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Developing a Novel Electromotor Concept

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Abstract

The scope of this master thesis is the product development of the production technology at Alva Industries AS during the spring of 2017. The master thesis is a continuation of the previous project thesis and is done at The Department of Mechanical and Industrial Engineering at the Norwegian University of Science and Technology. The work is part of the research and prototype laboratory TrollLABS, run by Professor Martin Steinert.

The startup company Alva has invented a novel production process for producing stators for electrical motors. Using a specially designed weaving loom, a three-phase pattern of conductive copper is woven and later cast in an epoxy resin. Compared to conventional production, this can provide tailored stator dimensions and a more light-weight design. The scope of this thesis is to evaluate the first prototype of the production process and further develop concepts for multiple shuttle controlling. For the development work, a wayfaring model and a rapid prototyping approach were used. As a contribution to the studies of the fuzzy front end of product development at TrollLABS, this methodology in context of Alva's work is discussed.

The resulting concept of garage sorting and reel handling is as far as the author is concerned an innovative solution within the field of weaving. The garage sorting needs further detailing before implementation. A detailed documentation of both the work that has been done and the methodology used during the time of the project is presented in this thesis. A positive employment certificate was received for the contribution of the project and master thesis.

Alva Industries AS has been granted funding from The Norwegian Research Council through the STUD-ent programme and will start the process of patenting the production technology. The collaboration with TrollLABS continues with another project thesis the coming fall. A proposition for further work is provided to help with Alva's continuing development.

Sammendrag

Denne masteroppgaven tar for seg utviklingen av produksjonsprosessen i Alva Industries AS i løpet av våren 2017. Oppgaven er en fortsettelse av prosjektoppgaven og er gjort på Institutt for maskinteknikk og produksjon på Norges teknisk-naturvitenskapelige universitet. Arbeidet er en del av TrollLABS, et forskning- og prototypelaboratorium ledet av Professor Martin Steinert.

Oppstartsselskapet Alva har funnet opp ny produksjonsprosess for statorer i elektromotorer. Ved hjelp av en spesialdesignet vevemaskin er et tre-fasemønster av konduktivt kobber vevet og siden støpt i epoxy. Sammenlignet med konvensjonell produksjon kan dette gi skreddersydde statordimensjoner og et lettere design. Rammen for denne oppgaven er å evaluere den første prototypen av produksjonsprosessen, og videre utvikle konsepter for kontrollering av flere trådsneller. For dette utviklingsarbeidet er wayfaringmodellen og hurtig prototyping anvendt. Som et bidrag til studier av tidlig-fase produktutvikling på TrollLABS er denne metoden diskutert i kontekst av Alvas arbeid.

De resulterende konseptene for garasjesortering og snellehåndtering er så vidt forfatteren er bekjent, innovative løsninger innen vevefeltet. Garasjesorteringen trenger videre detaljering før det kan implementeres. En detaljert dokumentasjon av både arbeidet gjort, så vel som metodologien brukt, er presentert i denne oppgaven. Positiv attest ble mottatt for bidraget i prosjektoppgaven og masteroppgaven.

Alva Industries AS har mottatt finansiering av Norges forskningsråd i forbindelse med STUD-ENT-programmet for studententreprenørskap. Bidraget vil muliggjøre patentering av produksjonsteknologien. Samarbeidet med TrollLABS vil fortsette med en ny prosjektoppgave den kommende høsten. Forslag for videre arbeid er gitt i oppgaven for å hjelpe Alva i sin videre utvikling.

Preface

This report concludes my studies of Product Development and Materials Engineering at the Department of Mechanical and Industrial Engineering at the Norwegian University of Science and Technology. It is a natural continuation of the previous pre-master thesis with the same name from the fall of 2016. The work has been done for Alva Industries AS, a startup company from the School of Entrepreneurship, to realise their novel production concept of stators for synchronous electric motors.

From my experience of early phase product development, a large degree of uncertainty must be anticipated. Even more so in a startup company. During the work with Alva, the general direction has been subject to change many times as new discoveries have been made. This is reflected in the master thesis as well as the pre-master thesis, and the link between the two. Hence the wayfaring methodology has been a well-suited mindset for the project. A detailed discussion of this model applied to the project is provided.

I would like to sincerely thank my supervisor Professor Martin Steinert for being so accessible with valuable inputs, and my co-supervisor Kristoffer Slåttsveen for his genuine interest and irrepressible good mood. To my colleagues and friends at ALVA; thank you for all the fun this has been, and the best of luck for the future.

Trondheim, June 11, 2017
Simen S. Pjaaten

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Chapter 1

Introduction

This chapter will introduce the reader to the frames of the project. In the background section, Alva's concept will be presented along with a benchmark against competitors. A summary of the previous work from the project thesis is followed by the motivation for this thesis from the perspective of Alva and TrollLABS. The initial problem description is given in its entirety, and the changes made during the time of the project is given along with reasoning. Some practical limitations of the work are clarified, and finally, a summary of the structure of the remaining thesis is presented.

1.1 Background

The stator is the static part and main cost driver of an electric motor. It is normally produced in a semi-automatic production line. These stators are of set dimensions. Thus the customer must often pick one that is over dimensioned. Alva wants to provide light-weight tailored stator designs through a fully automatic production process for customers like drone manufacturers where weight is important.

1.1.1 Alva's concept

Alva's technology is based on a patent from Martin Gudem, a former PhD at the Department of Mechanical and Industrial Engineering at NTNU. The invention was related to electromagnetic conductive materials (EMCM), and a proposition for application was electric motors. Jørgen Selnes and Sybolt Visser from the NTNU School of Entrepreneurship was given the opportunity to explore the technology. They came up with the idea of weaving a three-phase conductive pattern and casting it in epoxy to produce a stator. In June 2016, Alva was founded by Visser and Selnes, and a team of students were engaged for the development team.

Alva has invented a new motor design based on an ironless woven composite stator. This enables weight reduction and flexible stator dimension design, while still allowing for a fully automatic production. This production is based on a complex weaving process followed by a resin cast.

1.1.2 Comparison

Industrial stator production is a mix of automatic and manual work on a production line. It starts with machining the frame of the stator in laminated iron plates which are glued together. The copper wires are winded by specialised machines and further coupled manually. It is later cast in a polyester based varnish to ensure protection from water and dirt. These production lines are fast but not flexible to changes in dimensions. For customers like drone manufacturers, weight is crucial, and this is the type of customers Alva seeks to offer custom stator designs.

Another actor on the market of tailored low-weight electric motors is Thingap. This California-based company uses stamped copper sheets that are rolled up in layers, with composite sheets in between. The stamped sheets form conducting lines when coupled together, and it makes for a very thin and light-weight design. Thingap has been working with specialised customers like DARPA (2013, Thingap website). Alva intends to be a cheaper alternative. It has not successfully been found by the author if Thingap has an automatic production, but this can be where Alva has a competitive advantage.

1.1.3 Benchmarking

For benchmarking it has been sought to find companies that use similar production technologies as Alva. The scope of this thesis and the project thesis has dealt with the weaving part of the production, and thus the casting is excluded from the benchmark. Alva's approach to weaving is nontraditional for a series of reasons. First, copper wires are not widely used for weaving. Second, the wefts in industrial weaving are normally cut at the end of each crossing. This increases efficiency and reduces the complexity of the loom. For conductive wires, on the other hand, this is highly impractical for obvious reasons. Third, the advantages of litz wire result in a need for several reels. A three phase stator, as is the goal of Alva, needs three circuits and thus three litz wires. For the production prototype designed during the time of this master thesis, it was decided to use three reels per phase, adding up to nine reels in total. Each reel has its order in the weaving process that has to be organised. It is the complexity of reel sorting and handling that is the main difficulty of Alva's loom, and such technology has not been successfully found by the author.

1.1.4 Traditional Weaving

A brief introduction to traditional weaving will provide the reader with the necessary concepts and components that are used throughout this thesis.

In traditional weaving, the threads going along the fabrication line is called warps and serve as structural support. The weft, which crosses the warps, are contained in a shuttle. The warps are tread through two heddles that makes a gap by elevating every other thread and lowering the rest. Each time the heddles open, the shuttle passes through the open gap with the weft. The heddles close and further passes each other to make a new gap for the next weft. A woven cloth is made through this repeated process.

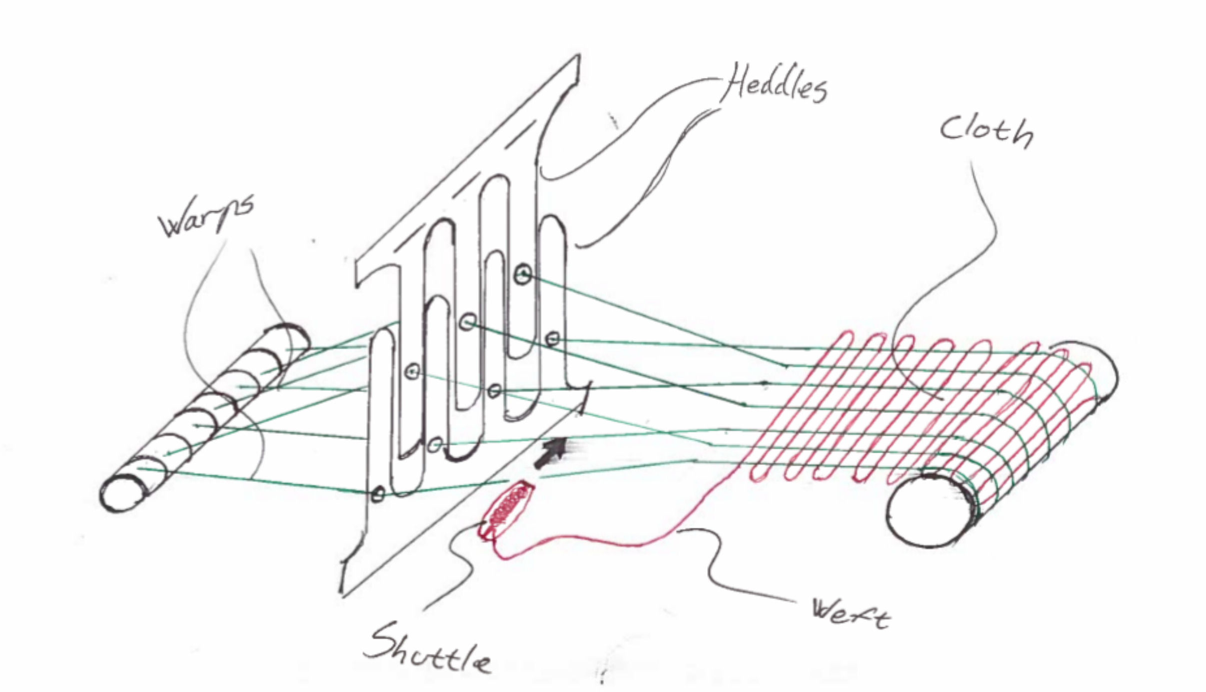


Figure 1.1: Traditional weaving and terms

1.2 Previous Work

During the time of the project thesis, a functional prototype of a semi-automatic multi-shuttle weaving loom was built. Of all the functionalities of the production line, the weaving was considered the most complicated. This first prototype had 33 shuttles of copper wires and 11 warps of glass fiber. Stepper motors and motor controllers were implemented to control the heddles. Parts for the reed and the multiple shuttle controller were completed, but not yet integrated into the machine. Thus the reels were manually handled as seen in figure 1.2a. A cloth woven in this machine was later rolled up to a two-layer cylinder of 8 cm diameter and successfully tested as a stator in a three-phase synchronous motor. This stator is seen in figure 1.2b. From building this machine, the team got a good understanding of what features were challenging and not. Handling and sorting multiple reels stood out as the function that brings most complexity to the current design. It was thus chosen as the starting point for this master thesis.

The main reason for not implementing an existing solution is that similar weaving technology was not successfully found. This is due to the multiple-reel factor, as well as continuous threads. By multiple-reel is meant both the factor that it is nine different reels and that these are grouped in three. Every reel has to have a specific order in the weaving process to successfully achieve the technical specifications of the product. During the project thesis, it was discussed multiple ways of solving the problem of continuous threads. In conventional looms, the threads are cut after passing the warps, but for conductive wires, it is a great advantage to keep the thread uncut. Alternatively, they could be soldered together after cutting, but this would inevitably require an intricate and detailed process, given the cross-section of the litz wire and the quantity of these. This approach was thus discarded during the project thesis.

(a) Manual handling of reels (b) A Manually Woven Stator

Figure 1.2: Alva's first production and product prototype

During the time of the project thesis, the startup company was figuring out routines for project management, product development and collaboration. In the specialisation course TMM4280 Advanced Product Development, Agile methodology, lean principles, and SCRUM framework were explored. Two unpublished articles were written in the context of Alva, reflecting on this. Through this work, a set of propositions for improvements were found, and SCRUM was implemented.

The project thesis was a part of the TrollLABS research on the fuzzy front end of new product development. This inspired the team to learn through prototyping. To iteratively develop sub-functions separately, we agreed that a modular approach was practical. The interaction between different parts of the machine would define requirements for each sub-function, thus creating a framework for the modularity.

1.3 Motivation

The goal of Alva is to achieve a functional prototype of the automatic production process as a proof of concept. Further, it is to patent this technology. As the master thesis is written in collaboration with TrollLABS, it is intended to use this work for research on fuzzy front end development in startups. For this reason, the work has been conducted with a deliberate focus on product development methodology. This is also valuable for Alva as a growing startup company. As technical staff is hired and development continues, it is crucial that the company assures effective development while capturing gained knowledge.

1.4 Problem Description

The problem description for the master thesis was worked out in collaboration with the supervisors and the contact at Alva. Given the nature of the project, product development for a startup company, it was expected that some changes were made along the way. The initial problem description is given in this section with a discussion on the changes that were made.

1.4.1 Initial Problem Description

The initial problem description was based on the previous work in the project thesis with Alva. In this thesis a concluding discussion of further work was presented, giving a natural starting point for this work. For academic reasons, it was expected to contribute to a publication in the interest of the research lab TrollLABS in the context of the development work. The problem description is given below:

Join in the further development of Alva's production method for an ironless stator component. Finish the first functional prototype and evaluate this. Benchmark the processes against existing technologies, and the production system as a whole against conventional production. Generate alternative concepts for multiple shuttle control. It is expected to produce an article based on the wayfaring method and rapid prototyping in Alva's work to be used as data for later metastudies.

- Finish the first functional prototype and evaluate results
- Compare concepts to conventional technology
- Benchmark Alva's production technologies
- Evaluate and create alternative solutions for multiple shuttle controlling
- Write an article on the work of Alva in a wayfaring/ rapid prototyping perspective

The supporting coach is Kristoffer Slåttsveen, the contact at ALVA is Jørgen Selnes.

1.4.2 Changes along the way

The development work was a dynamic process as external and internal factors changed during the time of the project. These changes affected the priority of functions for development. However, the scope of evaluating and creating alternative solutions for multiple shuttle controlling was the primary focus throughout the period. For this to be done, a natural starting point was evaluating the results of the first functional prototype.

An article discussing the wayfaring model in the context of Alva's development was started on but never finished. This was partly due to the amount of time it would require, and partly due to the weak contribution to the field of study. Because of the integral property of the company, only a limited part of the development could be used as material for discussion. For the interest of the company, it seemed more convenient to apply the discussion of methodology to all the development work. Thus the priority of the article was downgraded. Most of the material is, therefore, to be found in this thesis instead. The collaboration with TrollLABS will continue with another project thesis the coming fall, and this student will have access to all the work conducted through this master- and project thesis. Together with the further work of this student, the author believes an interesting article on the research of the fuzzy front end of product development in Alva can be written.

1.4.3 Limitations

Alva is a young startup company with a complex production technology in a well established market. These factors add up to a great deal of uncertainty and risk for possible investors. Thus, funding has proved difficult to acquire. This affects the efficiency of development. The workshop that Alva has access to through the School of Entrepreneurship is limited in space and available tools. The students in the development team have individual access to a series of more suitable workshops, but the machine can not be placed in any of these for collaborative work. The possibility of ordering custom made parts in desired materials is also restricted by economy.

The development team consists exclusively of engineering students. The collective experience and knowledge within the company are thus limited. Despite these factors, Alva has steadily developed the technology readiness level.

1.5 Further Structure

After providing the reader with an introduction to the context of the thesis, the further chapters will present the content. The method chapter presents the product development methodology and prototyping mindset that has been used throughout this work. The focus on its application for this project is intended as a further reference for the development team of Alva and the continuing research of trollLABS. Through concept development, a detailed documentation of the preliminary problem analysis and development is provided. A changing requirement made for a pivot point in this work that led to the development of the resulting concept. In the end, the results are presented along with a work assessment and a proposition of further work. This will hopefully be of great value for Alva's continuing journey.

Chapter 2

Method

This chapter will present the applied product development methodology and prototype mentality through the work of this master thesis. An argumentation for the suitability of the mentioned models, principles, and tools is conducted on the way. The Hunter-Gatherer Model has been the main inspiration for development, and the key elements for use in this project are underlined. Prototyping is an inherent aspect of this model, and the approach that has been used for this work is presented in the second section of this chapter.

2.1 Methodology

During the time of the master project and the prior project thesis, Alva has been in the early phase of its product development. The main goal has been to make a proof of concept to convince investors. To achieve this, while handling the mentioned uncertainty, a flexible approach to product development was sought. For the particular sub-functions that are contained in the scope of this thesis, the Hunter-Gatherer Model (Steinert and Leifer, 2012) has been the primary inspiration. Elements from other Product Development methods have been used, but are presented as they are used throughout the problem analysis and concept development.

2.1.1 Conventional Methodology in Startups

"A startup is not a smaller version of a large company. A startup is a temporary organisation in search of a scalable, repeatable, profitable business model" (Blank, 2012). Using this suitable description for Alva helps illustrate the many turns that were done regarding market and product during this project. Adding a radical innovation like that of a novel production method of electric motors makes for another element of uncertainty, supported by (Lynn and Akgün, 1998). There is empirical evidence that uncertainty leads to late design changes (MacCormack, 1998), underscoring what we expected from the development process beforehand. It was thus a need for Alva to implement a strategy with inherent agility, which accounts for late requirement changes. This by itself indicates that conventional development models like stage-gate (Cooper, 1990), where one freezes the design as early as possible (MacCormack, 1998) would not make a good fit.

Conventional methods like stage-gate divide a product development project in sequential, but often overlapping phases. According to Dombrowski et al. (2011) there are the following five phases: "research, product planning with the customer, design, and development which creates a prototype, testing of this prototype, manufacturing and assembly". Cooper (2001) states that "within NPD most companies use some form of the Stage-Gate process", indicating its popularity. Through 30 in-depth interviews with CEOs, innovation managers, and heads of R&D, Heck and Meboldt (2015) found that about 70% of the small to medium enterprises interviewed applied the stage gate process. One commonly mentioned strength of this process is its "capabilities as a management tool" (Ringen and Welo, 2013). By having defined gates, the development team are given go/no go for further work. Each passed gate represents a step closer to market and diminished uncertainty. Thus resources put into the development project is increased. But if unforeseen external or internal changes occurs, affecting the requirements of the product, the development must go through so-called crossgate iterations. And as Heck et al. (2016) points out, for small sized businesses, and thus even more so for a startup company, can the "consequences of crossgate iterations be existence-threatening". For Alva, an agile approach was much better suited. The reasons for choosing the Hunter-Gatherer Model will become apparent through the rest of this section.

2.1.2 The Hunter-Gatherer Model

The Hunter-Gatherer Model is a result of project-based research from Martin Steinert and Larry Leifer (2012) from the Center for Design Research (CDR) at Stanford University. It was inspired by Tim Ingold's "Lines: A Brief History" (2007). It is a dynamic and iterative methodology applicable to the fuzzy front end of projects with high level of ambiguity. A graphic representation of such a process is depicted in figure 2.1. In practice, the model proposes the use of iterative cycles of wayfaring ones way through the unknown ground of the problem at hand. Each iteration consists of the following steps. You start by plotting out a course - a promising solution space and define the critical functions that need to be tested. You then design, build and test a prototype that serves the purpose of answering questions about these critical functions. This will update the current knowledge of the problem and solution space. The design-build-test cycle is repeated until an innovative solution is found that can be brought back home for further engineering and conventional product development. The model emphasises agility, learning and speed. Hence the easier one can model the critical functions without spending resources and time, the better. The details of the use of prototypes are found in the next section. The main argument for wayfaring in an ambiguous solution space is the opportunity to abductively learn about fields that beforehand could not have been predicted. Steinert and Leifer (2012) argues that this is where truly innovative solutions, and serendipity findings, are found. According to Leikanger et al. (2016) the model includes four main aspects:

1. Probing ideas - exploring opportunities, using low-resolution prototypes to fail early and to enable abductive learning.

2. Merging multidisciplinarity - including all knowledge domains from the beginning, in order to uncover interdependencies and build interlaced knowledge.

3. Speed - planning based on short iteration timeframes, to maximise the number of iterations possible.

4. Agility - opportunistically choosing the next step and letting the development process shape the outcome, making room for serendipity findings.

Considering these four advantages of the model, a further discussion of what the author sees as key elements are discussed in greater detail.

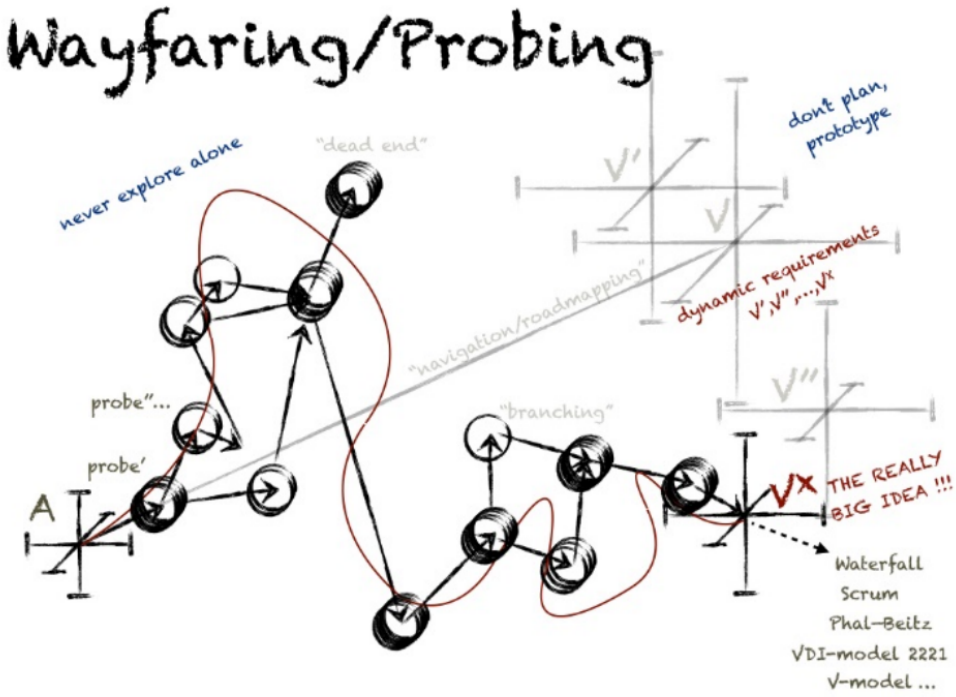


Figure 2.1: Hunter-Gatherer model for Product Development

Probing, experimentation and learning

The iterations of the Hunter-Gatherer model were further developed by Gerstenberg et al. (2015) to a concept called probing. The goal of probing is to learn by abduction and to fail early in the process, in order to reduce costly rework later in the process (Kennedy et al., 2014). Probing, depicted in 2.2, starts with divergent thinking while generating solutions to the problem and designing these. Later follows the important learning phase, where the team abductively learns about the problem and solution space by testing their guesses about critical functions with rapid prototypes. And last, based on the new findings, the team converges towards the most promising option. Gerstenberg puts it like this: "The abductive learning from repeating cycles of probing leads to wayfaring of opportunistically finding one's way through the project".

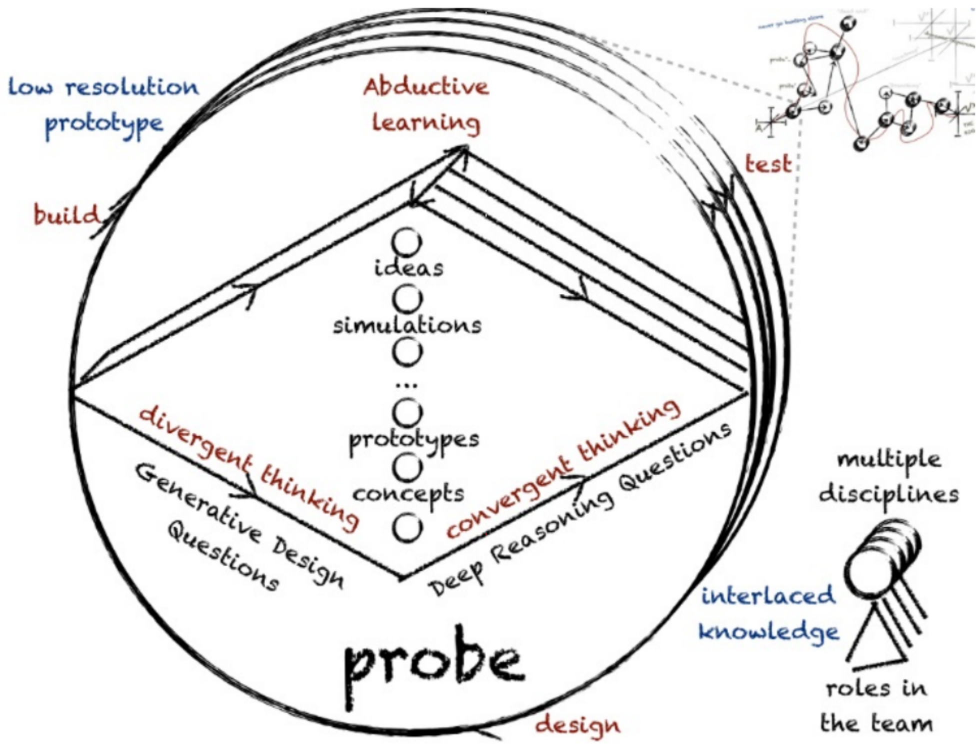


Figure 2.2: Probing Cycle

Probing enables a set of important principles that now will be highlighted.

Unknown unknowns and serendipity findings

One of the cruxes of Hunter-Gatherer model is to facilitate serendipity findings. As Baldwin and Clark (2000) argues, during the development of complex products "it simply is not possible for designers to know enough about the system to eliminate all uncertainty. Thus each new design is fundamentally an experiment. Its outcome may be guessed, but it cannot be known ahead of time". This is also supported by Schön (1987) arguing that the real challenge lies not in the treatment of well-formed/modelled requirements, but in the extraction of these, often unknown, requirements from real-world situations. The practical unknown unknowns are the core challenge.

Now, hunting for the unknown may sound similar to a trial and error approach, and so a clarification of the differences should be helpful.

Trial and error, and the power of experimenting

Trial and error is "the process of experimenting with various methods of doing something until one finds the most successful" (Oxford Dictionary). And this implies a bias toward action which is shared by the wayfaring method. Another shared property is the willingness to fail. Combining these can be viewed as the recipe for experimentation.

A thorough discussion on the topic of experimentation and its impact are found in Smith (2007). Among the many proposed definitions are "Something one does deliberately to see what happens". And in the lines of wayfaring, Smith argues that one experiment may be insufficient. "Sometimes, you might even need to conduct an array of experiments to map out uncertain territory to find your way". This calls for the famous quote of Thomas Edison: "I have not failed. I've just found ten thousand ways that won't work".

A viewpoint on failure is given by Thomke (2003) that draws an important distinction between failures and mistakes. "A failure is an experiment whose outcome is unexpected, which teaches you something. On the other hand, a mistake is a badly planned or conducted experiment whose outcome you cannot interpret, which thus teaches you nothing". But he further underlines that the goal is not to eliminate mistakes, but to maximise the ratio of failures to mistakes.

What however distinguishes trial and error from wayfaring may not be so obvious, but a proposal is presented here. The main difference lies not in what is done, but why it is done so. While trial and error focus strictly on making something work, the goal of wayfaring and probing is as much about learning. By the end of every experiment, "do a 360 degree scan of the surrounding space" (Steinert and Leifer, 2012), reflect and abductively learn.

The point is that experimentation can be an invaluable tool in the fuzzy front end of product development. Not only for the sake of finding a solution, but because "experimentation allows product designers to investigate a new technology, testing its limits without committing to how they will use it, or indeed, whether they will use it" (Smith, 2007).

Experimentation is a natural tool for the problem-solving human, and should not be underestimated by developers. A familiar analogy presented by Smith concludes this argument. "Consider how you search for a name in a telephone book. You probably turn to the most likely place in the book, splitting your uncertainty as to whether you are too far forward or too far back. You check where you are and try again to split your uncertainty as to being too early or too late. And so forth. Notice that at each step you magnify your uncertainty about whether you would be ahead of or behind the desired name."

Mindset and types of questions

There is also important differences in how you do trial and error that distinguishes it from wayfaring. Gerstenberg separates a probing cycle into two phases, a divergent followed by a convergent. The two phases are mainly characterized by different mindsets. According to Eris (2003, 2004), the divergent phase requires Generative Design Questions (GDQs), while the convergent requires Deep Reasoning questions (DRQs)(Graesser and McMahen, 1993). Leifer and Steinert (2011) states that the design process is, in fact, a "question driven process", and that it is a "general positive correlation between the numbers of questions asked during design activities and the project team performance". A Generative Design Question is one that keeps the solution space open or even opens it further. It inspires creativity and preserves ambiguity. The following convergent phase introduces the Deep Reasoning Questions. These types of question are positively correlated with learning according to Graesser. They aim to reduce the number of alternatives and seeks clarity from uncertainty. In pure trial and error, the focus is solely on fixing the problem which arguably only involves convergent thinking.

Speed

The last difference between the two methods again reflects back to why one does it. As previously stated, the goal of wayfaring is not only to find a solution but to learn while doing so. To do so, one should maximise learning to the use of resources. Practically this means to conduct as many probing cycles in as little time as possible. This brings us to the field of rapid prototyping which will be presented in the next chapter. But the take away here is to only focus on testing the critical functions and keep testing to ensure progression. ”Maximising learning and minimizing time stuck in solutions with dead ends” (Leikanger et al., 2016).

People

Another aspect of the Hunter-Gatherer model is to include all knowledge domains from the beginning. According to Leifer and Steinert’s ”Human Rule”, wayfaring is done in “agile teams with a maximum of skill diversity”. This is in order to discover interdependencies early and to build knowledge across multiple disciplines. An advantage of front loading multidisciplinarity work is the prevention of costly changes later in the development process.

A multi-disciplinary team provides a set of perspectives that cannot be resembled by one person alone. This is not only because the different technical expertise gives a broader solution space, different people will also take on roles in the group that provides team dynamics (Sjøvold, 2006). These roles are important in different stages of the development, and even different stages of a probing iteration. An example is how the role of the divergent thinker are balanced by the analyst. One may be better at asking generative design questions while another at asking deep reasoning questions.

On an individual level, Smith (2007) mentions one type of team member especially suited for concept development. The “T-shaped individuals”. These are people with broad knowledge of many fields, and in-depth knowledge of one or more.

Agility and the Fallacy of Frozen Requirements

This element of wayfaring is as much about an opportunistic mindset as it is about laying a foundation for serendipity findings. The iterative approach let the team aim in uncertain directions so that an open mind can find hidden gems in unexpected places. The Ambiguity Rule (Steinert and Leifer, 2012) reminds us that perseverance is key here. Only when sticking with the ambiguity, the team can “overcome path dependencies and model blindness to get a shot at the ‘really big idea’”.

A strong argument for this opportunistic mindset is ”the fallacy of frozen requirements” from the studies of Thomke and Reinertsen (1998). In conventional product development methods, requirements are frozen early on to prevent late changes. But according to Reinertsen findings, this is inconsistent with the actual experience. For thirteen years he gathered data from over thousand managers of product development that has attended his class at the California Institute of Technology. Reinertsen concluded that out of hundreds of projects, the requirements never remained stable throughout the design. This strongly indicates that late changes not only should be planned for but expected in a product development process. The development budget is often negotiated based on these early fixed requirements, and when further requirements are imposed by management or marketing, the budget is no longer to scale. This phenomenon is called Scope Creep.

It is one of the reasons "Changing requirements have a bad reputation among designers and engineers"(Smith, 2007). Probing focuses on testing the requirements, and updating them, until a satisfying solution is found and the requirements are verified. It also opens up the opportunity to test different solutions rapidly, choosing the most promising one in the end. These are elements found in set-based design that also "emphasises exploring and keeping the design space open" (Smith, 2007).

2.2 Prototyping

This section treats the field of prototyping and the impact it has had on this project. During the work of the project thesis, Alva agreed that prototyping was not only a way of testing designs but of communicating ideas and learning about the problem. Through prototyping, we were better able to collaboratively explore and evaluate concepts. As the team consists of students from different disciplines, prototyping made it easier for us to communicate less dependent on technical terms. Another argument for the bias towards building prototypes is that Alva is developing a new production technology. Thus the product itself can only be realised through a functional prototype of the production. During the project thesis, we built a functional semi-automatic machine from cheap materials by rough design. For the continuing work, a modular approach would allow subfunctions to be developed concurrently. With the second prototype, the level of detail was increased.

The prototypes for the work of this thesis, have been made in TrollLABS. This is a research and prototyping laboratory at the Department of Mechanical and Industrial Engineering at NTNU. This ”research project [is] aiming at understanding the development of radical new ideas in the very early phases of product development - the early fuzzy front end” (2017, NTNU website). The lab contains a range of machines for building prototypes, from very low fidelity such as cardboard and skewers to high fidelity such as custom circuit boards or detailed 3D-printing. The available machines and an inspiring community of DIY-ers (Do It Yourself), outlines the mindset of prototyping at TrollLABS.

2.2.1 What is a Prototype?

A classical definition of a prototype is “an approximation of the product along one or more dimensions of interest”, and comes from Ulrich and Eppinger (1988). According to Elverum and Welo (2015), prototypes includes physical and non-physical models, like sketches, CADs or functional pre-production models. Using this definition in combination with the Stanford d.school philosophy that simply defines it as ‘anything that takes a physical form’(Plattner, 2010), covers the prototypes that Alva have used throughout this project.

According to Erichsen et al. (2016), prototypes are more easily classified by their intention and their audience, not their form. He further proposes two dimensions for this classifying. The first is the intention, and spans from reflective to affirmative. Reflective prototypes are built for learning or feedback, and affirmative prototypes to conclude or to showcase. The other dimension reflects the audience, spanning from internal like the development team, to external target audience such as a customer. In the work of this thesis, internal, reflective prototypes have been most frequently used. These prototypes are ”learning tools” for product development teams, generally low-fidelity and often thrown out after the project. It is through interaction with prototypes the development team at Alva have learned about multiple reel weaving.

Low-Fidelity and Filtering

Low-fidelity prototypes are in line with the speed and agility aspect of probing solutions from sections 2.1.2 and 2.1.2. According to Edelman et al. (2009), ”High resolution media-models afford for parametric adjustments, while low resolution media-models afford paradigmic shifts”. This has to do with a concept known as design fixation; The more effort one puts into a concept, the more difficult it is to "kill your darlings". According to Elverum and Welo (2015) it is important to know how to prototype effectively in order to gain valuable learnings while reducing costs. Even quickly built, low-resolution prototypes could open the eyes of the development team to flaws in the design. A prototype that only resembles the functionality of interest is called a rapid prototype. For this project, rapid prototyping has been successfully used for preliminary problem analysis as well as concept generation.

An important thing to keep in mind within internal, reflective prototyping is the "filter" of the prototype (Lim et al., 2008). What is the purpose of the prototype? A specific function? Thermal properties? These types of questions act as filters for what is important to spend time on, and what is not.

CAD

Using Computer Aided Design (CAD) as a mean for rapid, iterative prototyping is according to Leifer and Steinert (2011) not well suited. "A sophisticated CAD prototype is least likely to be considerably changed in following iteration cycles". But as the author has experienced, if the computer model complexity is fairly low it can be a very efficient tool for communicating and saving ideas. Ullman (2002) argues for the many benefits of CAD. While not all of these apply to a prototyping setting, he does make the point that CAD as a design support system should "communicate information in the format, level of abstraction, and level of detail needed". CAD design requires a certain level of details, and so it is not applicable to the first phase of divergent concept generation. But for prototyping an assembly of different parts, trying to see how parts can fit and how they can be designed to interact with each other, we argue that CAD can be very helpful. Mainly because of the many types and possibilities of mates and constraints. When working with simple materials like cardboard and skewer sticks, it is easy and efficient to generate the shapes you want, but not so much so to make a prototype of actuation and movement.

2.2.2 Modularity

As Alva's production line is taking form, the functions and sub-functions of different parts become more defined. It was argued in the project thesis that a modular approach for building the machine would allow for iterative changes of sub-functionalities. This was further continued in the master thesis, where specific modules have been in focus.

As Baldwin and Clark (2000) points out, one must have "detailed knowledge about what the module contributes to the whole, as well as how different modules interact". This is even more important for team development where different people are responsible for different modules.

The power of modularity reflects on the previous point regarding prototype filters. If you successfully separate a module from the whole, it reduces the complexity of the problem and makes testing more efficient and more transparent. This way of breaking an engineering problem in sub-functions is common and mentioned in for instance Pahl and Beitz (2013), where they break the "overall function down into less complex sub-functions to describe the functionality less ambiguously and facilitate the subsequent search for solutions". The famous problem-solving tool for engineers called TRIZ (translated from Russian: theory of the resolution of invention-related tasks), is a set of 40 context-dependent principles that is meant to inspire solutions. The second principle, extraction (Altshuller et al., 2002), is focusing on the idea that extracting features from one complex part can help find a solution.

Smith (2007) provides a list of objectives modularity allow designers to achieve. To conclude with, the ones that were most helpful in this particular project are listed below.

- enable changing one part of the design without affecting other parts.
- simplify or accelerate product testing.
- manage product complexity.
- allow different parts of the design to be worked on concurrently.

2.2.3 Prototype-driven Spesifications

Kriesi et al. (2016) elaborates on the idea of using probing to create "dynamic functional requirements" for the product. For each iteration "one will deduct certain critical functionalities from the prototypes that need to be fulfilled". This means that the prototypes drive specifications more than the other way around.

This concept of prototype-driven specifications is another key point Alva has been using. The research of Schrage (1993) focuses on the cultures of prototyping. David Kelley, founder and chairman of IDEO, gives his opinion in an interview with Schrage. "Organizations intending to be innovative need to move from specification-driven prototypes to prototype-driven specifications". Schrage points out that cultures in which prototypes determine specifications, such as in small entrepreneurial companies, are more effective when information is scarce, and the outcome ambiguous. For Alva, the requirements of the production process have arisen from building the prototype from the project thesis. Unexpected problems were discovered along the way, and requirements were updated accordingly.

Chapter 3

Concept Development

This chapter presents the preliminary problem analysis and concept generation of the sub-functions dealt with in this thesis. This work was prototype-oriented, inspired by wayfaring. The problem scope dealt with the process of handling and sorting reels while weaving.

In the project thesis, it was decided to use continual wires as opposed to cutting and soldering. Keeping the wires uncut demanded a mechanical sorting problem of the reels of fair complexity. The reels would also have to be carried across the warps, while in modern looms only a thread segment is transported. Through prototyping, the problem was made physical and interactive. This method proved effective and provided tested requirements for further development work.

The resulting concepts are presented with the rest of the production process in the results chapter.

3.1 Garage Sorting

This section deals with the problem of sorting reels. A preliminary phase of rapid prototyping was conducted to make the problem tangible. Requirements were shaped through this work. These were used to evaluate the former solution. Concepts were then generated at a principle level. The development of these solutions was put on hold as a result of a change of the company's direction and priorities.

3.1.1 Weaving a Three-phase Pattern

To weave the conductive cloth of copper threads, a three-phase pattern as shown in figure 3.1 had to be made. This implied that three different routes of weft had to be made. To make Litz wire, each of these three phases consists of several threads contained in separate reels. The reels must be arranged in a sequence that assures correct weaving pattern.

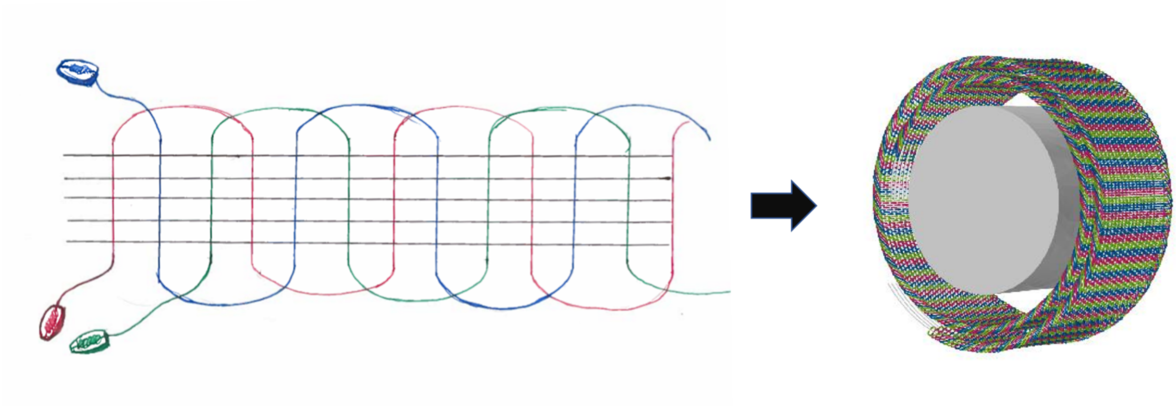


Figure 3.1: Weaving Principle

3.1.2 Previous Work

A solution for sorting reels was designed and built during the time of the project thesis and can be seen in figure 3.2. It was called the barrel garage and consisted of two large wheels on each side of the warp opening and a sliding rod. Every reel was placed in a shuttle, and the shuttles were sorted in garage spaces in the rotating wheels. The sliding rod, called a rapier, pushed the shuttles across the warps.

The solution was put on hold until the rest of the machine was up and running. At this point, it was not tested. It was argued in the project thesis that a prototype of lower fidelity should have been built to test the concept separately. When it later got implemented, it did not function as expected as the reels got stuck during transportation. Without a solution for sorting and handling the reels, the weaving had to be done manually so that a finished stator cloth could be cast and tested before the end of 2016. For Alva to succeed with a functional prototype of an automatic production process, a working solution was needed.

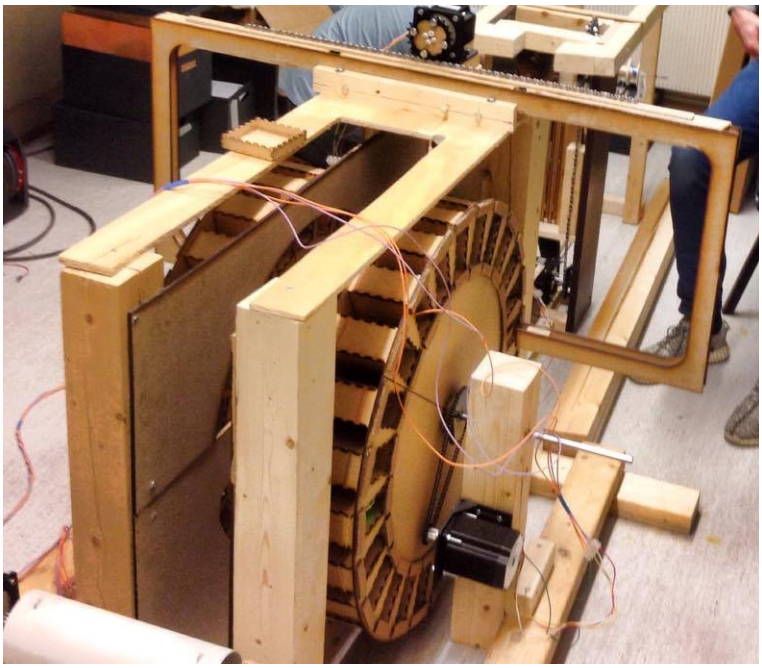


Figure 3.2: The Barrel Garage Prototype

3.1.3 Problem Interaction

In the start of 2017, Alva changed their target market and so the dimensions of the stator and hence the production machinery. It was also a natural time to do some reorganisation. Sorting and handling the reels were now of higher priority and was defined as the main scope of this master thesis. In order to evaluate and potentially re-design the existing solution, a solid understanding of the sequence of the reels during sorting was essential. Up until this point, this was done manually so we needed to define this tacit knowledge to requirements.

Sequence of reels

Using an older prototype of a loom, three reels of thread were used to create the desired pattern. Capturing some minutes of this weaving on video and speeding it up provided an easy and clear visualisation of the sequence. A still frame of this video can be seen in figure 3.3. A rapid prototype like this one takes a negligible amount of time and resources but provided essential insights. Like the fact that there is never more than two phases on one side of the warps, which dramatically reduces the capacity needed in the garages.

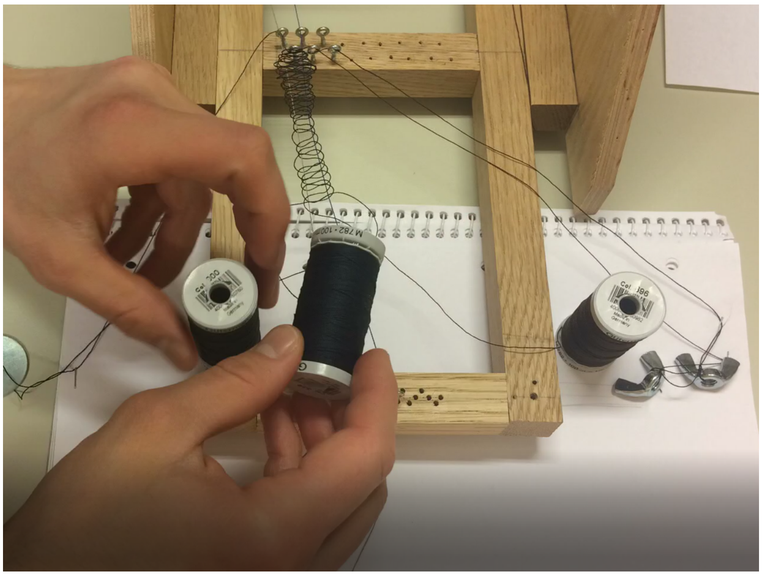


Figure 3.3: Still Frame of Weaving Video

A learning from the development of the barrel garage system was that the one responsible for motor controls should join in the development earlier. To understand the sequence of how multiple shuttles in each phase needed to be controlled, a simple simulation was conducted. With numbered post-it notes in colours representing the reels of the three different phases, and two disposable plates representing the garages, we made a principal control sequence. It was discovered that each garage only needed to hold two groups, so this sequence was compressed from three to two groups. The sequence for one garage was sketched for two and three groups as can be seen in figure 3.4. Again an interaction with a simple, rapid prototype effectively decoded tacit knowledge.

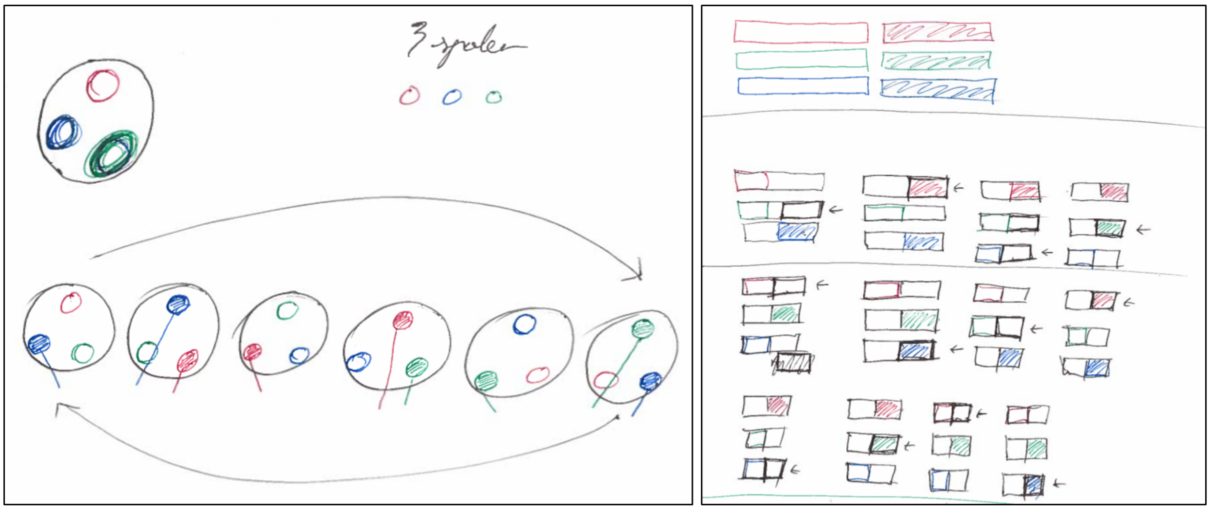


Figure 3.4: Sorting sequence

Evaluation of the first prototype

With a better understanding of the sorting, it was time to explore the other requirements for the garage. The following initial requirements were formed by the development team.

- It was decided that the reels would be carried by shuttles, and so a rapier was needed to push these shuttles across the warp. The garage needed to work well with this rapier.
- Another important feature was to minimise movement of the reels during sorting, in order to limit excess loose threads.
- Avoid complex controlling. Keep a number of needed actuators to a minimum.
- It was important that the sorting was done in a way that kept the side turns even on the cloth, to avoid bulkiness and to keep the wires the same length.
- Wires of the reels must be handled so that they don't catch on anything and get stuck.

The previous barrel garage solution was evaluated with respect to these requirements, resulting in the following summary.

+ Keeps the different phases from tangling up in each other
+ Easy to control, only one actuator needed.
+ Fits well with the rapier.
– Shuttles get stuck during operation.
– Keeps space for three phases on each side, but need only capacity for two.
– Moves a long way while sorting, extending threads unnecessary.

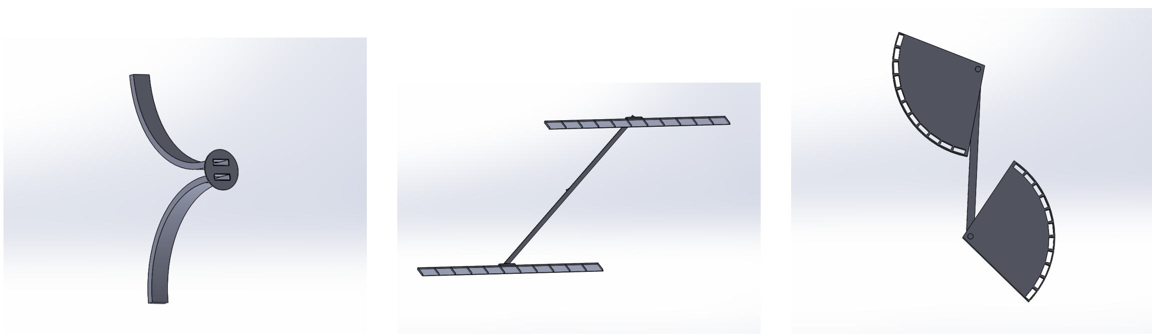
3.1.4 Concept Generation

Through an ideation session, some suggestions for further design was made using the requirements. They are shown in figure 3.5. The concept depicted in figure 3.5c was a redesign of the previous solution, reducing the movement of the reels while sorting. These designs were made using CAD, keeping the level of details to a minimum. The shape of the garages would need further redesigning according to updated shuttle design.

The concept depicted in figure 3.5a is based on the queue of each group of reels. The first reel of a group to cross the warps is the last to return. This is in order to make flat side turns on the finished cloth. The incoming group will fall into the pit pointing downwards and when the garage sorter is turned, the shuttles should return. The concept is prone to tangling and would be difficult to integrate with a rapier.

The second concept shown in figure 3.5b sorts each group on a line of floor spaces. It moves in a plane that should ease tangling ease interaction with the gripper. For the groups to switch place, it would have to travel a distance that makes for unnecessary extraction of thread, and actuation would be difficult to make each floor space match with the open warp space.

The third concept in 3.5c is considered the best solution of the mentioned ones. It sorts in the plane closest to the warps and thus tangling can more easily be avoided. This is also the plane that makes possible an uncomplicated interaction with the rapier. The two circle sectors rotate so each garage space can align with the open space of the warps, but still ensures that the groups don't collide.



(a) Garage 1 (b) Garage 2 (c) Garage 3

Figure 3.5: Different garage designs

The company decided to reprioritize the importance of sorting reels at this point, and instead focus on automating the rapier-shuttle interaction. The garage designs were thus put on hold. None of the concepts was tested, but the third concept seemed most promising. For the next production prototype, it was decided to use simple garages and rather design a solution for handling the reels efficiently.

3.2 Handling Reels

3.2.1 Introduction

The scope of this section is the development of a concept for handling the reels. First, the problem and its initial requirements are introduced. Then follows the wayfaring process of finding functional requirements for moving the reels through the opening of the warps while weaving. The focus is on the prototypes and the learning outcomes from these. Each iteration is referred to as a probe following the terminology from the theory section. The initial idea was to contain the reels in shuttles while pushing them across with a rapier. However, we wanted to explore other possibilities as well. A change to an initial requirement made for a pivot point late in this process. A design fixation was overcome as a result of this, and the final concept is presented in the next chapter.

3.2.2 Problem Description

For the new production prototype, it was agreed to use simplified garages and focus on handling the reels. The reels should be moved in a straight line through a narrow space of opening warps, from one garage to the other. One of these reels in a simplified garage is seen in figure 3.6. The reel needs to rotate freely as the wire is fed during transportation, but controlled rotation at the end in order to collect excess wire. Dimensions of the reel and the space in which it moves were given.

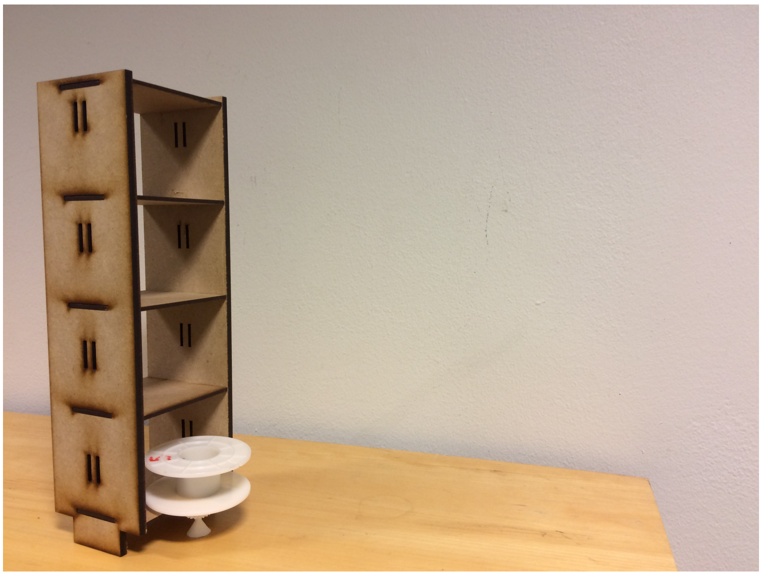


Figure 3.6: The reel shall move from one of these garages to another in a straight line

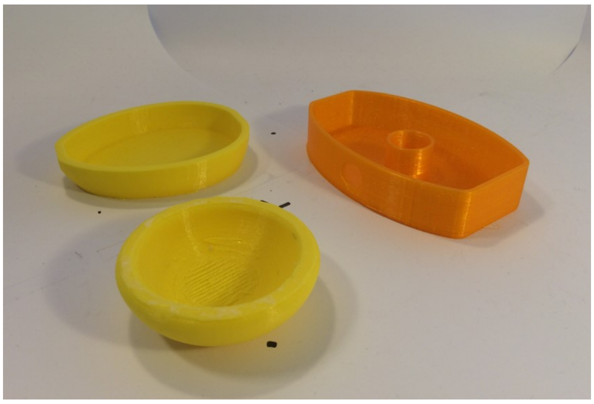
3.2.3 Shuttles and Rapier

The initial solution was to contain the reels in shuttles. The first shuttles were simple square boxes. To explore the possibility of still using this method, we wanted to test some different designs to check the feasibility of using a shuttle and rapier solution. With CAD software and a 3D-printer, a few different shapes were generated and tested in the machine (figure 3.7a). The final shuttle depicted in figure 3.7b moved significantly better than the first shuttles. Potential improvements were material finish, weight distribution and geometry.

In order to have actuated rotation of the reel for collecting wire, motors would have to be implemented to each shuttle. This would also require battery and sensors, and would add complexity to the shuttles.

To obtain an efficient sorting, a small garage was strived for. The diameter of the reel was already the primary dimensional constraint and shuttles to contain it would exceed this even further.

For these reasons, the development team decided to explore other principles of handling the reel without the use of shuttles.



(a) Different shapes were 3D-printed

(b) Last shuttle prototype

Figure 3.7: 3D-printed shuttles

3.2.4 External Gripper

A number of alternative principles were generated during ideation. To eliminate the use of shuttles, ideas for a gripper design came to mind that could be explored for the specific task. The gripper would serve the purpose of a rapier, but lift the reels instead of pushing them. This meant that the coupling between reel and gripper had to allow for free rotation and make sure that excess thread was collected when placing the reel. It was thought to be solved either by rotating actuation by the end of the movement, or adding resistance to the rotary joint so as to limit excessive thread.

Two general directions were defined: External and internal gripper. A traditional gripper is of the external fashion, while an internal gripper would hold the reel in place from inside the hollow centre. The external gripper seemed like the easiest solution to realise mechanically and was thus chosen as the starting point.

Based on simple sketches shown in figure 3.8, a prototype was built using the Meccano model construction system. This type of tools is perfect for testing concepts quickly. The realisation that the gripper needed three points of contact to maintain sufficient stability was noted. The driving wheel for rotation could, however, be one of these points. To make for a more stable behaviour, some self-stabilization in the contact between gripper and reel would have been preferable.

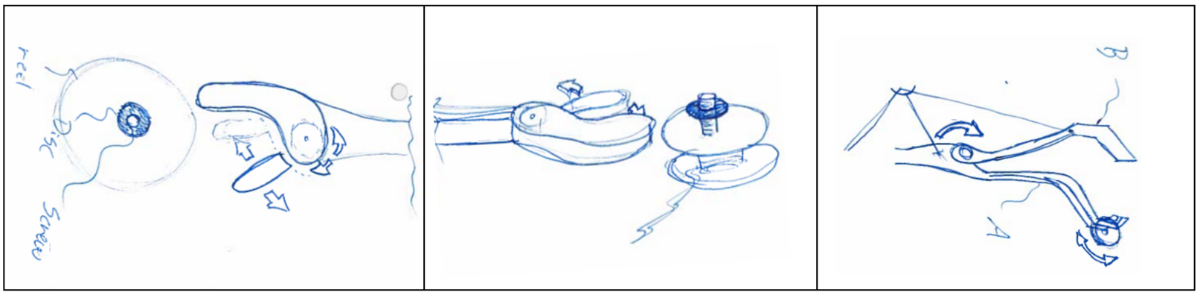


Figure 3.8: Sketches for an external gripper

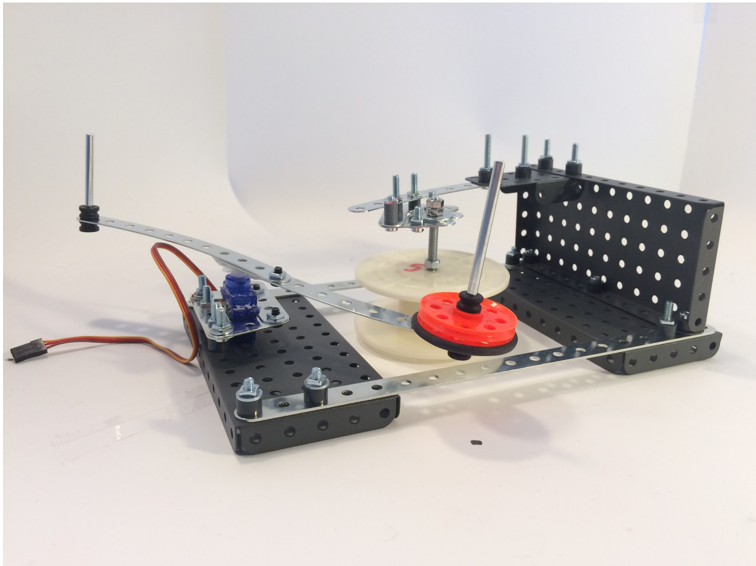


Figure 3.9: Rapid prototype using Meccano

3.2.5 Internal Gripper Screw

Even though an external gripper seemed easier to realise, we wanted to explore internal gripping due to the space restriction.

Principle Sketching

The first concept to test was a screw mechanism. The idea being that a gripper head moved into the reel by a lead screw mechanism. Using the bottom of the reel's hollow core as a reference for stabilising, the gripper was designed so that it would expand as it met this bottom. This expansion should lock the reel and gripper head by friction. By having a lead angle of zero at the top, the same mechanism could allow for free and possibly actuated rotation, allowing for the desired handling of excess thread. A tilting pin would assure that the gripper head moved back to the angled threads when reversed. A principle sketch is seen in figure 3.10.

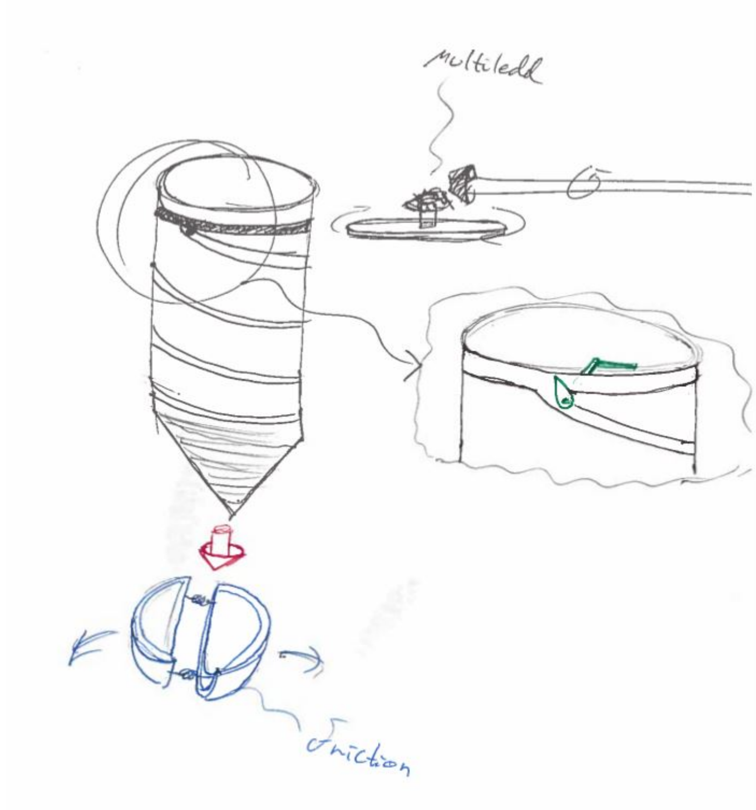


Figure 3.10: Sketch of an internal screw gripper

3D-printed Prototype

A CAD model was made from the drawings. It was split into necessary parts for 3D-printing and further assembly. When printed, the model revealed that the small mechanisms would need better tolerances to work, and were fragile to getting stuck. Given that the gripper was thought to be automated, reliable mechanisms were important. This was added as a new requirement.

Figure 3.11: 3D-printed prototypes

Sketch of Bearing

To conclude the evaluation of a screw mechanism for internal gripping, a rough bearing solution had to be designed. A sketch with the necessary parts was made, revealing the necessary complexity of the design (figure 3.12). A bearing for this internal gripper would require several features, while the external gripper could unite most in one part.

The internal screw gripper appeared less reliable than the external gripper. In order to make a satisfying internal gripper, the quantity of moving parts had to be reduced.

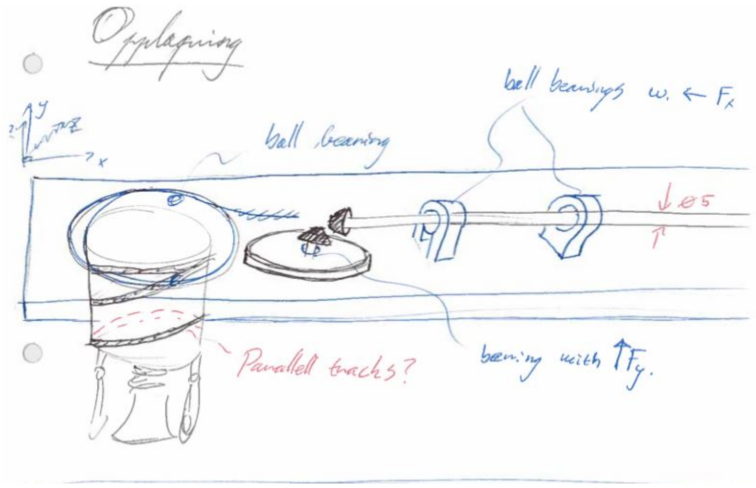


Figure 3.12: Sketch of bearing

3.2.6 Internal Expansion Gripper

One suggestion for a simpler mechanism was the idea of an expanding silicone washer. By pressing against the bottom of the reel, a silicone washer could make for sufficient friction against the walls. A fitting washer shape for the reel was milled from hard foam, and silicone rubber compound was poured into this (figure 3.13). The washer was tested between two metal washers on a bolt inside the reel, and the friction proved sufficient.

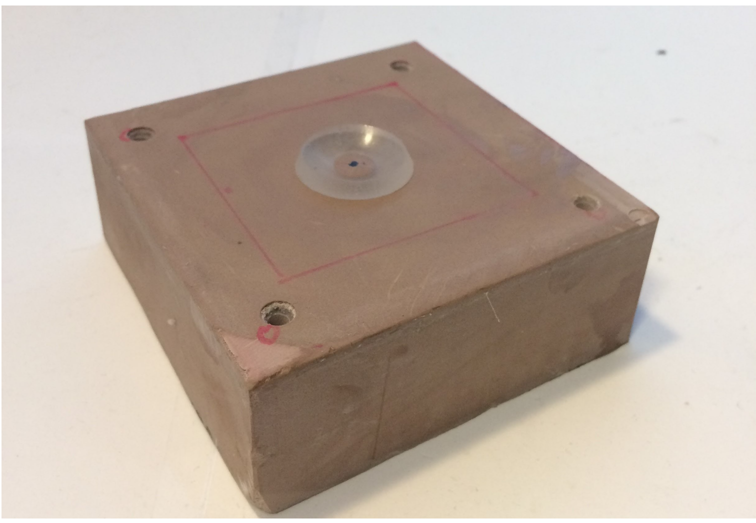


Figure 3.13: Silicone cast for expansion gripper

Polyjet 3D-print

The following challenge was to find a suitable mechanism. One idea was to use a ball pen as inspiration. Clicking to lock the silicone squeezed, and again to release it. Several ball pens were disassembled, and the separate parts were sketched as seen in figure 3.14. Then, the parts of the internal gripper mechanism and the parts from the ball pen were merged as can be seen in figure 3.15. These sketches were used to create the CAD files for the assembly in figure 3.16a.

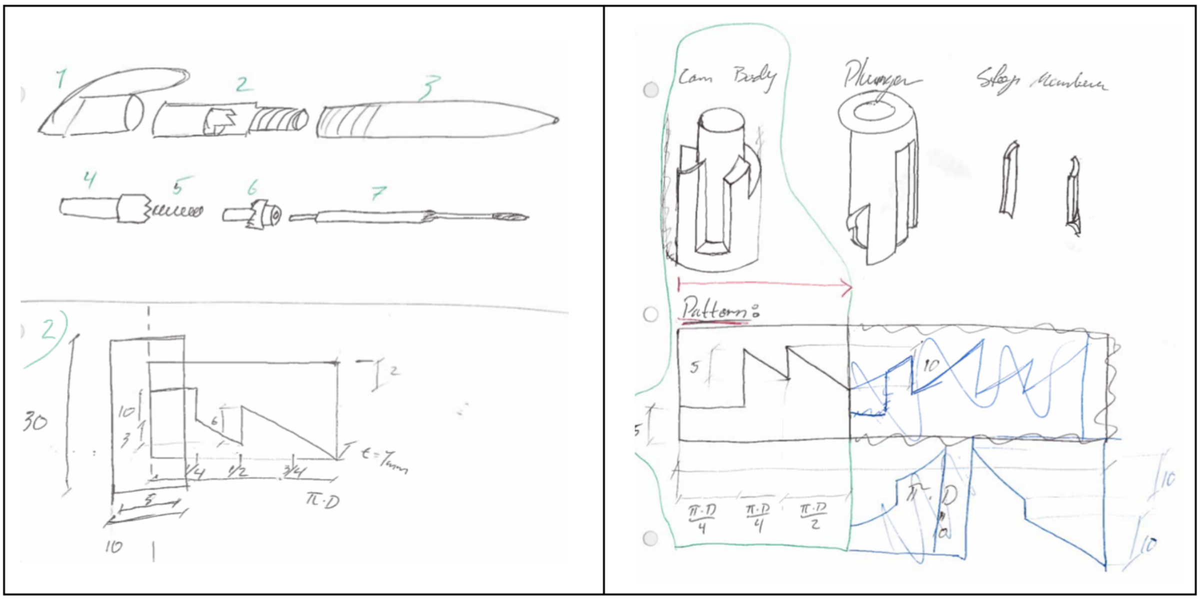


Figure 3.14: Sketch of a disassembled ball pen

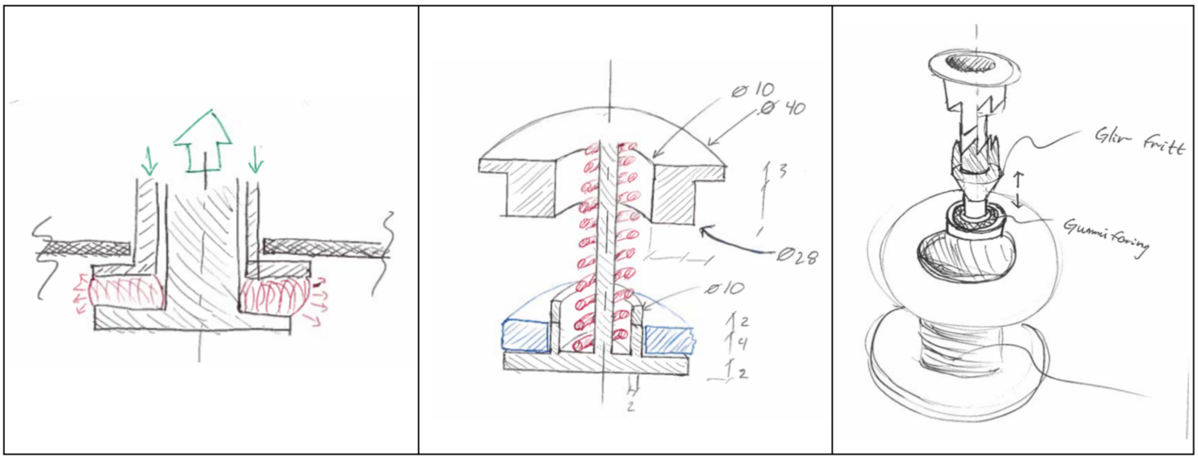


Figure 3.15: Sketch of the merged parts

The CAD files were then printed in an Objet poly jet 3D-printer(figure 3.16b). One of the advantages of this printer is that it can print assemblies. By the use of soft support material, multiple parts can be printed within each other. Unfortunately, the used tolerances were too small, and the parts did not fit together as intended. Adjustments were put on hold after the realisation that the gripper head was too long. The reel floor provided stabilisation and the necessary force against the silicone and was thus chosen as the end point. This meant that the gripper would have to operate in a height that was minimum twice the depth of the reel. This was for the gripper to hover over the reel before picking it up and after putting it down. Given the narrow space of the warp opening, there was not sufficient room for this movement without a more complicated bearing system. Again this argued against an internal gripping solution, and it was decided to explore the possibility of an external gripper further.

(a) CAD of expanding gripper (b) 3D print from Objet

Figure 3.16: Internal gripper with an expanding silicone washer

3.2.7 Stabilized External Gripper

The use of an external gripper would ease the design of the corresponding bearing. To ensure a stable connection between an external gripper and reel, it was thought of modifying the reels by adding a male or female connector. Such a connector was designed that allowed for free rotation. The modification of the reel was further equipped with gear for actuated rotation. The corresponding gripper head was designed in CAD, and the assembly can be seen in figure 3.17. For further design, this solution would have to be shortened, but the concept proved promising.

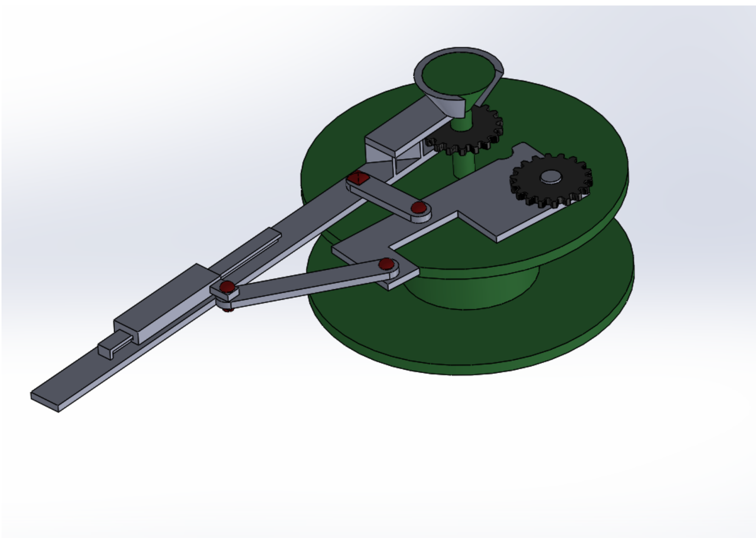


Figure 3.17: CAD of a stabilized external gripper

3D-print

The external gripper, as well as the counterpart for the reel, was 3D-printed. The gripper was designed so that it could be controlled by hand. The mechanism worked well, and so did the stabiliser. The driving mechanism and bearings still needed to be designed, but the concept seemed promising regarding stability and control.

Figure 3.18: Stabilized external gripper 3D-print

3.2.8 Evaluation of Internal and External Gripper Concepts

By probing these different concepts, the team now had a better idea of the solution space. External gripping could make for a less complicated mechanism and bearing system, compared to internal gripping. A visualization of the explored solution space is shown in figure 3.19.

After testing different shuttles, new directions were pointed out from point A. The way-faring journey started with probing an external gripper ("Gripper Arm") with a rapid prototype using Meccano. To find a more stable connection, a new direction towards an internal gripper screw was mapped out. After probing a few prototypes it was concluded that a more reliable mechanism was needed. The expansion gripper concept was explored by silicone casting and merging parts with parts from a ball pen. This solution was abandoned because of space restrictions and the need for a complicated bearing system. Finally, the stabilized external gripper was designed, combining knowledge from the previous probing cycles. This solution consisted of a reliable and stable mechanism, and needed no complicated bearing system. At this point, the list of requirements was updated. The resulting bullet points is seen below figure 3.19.

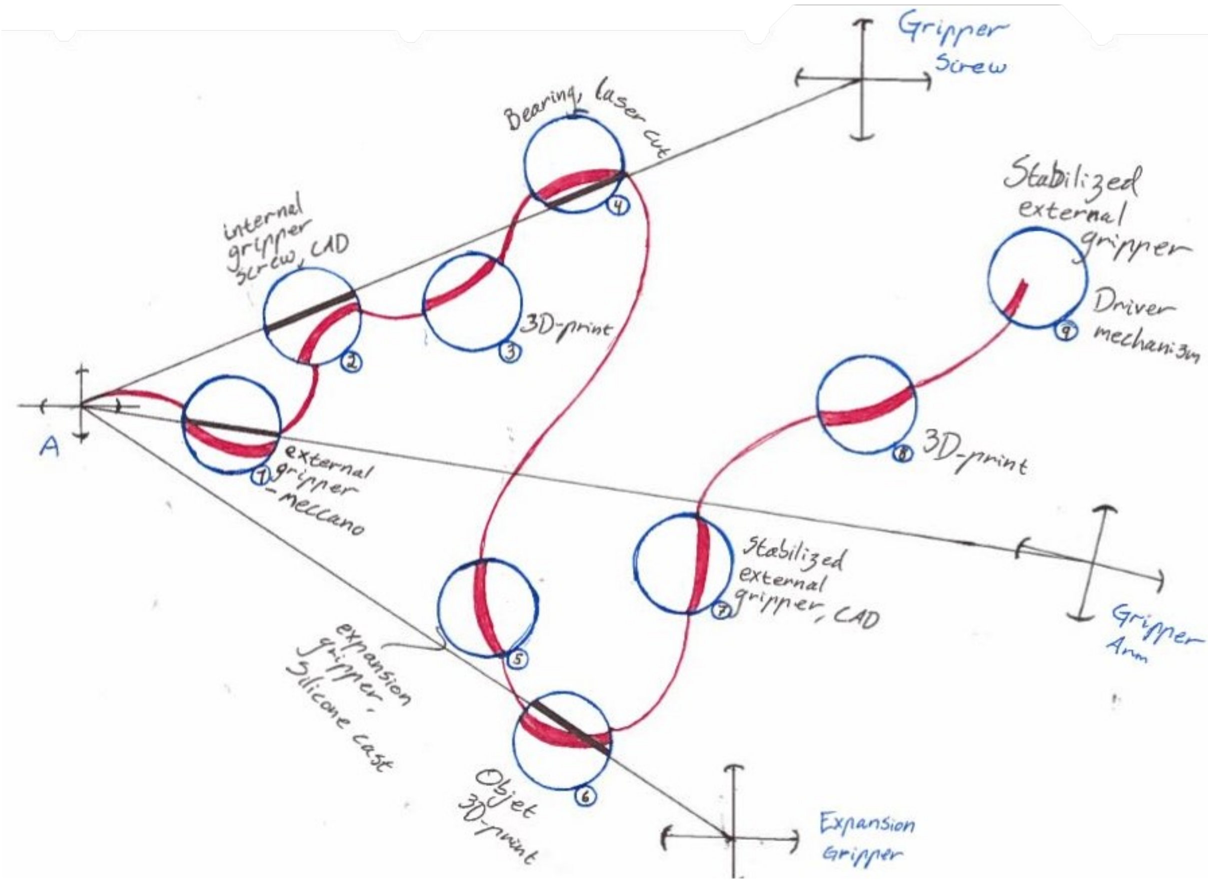


Figure 3.19: The wayfaring journey in the solution space of handling the reels

- Handle several reels
- Move within given dimensions
- Rotate freely during linear movement
- Gather excess thread
- Inherent self-stabilization
- Reliable mechanisms
- Make for uncomplicated bearing and actuation

Updated basis requirements

At this point, the given dimensions of the warp opening were changed. This updated requirement made all previous concepts unusable. A pivot point in the concept development was encountered, resulting in a new concept that can be found in the following chapter. The generated knowledge up to this point supported the further development, proving the strength of the wayfaring approach.

Chapter 4

New Concept Development

During the development of the gripper, the rest of the development team were designing and building the second prototype of the loom. This time with more detailed dimensions and custom-made aluminium parts. As functions in the old machine had been approved, they were no longer designed for easy removal and modular improvements. Thus the size of the machine was significantly reduced in the new design. We wanted to use the same reels for the new machine as these would still hold about the same amount of wire. This simplified the modular development of the gripper and garages.

Changing requirement

Though the size of reels was kept the same, the gap of the opening warps was reduced in the updated design. From a height of roughly 80 mm, it was now less than 30 mm. This change of initial requirement made previous gripper designs unusable. As complicated mechanisms had proved difficult to design in a fashion short enough, it was intended to search for a new perspective. To find inspiration, the TRIZ problem-solving tool was used to search for a principle that reduces "volume of moving object". Cross-referencing against different sacrificing factors, a series of principles were given as outputs. Out of these was the principle of extraction found promising.

Pivot point

As the gripper was thought to inherit all the functional specifications, all concepts generated so far were possible solutions for this. In hindsight, this was a type of design fixation. Extracting some functions from the gripper head and moving them to other components in the system would reduce the complexity of the gripper head, allowing it to be simpler and possibly reducing its height. If actuated rotation of reels were extracted and placed in the garage instead, the requirements for the gripper would be substantially simplified. The gripper would then only need to move the reel linearly while allowing extraction of wire. This fresh insight was brought to the workshop for ideation through rapid prototyping.

4.1 Rapid Prototype

Simple materials like cardboard, paper cups, hot glue, and magnets, were used to experiment with the reel movement focusing on picking the reel up, allowing free rotation, and putting it down. The idea of connecting the reel to the gripper by magnets seemed promising. This solution needed only the additional height of a magnet on top of the reel, still providing desirable stability, and friction of rotation. The gripper would only need to hover over the reel to pick it up and transport it across the warps.

Some mechanism was needed at the end garage in order to secure the reel's final position. To solve this, the idea of a mechanism that opens on the way in and closes when the reel is in place was thought of. To avoid use of sensors and actuators, this mechanism could interact with the gripper by means of a pin and slot. Further ideation led to a concept of a hinged arm on the garage with a pin following the shape of a slot in the gripper. The trail of the pin was sketched onto the gripper as to lead the garage arm away from the reel on the way in, and blocking it on the way out. When closing the garage arm, the reel was constrained enough to exceed the magnetic forces, and the reel stayed put.

For simple controlling of the gripper, it was sought only to have it move linearly back and forth. This imposed a restriction on the shape of the guiding lines. With scissors and cardboard, the shape of the lead was gradually shaped while moving the gripper until a satisfying movement of the arm on the garage were found (figure 4.1).

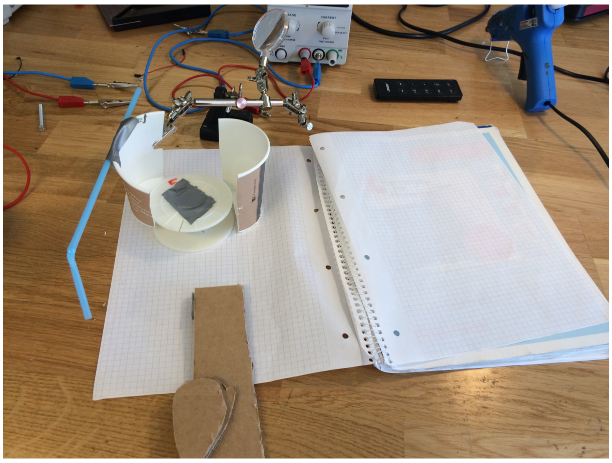
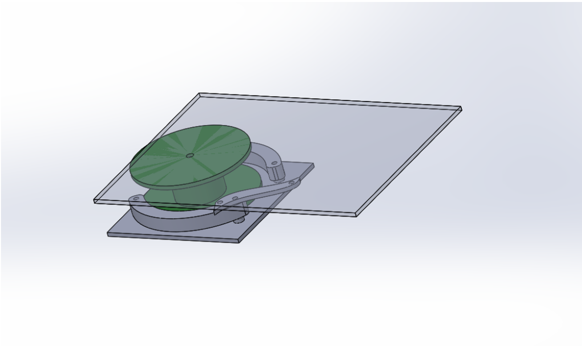


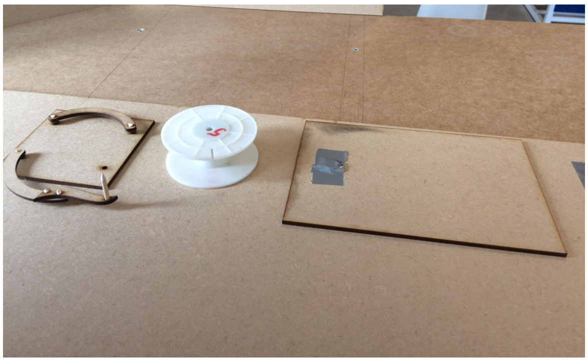
Figure 4.1: Rapid Prototype

4.2 First CAD and Assembly

Next, this rapid prototype was brought to a computer where the garage design was quickly designed using CAD, details kept to a minimum. It was then 3D-printed and laser cut. The higher fidelity prototype was used to physically test the concept to reveal flaws in the design. CAD and physical prototype can be seen in figure 4.2.



(a) CAD of arm concept



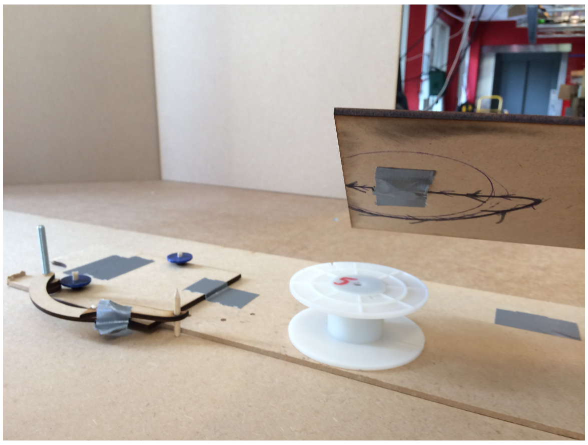
(b) Garage Arm Concept

Figure 4.2: First arm concept

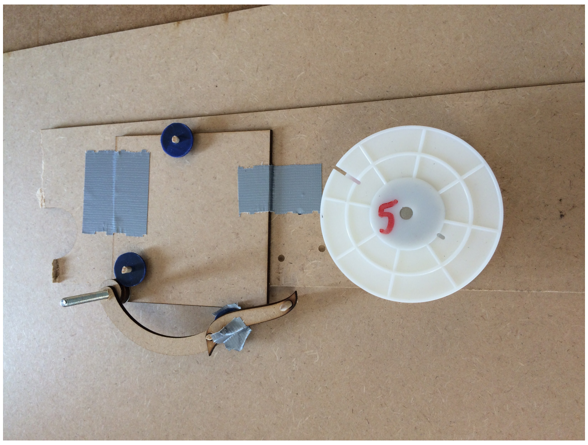
4.3 Guide Design

The functionality of the garage would later need to be integrated with the garage sorter (see section 3.1). The size of the garage floor should only be marginally bigger than the reel for this garage to be of the desired size. It was main priority at this point to explore the functionality of the concept, but later adjustments would have to be made to reduce the size. The first improvement was to reduce the fixed arm to a set of points sufficient to constrain the reel. These are seen in figure 4.3b.

The design of the guide shape was done by sketching the trail of the gripper while repeating its movement as seen in figure 4.3a. The function of the lead pin was to guide the arm away from the reel on the way into the garage, and blocking the reel on the way out.



(a) Sketching the guide trail



(b) Constraint points in blue

Figure 4.3: Designing guide trail

4.4 Guide Test

The guide sketch was taken to CAD where it was fit to the existing assembly and adjusted so it would not interfere with existing functionality. The 3D-printed design is shown in figure 4.4.

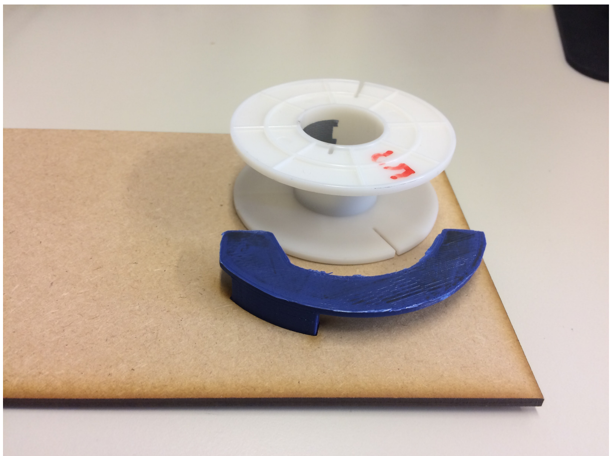


Figure 4.4: 3D-printed guide shape

The lead pin on the garage arm should follow the outside of the guide shape on insertion, and on the outside on extraction. This trail is shown in figure 4.5.

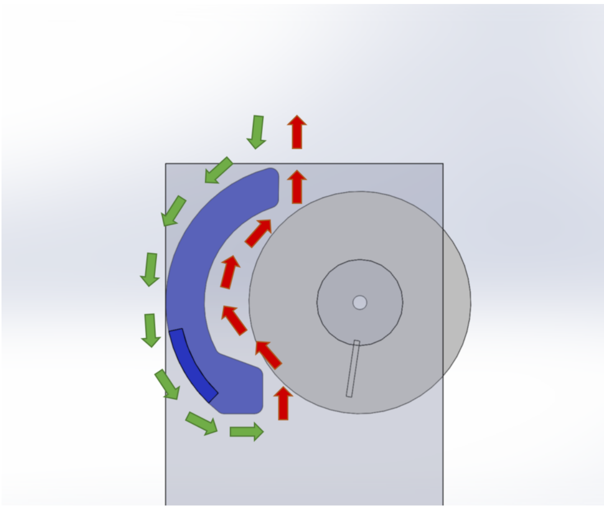
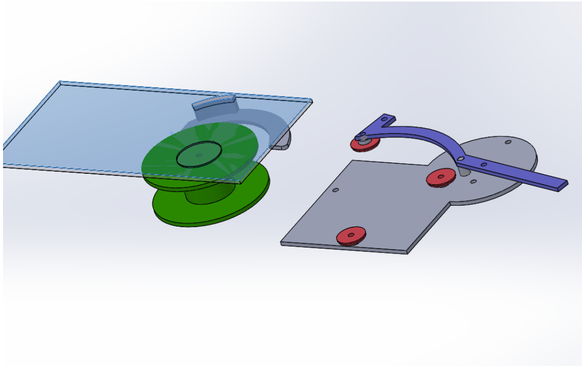


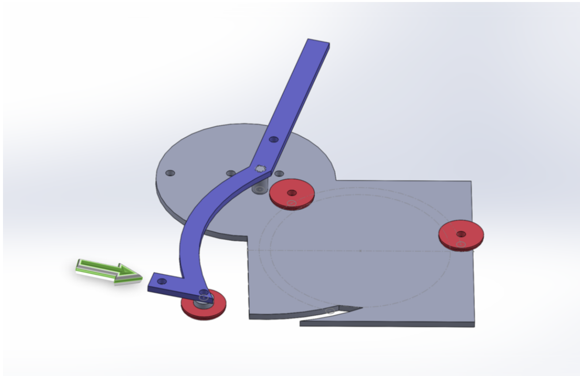
Figure 4.5: Trail of the lead pin indicated by arrows

4.5 Garage Arm and Lead Pin

Testing the concept proved successful, so the next step was to complete the mechanism for the arm. In order for the guide trail and the pin to interact without interfering with the reel, the lead pin was offset by a small distance from the arm. A rubber band was added as spring-load for the arm to move back to its initial position after interacting with the guide. the desired direction is shown in figure 4.6b. It is important that this spring-load is weak enough for the reel to push the arm away when it is picked up by the gripper at the starting garage. A CAD assembly served as a dynamic test to detect collisions, and the design was produced when this proved satisfactory. The CAD is seen in figure 4.6a.



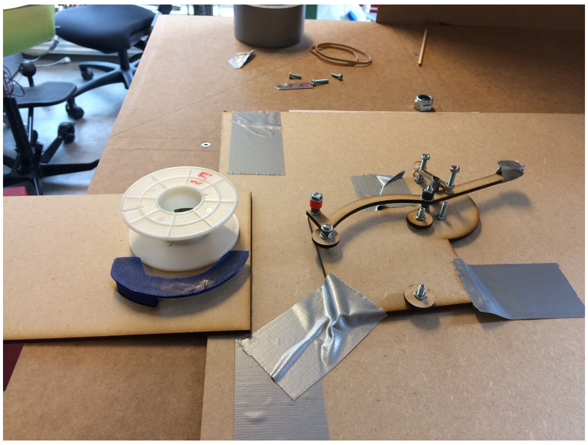
(a) CAD of garage arm in purple



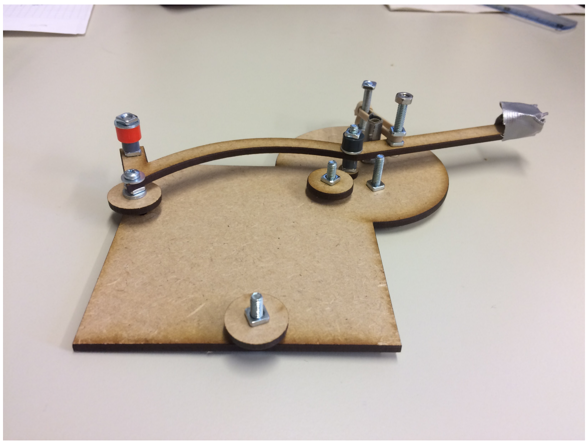
(b) Direction of spring-force

Figure 4.6: Garage arm concept

The assembled parts are seen in figure 4.7. The red lead pin interacted well with the guide trail, moving the garage arm as desired. The shuttle was successfully constrained by the mechanism.



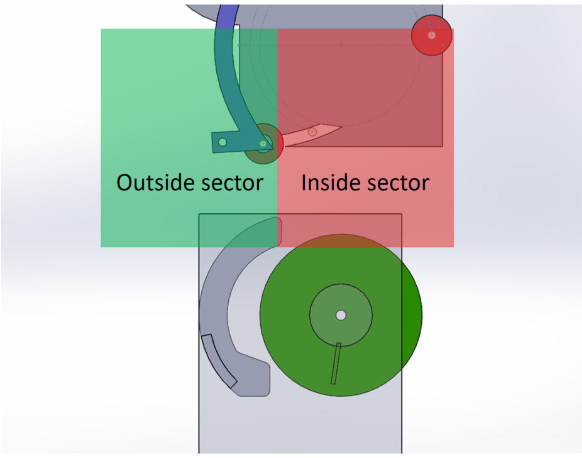
(a) Testing the garage arm. Gripper with reel is upside down



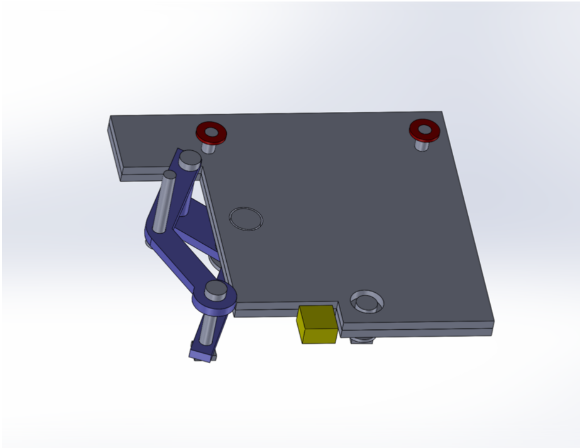
(b) Garage floor with garage arm. Lead pin in red.

Figure 4.7: Functional garage arm

For the desired movement of the garage arm, the lead pin had to follow the outside of the guide on insertion and the inside on extraction. This implied that the resting position of the garage arm had to be within the range of the outside guide as shown in green in figure 4.8a. If the lead pin rest in the red sector, it would follow the inside trail meant for extraction. The spring-loaded garage arm had to be adjusted, so the resting position was within the green sector. This could easily be fixed by adding a soft padding that constrain the spring-loaded force but allows the garage arm to compress it during extraction. Such a pad is added to an updated garage floor design in figure 4.8b.



(a) Sectors for the guide trail



(b) A soft pad shown in yellow

Figure 4.8: Adjustments of garage arm resting position

4.6 Compressed Design

With all functionality working, it was time to refine the design to make a satisfactory compact solution to fit the garage sorter. First, the gripper was made slimmer. The distance between the magnet and guiding trail was the constraining width. The old and the new design is seen in figure 4.9 for comparison.

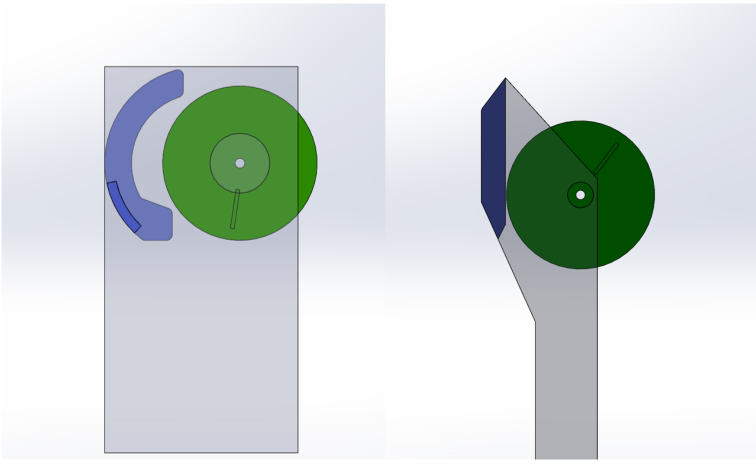


Figure 4.9: New gripper design to the right

Then the joint of the garage arm was moved underneath the place of the garage where the reel would go. This also let the lead pin more easily push the arm away on the way in. Iterations on this design were done, designing the arm so the original fit with the guide trail and lead pin would work. The spring mechanism was moved from its initial position to one in the front of the garage. Some adjustments had to made to regain the right equilibrium. The resulting design and the old for comparison is seen in figure 4.10.

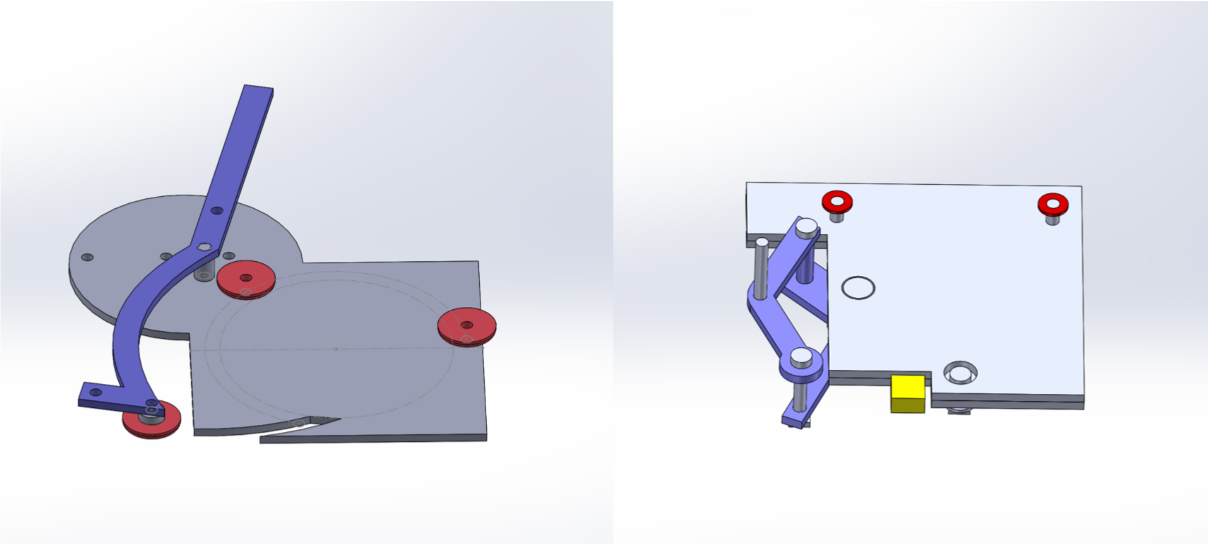


Figure 4.10: New garage floor design to the right

The last build of the compact design is seen in figure 4.11. This is the resulting design of the gripper and reel interaction.

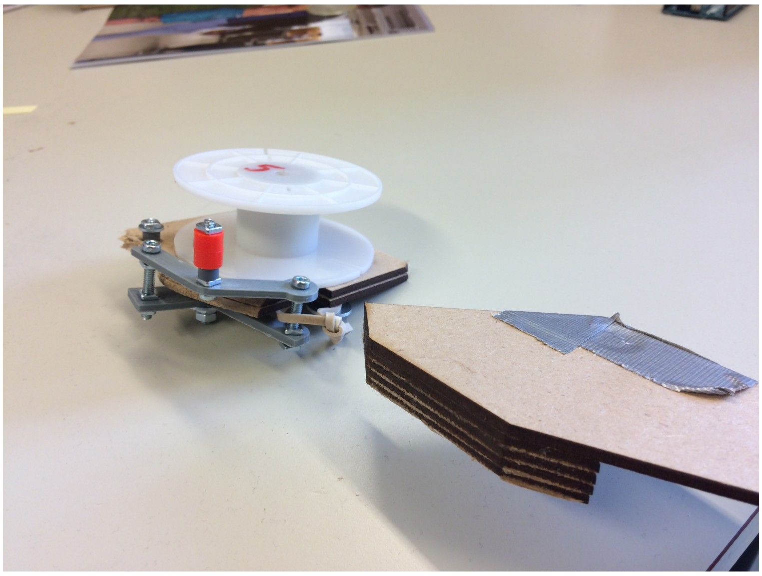


Figure 4.11: Last build of compact design

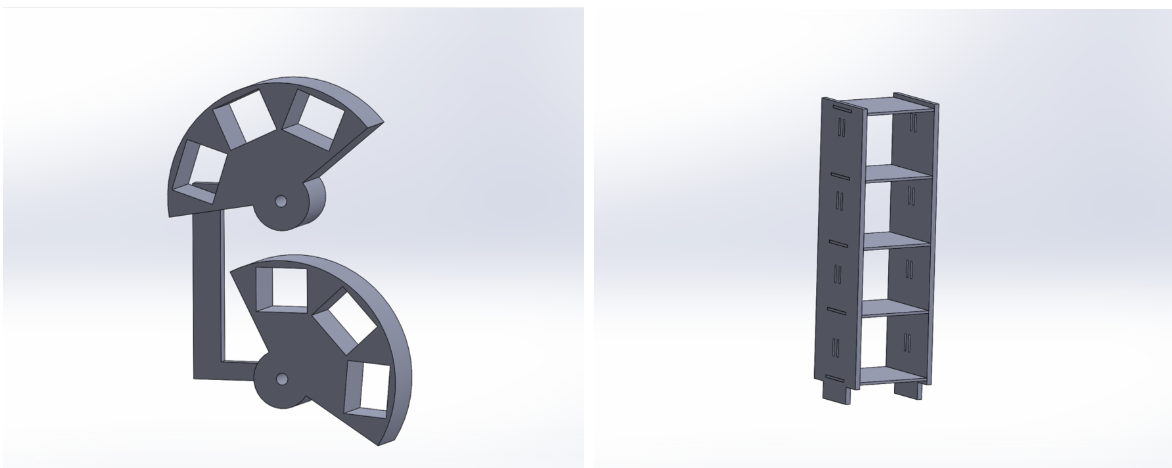
Chapter 5

Results

The resulting concept of garage sorting and reel handling is as far as the author is concerned an innovative solution within the field of weaving. This design was approved by the rest of the technical team, and the work with implementing it to the rest of the machine was started. A positive certificate was received from Alva for the work conducted through the project- and master thesis, and is found in appendix A. The company has been provided with access to all files. The concept was further refined in CAD and assembled in the remaining machine assembly by Magnus Becher in Alva to much appreciation.

5.1 Garage Sorter

The most promising garage solution is still on a concept level and was never finished because of the changed priorities during the time of the project. Compared to the former solution it should sort the reels more efficiently by grouping them in two. This reduces the amount of wire each reel must extract by moving during sorting. It operates in a plane that makes interaction with the gripper easy. The concept solution is a low-resolution CAD that aids to point out a direction for further work together with the problem analysis in section 3.1.3. For now, a simpler garage has been used as a substitution. The garage concept and its temporary replacement can be seen in figure 5.1



(a) Garage concept (b) Garage substitution

Figure 5.1: Garage

5.2 Magnetic Gripper

The magnetic gripper solution is ready for production after the work of fitting it to the rest of the machine. The concept has been tested successfully with a medium resolution prototype. It consists of a gripper, and a garage floor to be integrated into the garage sorter. The gripper interacts with the reel by a magnetic connection. This ensures stability and resistance to rotation in order to limit excess extraction of wire. A guiding slot is fixed on the underside of the gripper and interacts with a lead pin on the garage floor. This lead pin is the part of a rotating arm that opens up when the reel is inserted to the garage and closes when the gripper is retracted. This mechanism constrains the reel in its final position. Moving parts is reduced to a minimum to ensure mechanical reliability. The solution is considered easy to automate as it allows the gripper to move in a strictly linear line. Further detailing and ideas for implementation of functionality is discussed in the chapter for further work (chapter 7). A rendering of the gripper and the garage floor is shown in figure 5.2, and the implemented solution in 5.3.

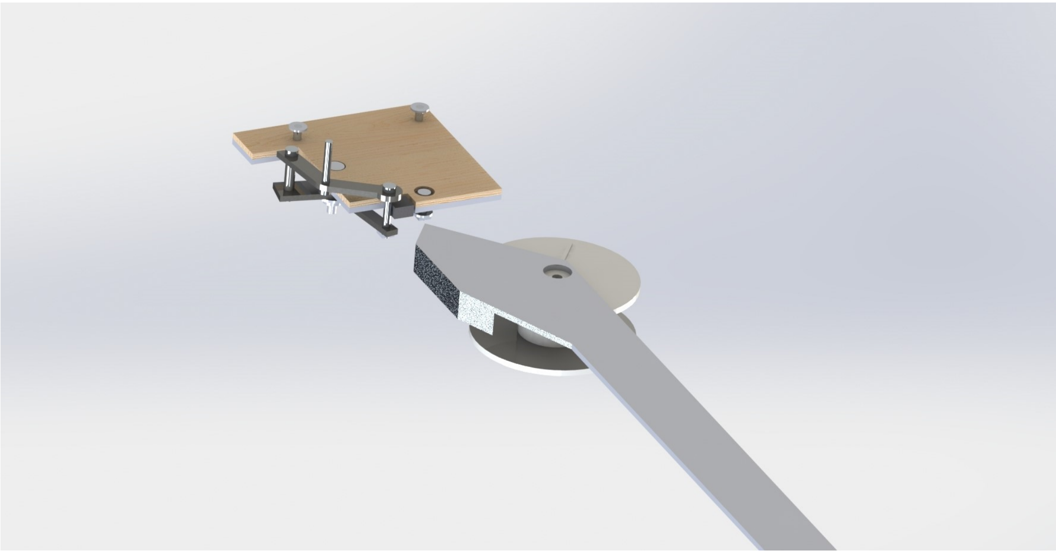


Figure 5.2: Rendering of final gripper concept

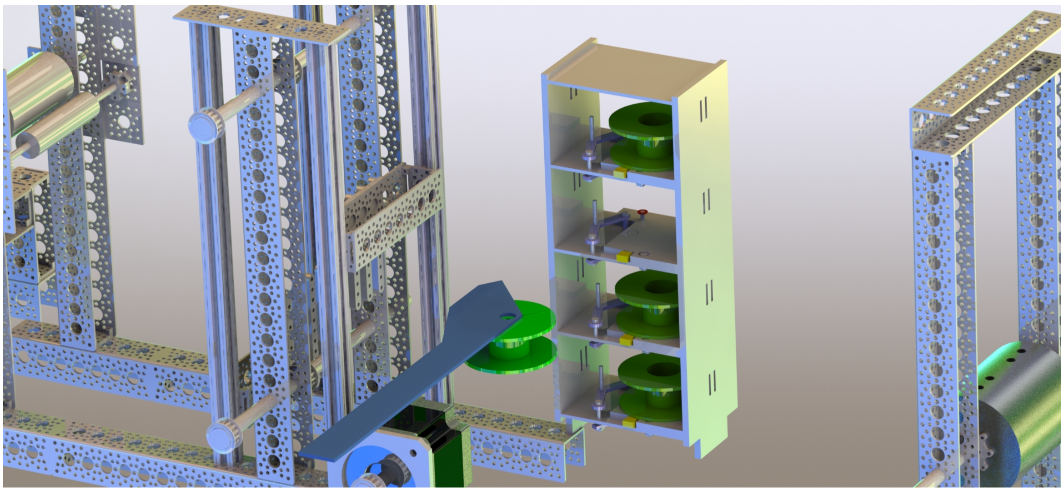


Figure 5.3: Implemented Gripper and garage

5.3 Production Prototype

The goal of the second prototype of Alva's production process is a proof of concept. The level of details is greatly increased from the first prototype. The modularity is compromised by the detailed custom parts, but the frames of the machine provide room for adjustments. It has nine warps of glass fiber that is split into two groups through the heddles. The heddles open automatically for weft insertion. The gripper and garage substitution will be implemented right after this gap as seen in 5.5. The woven cloth will be rolled up on a 3D-printed cylinder at the end of weaving. Finally, the cast will be performed manually.

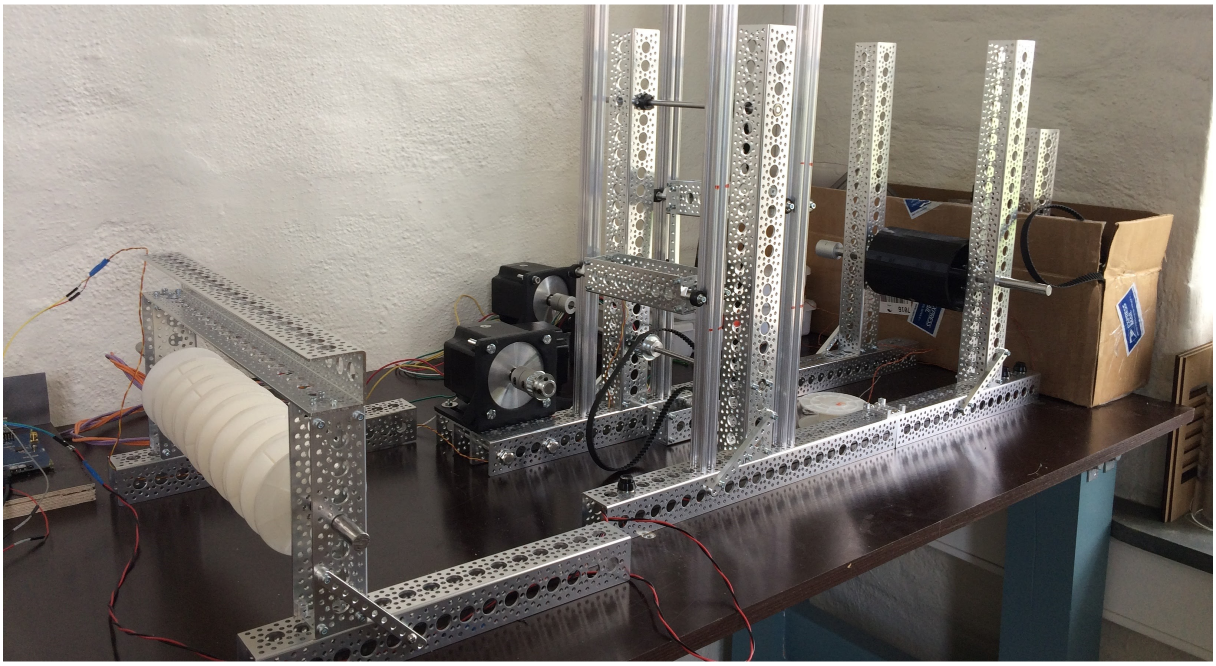


Figure 5.4: Production Prototype

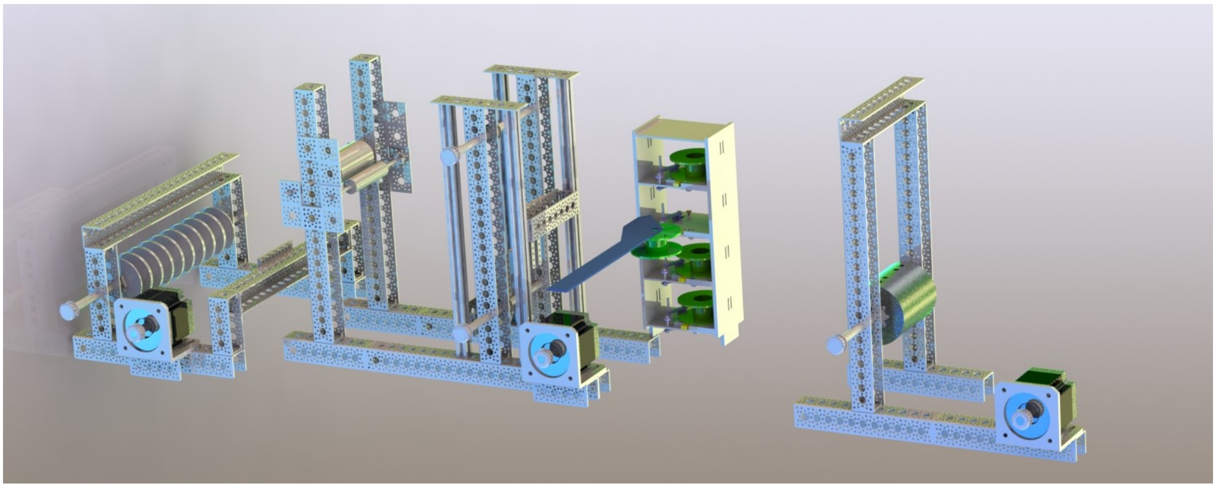


Figure 5.5: CAD of production Prototype

5.4 Product

The final product is a lightweight stator. The goal of Alva is that the production process can be applied to a variety of motor designs with better performance and lower production cost than existing motors on the market. The composite design is suitable for use in drones, and a concept design of a hub motor is seen in 5.6. In the long term, Alva intends to apply the production method to numerous industries beyond drones. Technology verification in the UAV segment will leverage the technology towards more conservative industries. Marine applications in thrusters and actuators, aerospace and defence applications in propulsion systems, energy applications in wind turbines and subsea generators, and transport applications in land-based vehicles are all candidate markets.

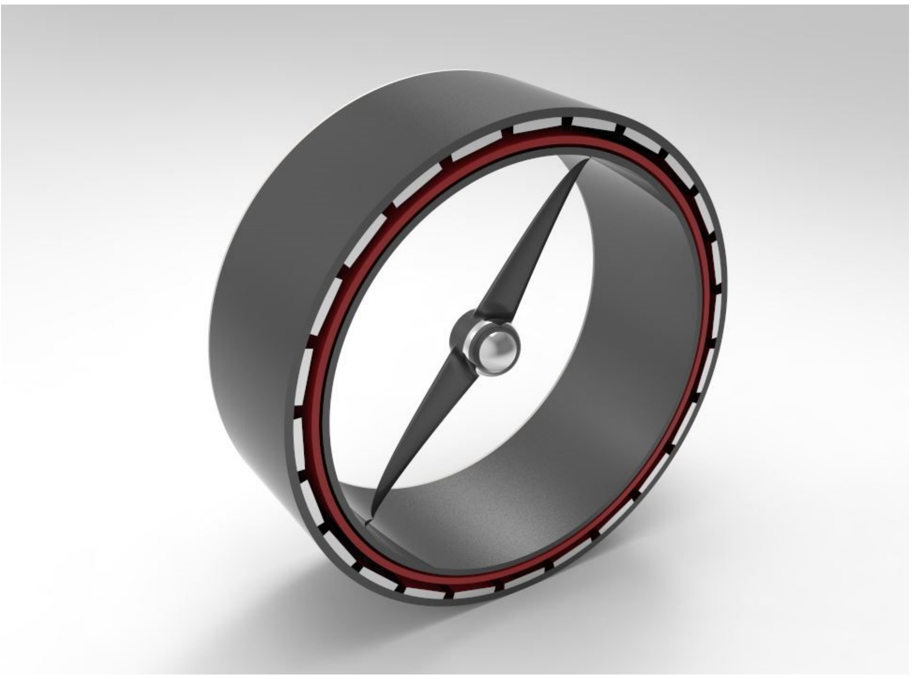


Figure 5.6: Hub motor concept

Chapter 6

Work Assessment

The work through this thesis was conducted with a deliberate focus on prototyping mentality. Inspired by the wayfaring model, the solution space has been explored through iterative design-build-test cycles. This approach proved valuable for use in a startup company where a high level of uncertainty was expected. Reasons to focus on development methodology were for Alva to find a suitable strategy for further product development, and to provide empirical data for the research at TrollLABS. For Alva, this is even more important as the technology grows more complex. The development through this thesis, compared to that of the project thesis was mostly done individually because of practical reasons. This provided insights of the pros and cons of teamwork in a development project.

6.1 Wayfaring

The Wayfaring Model was used to better cope with unexpected changes to requirements in comparison with more conventional methodologies like Stage-Gate. The occurrence of these changes was due to external and internal factors. The external factors changed as Alva has been searching and refining the business model throughout this early phase of development. Changing the targeted market makes for changes in the product which again affects the production method. Meanwhile, internal factors changed because the development work was conducted in a modular fashion, where team members were responsible for different functionalities. Changes to the production process have affected the interactions between these functionalities, which results in updated requirements for each sub-solution. The wayfaring model has been a great fit for this project in order to deal with these changes effectively. Using this model allowed for failing early as opposed to resource-draining rework later in the process. The rapid iteration cycles enabled faster learning and the agility to change direction in the growing solution space. It also made possible the exploration of different technologies, which is particularly beneficial for engineering students with limited experience.

6.2 Prototyping

Alva agreed to do prototype-oriented development for many reasons. It has been important as a proof of concept to make a prototype of the production process so that functioning stators can be produced. The prototypes were also used by the development team to communicate solutions.

6.2.1 Production Prototypes

The old production prototype built during the time of the project thesis was an internal, reflective prototype. It was low-fidelity, focusing on learning. The new production prototype is external and affirmative and thus high-fidelity. It is meant to function as the production of stators and as a showcase for stakeholders.

6.2.2 Gripper and garage

For this thesis, internal, reflective prototypes have been used for learning. They are an inherent part of the wayfaring model. For efficient prototyping, the functionality of focus for each prototype has served as a filter for what to test. For the most part, quick sketches have served as the principle basis, followed by a CAD with only necessary details. This CAD file has been the basis for the prototype, usually laser cut MDF or 3D-printed PLA. This allowed for a fast process of actualizing concepts for testing. The rapid prototypes of low fidelity required a minimum investment of resources. In addition to provide fast learning, this helped to overcome design fixations. As the second production prototype was designed and built, requirements for the modules were updated. One of these changes was the adjustment of the gap between the warps where the reels pass. This specific change proved the strength of the rapid prototyping approach. Working with dynamic requirements made changes like these much easier to deal with, and the result was a functional gripper concept. If a more conventional linear process was applied, it is likely that the resulting mechanism would have to be turned down or excessively reworked. Instead, it worked as a pivot point in the concept development by overcoming a design fixation. The resulting solution is a reliable mechanism that allows for the weaving of uncut wires. In the work of further detailing this solution, CAD software was very helpful. By interacting with the parts in an assembly, the dimensions could be fitted for a more compact solution. The iterative approach of building and testing after each improved CAD design was still used.

6.3 Modularity

The modular approach used in this project was due to two factors. First, the different sub-functions of the production prototype built during the project thesis were of varying quality. Some were approved as functional prototypes, while others needed re-designing. Second, the joint workshop did not satisfy the requirements for all fields of development. The small space put a restriction on the workflow, and there were limited tools available. Finding a common workspace proved difficult as the students in the project were not from the same departments of the university, thus access to ideal workshops on campus were difficult to organise and had to be paid for. The development of a concept for handling reels and organising these was therefore mostly done away from the rest of the machine and the technical team. This was probably one of the main reasons the mentioned change of warp opening size was communicated so late in the building process. A modular approach fitted well for developing a linear production process like this, mostly because each function in the sequence is well-defined. Through this experience, we argue that communication is essential for modular development to work well.

6.4 Multi-Disciplinary Teams

Because of the previously mentioned practical reasons, most of the development was done by one person. This naturally inhibited the factor of a multi-disciplinary team. Different technical expertise in a team creates interlaced knowledge from which a broader solution space can grow. Thus innovative solutions are more likely to be generated in multi-disciplinary teams. The development slowed down as time had to be spent reading up on unfamiliar fields. As Smith (2007) puts it: "the team is also more likely to have the skills needed without switching players". Another argument for why the product development, and particularly the fuzzy front end, would have been more efficient if done in a team, is that people in teams take on different roles that are complementary in the project. A divergent creative person is better at asking generative design questions while asking deep reasoning questions is easier for an analytical person. These different mindsets can be resembled by one person during the different phases of a probing cycle, but the potential will be reduced as opposed to a multi-disciplinary team.

When prototyping alone, there is one thing that is important to keep in mind. When prototyping internal, reflective prototypes in teams, an inherent focus on presentation naturally occurs. This pushes ideas towards physical realisation. If not aware of this, ideas can easily get stuck in one's mind, and eventually, lead to lost knowledge for the company.

Chapter 7

Recommendations for Further Work

The technical team at Alva still have many challenges ahead. After the garage sorter is designed and implemented with the gripper, an automatic weaving loom is within reach. For a complete production line, the process of casting the woven cloth in epoxy still needs to be engineered. A suiting strategy for this further product development can hopefully be inspired by the method chapter and the work assessment of this thesis. With the aid of grants and funding the process of patenting the production process can start, and technically experienced staff can be hired.

7.1 Gripper and Garage

A natural starting point for the development team is to design the garage sorting solution. The focus should be on good interaction with the gripper and on eliminating tangling. Further details on the problem are found early in the concept development chapter along with some principle solutions for use as a starting point. From experience with the first prototype of garage sorting from the previous period, it is obvious that testing before implementing is crucial. The wayfaring model and iterative design-build-test cycles as discussed in the method chapter of this thesis should be helpful. The gripper and garage floor are ready for final testing when produced in more rigid and non-magnetic materials like aluminium. If the need for actuated rotation of reels arises, it is suggested to implement this in the garage floor. An electromagnetic connection can be used on the garage floor to constrain the reel in place, and a slip ring and motor should allow for actuated rotation. The idea of an electromagnetic connection can also be explored as a replacement of the mechanical garage arm. This requires the use of sensors and controlling, but can provide a quick and reliable mechanism.

7.2 Other Processes

The work of this thesis has mainly been focusing on handling the reels. The gripper and garage sorter are the main parts of this functionality. Meanwhile, the rest of the loom has been designed and produced by Magnus Becher, Vilius Ciuzelis, and Anders Engebakken. When the automatic multiple-reel loom is functional, the next step is casting. Benchmarking of epoxy for conductive application is important preliminary work. The woven cloth is thought to be cast in epoxy resin to assure rigidness and protection. Further, the stator will undergo a series of tests providing essential data for further development and possible investors. Among interesting factors for examination is efficiency as a function of power per weight and heat generation during operation.

7.3 Method

A modular approach helps the speed of development, but should not prevent interaction between team members. The SCRUM framework can be a valuable tool to deal with this. More details on this framework are found in the unpublished article "Using Lean Product Development principles to detect waste and Scrum Strategy to deal with these" written during the work of the project thesis. The article is found in appendix C. It is important that the modules are well defined by the interaction with other sub-functionalities. If an interaction is changed, this must be reflected through updated requirements. An argumentation for the suitability of probing for this project is found in the method chapter of this thesis along with notes on prototyping mindset. An iterative approach should help the development team to learn faster while reducing unwanted rework like that of the first garage sorter.

It is strongly recommended to include all disciplines early on in the further development. Multi-disciplinary teams generate more innovative solutions from a broader solution space while collecting interlaced knowledge for the company. Inspiration for implementing this can be found from the wayfaring model in combination with the SCRUM framework.

7.4 The Future of The Company

Alva's production technology proved itself to be promising for further development by the Norwegian Research Council (NRC) this year, providing the startup company with the STUD-ENT grant. This funding will greatly help the company to reach its goals. Alva is currently hiring technical staff from the field of electric motor design and innovation. The STUD-ENT grant will help to improve the motor's technology readiness level (TRL) from 3 (Experimental proof of concept) to 6 (Technology demonstrated in relevant environment) by developing a functional prototype for a pilot customer. It will also contribute to the process of patenting the production method for composite stators. This funding will also give Alva the opportunity to provide a joint workshop for its technical team allowing for a much better collaboration environment. The lack of this has been a major disadvantage for the technical development. The ability to acquire necessary machinery and tools will also be appreciated by the technical team. A joint workshop allows the team members to work multi-disciplinary so that further development can be conducted more efficiently regarding results and interlaced knowledge. The lack of a joint workplace is considered the main reason the updated requirement of the open space of warps in the new machine was communicated so late. This event resulted in rework that could have been avoided. The following semester the collaboration with TrollLABS will continue through another project thesis with Alva. This thesis along with the project thesis will hopefully serve as a detailed documentation of both the work done and the methods used as well as a valuable guide for further development. Together with further work, the author hopes it can make for an interesting publication on the research of the fuzzy front end of product development.

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Appendices

Appendix A

Certificate

Employment Certificate

For **Mr. Simen Stenersen Pjaaten**, born on March 7th, 1992.

Simen Stenersen Pjaaten has been working for Alva Industries AS for the period of his Project- and Master Thesis (2016/17) at the Department of Mechanical and Industrial Engineering. Alva is a startup company from the NTNU School of Entrepreneurship developing a novel production method for electric motors.

His main responsibility has been the technical development and building of the first functional prototypes of the production method. This included principle sketches, CAD, and production of custom-made components. Pjaaten also contributed with studies and suggestions for improvement of the company's development method, including aspects of team-interaction.

Pjaaten has an outgoing and open personality and has developed great relationships with his team and colleagues. He has contributed with reflective viewpoints as well as creative ideas and accomplished his tasks conscientiously.

We have greatly appreciated Pjaaten's work and company throughout this period and wishes him all the best for both his professional and personal future.

NTNU Gløshaugen, May 31th 2017

Alva Industries AS

Jørgen Selnes
CEO

Appendix B

Risk Assessment

Enhet: Department of Mechanical and Industrial Engineering **Dato: 30.01.2017**

Linjeleder: Torgeir Welo

Deltakere ved kartleggingen (m/ funksjon): Martin Steinert, veileder/ Kristoffer Slåttsveen /co.veileder, Simen Pjaaten /student.
(Ansv. veileder, student, evt. medveiledere, evt. andre m. kompetanse)

Kort beskrivelse av hovedaktivitet/hovedprosess: Masteroppgave student Simen Pjaaten.

Er oppgaven rent teoretisk? (JA/NEI): *«JA» betyr at veileder innestår for at oppgaven ikke inneholder noen aktiviteter som krever risikovurdering. Dersom «JA»: Beskriv kort aktiviteteten i kartleggingskjemaet under. Risikovurdering trenger ikke å fylles ut.*

Signaturer: *Ansvarlig veileder: Martin Steinert* *Student: Simen Pjaaten*

ID nr.	Aktivitet/prosess	Ansvarlig	Eksisterende dokumentasjon	Eksisterende sikringstiltak	Lov, forskrift o.l.	Kommentar
1	Bruk av Trolllabs workshop.	DM	Romkort	Romkort		
1a	Bruk av roterende maskineri	DM	Maskinens brukermanual	Ukjent	Ukjent	
1b	Bruk av laserkutter	DM	Maskinens brukermanual	Ukjent	Ukjent	
1c	Bruk av 3D printer	DM	Maskinens brukermanual	Ukjent	Ukjent	
1d	Bruk av skjæreverktøy	DM	Ukjent			
1e	Bruk av samenføynigsmidler (lim og lignende.)	DM	Produktets brukermanual og datablad	Datablad	Ukjent	
2	Tilstedeværelse ved arbeid utført av andre.	Andre	Andres HMSRV2601	Andres HMSRV2601	Prosessavhengig	

3	Eksperimentelt arbeid	DM	Egen risikovurdering- må gjøres for hvert enkelt eksperiment		Prosessavhengig	

ID nr	Aktivitet fra kartleggings-skjemaet	Mulig uønsket hendelse/ belastning	Vurdering av sannsyn-lighet (1-5)	Vurdering av konsekvens: Menneske (A-E)	Ytre miljø (A-E)	Øk/ materiell (A-E)	Om-dømme (A-E)	Risiko-Verdi (menn-eske)	Kommentarer/status Forslag til tiltak
1	Bruk av Trolllabs workshop.								
1a-i	Bruk av roterende maskineri	Stor kuttskade	2	D	A	A	D	2D	Sørg for at roterende deler tilstrekkelig sikret/dekket. Vær nøye med opplæring i bruk av maskineri.
1a-ii		Liten kuttskade	3	B	A	A	A	3B	Vær nøye med opplæring i bruk av maskineri. Ikke ha løse klær/tilbehør på kroppen.
1a-iii		Klemskade	2	D	A	A	C	2D	Vær nøye med opplæring i bruk av maskineri. Ikke ha løse klær/tilbehør på kroppen.
1a-iv		Flygende spon/gjenstander	3	C	A	A	B	3C	Bruk øyevern og tildekk hurtig roterende deler (Fres og lignende.)
1a-v		Feil bruk-> ødelagt utstyr	3	A	A	C	A	3C	Vær nøye med opplæring i bruk av maskineri
1b-i	Bruk av laserkutter	Klemskade	2	D	A	A	C	2D	Vær nøye med opplæring i bruk av maskineri. Ikke ha løse klær/tilbehør på kroppen.
1b-ii		Brannskade	3	B	A	A	A	3B	Vær nøye med opplæring i bruk av maskineri. Bruk hansker ved håndtering av varme materialer.

1b-iii		Øyeskade-laser	2	D	A	A	C	2D	Bruk øyevern! Skru av laser når maskinen ved oppsett.
1b-iv		Brann	2	B	A	D	C	2B	Vær nøye med opplæring i bruk av maskin. Ha slukkeutstur tilgjengelig
1c-i	Bruk av 3D-printer	Brannskade	3	B	A	A	A	3B	Vær nøye med opplæring i bruk av maskin.
1c-ii		Innhalering av plast/ printemateriale	5	A	A	A	A	5A	Bruk åndedretsvern/ vernebriller
1c-iii		Feil bruk-> ødelagt maskineri	3	A	A	C	A	3A	Vær nøye med opplæring i bruk av maskin.
1d-i	Bruk av skjæreverktøy	Stor kuttskade	2	D	A	A	D	2D	Bruk skapre verktøy og riktig skjæreunderlag
1d-ii		Liten kuttskade	3	B	A	A	A	3B	Bruk skapre verktøy og riktig skjæreunderlag
1e-i	Bruk av samenføynigsmidler (lim og lignende.)	Eksponering på øyet	2	D	A	A	B	2D	Bruk øyevern, ha datablad tilgjengelig
1e-ii		Eksponering hud	4	A	A	A	A	4A	Bruk hansker, ha datablad tilgjengelig
1e-iii		Eksponering åndedrett	4	A	A	A	A	4A	Bruk åndedretsvært/ god ventilasjon. Ha datablad tilgjengelig.

1e-iv		Søl	4	A	B	A	A	4A	Ha papir/ rengjøringsmateriell tilgjengelig. Ha datablad tilgjengelig.
2	Tilstedeværelse ved arbeid utført av andre.	Se andres risikovurdering om sikkerhet betviles.	3	C	C	C	C	3C	Hold et øye med hva som foregår rundt deg.
3-i	Eksperimentelt arbeid	Vann-drukning	1E	A	A	A	D	1E	Bruk redingsvest i båt og lignende.
3-ii		Elektrisitet- strøm	3	B	A	A	A	3V	Typisk lite energi involvert. Bruk isolerte verkøty

Sannsynlighet vurderes etter følgende kriterier:

Svært liten 1	Liten 2	Middels 3	Stor 4	Svært stor 5
1 gang pr 50 år eller sjeldnere	1 gang pr 10 år eller sjeldnere	1 gang pr år eller sjeldnere	1 gang pr måned eller sjeldnere	Skjer ukentlig

Konsekvens vurderes etter følgende kriterier:

Gradering	Menneske	Ytre miljø Vann, jord og luft	Øk/materiell	Omdømme
E Svært Alvorlig	Død	Svært langvarig og ikke reversibel skade	Drifts- eller aktivitetsstans >1 år.	Troverdighet og respekt betydelig og varig svekket
D Alvorlig	Alvorlig personskade. Mulig uførhet.	Langvarig skade. Lang restitusjonstid	Driftsstans > ½ år Aktivitetsstans i opp til 1 år	Troverdighet og respekt betydelig svekket
C Moderat	Alvorlig personskade.	Mindre skade og lang restitusjonstid	Drifts- eller aktivitetsstans < 1 mnd	Troverdighet og respekt svekket
B Liten	Skade som krever medisinsk behandling	Mindre skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1uke	Negativ påvirkning på troverdighet og respekt
A Svært liten	Skade som krever førstehjelp	Ubetydelig skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1dag	Liten påvirkning på troverdighet og respekt

Risikoverdi = Sannsynlighet x Konsekvens
Beregn risikoverdi for Menneske. Enheten vurderer selv om de i tillegg vil beregne risikoverdi for Ytre miljø, Økonomi/materiell og Omdømme. I så fall beregnes disse hver for seg.

Til kolonnen "Kommentarer/status, forslag til forebyggende og korrigerende tiltak":
Tiltak kan påvirke både sannsynlighet og konsekvens. Prioriter tiltak som kan forhindre at hendelsen inntreffer, dvs. sannsynlighetsreduserende tiltak foran skjerpet beredskap, dvs. konsekvensreduserende tiltak.

MATRISE FOR RISIKOVURDERINGER ved NTNU

KONSEKVENS					
Svært alvorlig	E1	E2	E3	E4	E5
Alvorlig	D1	D2	D3	D4	D5
Moderat	C1	C2	C3	C4	C5
Liten	B1	B2	B3	B4	B5
Svært liten	A1	A2	A3	A4	A5
	Svært liten	Liten	Middels	Stor	Svært stor
	SANNSYNLIGHET				

Prinsipp over akseptkriterium. Forklaring av fargene som er brukt i risikomatrisen.

Farge	Beskrivelse
Rød	Uakseptabel risiko. Tiltak skal gjennomføres for å redusere risikoen.
Gul	Vurderingsområde. Tiltak skal vurderes.
Grønn	Akseptabel risiko. Tiltak kan vurderes ut fra andre hensyn.

Appendix C

Project Thesis

PROJECT THESIS

Developing a Novel Electromotor Concept

Simen Stenersen Pjaaten
Fall 2016
DEPARTMENT OF ENGINEERING DESIGN AND MATERIALS
NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY
SUPERVISORS: RALF MARTIN STEINERT
& KRISTOFFER BJØRNERUD SLÅTTSVEEN

THE NORWEGIAN UNIVERSITY
OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF ENGINEERING DESIGN
AND MATERIALS

PROJECT WORK FALL 2016
FOR
STUD.TECHN. Simen Pjaaten

EMCM - Developing a novel electromotor concept

Join the development team of EMCM and help developing the new concept, including fabrication methods. Initial starting point is to evaluate weaving technology. Task are:

- generate concepts,
- build prototypes and parts
- build test setups
- test and compare alternatives
- judge concepts
- generate functional prototypes

Also, it is expected to contribute to one or more scientific publications during the project/master thesis.
The supporting coach is Kristoffer Slåttsveen, the contact at EMCM is Jørgen Selnes.

Formal requirements:

Students are required to submit an A3 page describing the planned work three weeks after the project start as a pdf-file via “IPM DropIT” (http://129.241.88.67:8080/Default.aspx). A template can be found on IPM’s web-page (https://www.ntnu.edu/ipm/project-and-specialization).

Performing a risk assessment is mandatory for any experimental work. Known main activities must be risk assessed before they start, and the form must be handed in within 3 weeks after you receive the problem text. The form must be signed by your supervisor. Risk assessment is an ongoing activity, and must be carried out before starting any activity that might cause injuries or damage materials/equipment or the external environment. Copies of the signed risk assessments have to be put in the appendix of the project report.

No later than 1 week before the deadline of the final project report, you are required to submit an updated A3 page summarizing and illustrating the results obtained in the project work.

Official deadline for the delivery of the report is 13 December 2016 at 2 p.m. The final report has to be delivered at the Department’s reception (1 paper version) and via "IPM DropIT".

When evaluating the project, we take into consideration how clearly the problem is presented, the thoroughness of the report, and to which extent the student gives an independent presentation of the topic using his/her own assessments.

The report must include the signed problem text, and be written as a scientific report with summary of important findings, conclusion, literature references, table of contents, etc. Specific problems to be addressed in the project are to be stated in the beginning of the report and briefly discussed. Generally, the report should not exceed thirty pages including illustrations and sketches.

Additional tables, drawings, detailed sketches, photographs, etc. can be included in an appendix at the end of the thirty-page report. References to the appendix must be specified. The report should be presented so that it can be fully understood without referencing the Appendix. Figures and tables must be presented with explanations. Literature references should be indicated by means of a number in brackets in the text, and each reference should be further specified at the end of the report in a reference list. References should be specified with name of author(s) and book, title and year of publication, and page number.

<u>Contact persons</u>:

At the department	Martin Steinert, Kristoffer Slåttsveen
From the industry	Jørgen Selnes

Martin Steinert
Supervisor

NTNU
Norges teknisk-naturvitenskapelige universitet
Institutt for produktutvikling og materialer

Abstract

The early product development phases in the start-up company Alva is the basis of this project thesis. Using an iterative prototyping approach, we are developing a stator for a three-phase synchronous motor and the production method of this. The goal of this early phase is to get a first functional prototype of the primary production stage up and running. This is in order to learn and to make a proof of concept. The team of seven engineering students have made a functional prototype of a semi-automatic multi-shuttle weaving loom. A master thesis will continue the work of this project thesis, with the goal of a fully functional prototype of the complete production system by the summer of 2017.

Keywords: three-phase synchronous motor, industrial weaving loom, multiple-shuttle weaving, epoxy, iterative prototyping, Lean Product Development, Agile Product Development, SCRUM, start-up

Preface

When starting this project I knew I was going to explore a lot of new areas. In terms of different fields of engineering, collaboration, project management, and applied product development methodologies. Alva showed me a concept that immediately triggered my curiosity, but that also seemed highly ambitious. We were to tackle the electric motor industry, and challenge a most established and refined production technology.

The two founders of Alva, Jørgen Selnes and Sybolt Visser, had explored a patent from the Institute of Product Development and Materials. The technology was based on implementing a copper wire in an epoxy resin to obtain a conductive composite material called EMCM - Electromagnetic Composite Material. The founder, Martin Gudem, suggested several uses of this technology, one of these as components in electric motors. But Visser and Selnes were given the freedom to do what they wanted with it.

After a long time of trial and error, the two students had not found a suitable way of producing the material and was near to giving up. But after a rapid prototyping session with Kongsberg Innovation, august 2016, they came up with something new. By weaving copper wires together with strengthening fibres they could make a conductive cloth. It would then be rolled together to form a cylinder, like a rotor or a stator component of an electric motor. The shape would be held by casting the component in epoxy. With a simple motor controller they could confirm that the cylinder were indeed producing a desired electromagnetic field. The simple prototype impressed several Norwegian tech companies, such as Kongsberg, FMC, IKM Elektro and El-Torque. Now they wanted to prove that such a cloth could be produced automatically.

Some of the advantages of this technology were less capsuling of the stator, possibility of higher efficiency density and less cogging torque. Weaving would give the opportunity of changing the support of the copper. Iron could increase permeability, whilst carbon fiber could provide mechanical strength.

With the agility of this production method, Alva wanted to offer customers a tailored electric motor for their need. They started looking into the subsea- and windmill market to find a suitable application for their product.

Jørgen and Sybolt soon realised that they needed a bigger, more versatile team to accomplish what they wanted. That's when Stian Bjørnes, Anders Engebakken, Vilius Ciuzelis, Amund Marton and I joined. Stian is an electric engineering student writing a project thesis where he will test Alva's composite stator prototype. Anders, a production engineering student, has experience with composite materials and composite casting from DNV GL Fuel Fighter. Vilius, engineering cybernetics, has experience with the control system of the Fuel Fighter. Amund, also with experience from Fuel Fighter, has a genuine interest for weaving technology. I joined as a product developer to help develop concepts, writing my project- and master thesis about this process.

In the early phase of working with Alva, Selnes pointed out some challenges he expected developing this technology. In order to explore these, he wanted to get a functional weaving machine up and running as soon as possible.

Table of Contents

Chapter 1

Introduction

This project thesis is about the early product development stages in the start-up company Alva. The problem description asked to generate and evaluate concepts, build prototypes, parts, and test setups. It was decided that we would start by evaluating weaving technology.

The weaving technology referred to is a set of production stages that makes up Alva's production concept for a conductive cloth that can be used as a stator or rotor in an electric motor. First, copper wires and glass fibers are woven in a specialized industrial loom. Then the woven cloth is rolled up in several layers to form a cylinder which in the end will be cast in an epoxy resin.

After an introduction of the theoretical and technological terms needed to read the paper, the method of this project will be explained. A discussion of Alva's approach to prototyping, project management and product development methodology are found here. The latter two subjects were elaborated in two papers written in the specialization course TMM4280 Advanced Product Development. In order for the reader to understand the purpose of the prototypes, Alva's concept is first explained thoroughly before the current prototypes are presented.

There is still much work left before we have a functional prototype of an automated production process. The knowledge gained in this early phase will however be of tremendous value when Alva continues to explore these technologies. The work in this project thesis will be extended through a master thesis, and a proposition of the continuing path is suggested at the end of this paper.

Chapter 2

Theory and technology

This chapter will provide an introduction of the necessary concepts in order to understand the technical terms used throughout the thesis. Given the mix of technologies that currently makes the basis for Alva's concept, the connection of the following sections might seem a bit vague. The reader is welcome to skip the chapter, only to use it when referred to in the following text. The author have however tried to bring across the concepts in a short, uncomplicated manner.

2.1 Traditional weaving

In weaving, the threads going along the fabrication line is called warps as indicated in figure 2.1. These will serve as structural support. The weft, which crosses the warps, will be copper wires. There is the possibility to insert other materials in both warps and weft to manipulate certain parameters. In order to weave, the warps are opened by elevating every other thread, and dropping the others, like opening a pair of scissors. This is actuated by heddles, through which the warps are thread. The weft then passes through the open gap. The heddles closes and further passes each other to make a new gap for the next weft. Every time a new weft is passed through, a reed pushes towards the woven cloth in order to keep it even and tight.

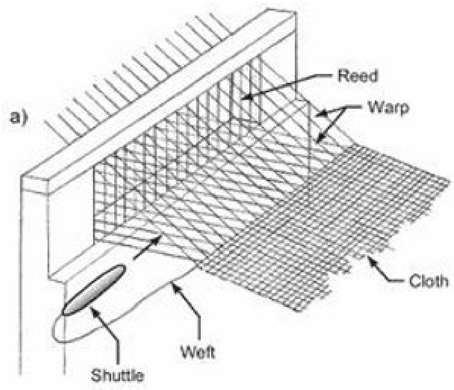

Figure 2.1: The essential components in shuttle weaving

2.2 Rapier weaving

A rapier loom uses a rapier instead of a shuttle to carry wefts. A rapier is an effective two-part device as shown in figure 2.2. The feeding rapier carries the weft half-way across the cloth where it meets its counterpart. The receiving rapier grabs the weft and carries it the last part of the way. The weft is cut at the starting point, and the process continues like in traditional weaving.

Figure 2.2: The receiving rapier meets the feeding rapier mid-way across the warps

2.3 Synchronous motor

Alva's stator design is meant for a three-phase synchronous motor configuration as illustrated in figure 2.3. A synchronous motor has the property that its rotor is synchronized with the frequency of the stator field. With a three-phase AC supply the stator will have a revolving magnetic field (RMF). In figure 2.4 we can see how the magnetic field strength of each of the three phases changes over time periodically, creating the RMF. The rotor will wish to align to the strongest field at any given time. The three phases are equally distributed over the period by a 120° phase shift. For a cloth to be working as a stator, the different threads needs to coupled in such a way that three phases can be isolated from each other, and controlled separately. This will be explained in chapter 4 of the paper.

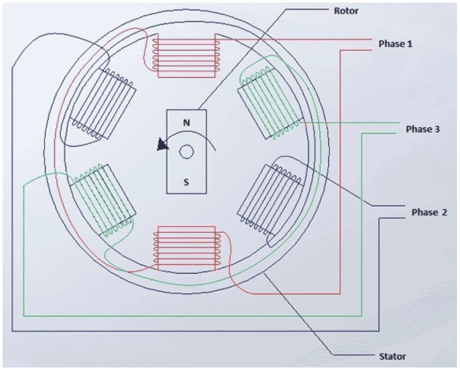

Figure 2.3: Illustration of a three-phase synchronous motor with six slots

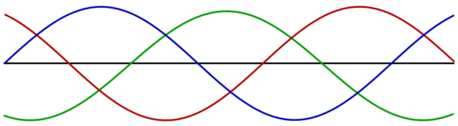

Figure 2.4: The three phases are shifted 120° from each other. Time on the x-axis.

The speed of a synchronous motor is given by

$$Ns = 120\,\frac{f}{P} \tag{2.1}$$

Where Ns is the speed in rotations per minute of the motor, f is the AC supply frequency in Hz, and P is the number of slots of the stator.

2.4 Eddy current

Permeability is the property of leading a magnetic field and therefore an important quality of a stator in a synchronous motor where permanent magnets are in the rotor. This is the reason why it is common to have the copper wires wound around an iron core in the stator. It makes the magnetic fields travel longer as iron is very permeable. But in addition to having great permeability, iron also is inductive. When a magnetic field is changing outside iron, a current is induced in the iron itself. This is called an eddy current and represents a loss of efficiency. To reduce this effect, it is common to laminate the iron core as seen in figure 2.5.

In Alva's first prototype design there is currently thought to have no iron. This means the magnetic field dies off quickly. As indicated in figure 2.6, the magnetic field in blue will tend to travel from magnet to magnet and not through the stator. If there is no material added to increase permeability, the thickness of the active

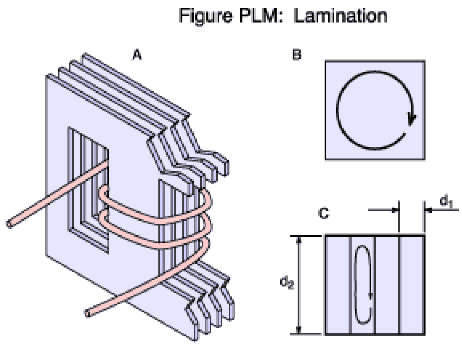

Figure 2.5: Figure A, a laminated core. B and C illustrates the correlation between volume and Eddy current.

region of the stator is greatly limited. Any additional thickness will add more weight, but little torque.

Calculations done by Stian Bjørnes at Alva shows that a thickness above 10mm will gain little torque in the test motor.

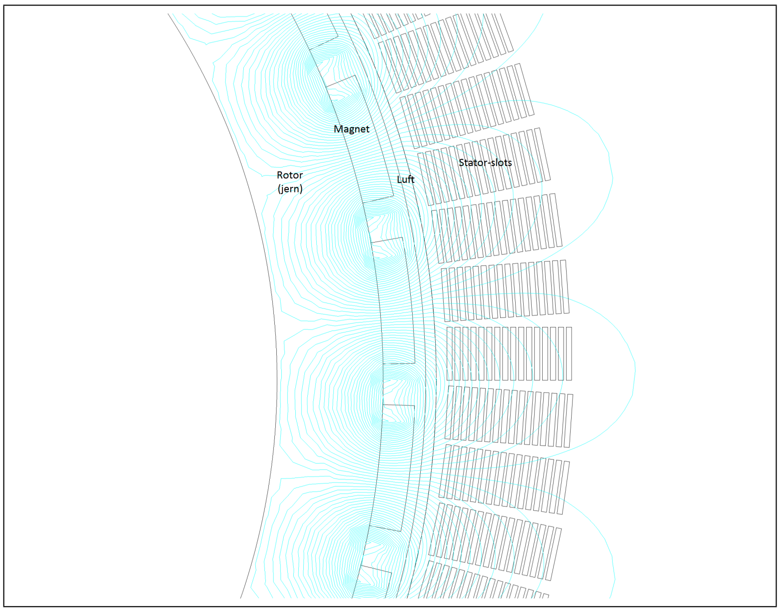

Figure 2.6: The magnetic field in blue will die off as they travel through the layers of the stator.

2.5 Hysteresis loop

Another effect of having iron in a electric motor component is hysteresis. This is the permanent effect of an external force working on a system. In this case the magnetic field of the iron after the outer magnetic field is changed or removed. The atomic dipoles of the ferromagnetic material will be oriented according to its outer magnetic field. But when the outer field is removed, not all of these dipoles will return to their initial orientation. In figure 2.7 one can follow the flux density B, in Tesla, of a magnetic steel as the outer magnetic field strength H, in Henry, changes. Starting at origo, the outer magnetic field is turned on and the magnetic flux density grows as indicated by the slope OA. But when the outer field is turned off again, as the ABC curve indicates, the flux density does not go back to its initial value, but acts as if a plastic change has occurred. This effect is magnetic Hysteresis. Following the slopes further will show the appearance of a Hysteresis loop. A well suited material for use in a stator would be one minimizing the area inside this loop. Iron is well known for its magnetic plasticity abilities, so hysteresis does represent losses in conventional motors. For this reason, a laminated silicon steel alloy is often used for stator applications as it reduces the area of the Hysteresis loop.

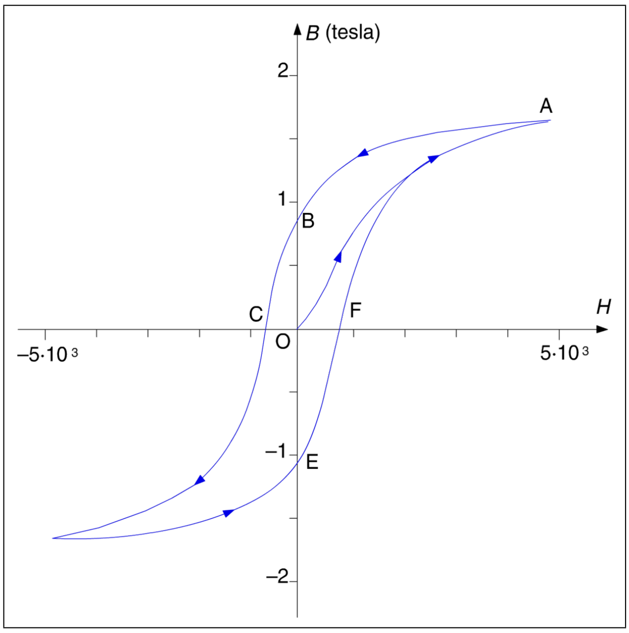

Figure 2.7: A typical hysteresis loop

2.6 Resistance as a function of temperature

Copper wire changes resistance with temperature according to the following equation.

$$\frac{dR}{R_s} = \alpha\, dT \tag{2.2}$$

Where dR is change in resistance, Ohm. R_s is the standard resistance from reference tables. α is the temperature coefficient of resistance $(°C)^{-1}$ and dT is change in temperature from reference temperature.

As an example, let's say a meter of copper wire of diameter 0,3mm has a resistance of 0,25 Ohm at 20°C. Now, at 80$°C$, what will be the difference of resistance in the same wire?

Given $\alpha = 4,29 * 10^{-3}(°C)^{-1}$ for copper (Toolbox, 2011), the resistance will increase by:

$$\frac{dR}{R_s} = \alpha\, dT \rightarrow dR = \alpha\, dT * R_s \tag{2.3}$$

$$dR = 4,29 * 10^{-3} * (80 - 20) * 0.25\, Ohm = 0,064\, Ohm \tag{2.4}$$

That is a $25,6\%$ increase. In other words, resistance increasing by temperature rise is an important source of efficiency loss.

2.7 Cogging torque

The last electromagnetic effect to be mentioned is cogging torque. If the stator has slots of permanent magnets, it creates a disjointed magnetic field. The rotor will tend to have some jerkiness at lower speeds. This effect dies off at higher speeds because of the moment of inertia. Without iron, cogging torque will not appear and thus leave the electric motor running smoothly.

2.8 Epoxy

Epoxy is a thermoset polymer with high mechanical properties, temperature- and chemical resistance. By cross-linking a synthetic resin known as epoxy resin, it can be made in two ways. Either by adding a hardener with which the epoxy creates the chemical bondings with, or by heating it up so it bonds with itself. To avoid air bubbles, it is common to cure epoxy in autoclaves, chambers with controlled low pressure and temperature. When hardening, epoxy keeps its initial shape and size very well, which limits the creation of inner tension in the material.

In figure 2.8 you can see the chemical reaction of an epoxy resin, Epichlorohydrin, and a hardener, Bisphenol A. This is the most common epoxy, and probably the one you will get when buying two-component epoxy in your local hardware store. Hydrogen Chloride is a byproduct of this reaction, though it is not shown in this figure.

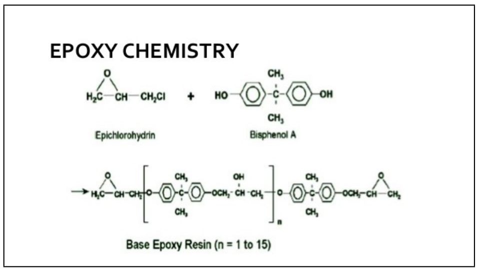

Figure 2.8: A visual representation of the chemistry equation

Chapter 3

Method

This project thesis, with basis in the problem description and the specialization course, has been a mixed approach of theory and practice. The problem description is focused around prototypes and testing concepts, while the specialization course had a very theoretical approach to everything from methodologies to collaboration in product development. This chapter is meant to reflect on the way we have worked in Alva, and hopefully give reason to why we chose to do it this way. First, a reflection around the power of prototyping in our specific case is presented. Following this is the abstracts of the two articles with Alva in focus that was written during the specialization course TMM4280 Advanced Product Development. The complete articles are found in the appendix.

3.1 Prototyping

The practical approach of this project is mainly done through prototyping. By prototyping we mean any representation of functionality, aesthetics or feel of the product that is made or used in order to gain insight or share ideas to colleagues, customers or collaborative partners. In the early phases we focus on prototyping for learning, inspired by Leifer and Steinert (2011). We early decided that it was through prototyping we would best be able to collaboratively explore and evaluate concepts. The team had not worked together before and we were all engineering students from different fields. Prototyping is a more universal language, free of technical terms, which made it easier for us to communicate.

If we would build the complete model with CAD software, specifications would have to be set from the start. We concluded this would slow us down, and decided that building specifications from prototypes was a more suitable approach for both the team and the project. Using CAD software would also make concepts less tangible than a physical prototype and would need to be high fidelity from the start. We claim that it is easier to adjust resolutions depending on the situation when making physical prototypes compared to CAD models.

We wanted to use iterative learning in the development process in order to learn faster. Starting with cobbled up, low resolution prototypes and building on to functional prototypes. This is supported in the findings of Elverum and Welo (2016) stating: ”frequent creation of low-fidelity prototypes is an effective strategy to quickly learn and develop new solutions”. The importance of low fidelity is not only to increase the speed of prototyping, it is also important in order for team members to let go of their personal favorite ideas or ”kill their darlings”.

Alva’s concept is quite complex as it mixes many different fields of engineering. But the linear order of the production method makes it easier to separate the concept into part problems. This gives us the freedom to explore each aspect separately and simultaneously and increases the speed of learning considerably. A study of front loading product development projects by Thomke and Fujimoto (1999) stated that ”earlier identification and solving of a set of problems for a given developmental task can lead to faster and more efficient product development”. For Alva as a start-up company that currently has no return on investments, it is crucial to reduce lead time.

Another important factor was that no one in the team had previous experience with industrial looms. A multiple-shuttle loom undoubtedly adds a lot of complexity. In order to develop a machine that operates well, we needed experience. This too spoke in favour of building a functional weaving loom early in the development process. A mindset that supports this idea is studied by Buchenau and Suri (2000). Experience Prototyping is to ”understand, explore or communicate what it might be like to engage with the product, space or system we are designing” .

3.2 abstract, SCRUM framework

This paper uses Lean Product Development principles to detect wastes in a start-up company with high level of ambiguity in both market and Product Specification. The author uses his own experience from working with a start-up in a fresh team as the object of discussion. The Project Managers of the company are highly motivated with both economic and engineering background, and they have assembled a broad, cross-disciplinary engineering team. This paper discusses the wastes that have been encountered so far in the process from a Lean perspective, and further how to implement a Scrum strategy for eliminating most of these.

3.3 abstract, Agile Product Development

This article discusses how Alva, a startup company from NTNU, compares to the original six characteristics of Agile Product Development management as defined by Nonaka and Takeuchi in their study from 1986 (Hirotaka Takeuchi 1986). It will introduce the studies of Nonaka and Takeuchi as well as the product development management in the Alva company. The six characteristics that will be discussed are built-in stability, self-organizing project teams, overlapping development phases, multilearning, subtle control and organizational transfer of learning. Through discussion it becomes apparent that Alva's greatest challenges lies in shared office space, access to multi-disciplined workshops, scheduling and coordination of coherent goals.

Chapter 4

Concept development

A detailed description of each production stage, as well as the product itself, are found in this chapter. The different solutions considered are presented, together with the challenges they bring. In order to find the best solutions to these challenges, some have been benchmarked against excisting technology.

4.1 Design of a stator

The desired output of the production method is at first a stator for a three-phase synchronous motor. Stian Bjørnes on the team will later test the component in a test rig. This will be an excellent benchmark against conventional stators as we have detailed data under identical conditions.

The woven cloth will be rolled up to a multi-layered cylinder after weaving, and cast in epoxy to keep its shape. The cloth will consist of three groups of wiring that is woven across the length in wefts. If we take a look at a conventional three-phase wiring design and roll it out it will look like that of figure 4.1.

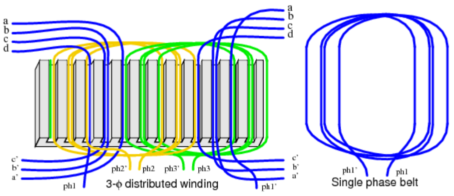

Figure 4.1: Visual representation of the wiring of a three-phase stator

In the cloth, the three colours representing the three phases will also represent the three groups of wefts. Each group of wefts will follow the same pattern in the weaving process.

There is also possible to include other materials as weft, to increase the permeability or secure a more rigid component. In the first functional prototype only wefts of copper will be used. We use small cross-sectional area to reduce skin effects (Fink and Beaty, 2000). However, there will always be a finite number of threads and therefore a discrete amount of copper.

In addition to wefts, a woven pattern has warps. In Alva's cloth, the warps are mainly for structural purposes. Simple fabrics will be well suited for this application, but it would also be possible to add for instance iron to increase permeability.

There are two factors that impose restrictions on the thickness of the stator. The first is low permeability. Without any iron, as in the first prototype, the magnetic field of the rotor will not travel very deep into the stator. Increasing the thickness above this limit does not generate more torque, and thus represents efficiency loss.

The second factor limiting the thickness is that the slots of the layers need to stack correctly. The circumference increases with increased diameter, so any additional layer will cause a slight shift of the slots. This can be adjusted with additional wefts for every layer. We have not considered a solution for this.

The cylindrical multi-layered stator will be cast in epoxy to keep its shape. Different materials can be mixed into the epoxy, like iron powder to increase permeability.

4.2 Weaving loom

There are several possible ways to weave a cloth, but we have mainly considered two paths; shuttle-less weaving with rapier, and multiple-shuttle weaving.

4.2.1 Rapier loom with coupling strips

A rapier loom (section 2.2) uses a rapier instead of a shuttle to carry wefts across the open warps, and weft needs to be cut for every crossing. This means the copper wires will need to be coupled to its corresponding phase after weaving. The major challenge with such a machine is that there will be a lot of wires and therefore a lot of precision coupling. In order to solve this problem there was thought of adding two three-component strips alongside the cloth as in figure 4.3. The strips consist of an isolating material with a conductive material on top. The conductive material will be split in order to secure correct coupling.

The arrow in figure 4.2 indicates the way of the rapier and the current weft. The strip of the corresponding phase to that of the weft is kept down while the remaining two are lifted. This ensures the copper wire only touches the conductive part of the right strip.

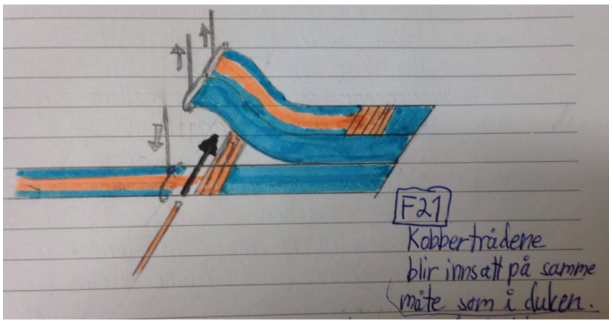

Figure 4.2: Conductive material in orange, and isolating in blue

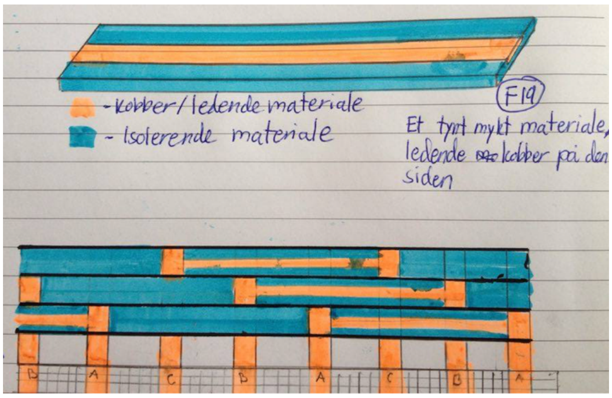

Figure 4.3: Conductive material in orange in part-wise patterns for coupling correctly

4.2.2 Multiple-shuttle loom

A multiple-shuttle weaving loom uses one shuttle for every thread that needs separate controlling. In our case, that means one shuttle for every copper wire. With so many shuttles, the main challenge is controlling them. The first concept to be tested is a revolver barrel solution like that of fig 4.4. One of these open barrels on each side of the cloth will store all shuttles and rotate to send or receive the right shuttle at the right time.

Multiple-shuttle weaving is the first concept Alva will test.

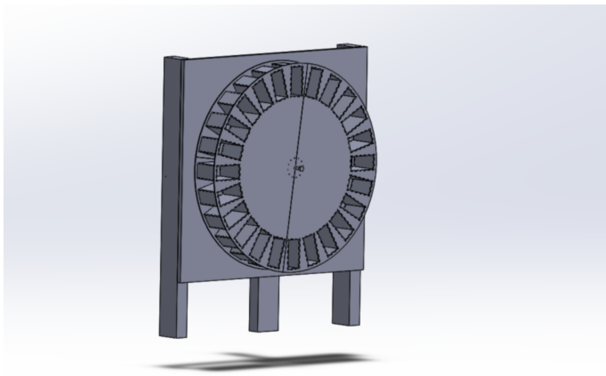

Figure 4.4: A CAD model of the revolver barrel solution

4.3 Rolling up the woven cloth

For the cloth to get the cylinder shape of a stator, it will be rolled up after weaving. With this comes the challenges of fastening and later releasing the cloth. Benchmarking against filament winding (fig.4.5) gave us the idea of using a buffer length at the start of the cloth as in figure 4.6. The friction from this buffer should be sufficient to fasten the cloth. A buffer will also be used at the end of the cloth, going a few rounds around the cylinder to lock all layers in place.

Any defects in the cylinder will affect the properties of the stator. It is therefore important that the cloth is kept tight while rolling up, to avoid dents and lumps. To ensure this even stretch at all times, we want to implement a gripping device to keep the cloth firm in place when it is cut.

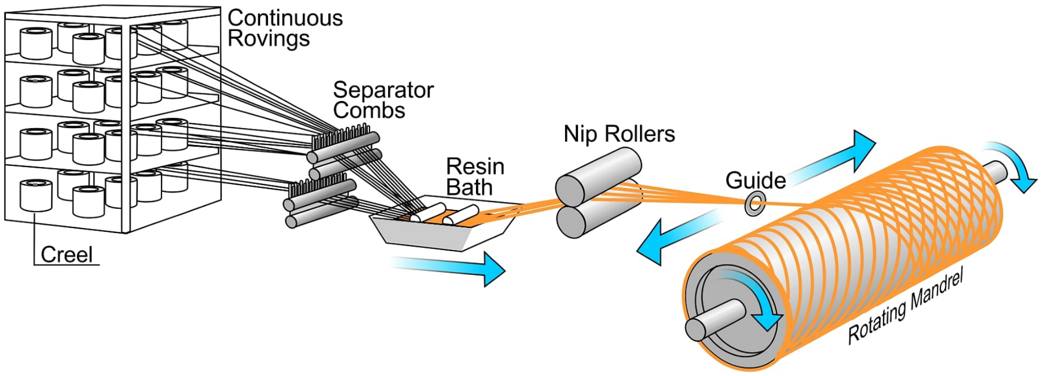

Figure 4.5: The concept of Filament winding

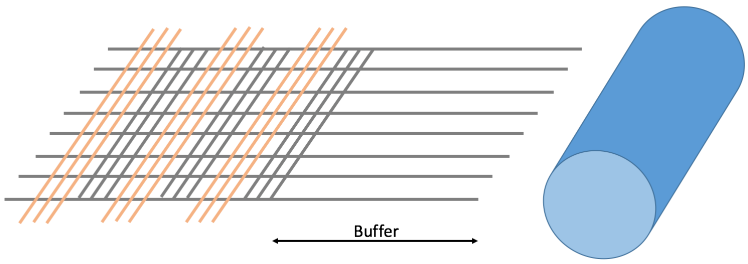

Figure 4.6: Illustration of buffer length

4.4 Cast in epoxy

The cloth will be held together by an epoxy resin. This will keep the structure in place after it is woven and rolled up. We have considered two ways of applying the epoxy: Pass the cloth through a bath of epoxy like in filament winding figure 4.5, or soak the entire cylinder in epoxy. The first approach, passing the cloth through an epoxy bath, will hopefully ensure better filling throughout all the layers.

It is important that the epoxy is of such character that it both is suitable for production and operation of the stator.

In production, the component will have to be baked in an oven to cure the epoxy. A challenge that comes with this is the different thermal properties of the copper wires, the warps and the epoxy itself. Different thermal expansion rates will create inner tension within the material. And so will the total transformation properties after complete curing do.

When the stator is operating, the resistance in the copper wires will generate some heat according to section 2.6. It is important that the epoxy can withstand these temperature changes as well as transport it away from the copper wires.

The epoxy could contain iron powder to increase permeability, but will not in the first prototype.

Chapter 5

Prototypes

Learning through prototyping was a clear principle in Alva from the start. The idea was complex, but the production phases had a clear order, ending in the product itself. We decided that we needed to start with the first production stage, weaving. When the weaving machine was up and running, we could start to test rolling, casting in epoxy, and finally the produced stators.

The team agreed that the best way to learn the workings of an industrial loom was to build one ourselves. Drawing by hand or using CAD would be difficult as we had no clear idea of the concept, the proportions or how the different parts would fit together. We wanted to make specifications from the prototypes, using an iterative approach to take us further towards a solid concept.

5.1 Alva's first loom

The first prototype was simply cobbled up by Selnes and Visser in a garage to prove that it was indeed possible to weave a cloth of thread and copper wires. This was before the rest of the team joined Alva. It is completely manual, so the copper wire needs to be fed alternatingly over and under every warp.

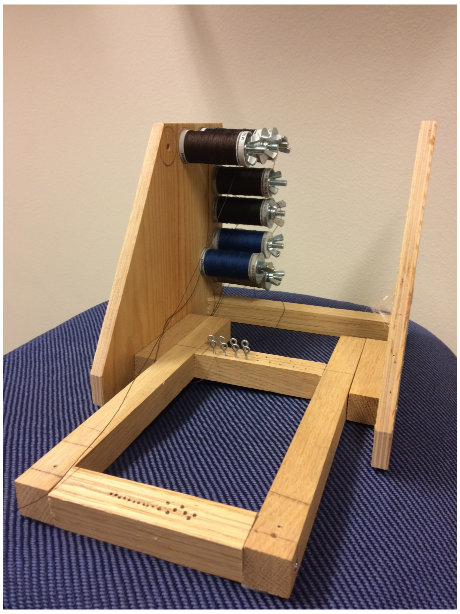

Figure 5.1: Alva's first prototype, a cobbled up manual loom

5.2 Model loom

The second prototype was also cobbled up using parts from the first prototype and laser-cut medium-density fiberboard. The goal was to learn how a simple loom work, as well as how to operate the available machines in the work shop. From building the prototype and the prototype itself, we could more easily start to sketch up a design for the first functional prototype.

Figure 5.2: Alva's second loom

5.3 Roll up

The first roll up prototype was built to roughly test how different angles affected the stretch in the cloth. We tried to see if there could be a segment of this rolling where the cloth was more loose, in order to pull it through the epoxy bath.

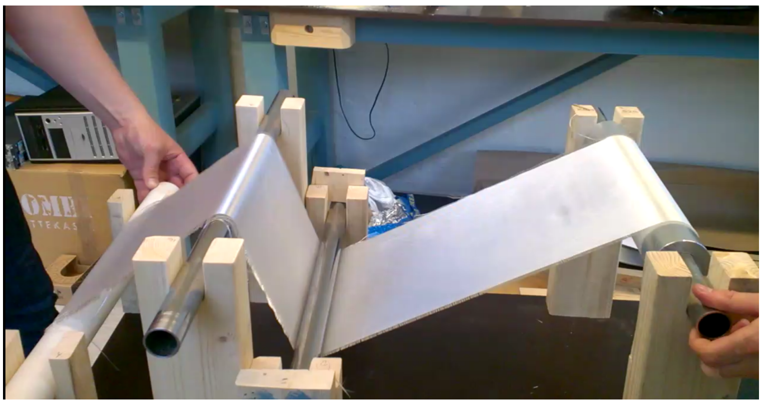

Figure 5.3: First roll up prototype

5.4 Functional prototype

5.4.1 Intention and goals

We had a set of goals for the first functional prototype. The most important one was to make a fundament for all processes to be explored. With the weaving loom up and running, we could start thinking about the roll up and cast of the cloth, and finally to start evaluating the process and product as an integrated whole. And we needed the experience of operating the machines to be able to evaluate the solutions. To be able to explore further with this prototype, we wanted it to be spacious and modular.

An important challenge was to implement the operation of multiple shuttles. It was difficult to picture the movement of all these wires on paper or to simulate the dynamics with CAD. We had to make the loom in order to wrap our heads around this.

We also had an electrical engineering student and a motor control enthusiast on our team that was practically trembling to start testing and developing control functionalities. And we had already received an order of several stepper motors and motor controllers.

Stian Bjørnes had collected the data for the test rig that we would later use, so we knew exactly the dimensions we were working with. The diameter of the rotor is 8 cm, and the supply current operates between $0 - 3\ kHz$. He wanted to start with a two layer stator of six slots to start testing the stator as soon as possible.

And last, the goal of the first functional prototype was to clarify what were our main challenges. Selnes had a pretty clear idea of what the different production stages would be, and had thought a lot about the challenges that would come with these. We now needed to see if he was right.

5.4.2 Method

We made the models with CAD after discussing each part solution. Most of the parts were made using laser cut MDF, standard bolts and screws, and left over wood from the work shops. A framework was made of solid wooden planks and the part solutions were mounted as the parts were designed and made. Motors and electronics were implemented after a manual verification of correct functionality.

5.4.3 Result

The picture in figure 5.4 shows how far the prototype has come for the time being. The reed, and the first multiple shuttle controlling concept, the revolver barrels (fig 5.5) are not yet implemented. This means the wefts and the reed still needs to be manually controlled in order to weave. The heddles are automated and is set in motion by a button in the foundation. There are 33 wefts, of which all are copper wires. 11 for each of the three phases, as can be seen of the red, green and white spools in figure 5.4.

The machine is made bigger than it needs to be in order to make possible future changes of concepts. So far, the modular fashion of the machine works very well. It is fairly easy to change one part of the machine without affecting the others.

Figure 5.4: Alva's first functional loom prototype

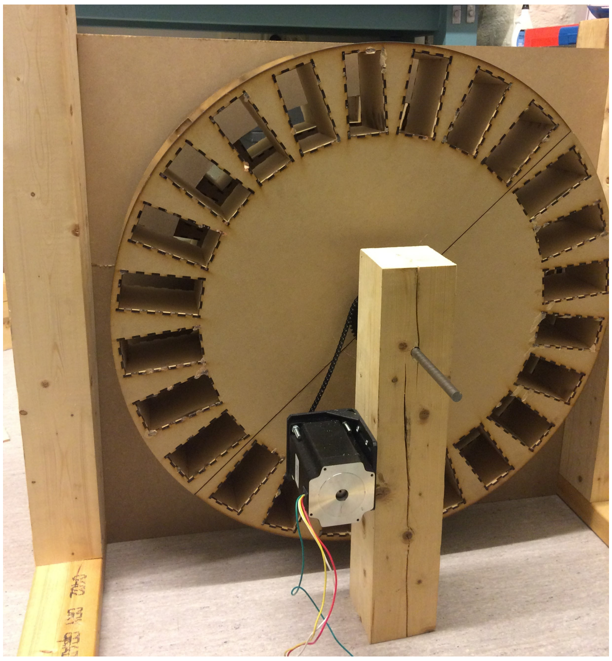

Figure 5.5: The revolver barrel concept to control multiple shuttles

We have learnt a lot from making the first prototype of the weaving loom. Everything from using the right terminology to a better understanding of the workings of such a machine. We believe that we are now much better suited to collaboratively and individually explore new concepts as our understanding of the dynamics of a weaving loom have matured through building it. We have also learned what works for everyone in the team when it comes to practical things like what CAD-file format to use.

The main challenge we are facing now is to make an automated control of multiple shuttles. Not only to prove the concept, but to make the machine efficient enough to free up time to test the other production stages.

Chapter 6

Summary

This thesis is based on the early product development phases in the start-up company Alva. The product is a stator for a three-phase synchronous motor and the production method of this. Production stage are as follows: First weaving copper wires and glass fiber in a multiple-shuttle industrial loom. Then rolling up the woven cloth to form a multi-layer cylinder which in the end will be cast in an epoxy resin. The goal of this early phase was to get a first functional prototype up and running, in order to learn and make a proof of concept.

6.1 Method

There were no defined product development strategy at the start of this project. Alva is a startup company that still figures out its routines for management, product development and collaboration. Through a study of wastes using principles from lean product development, as well as the concept of agile product development we are continuously improving. Two articles were written about the project management and product development methodology in Alva during the specialization course TMM4280 Advanced Product Development. The findings and suggestions for further work is found in the method chapter and the complete articles are found in the appendix of this thesis. The SCRUM project management framework was implemented as the team agreed on an agile approach.

The team agreed on an iterative prototyping approach in order to speed up the process of getting to the first functional prototype of the weaving loom.

6.2 Results

At this point, a semi automatic weaving machine is up and running. It has 33 shuttles of copper wires and 11 warps of glass fiber. Stepper motors and motor controllers are implemented to control the heddles. Parts for the reed and the multiple-shuttle controller is ready, but not yet integrated in the machine. When woven, the cloth will be rolled up to a two layer cylinder of 8 cm diameter to be tested as stator in a three-phase synchronous motor. Controlling the multiple coils of copper wires separately will be a crucial part of the machine, as it is considered the function that brings most complexity to the current design. The goal for the summer of 2017 is a complete functional prototype, with all production stages implemented.

Chapter 7

Further work

Alva's goal for the summer of 2017 is to have a complete functional prototype of the production method. Through benchmarking and iterative prototyping we will continue to learn and develop the concept. We will consider implementing new prototyping approaches such as rapid prototyping and set-based prototyping.

7.1 Benchmarking

Benchmarking will be a greater part of the master thesis. Weaving is an old and well documented technology that is still an important part of manufacturing today. With the greater understanding of these concepts gained through working with this project thesis, it will be easier to seek out the relevant information. When we have reached our goal of a functioning weaving loom, it is time to develop and integrate the other production phases. We know there is a lot of knowledge on the field of filament winding and epoxy at the Department of Engineering Design and Materials, and hope to do interesting findings here.

An electric motor company called Thingap Thingap (2016), have done some really interesting innovations. Unfortunately we have not been able to establish contact with the company, but they have made some interesting patents (Graham, 2005).

Another interesting company is Hampshire based Printed Motor Works who ”pioneered the development of the in-wheel electric motor” (Pancake, 2016). They have an external rotor series that Alva wants to look further into.

Some interesting trends in fabrics are worth mentioning. Adidas now knit their ”adiZero Primeknit” running shoe in one single piece, plus the sole of the shoe (Adidas, 2012). This is done in high-technology knitting machines in Germany. It is an example of producing fabrics with integrated geometry.

Google and Levi's released a collaborative jacket with woven "smart garment"(Commuter, 2016). It proves that someone is able to weave conductive circuits into fabric. Google have lately been very generous in their open source approach innovation, and Alva is interested to see the progression. Another interesting TEDx talk from Philadelphia in 2014 given by Geneviève Dion, also talks about smart garment (Geneviève Dion, 2014).

7.2 Prototyping

It is through prototyping we have developed the concept, and will continue to do so. Low-fidelity prototypes has proved to work as a way of bringing the project forward as well as a way of communicating ideas. The step from low-fidelity to functional prototypes was stressed in this early phase as the development of the other phases depended on the weaving loom. However, with the modular base we intended to welcome furter iterations on the functional prototype of the loom. In the next phase we will consider implementing a more rapid prototyping approach in order to learn more before moving to the functional prototypes (Kriesi et al., 2016).

An idea that we will also consider is set-based prototyping (Kennedy et al., 2014). When a functional weaving loom is up and running, the possibility to try different approaches to the following stages arises. This is also the power of the modular approach we have used.

We are excited to have the weaving loom up and running, though there is still some functionality that needs to be implemented. The prototyping starting point for the master thesis is to finish the weaving loom and to start learning about the roll-up and epoxy casting production stages. Alva is in search for an application for the first functional stator prototype that has some show effect. With all the possible applications of this technology, we want to pick one that is both fun to work for, and that will impress stakeholders.

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Appendices

NTNU	Kartlegging av risikofylt aktivitet	Utarbeidet av	Nummer	Dato	
		HMS-avd.	HMSRV2601	22.03.2011	
		Godkjent av		Erstatter	
HMS		Rektor		01.12.2006	

Enhet: **Institutt for Produktutvikling og Materialer** **Dato:** **20.09.2016**

Linjeleder: **Torgeir Welo**

Deltakere ved kartleggingen (m/ funksjon): Martin Steinert, veileder/Kristoffer Slåttsveen, Coach/Simen Pjaaten, Student.

Kort beskrivelse av hovedaktivitet/hovedprosess: Prosjektoppgave Simen Pjaaten.
Developing a production method for rotor/stator in an electric motor.

Er oppgaven rent teoretisk? (JA/NEI): NEI

Signaturer: *Ansvarlig veileder: Martin Steinert* *Studenter: Simen Pjaaten*

ID nr.	Aktivitet/prosess	Ansvarlig	Eksisterende dokumentasjon	Eksisterende sikringstiltak	Lov, forskrift o.l.	Kommentar
1	Bruk av Trolllabs workshop.	SP	Romkort	Romkort		
1a	Bruk av roterende maskineri	SP	Maskinens brukermanual	Ukjent	Ukjent	
1b	Bruk av laserkutter	SP	Maskinens brukermanual	Ukjent	Ukjent	
1c	Bruk av 3D printer	SP	Maskinens brukermanual	Ukjent	Ukjent	
1d	Bruk av skjæreverktøy	SP	Ukjent			
1e	Bruk av samenføynigsmidler (lim og lignende.)	SP	Produktets brukermanual og datablad	Datablad	Ukjent	
2	Tilstedeværelse ved arbeid utført av andre.	Andre	Andres HMSRV2601	Andres	Prosessavhengig	

2	Tilstedeværelse ved arbeid utført av andre.	Andre	Andres HMSRV2601	Andres HMSRV2601	Prosessavhengig	
3	Eksperimentelt arbeid	SP	Egen risikovurdering- må gjøres for hvert enkelt eksperiment		Prosessavhengig	
4	Reise	Andre			Ukjent	

Enhet: **Dato:**

Linjeleder:

Deltakere ved kartleggingen (m/ funksjon):
(Ansv. Veileder, student, evt. medveiledere, evt. andre m. kompetanse)

Risikovurderingen gjelder hovedaktivitet: Masteroppgave student xx. Tittel på oppgaven.

Signaturer: *Ansvarlig veileder:* *Student:*

ID nr	Aktivitet fra kartleggings-skjemaet	Mulig uønsket hendelse/ belastning	Vurdering av sannsyn-lighet (1-5)	Vurdering av konsekvens: Menneske (A-E)	Ytre miljø (A-E)	Øk/ materiell (A-E)	Om-dømme (A-E)	Risiko-Verdi (menn-eske)	Kommentarer/status Forslag til tiltak
1	Bruk av Trolllabs workshop.								Vær nøye med opplæring i bruk av maskineri.
1a-i	Bruk av roterende maskineri	Stor kuttskade	2	D	A	A	D	2D	Sørg for at roterende deler er tilstrekkelig sikret/dekket.
1a-ii		Liten kuttskade	3	B	A	A	A	3B	Ikke ha løse klær/tilbehør på kroppen.
1a-iii		Klemskade	2	D	A	A	C	2D	Ikke ha løse klær/tilbehør på kroppen.
1a-iv		Flygende spon/gjenstander	3	C	A	A	B	3C	Bruk øyevern og tildekk hurtig roterende deler (Fres og lignende.)
1a-v		Feil bruk - ødelagt utstyr	3	A	A	C	A	3C	Opplæring.
1b-i	Bruk av laserkutter	Klemskade	2	D	A	A	C	2D	Ikke ha løse klær/tilbehør på kroppen.

1b-ii		Brannskade	3	B	A	A	A	3B	Bruk hansker ved håndtering av varme materialer.
1b-iii		Øyeskade-laser	2	D	A	A	C	2D	Bruk øyevern! Skru av laser når maskinen ved oppsett.
1b-iv		Brann	2	B	A	D	C	2B	Ha slukkeutstur tilgjengelig.
1c-i	Bruk av 3D-printer	Brannskade	3	B	A	A	A	3B	Vær oppmerksom.
1c-ii		Innhalering av plast/ printemateriale	5	A	A	A	A	5A	Bruk åndedrettsvern/ vernebriller.
1c-iii		Feil bruk - ødelagt maskineri	3	A	A	C	A	3A	Opplæring.
1d-i	Bruk av skjæreverktøy	Stor kuttskade	2	D	A	A	D	2D	Bruk skarpe verktøy og riktig skjæreunderlag.
1d-ii		Liten kuttskade	3	B	A	A	A	3B	Bruk skarpe verktøy og riktig skjæreunderlag.
1e-i	Bruk av samenføynigsmidler (lim og lignende.)	Eksponering på øyet	2	D	A	A	B	2D	Bruk øyevern, ha datablad tilgjengelig.
1e-ii		Eksponering hud	4	A	A	A	A	4A	Bruk hansker, ha datablad tilgjengelig.

1e-iii		Eksponering åndedrett	4	A	A	A	A	4A	Bruk åndedretsvært/ god ventilasjon. Ha datablad tilgjengelig.
1e-iv		Søl	4	A	B	A	A	4A	Ha papir/ rengjøringsmateriell tilgjengelig. Ha datablad tilgjengelig.
2	Tilstedeværelse ved arbeid utført av andre.	Se andres risikovurdering om sikkerhet betviles.	3	C	C	C	C	3C	Hold et øye med hva som foregår rundt deg.
3-i	Eksperimentelt arbeid	Bil-trafikk. Krasj/ulykke	2	D	B	D	B	2D	Sjekk av bil før kjøring, kommunikasjon innad om evt endringer som har blitt gjort på bilen før kjøring. Kommunikasjon innad også når det gjøres endringer på bilen som kan påvirke sannsynligheten for hendelse.
3-ii		Elektrisitet- strøm	3	B	A	A	A	3B	Typisk lite energi involvert. Bruk isolerte verkøty
4	Reise	Ulykke	1	E	E	E	A	1E	Fly med anerkjent fly/transportselskap. Kan påvirkes i meget liten grad.

Sannsynlighet vurderes etter følgende kriterier:

Svært liten 1	Liten 2	Middels 3	Stor 4	Svært stor 5
1 gang pr 50 år eller sjeldnere	1 gang pr 10 år eller sjeldnere	1 gang pr år eller sjeldnere	1 gang pr måned eller sjeldnere	Skjer ukentlig

Konsekvens vurderes etter følgende kriterier:

Gradering	Menneske	Ytre miljø Vann, jord og luft	Øk/materiell	Omdømme
E Svært Alvorlig	Død	Svært langvarig og ikke reversibel skade	Drifts- eller aktivitetsstans >1 år.	Troverdighet og respekt betydelig og varig svekket
D Alvorlig	Alvorlig personskade. Mulig uførhet.	Langvarig skade. Lang restitusjonstid	Driftsstans > ½ år Aktivitetsstans i opp til 1 år	Troverdighet og respekt betydelig svekket
C Moderat	Alvorlig personskade.	Mindre skade og lang restitusjonstid	Drifts- eller aktivitetsstans < 1 mnd	Troverdighet og respekt svekket
B Liten	Skade som krever medisinsk behandling	Mindre skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1uke	Negativ påvirkning på troverdighet og respekt
A Svært liten	Skade som krever førstehjelp	Ubetydelig skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1dag	Liten påvirkning på troverdighet og respekt

Risikoverdi = Sannsynlighet x Konsekvens
Beregn risikoverdi for Menneske. Enheten vurderer selv om de i tillegg vil beregne risikoverdi for Ytre miljø, Økonomi/materiell og Omdømme. I så fall beregnes disse hver for seg.

Til kolonnen "Kommentarer/status, forslag til forebyggende og korrigerende tiltak":
Tiltak kan påvirke både sannsynlighet og konsekvens. Prioriter tiltak som kan forhindre at hendelsen inntreffer, dvs. sannsynlighetsreduserende tiltak foran skjerpet beredskap, dvs. konsekvensreduserende tiltak.

MATRISE FOR RISIKOVURDERINGER ved NTNU

KONSEKVENS	Svært alvorlig	E1	E2	E3	E4	E5
	Alvorlig	D1	D2	D3	D4	D5
	Moderat	C1	C2	C3	C4	C5
	Liten	B1	B2	B3	B4	B5
	Svært liten	A1	A2	A3	A4	A5
		Svært liten	Liten	Middels	Stor	Svært stor
		SANNSYNLIGHET				

Prinsipp over akseptkriterium. Forklaring av fargene som er brukt i risikomatrisen.

Farge		Beskrivelse
Rød		Uakseptabel risiko. Tiltak skal gjennomføres for å redusere risikoen.
Gul		Vurderingsområde. Tiltak skal vurderes.
Grønn		Akseptabel risiko. Tiltak kan vurderes ut fra andre hensyn.

USING LEAN PRODUCT DEVELOPMENT PRINCIPLES TO DETECT WASTE AND SCRUM STRATEGY TO DEAL WITH THESE

Simen Stenersen Pjaaten

This paper uses Lean Product Development principles to detect wastes in a start-up company with high level of ambiguity in both market and Product Specification. The author uses his own experience from working with a start-up in a fresh team as the object of discussion. The Project Managers of the company are highly motivated with both economic and engineering background, and they have assembled a broad, cross-disciplinary engineering team. This paper discusses the wastes that have been encountered so far in the process from a Lean perspective, and further how to implement a Scrum strategy for eliminating most of these.

Keywords: lean product development, startup, agile product development, scrum.

1 Introduction

Every start-up company shares one common condition; they deal with extreme uncertainty. It can be tempting to start out with whatever is known by the company, and work your way from there. Lean methodology rather suggests the focus being on reducing risk, and coping with the ambiguity of an early phase start-up.

2 The vaule and wastes of start ups

2.1 Definition of value

[Mascitelli, 2007], defined value in Lean Product Development as:

"Any activity or task is value-adding if it transforms a new product design (or the essential delivarebles needed to produce it) in such a way that the customer is willing to pay for it". Waste is whatever does not fit the above definition. This is essentially the backbone of Lean Product Development. Emphasizing that whatever value the customer is not willing to pay for no longer defines as value.

Now for a closer look at wastes. This list is based on the work of [Mascitelli, 2007] and [Oppenheim, 2004] on wastes in Lean Product Development, but is reworked by the author to better fit a start-up with market and product ambiguity. They are further sorted in three categories, or sources of waste. First those generated by a weak or undefined organisational structure as is common in startup companys. Secondly are wastes generated by a lack of direction, such as or poor knowledge of the market or simply not knowing what the product will turn out to be. The third category is simply whatever wastes start-up encounters by being a new team, a new company, and even by being new in entrepreneurship. The three categories, and their wastes will first be listed before a more thorough discussion.

2.1.1 Waste as a result of weak organisational structure

Working on the same thing
Extra processes and relearning
Chaotic work environment
Unused employee creativity
Poor communication across functional barriers
Learnings being stuck in someone's head or lost
Delays (waiting)

2.1.2 Waste generated by unclear directions

Unclear idea of Customer value
Poorly defined Product Requirements
Working with the wrong thing
Overdesigning
Disruptive changes to Product Requirements
Partially done work

2.1.3 Waste generated by lack of experience and routines

E-mail overload and learning management tools
Unclear roles and responsibilities
No established suppliers or ordering routines
Different levels of dedication

2.2 Waste as a result of weak organisational structure

When starting a company, a well working organisational structure is hard to obtain at first try. People are brought into the project as it moves forward and makes it hard even to predict the staff of the company. Often entrepreneurs starting the project with great enthusiasm tries to gather good people they want to work with, more than filling actual team roles and positions. This is likely to create unbalanced teams.

It may be difficult to imagine a realistic communication flow between different team members before putting the team together. But communication is essential in a Product Development project as learnings are crucial assets for the company. If no structure is strived for, team members will form teams as they go. This is a common source of wastes, as will become clear through the following discussion.

Typically, an enthusiastic project leader wants to be a part of every decision in the development process, meaning he needs to be present in all teams. This causes three problems.

First, the leader may gain good knowledge of the teams' progress. But the teams does not communicate their learnings across these functional barriers except for what the project leader may bring across.

This lack of communication can cause teams to do *extra processes and relearning.* Different solutions for the same problem causes teams to go in separate directions, and will cause partly done work as one direction is eventually chosen.

Third, the teammates may not feel the *necessary responsibility and ownership* for the project that comes from making their own decisions.

If the project leader takes this role, it is also likely to be his ideas and solutions that are fed to the development teams to refine. This causes *unused employee creativity*, and unexplored solutions.

2.3 Waste generated by unclear directions

A start-up company with new technology may find challenges as to what market to go into. Not knowing the market makes it hard to define directions for the company. Unclear directions is a source of many wastes.

It is probable that at some point *disruptive changes to Product Requirements* will occur. Former work may lose value and *partially done work* will be left as just that. Employees may also find it frustrating to realize they have been *working on the wrong thing.*

There is however common, if going in the right direction, that waste is generated by *overdesigning.* This means the company is designing features in the product beyond what the customer wants or needs.

2.4 Waste generated by lack of experience and routines

Experience and routines are valuable assets for any company. These are easy to forget as their nature often are formed as subconscious decisions. Routines such as what to order from what supplier on organisational level, or frequency and medium of communication on team level means big differences in time consumption.

In the development phase it is not always easy to know what, or how much materials are needed for the next period of time. Not only is this difficult, but the organisation may not even know where to order it. Getting the right supplier often turns into a game of chance, and much time and money could potentially be wasted if not ordering from the best alternative.

When joining a start-up team today there are most certainly one or two communication channels that not all team members have tried before. In addition these channels often have a corresponding app for you phone. And this is just for communication. In addition there's calendars, safe data clouds deposits and so on. Getting accustomed to tools like this may take a little while and cause a fair bit of frustration, depending much on your general experience and understanding of such tools. These learnings are not creating any value for customers, and one should be careful to implement more tools than necessary.

Back to putting together the team, often as a mix of people you would like to work with more than specific people that fits certain roles in the team. If the team is put together more or less randomly, the roles will form thereafter. This weak definition of roles means responsibilities may overlap, or worse; not be covered. Overlapping responsibilities causes extra processes and relearning, while uncovered responsibilities causes flaws in the development process that are discovered too late. Hiring people on unclear premises can return in employees with different expectations and level of dedication to the project.

3 Scrum, a strategy to reduce waste and keep moving forward

This discussion will use Scrum as a framework for finding ways to cope with some of the wastes earlier discussed in this paper.

3.1 What is Scrum?

Scrum is originally a software development framework, but it's appliance has proven useful in other Development Processes as well. Scrum focuses on agile goals, where the market or product specifications is not clearly defined at the start of the project.

The team starts by making a Product Backlog, a thought through and prioritized to-do list, that aims to define all properties of the product. The items of the Product Backlog should be prioritized so that a balance of low risk, high business value, and low development effort comes first.

The flexibility of Scrum comes through use of sprints. A timebox of one to four weeks where team members chooses a set of tasks to move from the Product Backlog to the Sprint Backlog.

The Scrum framework also defines three roles, but this does not imply that conventional product development roles can co-exist. The three roles are Product Owner, Scrum Master and Development Team.

The Product Owner has responsibility for representing the customers and other stakeholders, and communicating their needs and wants to the company. These should clearly be visible through the Product Backlog. He or she shall not decide how technical solutions are reached, but focus on the business case of the project. This role shall not be mixed with that of the Scrum Master.

The Scrum Master's main responsibility is to make sure everything is arranged for the Development Team. He is the team facilitator. His role includes defining and communicating the Backlogs in such a way that the Development Team know what to do, but also to encourage self-organization.

The Development Team are responsible for the actual work and progress of the project. This is achieved by incrementally adding value to the product through activities such as analysing, designing and testing.

3.2 Implementing Scrum for a start-up team

With reference to a start-up company with a technical solution, such as a patent, a rough implementing strategy will further be discussed.

First, the product Backlog needs to be defined. Backlogs are often subject for change now and then, so prioritizing whatever activities reduces most risk in the starting phase is a good idea.

Whoever has most idea of the former market strategy are most fitted for being the Product Owner. The Scrum Master needs to be pragmatic and know how to work around whatever stands in the way for development. This role should also include making sure everyone is comfortable with whatever management tools are included in the project, and that unnecessary e-mailing is avoided.

Now plan a sprint for the next timebox, typically two weeks. The Product Owner should make sure the Product Backlog is customer oriented, and that the Sprint Backlog is reasonably prioritized.

4 Conclusion

In this paper the wastes of a typical start-up company has been discussed from a Lean Product Development perspective. Using an Agile Development Strategy known as Scrum, guidelines to reduce these wastes have been worked out. All wastes discovered in the first section of the paper have been dealt with except one, chaotic work environment. This is an ever-returning challenge for start-ups, and probably the origin of the cliché story of startup companies in garages and basements.

The Scrum strategy should reduce the amount of *extra processes and relearning* as all team members have a better of idea of what everyone is doing in the current sprint.

Assigning all tasks and actions to members also gives a clear idea of who has responsibility for what. Team members gets to choose themselves what tasks they are to work with, on accord with the amount of work they are capable of doing that sprint, also balancing out *differences in dedication*. It should also reduce the amount of waiting, as everyone should best be able to predict the available time at hand themselves. The defined responsibility also gives employees the opportunity to *explore their creativity* and to *feel ownership for the product* and the progress in developing it. What before was left in each department and had to be communicated around *functional barriers*, now are exchanged at least every two weeks for the project to move forward. Everybody gets to learn from everyone, without learnings going through the project leader or gets lost on the way.

The Product Owner makes sure that the project always moves towards *value for the customer* and brings the customer needs and wishes to the table every time goals are set and evaluated. This *prevents disruptive changes* to Product Requirements due to bad understanding of customer needs. It also assures the team members are *working on the right thing*, and not *overdesigning* when doing so.

The clearly defined goals, with focus on functioning Product increments also prevents *partially done work*.

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INTEGRATING AGILE PRODUCT DEVELOPMENT IN ALVA

Simen Stenersen Pjaaten

This article discusses how ALVA, a startup company from NTNU, compares to the original six characteristics of Agile Product Development management as defined by Nonaka and Takeuchi in their study from 1986 [Takeuchi and Nonaka, 1986]. It will introduce the studies of Nonaka and Takeuchi as well as the product development management in the ALVA company. The six characteristics that will be discussed are built-in stability, self-organizing project teams, overlapping development phases, multilearning, subtle control and organizational transfer of learning. Through discussion it becomes apparent that ALVAs greatest challenges lies in shared office space, access to multi-disciplined workshops, scheduling and coordination of coherent goals.

Keywords: startup, agile product development, SCRUM, subtle control.

1 Background

1.1 Agile Product Development

Even though Agile Product Development can be traced back to the 1930's, we normally see Agile Software Development as the source of where it came from. This software development methodology is based on a manifest from 2001 written down by 17 acknowledged software developers known as the Agile Alliance. Their work was titled "Manifesto for Agile Software Development". It is cited in its whole underneath.

But Agile Product Development originates from another, less known source from 1986. A study titled The new product development game from Takeuchi and Nonaka (Hirotaka Takeuchi 1986). The paper suggests companies "Stop running the relay race and take up rugby". It is meant to describe another way of communicating between departments in product development. A relay race illustrates the typical flow of product development. Where designers initially picture an idea before sending it to the engineers which again sends it further to economics and marketing in a very sequential matter. In rugby on the other hand, the ball (consider this the idea in prod-

Exhibit 1.1 Manifesto for Agile Software Development

We are uncovering better ways of developing software by doing it and helping others do it. Through this work we have come to value:

Individuals and interactions over processes and tools
Working software over comprehensive documentation
Customer collaboration over contract negotiation
Responding to change over following a plan

That is, while there is value in the items on the right, we value the items on the left more.

Kent Beck, Mike Beedle, Arie van Bennekum, Alistair Cockburn, Ward Cunningham, Martin Fowler, James Grenning, Jim Highsmith, Andrew Hunt, Ron Jeffries, Jon Kern, Brian Marick, Robert C. Martin, Steve Mellor, Ken Schwaber, Jeff Sutherland, and Dave Thomas.

Figure 1: The Agile Manifesto

uct development) is passed between the different roles all the way through the game.

By analyzing the development process of six products from different companies, the japanese authors discuss six common characteristics. These characteristics, taken as a whole, “can produce a powerful new set of dynamics that will make a difference.” They are as follows:

(1) Built-in instability

(2) Self-organizing project teams

(3) Overlapping development teams

(4) “Multilearning”

(5) Subtle control

(6) Organizational transfer of learning

The six characteristics will be discussed in the specific case of ALVA, after a short introduction to the company.

1.2 introducing ALVA

Alva was founded by Jørgen Selnes and Sybolt Visser in the spring of 2016. After spinning around an idea from Martin Gudem, a former PhD student from the Institute of Product Development at NTNU, the two entrepreneurship students came up with a concept. They wanted to weave a composite cloth with conductive properties. The cloth would further be rolled up to a cylinder so that it could be used as a stator or rotor in an electromotor. Selnes and Visser wanted to develop the concept as an agile, yet effective production method and decided to look for people to join their team.

Today, ALVA consists of seven students. Four of them are doing technical development while two are doing market research. After a chaotic start, the managers were looking for a project management tool to help with planning. They decided to implement SCRUM, using a student report to back their decisions[Pjaaten, 2016]. Alva is still in search of ways to implement more lean and agile, both in project management, and product development.

2 Implementation

2.1 Built-in Instability

Built-in instability is commonly achieved by giving the development teams intensely challenging goals and lots of freedom. This extraordinary framework pushes the project in extreme directions.

By the very nature of ALVA's concept there exists very challenging goals. This production method has not been done before. Several technologies need to be understood and tailored for the specific task at hand. Not only in terms of shape and size, but material properties like conductivity and thermal expansion rates. In addition, changing the conventional design of an electromotor makes it more difficult to simulate in common computer software. This acquires an immense amount of creativity in the development team.

By terms of freedom, the team were restricted to some degree given the general lines of how the solution would need to be. This may be more restrictive than necessary.

2.2 Self-organizing project teams

Self-organizing project teams occurs when three conditions are in place: autonomy, self-transcendence, and cross-fertilization. By self-transcendence Takeuchi and Nonaka means that teams pursue contradictory goals, or in other ways goals that are very hard to achieve. This leads teams to question established rules, and further seek big discoveries. Cross-fertilization happens when teams are put together of widely different people. When forced to communicate by simply sharing work space, their mindsets blends and the work one does becomes more altruistically motivated.

With the scrum management tool, ALVAs development team is highly autonomous. Every week they set out new goals for themselves. Everyone has got the responsibility to reach their goal. How they get there is up to each team member individually.

The organizations mission to make a production method that is both agile and effective is usually a contradictory one. This is typically a strategy to differentiate in a market. But with self-transcendence, as Nonaka and Takeuchi calls it, often comes the big breakthroughs. When it comes to cross-fertilization, ALVA has a way to go. Team members are spread out on different offices, which prevent this kind of interaction. First, a bigger office with room for all needs to be provided. And second, a work shop which facilitates all the machines and materials that are needed for prototyping. Given that ALVA is a startup company, this is a crucial challenge. They do not have office space for all team members combined. And each team member has access to their own work shop with facilities suited for their field of studies. At NTNU, there are strict security rules for all workshops. This makes it hard for startups to collaborate on multi-disciplined engineering projects like ALVAs one.

Last, it is worth noting that this is only a full time job for two of the team members. The five other students do this as a part time job. Not only does it make the work flow uneven, it is also hard to find a time that fits everyone.

When all this is said, ALVA is aware of these pain points and is eager to do something about it.

2.3 Overlapping development phases

Overlapping development phases is partly the essence of the rugby approach. In conventional product development, a delay would make all other groups forced to wait for the problem to be fixed. With the rugby approach and a self-organizing team, a problem causing delays causes more work pressure on the task. This dynamic keeps everyone busy, reducing waiting while pushing the project forwards.

This is a challenging point for ALVA because of three factors. First, two of the team members are writing a thesis based on the project, and needs to work more strictly within their discipline. Second, the company needs to provide a working component, a woven conductive cloth, to have a proof of concept. This is important as startups need funding. And last they want to develop their manufacturing process to show that it is possible to automate this process. This is three limitations that makes it hard for ALVA to collaborate on one thing at the time. But the three different goals can be defined in such a way that the aim of one more strongly relies on the other.

2.4 Multilearning

Multilearning is learning along two dimensions, across levels and functions. By level is meant the level of unit such as individual, group or even corporate. The companies in the 1986 study showed a strong willingness to learn new skills. By putting together teams without previous experience with the technology at hand, or by encouraging employees to seek new knowledge.

The team members in ALVA are all students, both used and skilled in learning. Because of the little size of the company, learnings flows more easily and naturally. Since day one, there has been a strong culture to document ideas and learnings along the way. Later, when ALVA might grow bigger and more diverse, this culture will pay off. As these kind of tools become more important, it will already feel natural for the employees.

With the SCRUM tools, the team members exchange more information about their work than they would with many other types of management. This makes it easier for everyone to get a better understanding of what different disciplines involve.

2.5 Subtle control

Subtle control is the way managements keeps creativity blossom without turning a project into complete chaos. This subtle control is achieved through a mix of peer pressure and self-control and providing enough checkpoints to keep a general direction.

It has been mentioned that ALVA implemented SCRUM early on. One of the great things about this framework is the use of subtle control.

Typically, the product manager makes sure to put adequate goals up for the members of the development team to take. This insures the company's interests, while giving team members freedom to choose what to work with. In this way, a creative environment is provided, with the company's goals in focus.

The peer pressure is lost because of the mentioned problem of team members being spread out on different offices.

2.6 Organizational transfer of learning

Organizational transfer of learning is also a focus for many of the projects in this study. Nonaka and Takeuchi saw that common practice was to turn their creative and resourceful developers to new projects so their knowledge could further benefit other projects and teams in the company.

This is yet to see, and not yet relevant for ALVA.

3 Conclusion

We have seen in this discussion that ALVAs greatest challenges lies in lack of shared office space, access to multi-disciplined workshops, scheduling working hours and coordination of goals.

With a shared office, and a multi-discipline workshop, ALVA becomes more cross-fertilized. This would hopefully contribute to several positive effects. Team-members unconsciously become more aware of what other team-members work with, struggles with, and learns from. This feedback into their own goals and work, to better fit everyone. Incompatible ideas are much sooner discovered, and avoided. Better self-organizing project teams also comes as a result of these altruistic goals, as the team has a shared idea of where to go. The company also profits from the multilearning going on in the shared space, tearing down the communication barrier between people from different disciplines.

ALVA still have several slightly conflicting goals with equal time pressure, which makes it harder to cooperate. These goals should be revised as it would be of great help if they were more coherent. Instead of helping each other move forward, any helping hand becomes an obstacle for progression for one part. This would also bring out the positive effect of having overlapping development phases. Whenever a problem comes up that needs to be solved, it is of everyone's interest to fix it as soon as possible.

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