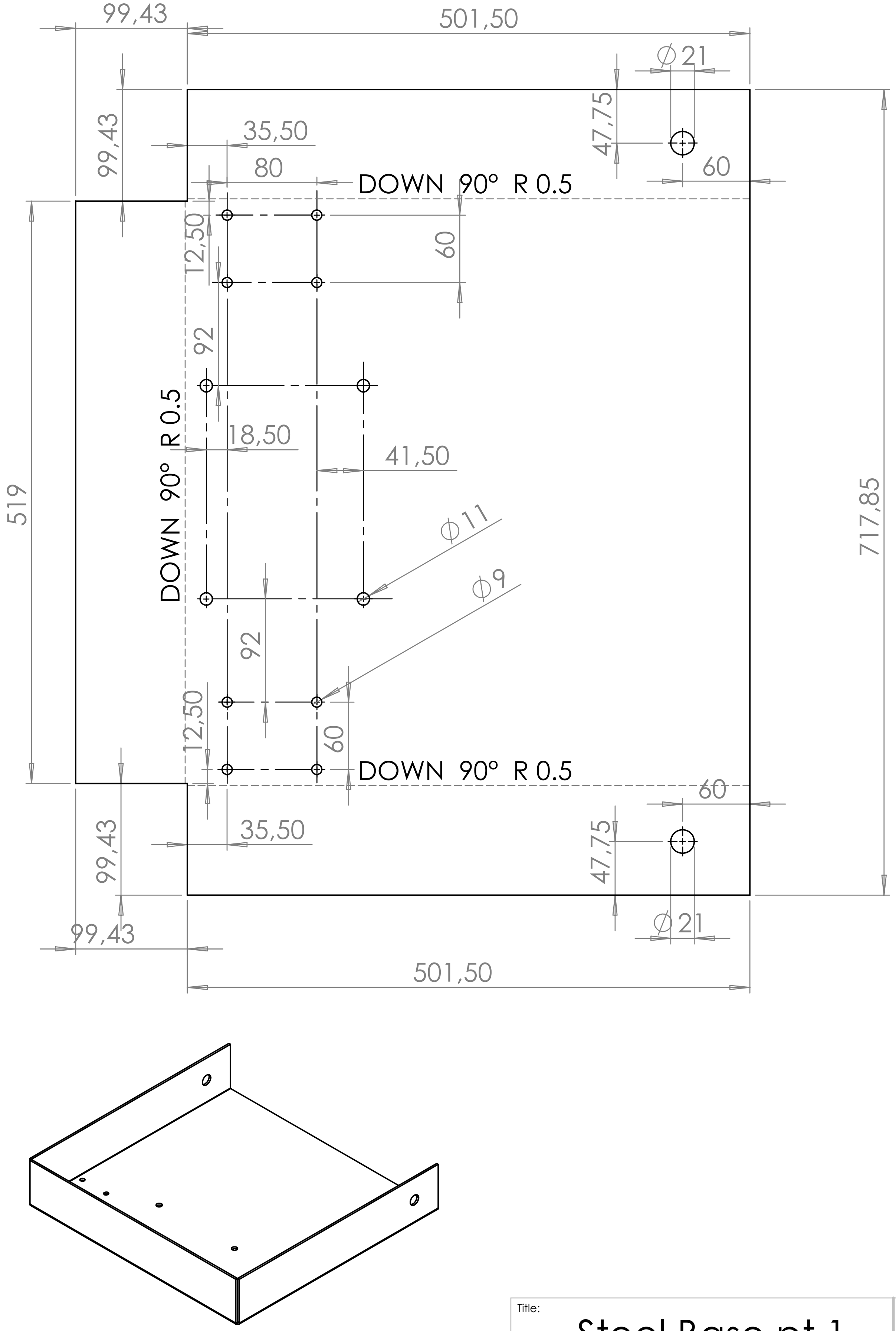


Title:
Steel Base pt.2

A4

SCALE:1:10

SHEET 1 OF 1



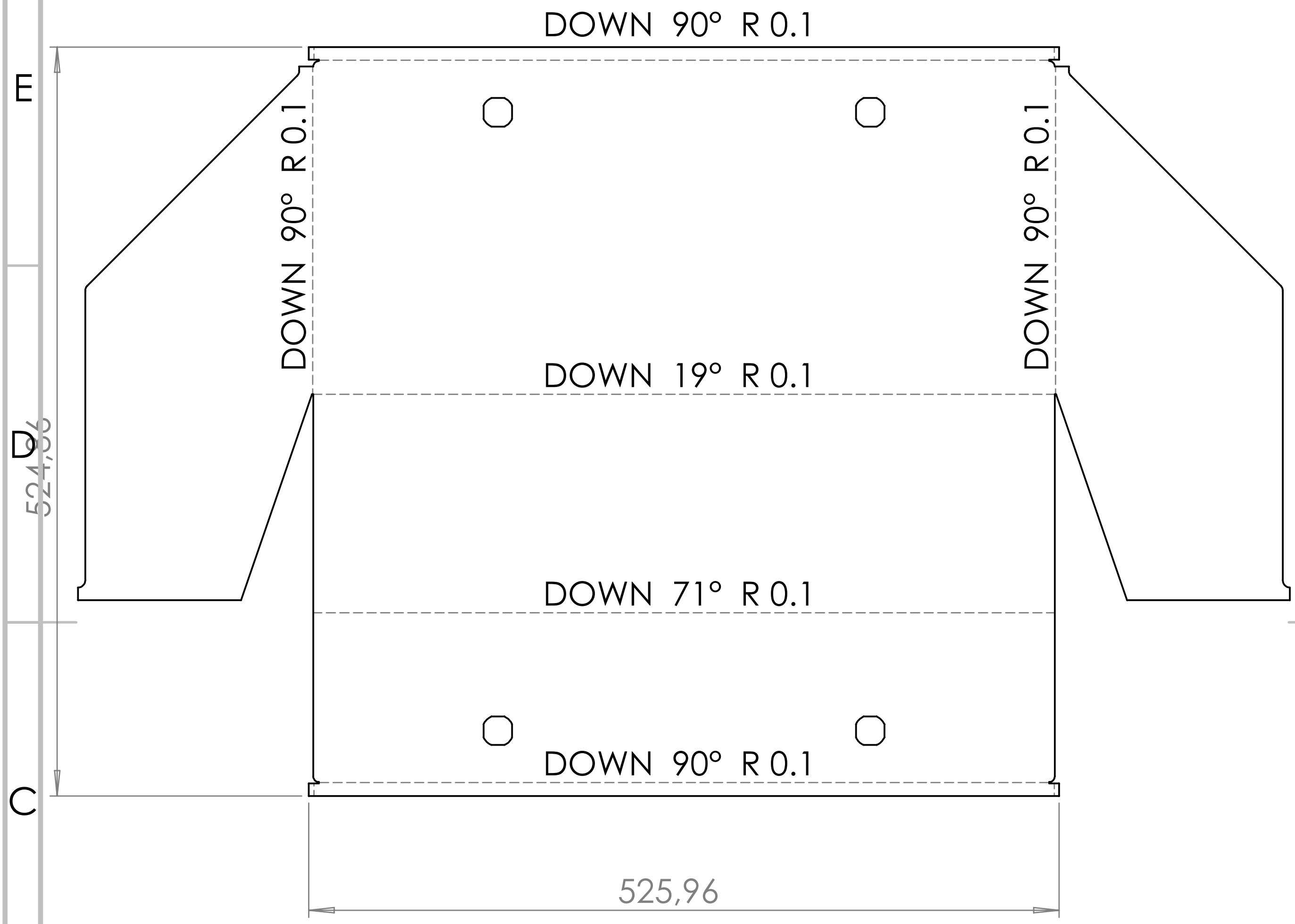
Title:

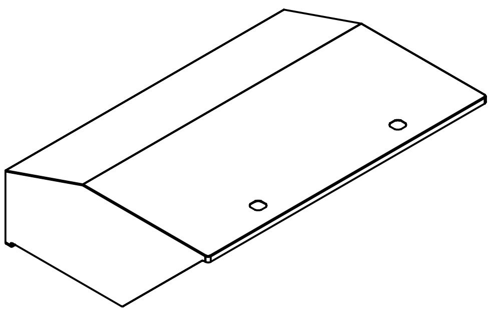
Steel Base pt.1

A4

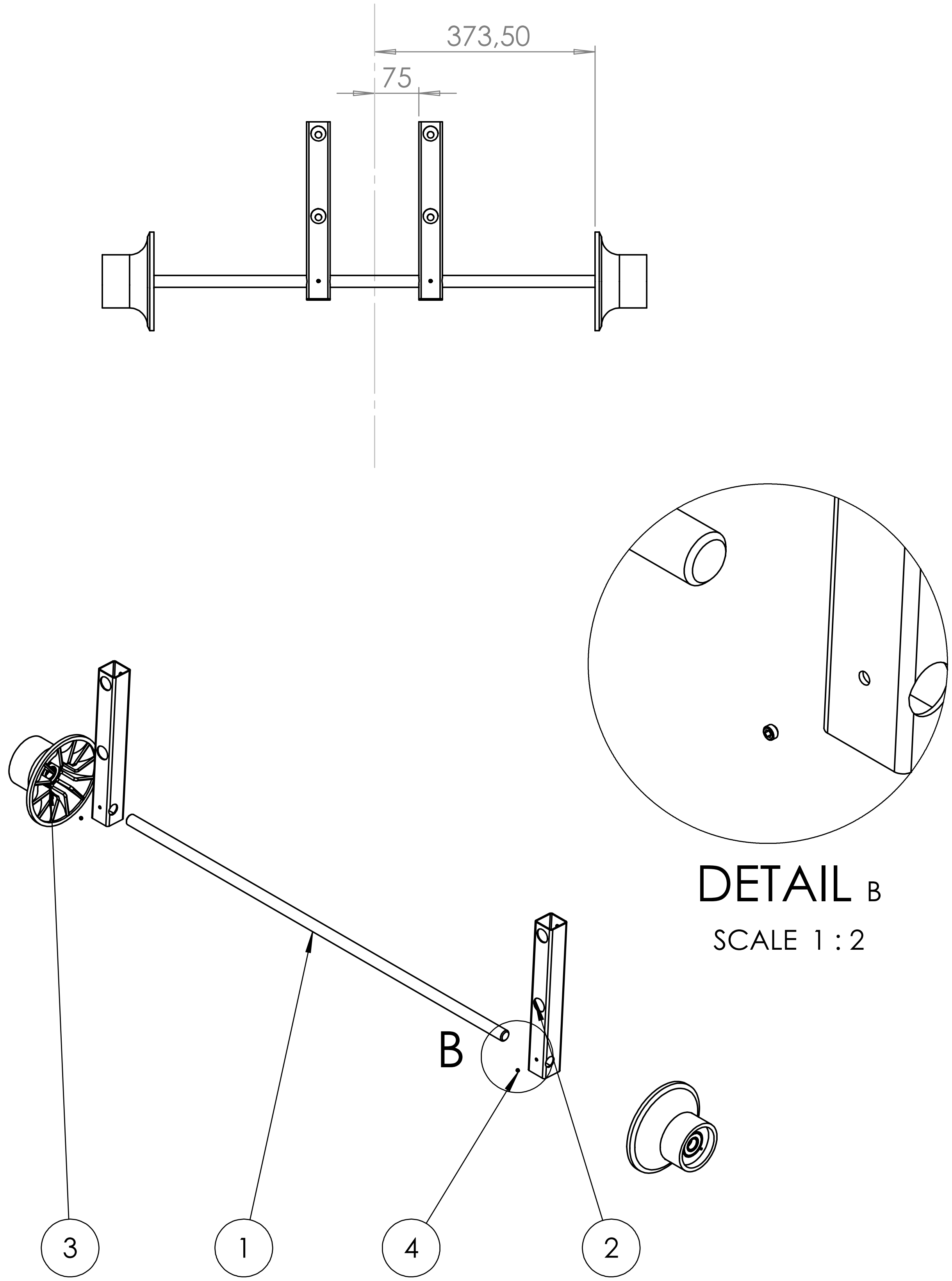
SCALE:1:10

SHEET 1 OF 1





Title	A4
Aluminum lid	
SCALE:1:10	SHEET 1 OF 1



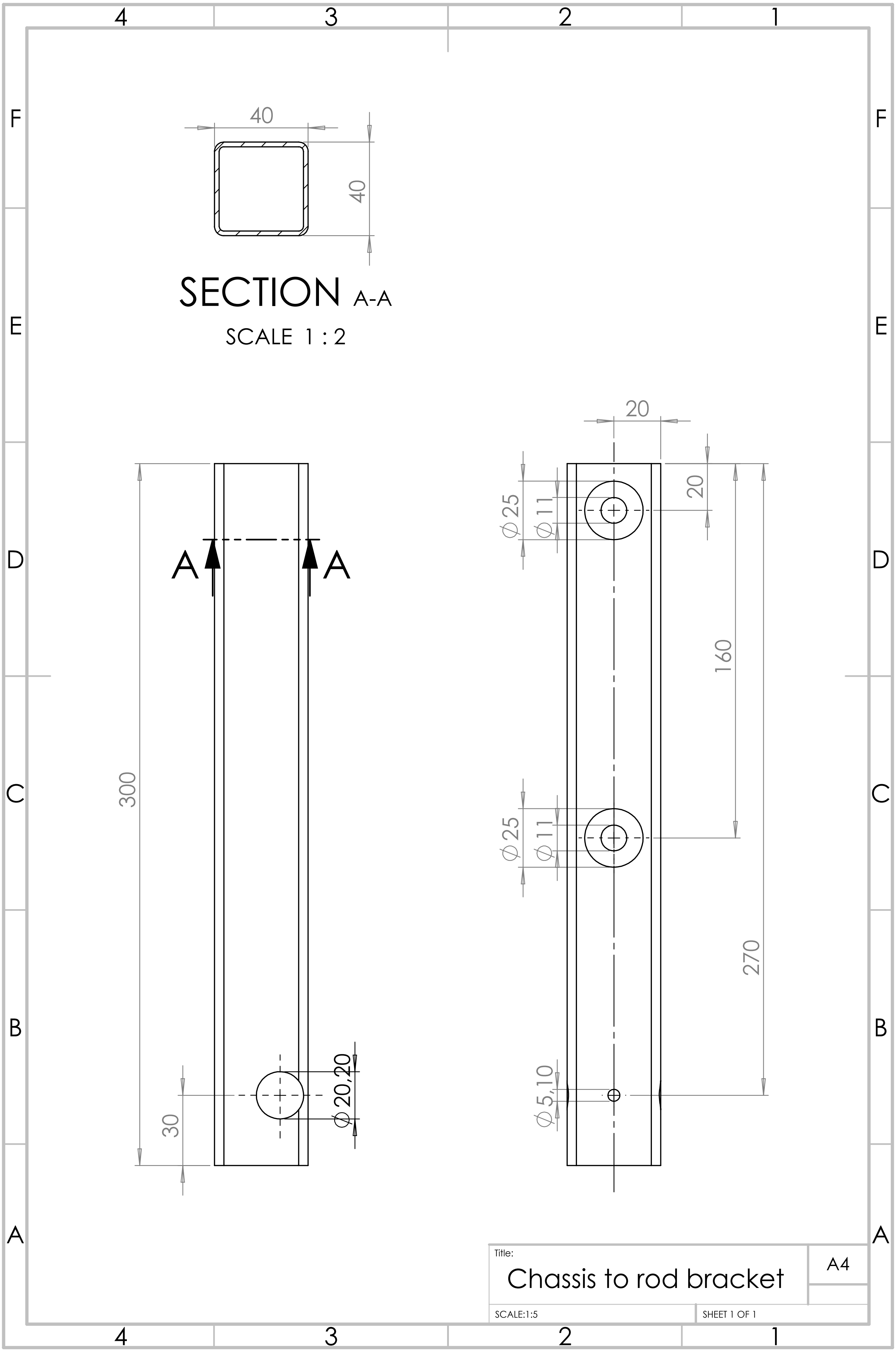
ITEM NO.	PART NUMBER	QTY.
1	Rod, Ø20mm, L95cm	1
2	Chassis to Rod Bracket	2
3	Rail Wheel	2
4	ISO 4026 - M5 x 3-N	2

Title:
Rail Wheel Assembly

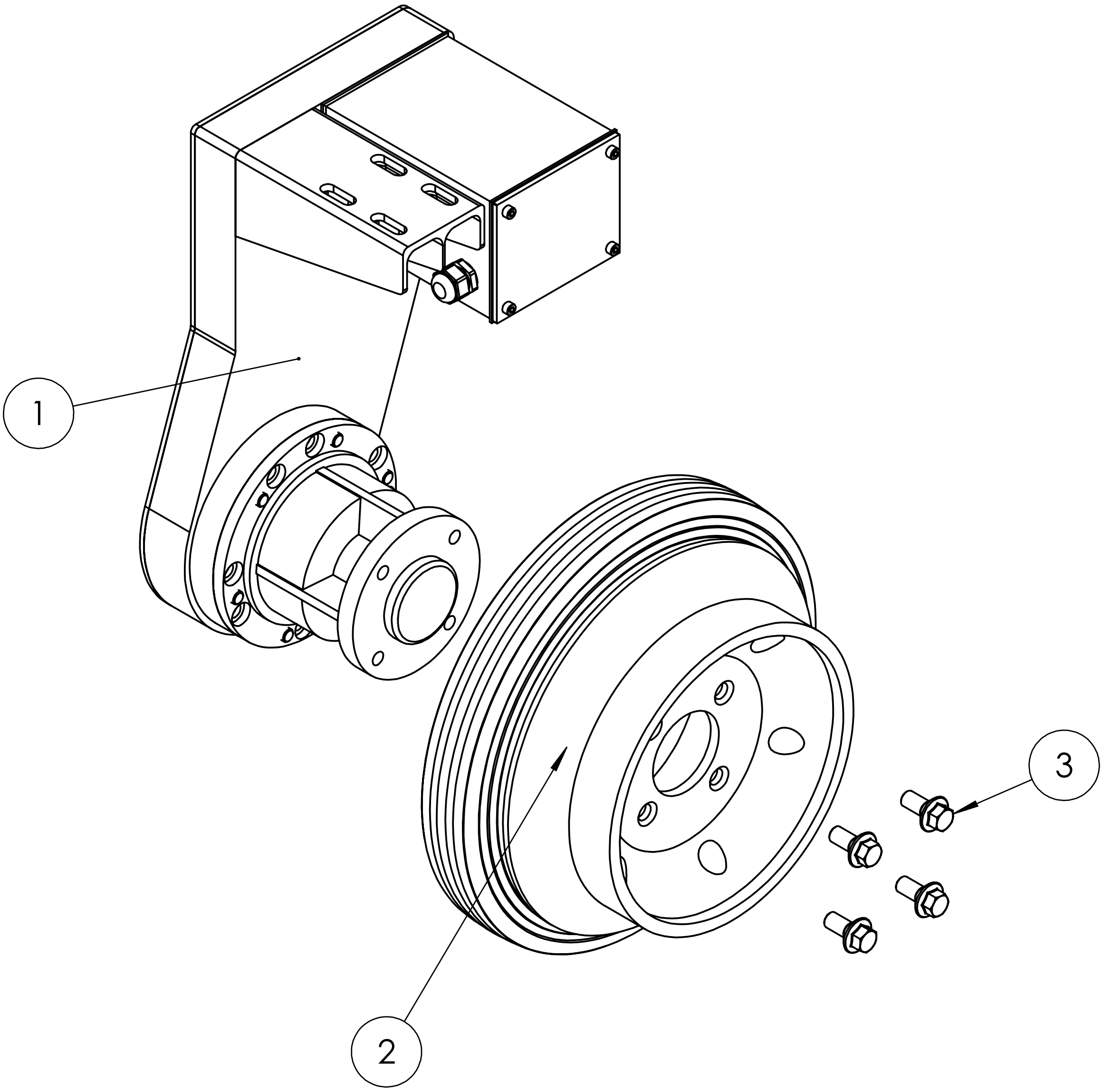
A4

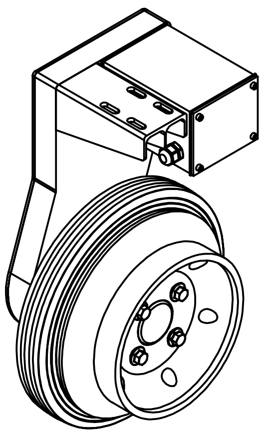
SCALE:1:10

SHEET 1 OF 1



40
40
SECTION A-A
SCALE 1 : 2
20
20
Ø25
Ø11
160
300
A
A
Ø25
Ø11
270
Ø 20,20
30
Ø5,10
Title:
Chassis to rod bracket
A4
SCALE:1:5
SHEET 1 OF 1





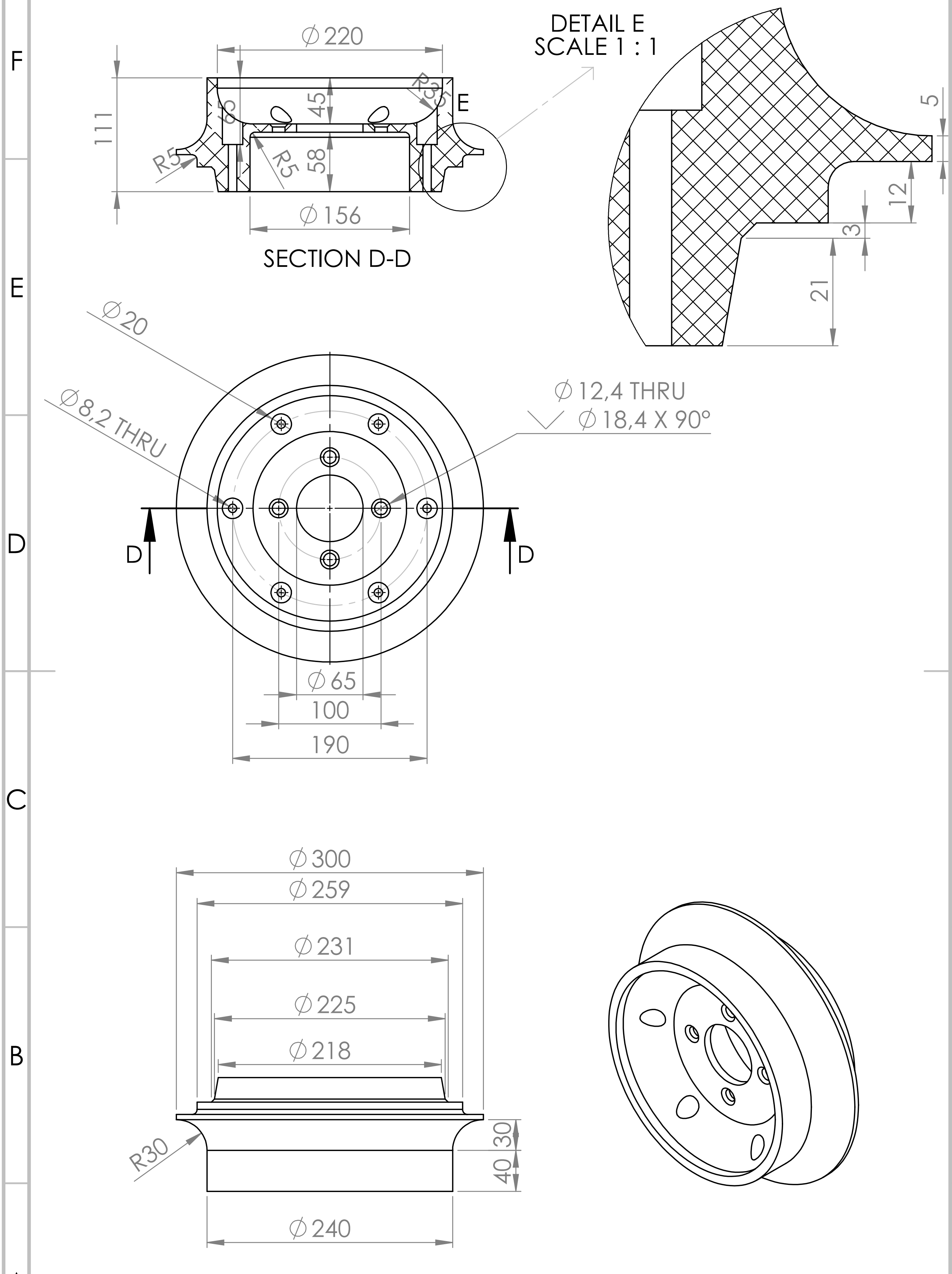
ITEM NO.	PART NUMBER	QTY.
1	Mirror Propulsion Foot	1
2	Complete Propulsion Rail Wheel	1
3	M12	4

Title:
Mirror Propulsion Unit

A4

SCALE:1:20

SHEET 1 OF 1



Title

New Rail Propulsion Wheel

A4

SCALE:1:5

SHEET 1 OF 1

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