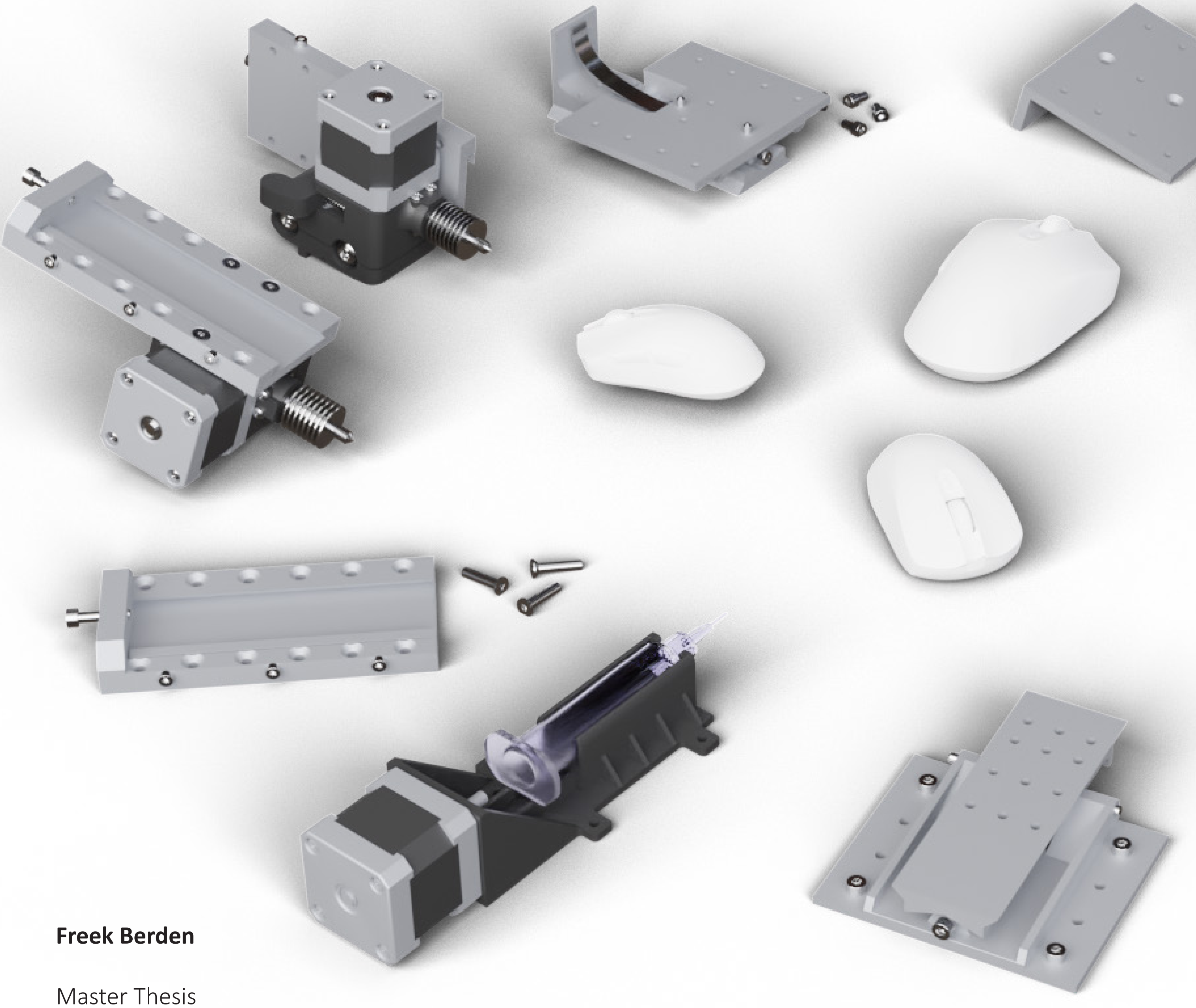
Hybrid CNC Manufacturing

Flexible manufacturing system in support of the Transcended manufacturing process



Freek Berden

Master Thesis
Msc. Integrated Product design
Delft University of Technology

Master Thesis
September, 2021

Freek Berden

Msc. Integrated Product design
Delft University of Technology

Supervisory team
Ir. Minnoye, A.L.M.
MSc. Dam, J.J.F. van

Delft University of Technology
Faculty of Industrial Design Engineering
Landbergstraat 15
2628 CE Delft

The Netherlands

Hybrid CNC Manufacturing

Flexible manufacturing system in support of
the Transcended manufacturing process

Preface

Before you lies the thesis "Hybrid CNC manufacturing, a flexible manufacturing system in support of the Transcended manufacturing process" as the completion of my studies at the TU Delft, Integrated Product design. Graduating during covid went with ups and downs, but through all of it we live and learn, and I want to thank some people who helped during the process and my studies.

Firs I would like to Thank my supervisors Sander Minnoye and Joris can Damm for giving me the opportunity to work on this project. I want to then you for your understanding, your support and guidance throughout the process. I endured many challenges and I would not have managed without your guidance.

Secondly I would like to thank Jacqueline Koopman, you helped me get through the last parts of the project and without you I would have never finished the project like I did.

Of course I also would like to thank my parents and my family for their support throughout all of my studies pronlonged as they might have been.

I would like to thank my friends and my room mates for being understanding and for making my student life like it is. I would especially like to thank Roeland and Thomas for pulling me out of the graduation rabbit hole, and for trying to keep me sane.

And at last I would like to thank Jan Koudijzer, for his support and for giving me the opportunity to prototype this project, which was a big goal for me.

Content

Introduction

1

1.1 Executive summary

Transcended manufacturing is a new emerging manufacturing paradigm in response to the rising need for mass personalisation and ultra-personalised products. Through product personalisation, people can assert their identity in an increasingly impersonal world. But the one-off a kind nature of ultra-personalised make them hard to manufacture with traditional fabrication methods. Transcended manufacturing uses automation and digital manufacturing to manufacture ultra-personalised products. Hybrid fabrication is a digital manufacturing technique that combines multiple processes to provide new process capabilities. Hybrid manufacturing is still underdeveloped but could improve the field of personalised products and transcended manufacturing with its versatility and flexibility.

The project goal was to research hybrid fabrication and find and develop opportunities that may benefit Transcended manufacturing and ultra-personalised products.

The project started with an analysis of the current situation of digital manufacturing and the industry. The study resulted in multiple opportunities for hybrid fabrication and transcended manufacturing, from new processes that can be used for personalised product fabrication, to versatile and flexible manufacturing.

With the opportunities of hybrid fabrication defined, a future vision, a production scenario and exemplary product are created. These scenarios are used to ideate, conceptualise and develop a hybrid fabrication workstation. The future of hybrid fabrication looks bright but early adoption of hybrid manufacturing is in product research and development.

The workstation is further embodied and a prototype is created to showcase and kickstart hybrid fabrication and personalised product development. The prototype addresses reconfigurability and flexibility in hybrid systems and provides a platform and framework for hybrid manufacturing.

The future of hybrid manufacturing and transcended manufacturing looks promising. As the industry 4.0 grows and transcended manufacturing and hybrid fabrication mature, the new way of manufacturing ultra-personalised products can include hybrid fabrication systems.

1.2 Glossary

Bespoke product
A unique product that is custom made and tailored to the user’s request

CNC
Numerical control is the automated control of machining tools by means of a computer.

Capacity flexibility
The ability of the manufacturing system to vary the production volume of products and the ability to contract or expand. Including Volume flexibility and expansion flexibility.

Cellular Manufacturing System(CMS)
Provide flexibility and efficiency through the clusering of multiple different machines in production cells that efficiently accomplish a part of the manufacturing process.

Co-creation
A method to create products where input from consumers plays a central role from beginning to end of the process.

Configure to order (CTO)
Manufacturing strategy that answers to the need for customisation and the demand for responsiveness. CTO is a hybrid model that combines MTS & MTO. In CTO a set of components (subassemblies) are built to stock, whereas the end products are assembled to order.

Cyber-Physical System (CPS)
Combination of computer science, information and communication technologies for the interaction between the physical and the cyber world. Sensors, controllers and actuators are used for the monitoring of processes while the cyber space is responsible for data analysis to make strategic decisions.

Cyber-Physical-Production
Systems (CPPS) production system that consist out of autonomous and cooperative elements that are connected across all levels of production from processes through machines up to production and logistics network.

Dedicated manufacturing line (LMS)
Manufacturing with dedicated manufacturing lines where cost-effectiveness is reached with pre-planning and optimisation.

Flexible manufacturing system (FMS)
A flexible manufacturing system that provides on demand flexibility by generalised flexibility based on predicted variations.

Fused deposition modelling (FDM)
3D printing method where polymer material like PLA is melted and deposited in layers, gradually building up a shape.

Hybrid fabrication
Hybrid fabrication combines multiple different fabrication processes and performs multiple process steps in a single system to create a new fabrication process.

Industry 4.0
The transformation of the entire industrial production through the merging of digital technology and the internet with traditional manufacturing processes

Integrated electronics
Integrating electronics in the fabrication process to create parts that have electronics embedded in them.

Make to order (MTO)
Manufacturing strategy that begins after the customer’s order is received. The MTO model offers great customizability and personalisation and requires less inventory stockpiling.

Make to stock (MTS)
Manufacturing strategy where stock products are made in advance, and product inventory is stockpiled to provide responsiveness and quickly fulfil orders

Mass customisation
Mass production paradigm that with the use of lean and agile manufacturing strategies lets customers select or eliminate certain design criteria to suit their needs.

Mass personalisation
Mass production paradigm that with the use of digital manufacturing strategies creates unique products fitted and personalised to the customer to suit their needs.

Matrix production
Matrix production is a new emerging production system that is versatile and can efficiently adapt to manufacturing uncertainty and demand by dynamicaly adapting processes to production demand.

Operation Flexibility
The ability of a system to produce a set of products using different machines, materials and sequence of operations. Including operation flexibility, material handling flexibility, routing flexibility and control program flexibility.

Product Flexibility
The ability of a manufacturing system to make a variety of part types. The ability of the system to adapt to changing demands for various products. Including machine flexibility, process flexibility, production flexibility and part flexibility.

Product platform architecture
Product platform architecture defines product compatibility/interchangeability and its functional features and components. It covers the market and individuals needs and considers the product family and the perceived value of the product family to the market.

Reconfigurable Manufacturing system (RMS) Reconfigurable manufacturing system that provides on demand flexibility through modularity and reconfigurability in order to quickly respond to changes in market requirements

Stochastic manufacturing
Dealing with the randomness of processes and process demand in manufacturing.

Transcended manufacturing
The manufacturing method that uses product independent process steps to make one-of-a-kind products at a mass-production output capacity

1.3 Introduction

In our modern society, mass-produced products are readily available, advertised and desired; however, there is a growing demand for individualism which speaks to our personality and culture (Grant, K.E,2013). Through product personalisation, people can assert their identity in an increasingly impersonal world. But the one-off a kind nature of ultra-personalised make them hard to manufacture with traditional fabrication methods. The industry's response to the need for personalisation was to provide mass customisation to the consumer with the use of lean and agile manufacturing strategies. Mass customisation lets customers select or eliminate certain design criteria to suit their needs.(Franke, N., Schreier, M., 2008).

We are at the start of a new industrial revolution. The current industry 3.0 is transcending into industry 4.0 by transforming the entire industrial production and merging digital technology and the internet with traditional manufacturing processes (Davies, 2015). Through this revolution and advances in digital manufacturing, the possibilities for manufacturing personalised products are changing.

The Center of Design for Advanced Manufacturing (CDAM) at the TU Delft is at the front of these developments and is researching advanced manufacturing, including transcended manufacturing.

Transcended manufacturing is an emerging manufacturing strategy developed by (Kromhout, B., 2020). Transcended manufacturing is a method that uses automation and digital manufacturing to manufacture truly unique ultra-personalised products.

Hybrid fabrication is among the new digital fabrication processes that are emerging. Hybrid fabrication is a digital manufacturing technique that combines multiple digital fabrication processes to provide new process capabilities.

Transcended manufacturing is achieved by linking multiple standalone digital fabrication stations together, using the flexibility and customizability provided by these digital fabrication stations. In addition to typical digital fabrication, hybrid manufacturing could improve the field of transcended manufacturing and enable the production of ultra-personalised products with its versatility and flexibility.

This project aims to explore hybrid fabrication and to research, find and develop opportunities that may benefit Transcended manufacturing and ultra-personalised products.

1.4 Festo

Festo, a partner of CDAM and a partner in this project, has provided support and expertise to the project. Festo is a worldwide leader in factory automation and a market leader in technical training and development. A part of festo is Festo didactic, a leader in industrial education – be it with equipping technical training institutes or offering training and consultancy to processing industrial companies ("The Companry, n.d.).

Festo observed that within their Industry 4.0 'CP Factory' the need for mass-customisable production was growing. Therefore Festo developed a CP Factory (Cyber-Physical Factory) reflecting the new developments in Industry 4.0 network production and offers a modular Smart Factory system for teaching and research purposes. CP Factory illustrates the practical implementation of a networked factory and can be used to represent the entire value chain.

J. Koudijzer from Festo helped by providing his insight from the industry and supplying parts for prototyping.

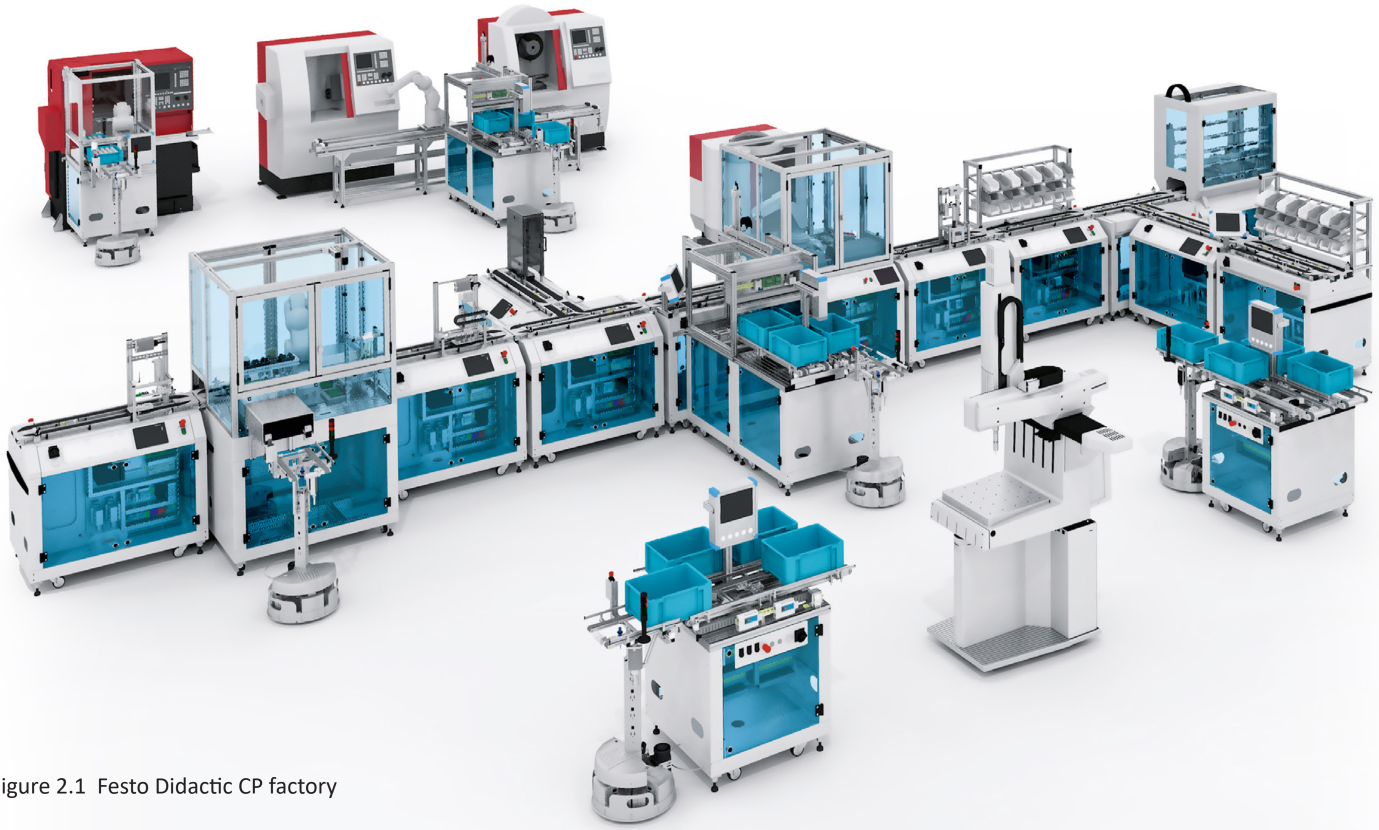


Figure 2.1 Festo Didactic CP factory

1.5 Assignment

To implement transcended manufacturing and create ultra-personalised products, a standalone hybrid fabrication station is needed. This project goal is to research hybrid manufacturing and develop a hybrid CNC fabrication system for transcended manufacturing that combines multiple fabrication techniques to make one-of-a-kind products.

In support of the project goal, the following research questions are formulated:

- What are the benefits and opportunities of hybrid fabrication systems?
- How does hybrid fabrication enable ultra-personalised product fabrication?
- How could hybrid fabrication enable transcended manufacturing and bespoke manufacturing?

To validate the hybrid fabrication system, an example use case will be created that can perform hybrid fabrication and show the potential of transcended manufacturing.

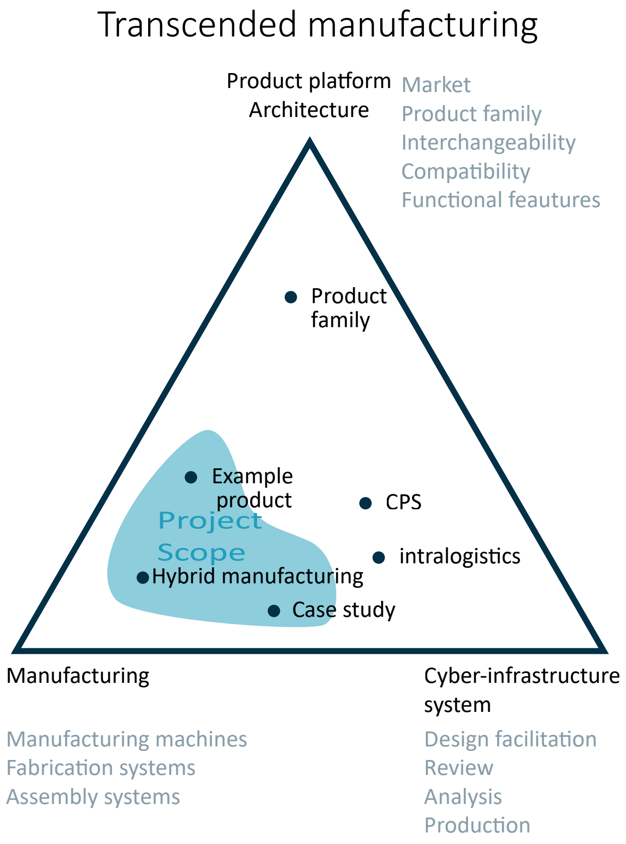


Figure 1.1 Project scope

1.6 Approach

As designers, it is our task to identify problems, create ideas and develop solutions. This project will follow the design thinking approach and the double diamond method of divergence and convergence (Figure 1.3).

The first stage of the process is to explore and analyse the context. During the analysis stage, the broad context is examined, after which opportunities can be synthesised and defined. With the opportunities identified and defined the ideation can start. From these opportunities a design vision is developed and future scenarios are created to support the ideation processes. During ideation, solutions are explored and developed into concepts. Through concept evaluation, a concept solution is picked to be further developed. The last stage of the process is the design embodiment of the proposed concept solution. A final design solution is developed, validated and presented (Figure 1.2).

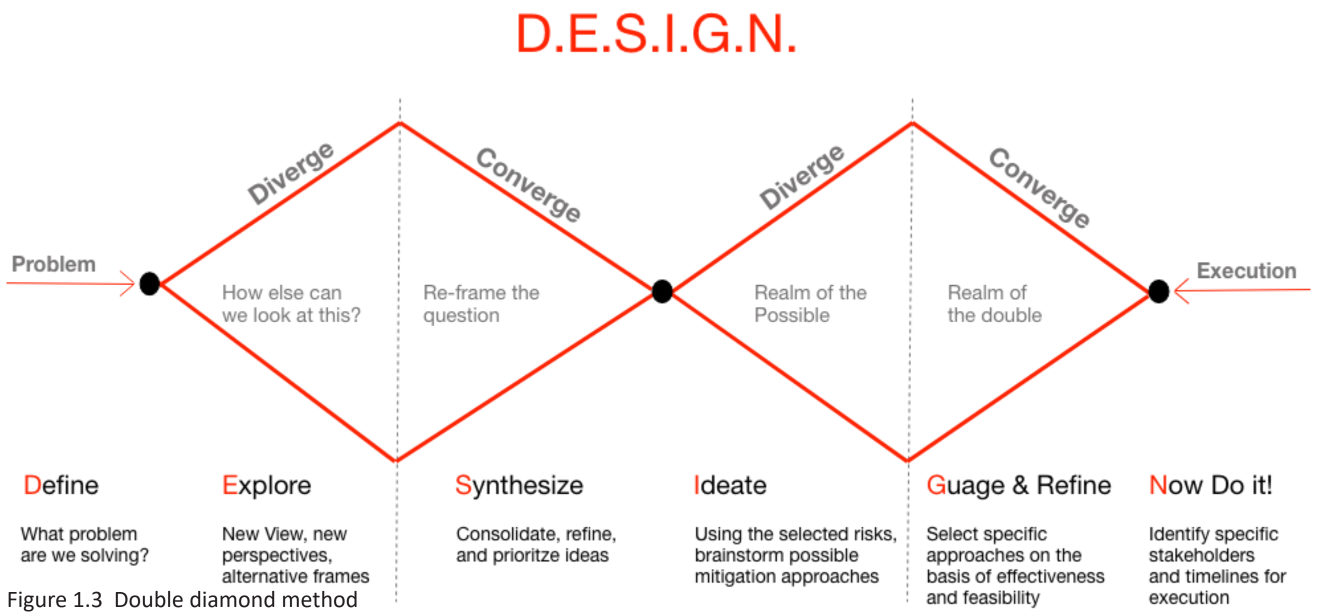


Figure 1.3 Double diamond method

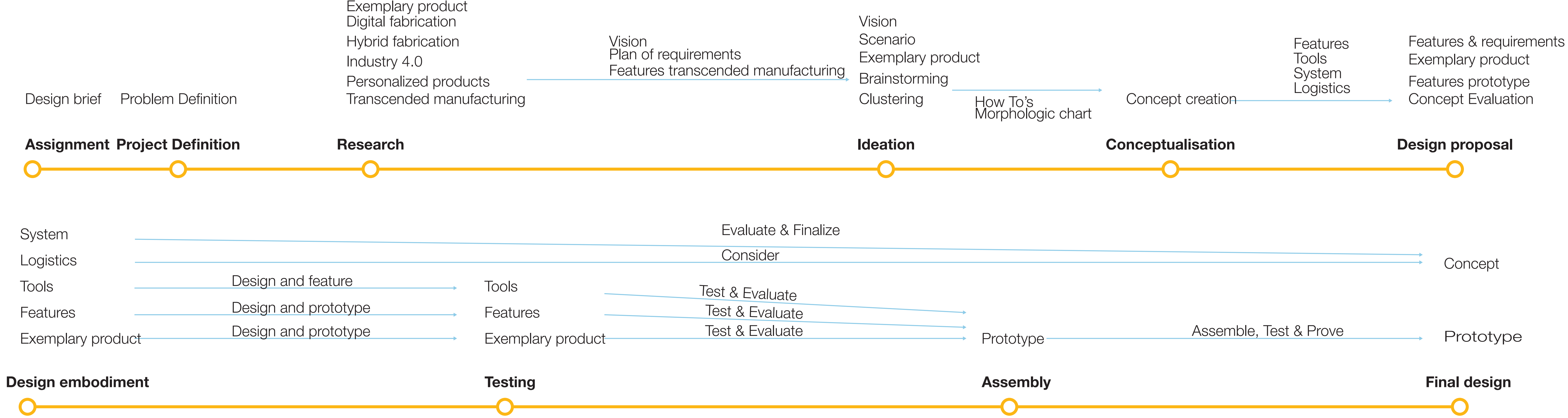


Figure 1.2 Approach

Analysis

In this chapter is about the analysis phase of the project, this phase takes a broad look at the context of the project, current industry are explored and we look at the market changes, manufacturing practises and synthesize opportunities

2

2.1 Evolution of the industry

The industry is constantly improving and changing. To understand current practices and the state of the industry, we look at how the multiple industrial revolutions shaped today's world. We take a look at the technological advancements and the production paradigms of that period.

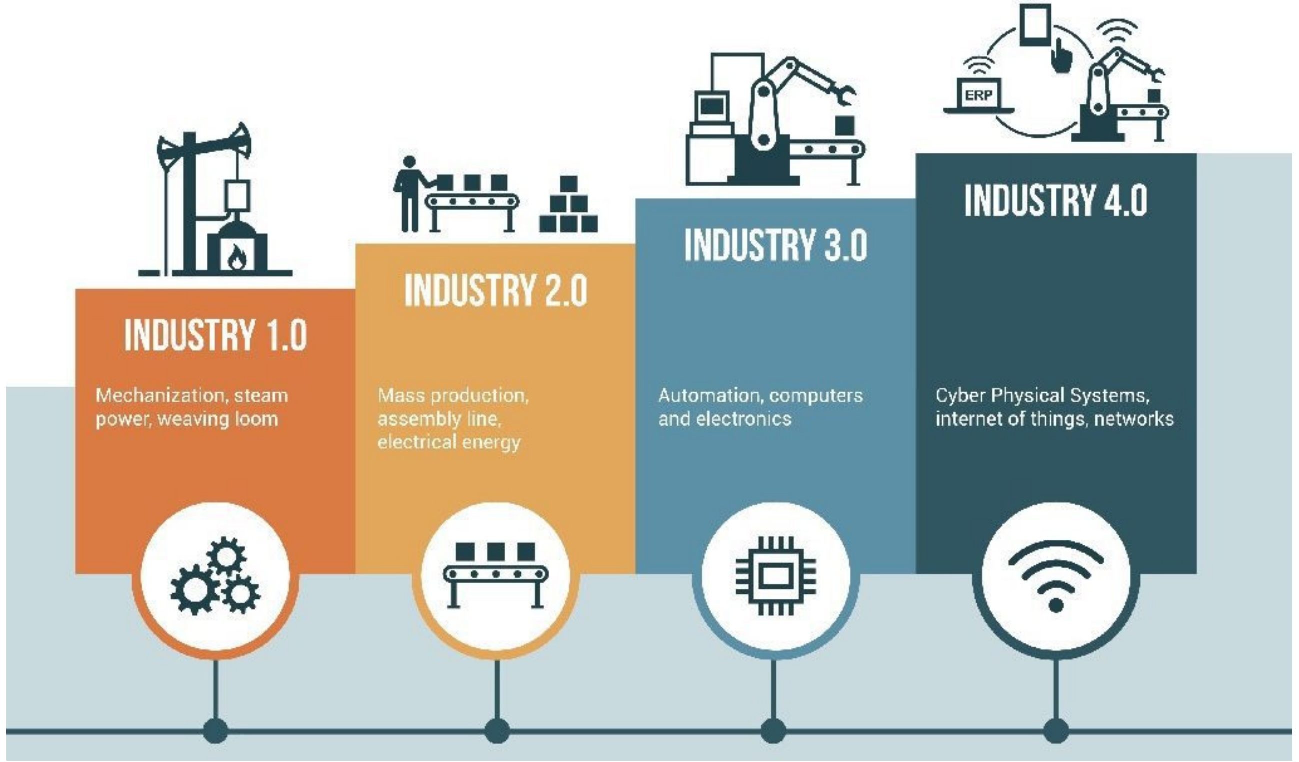


Figure 2.1 Industrial revolutions

2.1.1 First industrial revolution

During the late 18th century, the first industrial revolution, steam power and machine tools drastically improved productivity. This period is characterised with craft production, products created per the customer request with high production cost and without the use of a manufacturing system. A single craftsman or a team of craftsmen create each part of the product (Hu, 2013).

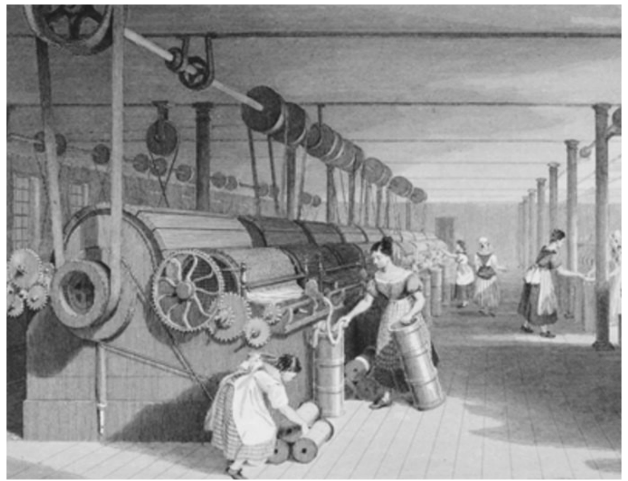


Figure 2.2 Craft production

2.1.2Second industrial revolution

The second industrial revolution was with the introduction of the assembly line and electricity to the manufacturing process. It started the mass production paradigm, and it was now possible to create a high volume of identical products at low unit cost through large scale manufacturing. However, this kind of production offers low product variety, as Henry Ford mentioned: "Any customer can have a car painted any colour that he wants so long as it is black".

Figure 2.3 Ford assembly line

2.1.3 Third industrial revolution

The introduction of electronics, computers, informational technology (IT) and automation spearheaded the third industrial revolution. Global competition and consumer demands for more product variety led to the development of "mass customization". Flexible and reconfigurable manufacturing systems are utilized to achieve high product variety at competitive cost. (Hu, 2013)

2.1.4 Fourth industrial revolution

Currently, we are at the start of a new industrial revolution, moving from industry 3.0 to industry 4.0. Industry 4.0, which is defined by the transformation of the entire industrial production through the merging of digital technology and the internet with traditional manufacturing processes (Davies 2015), makes use of sensors and actuators communicating through a network, enabling the connection between machines, tools, systems, customers, workers and products. Everything around the production and manufacturing operation of products are digitally connected, providing a highly integrated value chain. This integrated value chain also enables the integration of personalised products at high output capacity. With the customer in the process, we shift to a new manufacturing paradigm, "personalised production" where production and product are tailored to their personal needs.

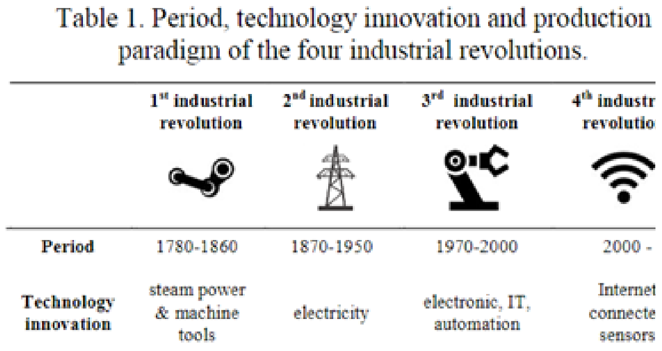


Table 1. Period, technology innovation and production paradigm of the four industrial revolutions.

	1st industrial revolution	2nd industrial revolution	3rd industrial revolution	4th industr revolutio
	⚙	⚡	🤖	📶
Period	1780-1860	1870-1950	1970-2000	2000 -
Technology innovation	steam power & machine tools	electricity	electronic, IT, automation	Internet connecte sensors

Figure 2.5 Production paradigms

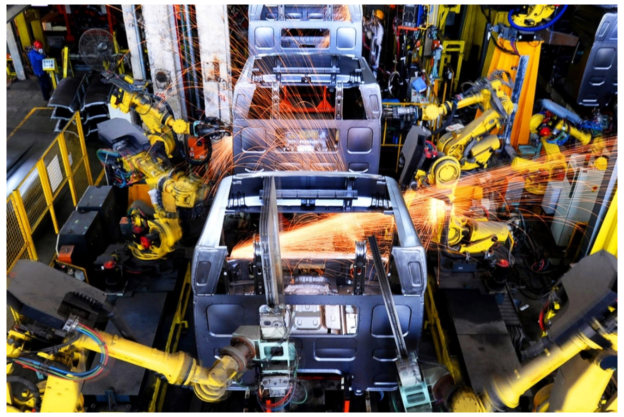


Figure 2.4 Mass porudction automation

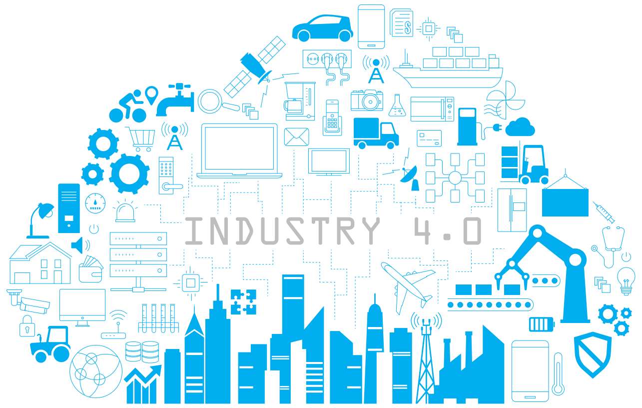


Figure 2.6 Industry 4.0

2.1.5 Conclusion

Advancements in technology have given rise to new possibilities. The industry transitioned from small scale personalised craft production to more generalised mass production. Now the industry is moving back to more customised and personalised production through automation. With the rise of industry 4.0 and digital manufacturing, personalised products can be manufactured at high output capacity.

2.2 Mass personalisation

With the new possibilities that advancements in the industry made possible, consumer demand is changing. The global market and its increasingly diverse customers are shifting towards an increasingly personalised market. In modern society, mass-produced products are readily available, advertised and desired; however, there is a growing demand for individualism (Grant et al., 2013). Product personalisation lets people assert their identity in an increasingly impersonal world (Jordan, 2000).

2.2.1 Changing Market

When given a choice, consumers prefer personalised products over standardised, mass-produced products (Choi, Lee and Taylor, 2016). Firms are competing for customer attention and are increasing their product variety to match the customer’s personal needs. With the increasing availability of products to consumers, the consumer can choose between personalised and non-personalised products. The global market is a highly competitive market in which consumers have the freedom to choose and are not limited to location. In this new personalised market, companies will be manufacturing products individually tailored to each customer (Berry, Wang and Hu, 2013).

Companies are responding to the market change and are creating value in product variety. The online database project the configurator database, shows that many companies are moving to provide personalised products. With over 1350 listed companies in 17 different industries, the personalised product market is emerging (Configurator Database, n.d.). Many of these companies are niche manufacturers and start-ups. However, some big brands are also adding personalisation options to their product lines to increase sales and keep up with competition.

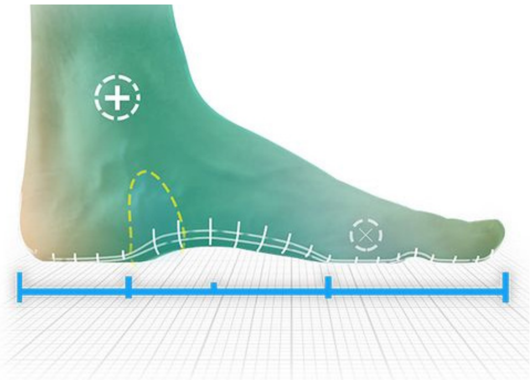


Figure 2.7 Fit my foot orthotics shows

The increasing need for personalised products is creating new challenges and possibilities in manufacturing. While customers are happy to spend a little more on personalised products, they want the same responsiveness and ordering experience as mass-produced standardised products. This leads to a need for on-demand manufacturing to meet the consumer’s needs and expectations (Childs, Dalgarno and McKy, 2005).

The company FitMyFoot is a good example of how they use digital manufacturing to provide bespoke products. The company uses hundreds of 3d printers that work around the clock to offer on-demand personalised footwear to its customers. Customers create their own foot scan using their mobile phone, and within 14 days, the customer can expect their personalised footwear at their door.

Figure 2.8 The configurator database

2.2.2 Personalised manufacturing

To meet the demands of the personalisation trend, a new branch of manufacturing is emerging. While widely used lean and agile manufacturing methods are used to provide product variety at a mass-production scale by streamlining the manufacturing process and giving the consumer customisation options. A new kind of manufacturing is developing to meet the increasing demand for personalised products and the growing complexity personalised products bring to the manufacturing process. This new way of manufacturing, as introduced by Ben is called Transcended manufacturing, defined as: “The manufacturing method that uses product independent process steps to make one-of-a-kind products at a mass-production output capacity” (Kromhout, 2020). Like the trend, transcended manufacturing aims to provide increased product variety at low extra cost and lead time. However, mass-producing personalised products comes with a trade-off, the additional complexity of ultra personalised products leads to an increase in manufacturing time. Therefore, Transcended manufacturing sacrifices output volume to increase product variety, as shown in Figure 2.9.

> **Transcended manufacturing:**
> *“The manufacturing method that uses **product independent process steps** to make **one-of-a-kind products** at a **mass-production output capacity**”.*

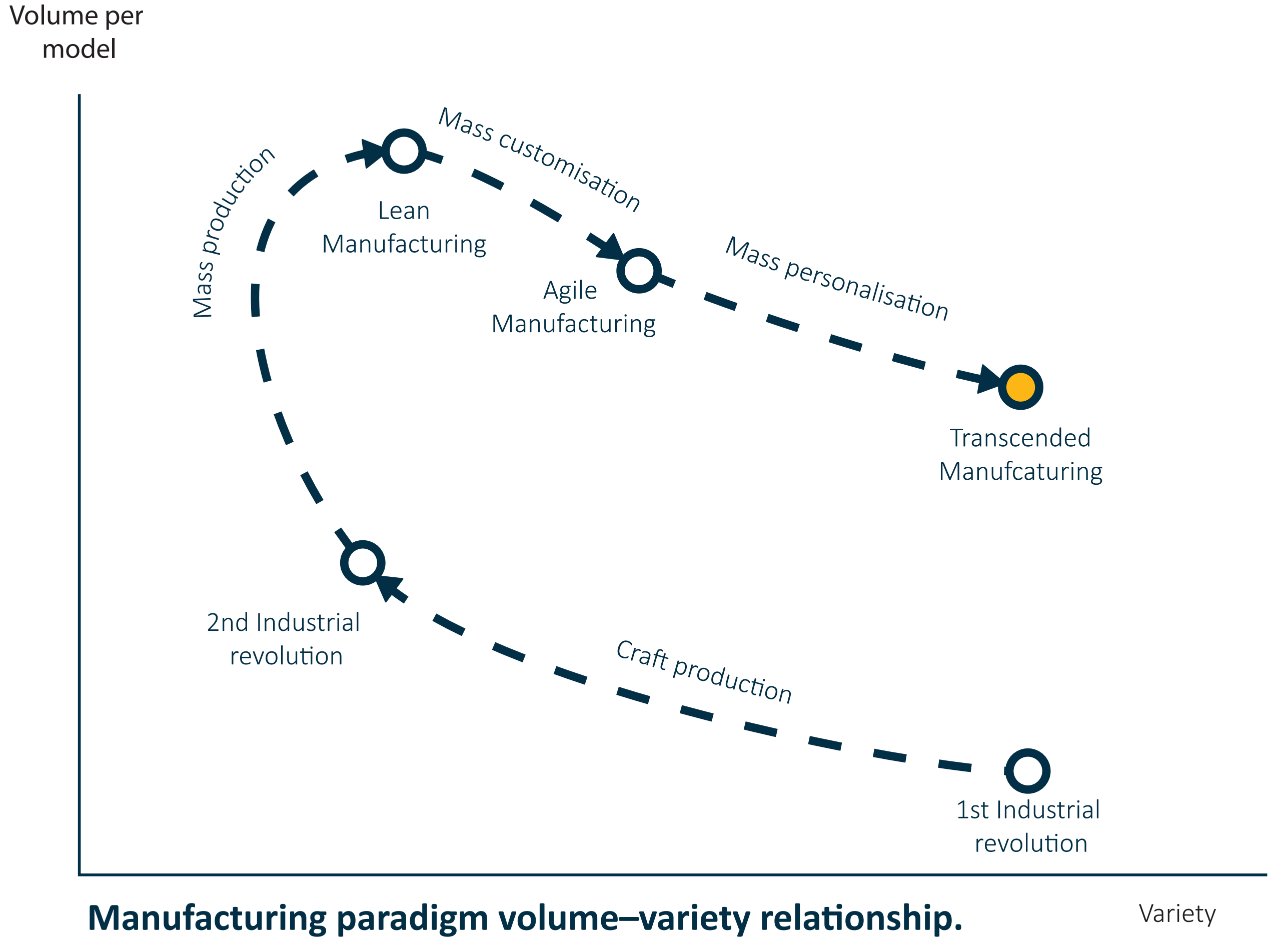


Figure 2.9 Manufacturing paradigm volume-variety relationship

2.2.3 Bespoke products

Product personalisation is trending and there are many ways to personalise a product. To emphasise the personalisation side of the products, the term "bespoke product" or "ultra-personalised product" is used by businesses for products that are tailored to the customer's measurements or specifications. The word bespoke is used by tailors referring to a bespoke suit, which is custom-made to the client's requests and measurements. Now other industries are starting to adopt the term bespoke, referring to bespoke design as an item that is custom made for the user (Katana, 2021) For this research, we will refer to bespoke products as "A product that is custom made and tailored to the user's request".

The key difference from mass customisation is that ultra-personalised products have unique parts manufactured and tailored to the customer's needs, in contrast to mass customisation, which combines standardised elements to create unique products.

For example, a customised shoe is manufactured by combining standardised parts to fit the customer's needs, while a bespoke shoe is tailored to the customer's fit and needs. For mass customisation, components and materials can be produced and stockpiled in advance. However, personalised products have parts that need to be manufactured on demand, specific to the customer's measurements and requests.

Bespoke product:
"A unique product that is custom made and tailored to the user's request".

Figure 2.10 Bespoke suit

Figure 2.11 Tailor made

2.2.4 Product personalisation

Product personalisation can be categorised in three areas; fit, performance and aesthetics. While a product could be personalised in only a single area, bespoke products are often personalised in multiple areas.

Fit: specifically fitted to the customer.

Performance: personalised on its features and how the product performs.

Aesthetics: personalised on the aesthetic preference of the customer.

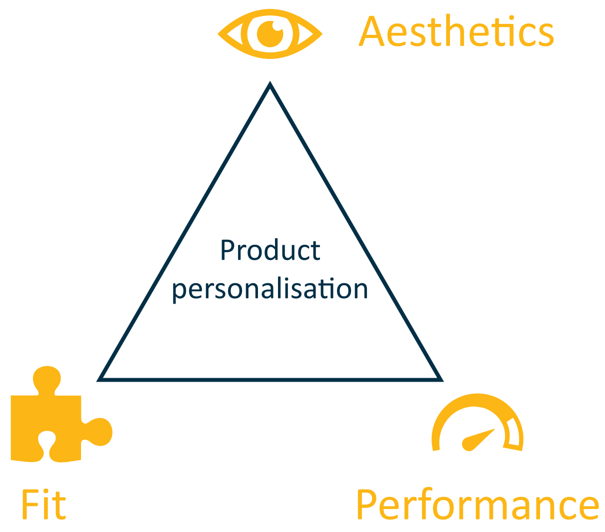


Figure 2.12 Personalisation areas

Manufacturing strategies

Traditional mass manufacturing deploys the Make to Stock (MTS) strategy, with MTS stock products are made in advance, and product inventory is stockpiled to provide responsiveness and quickly fulfil orders. On the other hand, the make to order (MTO) strategy begins after the customer's order is received (Rajagopalan, 2002). The MTO model offers great customizability and personalisation and requires less inventory stockpiling; however, MTO lacks responsiveness because it can only be manufactured after ordering. Configure to order (CTO) answers to the need for customisation and the demand for responsiveness. CTO is a hybrid model that combines MTS & MTO. In CTO a set of components (subassemblies) are built to stock, whereas the end products are assembled to order. CTO offers both mass customisation and quick response to order fulfilment (Cheng et al., 2002).

To create personalised products the consumer needs to be involved in the creation process. With MTO and CTO users can input their personal preferences, and the system derives the personalised product fulfilling the customer's needs (Zheng et al., 2017).

With the help of co-creation, companies are able to provide personalised products to the customer. A successful example in the field of mass customisation following the CTO model is "Nike by You" with which customers can configure the aesthetics of their shoes (Figure 2.13).

Personalisation complexity

Personalisation and customisation are great, but too many options complicate manufacturing and can impact the ordering experience. Personalisation complexity has to be taken into account when designing personalised products. Giving the customer too many options to choose from can adversely affect the user's choice while unnecessarily complicating manufacturing. "Customers prefer standardised products over personalised alternatives when the range of personalisation is excessive. Customers are more likely to select standard products over personalised alternatives when faced with inordinately complex decision-making."(Choi, Lee and Taylor, 2016). Personalisation should be balanced, and the personalisation features need to be weighed carefully. A good example is the inlay soles of the earlier mentioned FitMyFoot, where the customer customises and chooses the soles' aesthetics. At the same time, a program determines the shape of the sole with an app that scans the user's feet.

Figure 2.13 Nike by you

2.2. 6 Conclusion

The need to differentiate and express individual identity through product personalisation is increasing in modern-day society. Markets are adapting to the demand for personalised products, and increasingly more companies are providing personalised and customised products to their customers.

Customers expect similar responsiveness and ordering experience as regular mass-produced products. To meet the demand of mass personalised products, transcended manufacturing is being developed. Transcended manufacturing uses product-independent process steps to make one-of-a-kind products at a mass-production output capacity.

The personalisation trend brings a new category of products called: bespoke or ultra-personalised products. Bespoke products are unique products that are custom made and tailored to the user's request.

Product personalisation and customisation can be categorised into 3 areas: fit, performance and aesthetics. Products personalised on fit are specifically fitted to the customer. Products personalised on performance are personalised on their features and how the product performs. Products personalised on aesthetics are personalised on the aesthetic preference of the customer

To create personalised products, the consumer needs to be involved in the creation process. Make to order (MTO) provides great personalisation possibilities but lacks responsiveness. Make to stock provides quick order fulfilment but lacks personalisation. Configure to order (CTO) model combines MTO & MTS to allow user input and provide fast order fulfilment.

Personalisation complexity has to be taken into account when designing personalised products. Giving the customer too many options can adversely affect the user's choice and unnecessarily complicates manufacturing.

2.3 Digital manufacturing

Digital manufacturing is the integration of computer systems in manufacturing. Computers are deeply entrenched in manufacturing systems and have given rise to agile manufacturing, computer integrated manufacturing, and cloud manufacturing paradigms. The digital manufacturing space is analysed to provide context to the technologies that enable modern manufacturing and find how these can facilitate personalised product manufacturing.

2.3.1 Internet of Things (IoT)

Advancement with the internet has led to an increasingly global community where the world is interconnected. The internet of things is the inter-networking of physical devices, software, sensors, actuators and other items embedded with electronics and network connectivity that enable these objects to collect and exchange data. IoT is a crucial pillar of Industry 4.0. Connectivity allows Industry 4.0 to monitor and keep track of products, workstations, storage locations, equipment and other entities in the manufacturing process (Bortolini et al., 2017).

2.3.2 Industry 4.0

Based on technological advances in adaptive robotics, data analytics and artificial intelligence, simulation, embedded systems, communication and networking such as Industrial Internet, cloud systems, additive manufacturing and virtualisation technologies (Ustundag and Cevikcan, 2017). The current industry 3.0 is transcending into Industry 4.0 with the digitalisation of the manufacturing process. The connection and integration of manufacturing and service systems are used to increase product quality and product diversity. The resulting smart-systems optimise the process while decreasing production cost. The goal of Industry 4.0 is to achieve smart-factories with the embodiment of cyber-physical systems (CPS).

2.3.3 Cyber-Physical System (CPS)

Cyber-Physical-System combines computer science, information and communication technologies for the interaction between the physical and the cyber world. Sensors, controllers and actuators are used for the monitoring of processes while the cyber space is responsible for data analysis to make strategic decisions (Yan, Zhang and Fu, 2019). Cyber-Physical-Production Systems (CPPS) combine the latest developments in CPS and manufacturing to create CPPS that consist out of autonomous and cooperative elements that are connected across all levels of production from processes through machines up to production and logistics network (Monostori et al., 2016). These CPPS are paving the way for Smart factories which have many potentials like the realization of individual customer requirements, control of dynamic business and engineering processes or an optimized decision making process. For this research the potential for automated production of personalised products is most relevant. Figure 2.14 shows an proposed intralogistics focused CPPS.

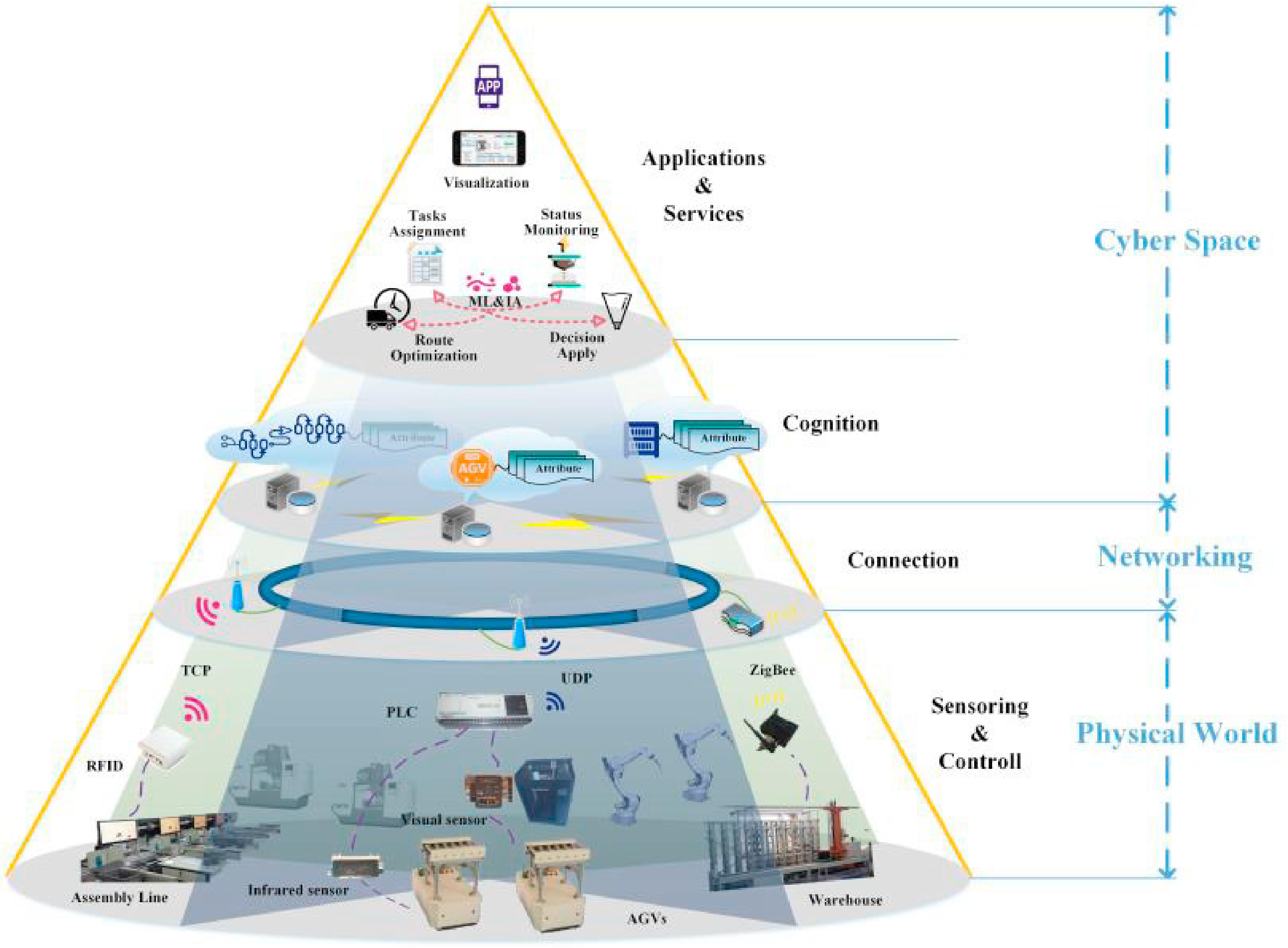


Figure 2.14 Intralogistics focused CPPS (Yan, Zhang and Fu, 2019).

2.3.4 Additive manufacturing

Additive manufacturing, also known as manufacturing with 3D printing, creates parts by adding material to the part and building up a shape. The most common process is Fused deposition modelling (FDM), with FDM polymer material like PLA is melted and deposited in layers, building up a shape. Countless additive manufacturing processes and solutions exist varying in finish, speed,accuracy, material and size (Figure 2.17) Building up a shape layer by layer creates form freedom and offers part complexity with fewer design constraints.

Additive manufacturing is a part independent process that can produce parts with little initial investment. The low starting cost makes additive manufacturing great for creating small production runs and unique part manufacturing. Unlike traditional injection moulding, which is effective with large batch sizes of the same part, spreading the investment cost over thousands of parts (Figure 2.16).

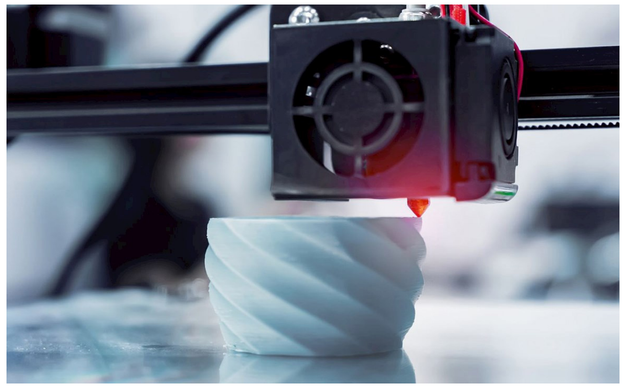


Figure 2.15 FDM 3D printing

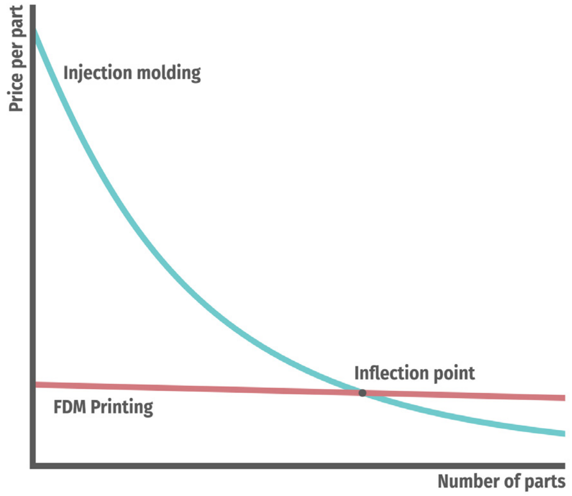


Figure 2.16 Cost per part, FDM vs injection molding (Maagdenberg, 2020).

Figure 2.17 Map of commercially available AM technologies, (3D printing media network, n.d.)

Additive manufacturing still requires post-processing, and it is hard to achieve the same quality as injection moulded parts. Improvements like vapour finishing, soluble supports or other 3D printing techniques like SLS printing improve the possibilities and achievable quality of 3D printed parts.

Additive manufacturing is excellent for bespoke products, the process excels at creating affordable one-of-a-kind parts. Additive manufacturing could be used in the production of ultra-personalised shapes and products personalised on fit.

Takeaways

- Can improve tolerances
- Can create new possibilities
- System efficiency is a concern.
- Long process time, and different requirements.
- Quality not up to par with injection moulding

2.3.5 Stochastic manufacturing

Uncertainty in demand highly influences the effectiveness and process planning of manufacturing systems. The randomness and uncertainty leads to production plans and stochastic models that address these problems. As mentioned in chapter 2.3.2, multiple manufacturing methods emerged that deal with the uncertainty and need for quick response to keep production cost low. Such as lean manufacturing, agile manufacturing and transcended manufacturing. With this, production systems appear like cellular production and matrix production.

Cellular production
Cellular production or a Cellular Manufacturing System(CMS) is widely used for lean and agile manufacturing. Cellular manufacturing aims to provide flexibility and efficiency (Kia et al., 2014). With CMSs multiple different machines are clustered in production cells that efficiently accomplish a part of the manufacturing process. The product moves between the production cells, each station completing a part of the production process.

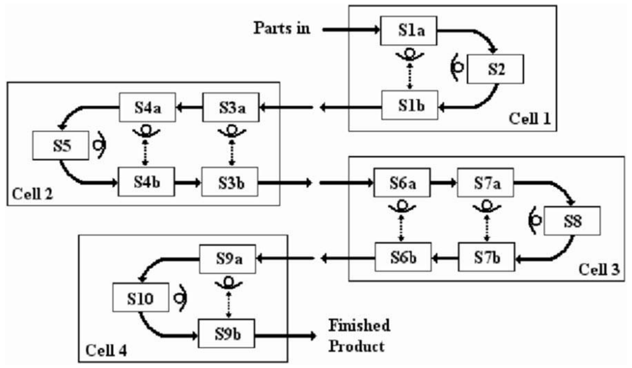


Figure 2.18 Cellular manufacturing.

CMSs groups parts into families based on similarities like size and manufacturing operation and are assigned the same manufacturing cell. CMS improves manufacturing performance by focusing on layout design to arrange machines, tools and equipment in the most efficient way (Esmaeilian, Behdad and Wang, 2016). With CMSs, individual clusters can be reconfigured, rapidly facilitating changes, providing flexibility and efficiency.

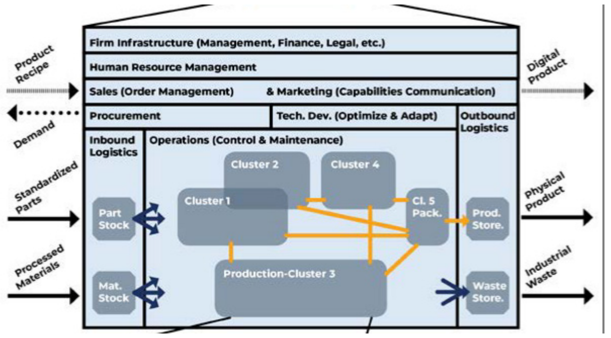


Figure 2.19 Cellular manufacturing Transcended manufacturing (Kromhout , 2020)

Figure 2.20 Matrix production rerouting parts (Bányai et al., 2019).

Matrix production
Matrix production is a new emerging production system that is versatile and can efficiently adapt to manufacturing uncertainty and demand.

Matrix production is similar to cellular production as it uses production cells that perform parts of the manufacturing process. While cellular manufacturing is more linear and has dedicated cells for process steps, matrix manufacturing uses automated logistics to move parts between a grid of flexible standardised manufacturing cells. These manufacturing cells can perform process steps and adapt the available process steps to production demand. Matrix production is highly adaptable and versatile, dynamically routing parts through different stations. Furthermore, malfunctions or maintenance has minimal impact on the production by rerouting parts to other cells (Bányai et al., 2019).

Matrix production uses state of the art logistics and CPS to provide a versatile production process. Matrix production is still in development, KUKA robotics has a matrix production facility using industrial robots in production cells that can be individually expanded and reconfigured with process-specific equipment. Their facility uses AVGs to handle the logistic task of managing and warehousing, tools, parts and materials (Figure 2.21).

Matrix fabrication is easily expendable, increasing or decreasing cell usage for the required production. (Industrie 4.0: matrix production | KUKA AG, 2021) Like KUKA's prototype facility targeted at the automotive spare parts industry, matrix production is helpful for manufacturers to provide a high variety of parts with uncertain product demand. However matrix production is still in development and requires large intial investment in CPS and machines.

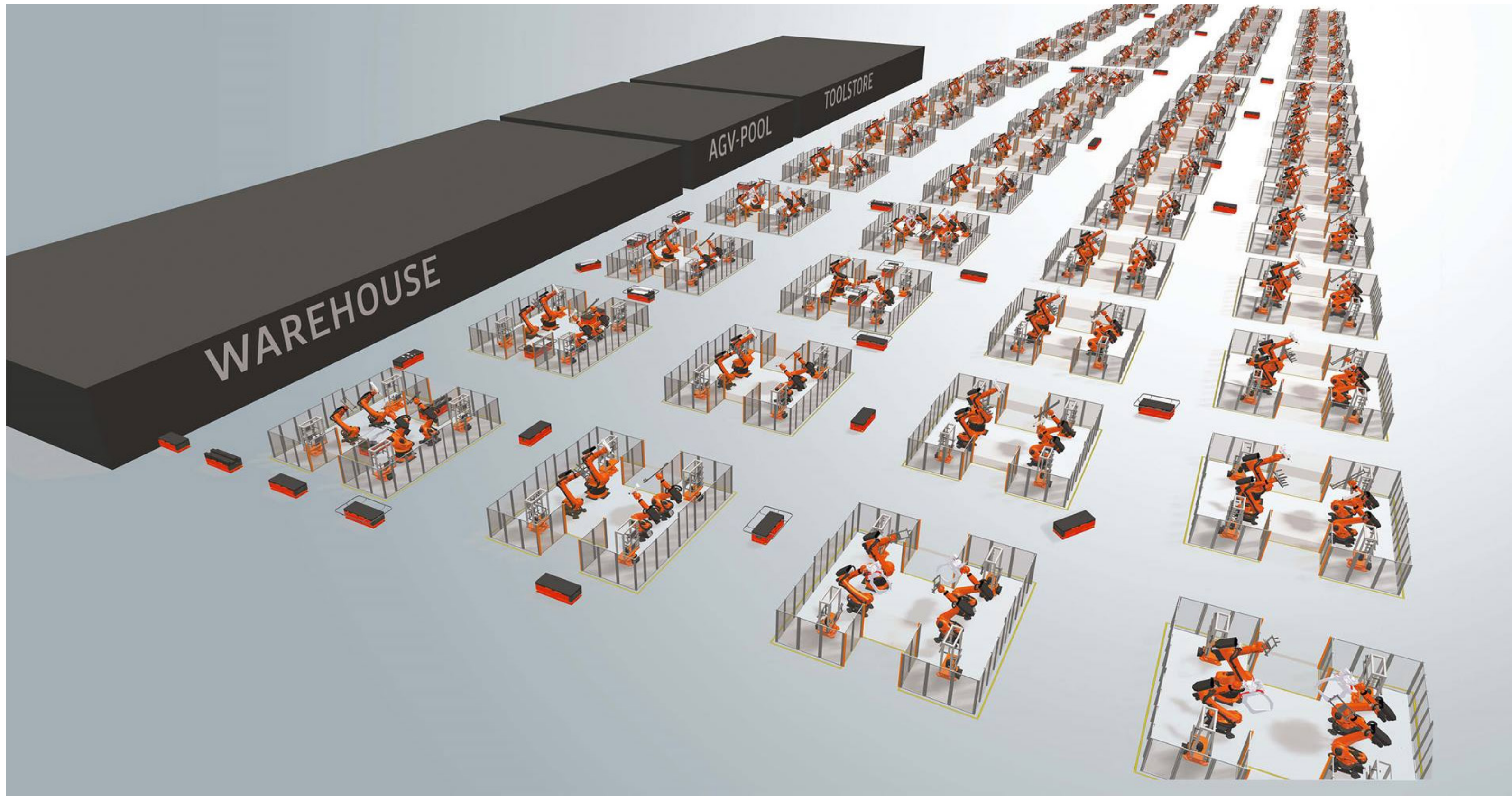


Figure 2.21 Matrix production factory concept (KUKA AG, 2021)

2.3.6 Flexible and reconfigurable manufacturing

Meeting the demands of mass customisation and mass personalisation flexible and reconfigurable manufacturing systems (FMS & RMS) are finding their way into the industry. FMS & RMS are able to quickly accommodate and adapt product family changes and are a must for manufacturing one of a kind products. Flexibility can be viewed as the capacity of a system to change and assume different positions or states in response to changing requirements with little penalty in time, effort, cost, or performance (Toni and Tonchia, 1998).

Flexibility and reconfigurability of manufacturing systems are system paradigms that aim at achieving cost-effectiveness and rapid system changes as needed by incorporating flexibility and reconfigurability in to the system (Wiendahl et al., 2007). While RMS aims to provide on demand flexibility with modularity and reconfigurability, FMS provides a more generalised flexibility based on predicted variations. Compared to Dedicated manufacturing lines (DMLs) where cost-effectiveness is reached with pre-planning and optimisation RMSs and FMSs are reaching cost-effectiveness by reducing lead time, quick manufacturing modifications and technology integration.

Being able to change and adapt to product changes enables RMS and FMS systems to be used across multiple product life cycles achieving long term investment efficiency. While the start investment is higher than DML's this long term investment efficiency enables RMSs and FMSs to still be cost-efficient. The Festo CP Factory is an example of a reconfigurable manufacturing system, and Kuka matrix production is an example of a flexible manufacturing system. Figure 2.24 shows the characteristics of the three methods.

In the literature multiple types of flexibility in manufacturing systems have been identified and can be combined in 3 areas of flexibility relevant to transcend manufacturing: product flexibility, capacity flexibility, and operation flexibility (El Maraghy, 2006). The full list of flexibility types and their definition can be found in appendix 6.2.

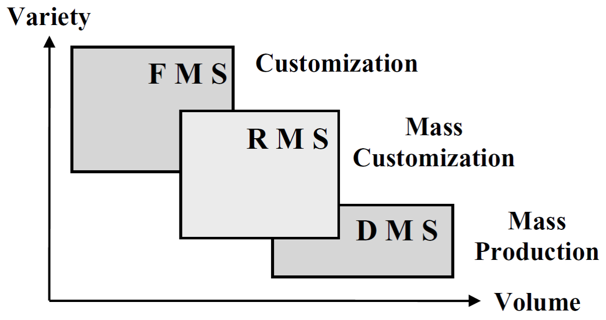


Figure 2.24 Manufacturing paradigms (Hu, 2005).

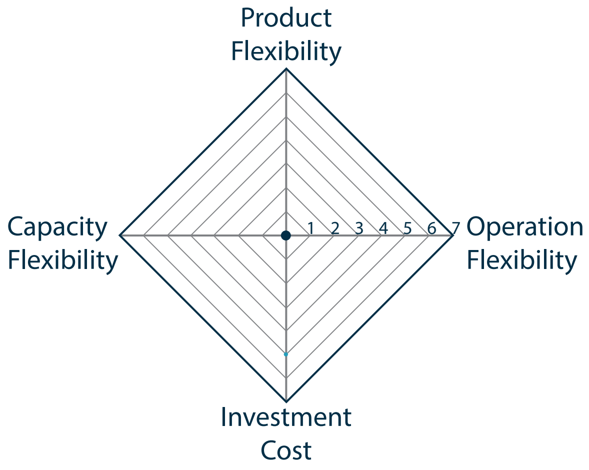
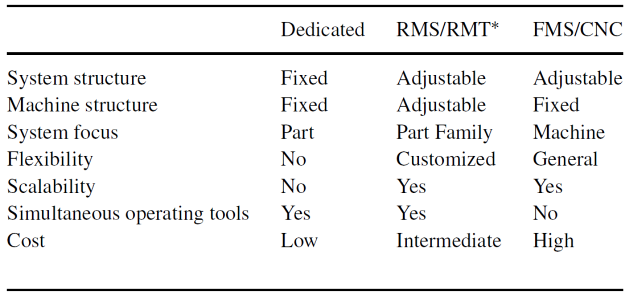


Figure 2.23 Flexible manufacturing system attributes.



	Dedicated	RMS/RMT*	FMS/CNC
System structure	Fixed	Adjustable	Adjustable
Machine structure	Fixed	Adjustable	Fixed
System focus	Part	Part Family	Machine
Flexibility	No	Customized	General
Scalability	No	Yes	Yes
Simultaneous operating tools	Yes	Yes	No
Cost	Low	Intermediate	High

Figure 2.22 Characteristics of dedicated, flexible and reconfigurable manufaturing systems (Koren, 2005).

Figure 2.25 Festo CP factory, reconfigurable manufacturing system

Product Flexibility

The ability of a manufacturing system to make a variety of part types. The ability of the system to adapt to changing demands for various products. *Including machine flexibility, process flexibility, production flexibility and part flexibility.*

Capacity flexibility

The ability of the manufacturing system to vary the production volume of products and the ability to contract or expand. *Including Volume flexibility and expansion flexibility.*

Operation Flexibility

The ability of a system to produce a set of products using different machines, materials and sequence of operations. *Including operation flexibility, material handling flexibility, routing flexibility and control program flexibility.*

System attributes

Combining the 3 areas of flexibility with the investment cost of a system gives 4 attributes with which can be used to evaluate flexible manufacturing systems (Figure 2.23). The ideal manufacturing system has high product flexibility, capacity flexibility and operation flexibility while having low investment cost. The price premium of personalised products and the possibilities of reusing the system across multiple product life cycles can justify the higher investment cost required for personalised product production; However, tradeoffs have to be made between flexibility and investment cost.

2.3.7 Conclusion

Computers are deeply entrenched in manufacturing systems and enable the industry 4.0 to increase product quality and product diversity. The integeration of IoT and the implementation of CPPss are paving the way for smart factories that can respond to individual customer requirements and fabricatie personalised products.

Additive manufacturing excels at fabrication of one-of-a-kind parts, while additive fabrication techniques like FDM are not jet up to par with the quality of injection moulded parts. The flexibility provided by additive manufacturing makes it very beneficial for personalised products fabrication.

Uncertainty in demand highly influences the effectiveness and process planning of manufacturing systems. Stochastic manufacturing models are developed to deal with manufacturing uncertainty, the adaptability and versatility of matrix production make it ideal for MTO strategies.

Meeting the demands of mass customisation and mass personalisation flexible and reconfigurable manufacturing systems (FMS & RMS) are finding their way into the industry. FMS & RMS are able to quickly accommodate and adapt product family changes and are a must for manufacturing one of a kind products. The feasibility of flexible manufacturing systems can be evaluated on 4 attributes product flexibility, capacity flexibility, operation flexibility and investment cost.

2.4 Transcended manufacturing

Transcended manufacturing is complex; product design, co-creation, manufacturing, assembly, fabrication, logistics, and much more come together in TM. As proposed by (Berry, Wang and Hu, 2013) on personalised product manufacturing. Development in the following areas is required to enable transcended manufacturing: product platform architecture, manufacturing, and Cyber-infrastructure systems.

2.4.1 Transcended manufacturing process

Figure 2.26 shows the production process of transcended manufacturing from design to production and delivery. A product starts with product architecting. With market analysis based on trends and developments, a product direction is researched and defined, resulting in the creation of a product family. The personalised product design has to consider how the customer influences the co-creation process and which parts of the product will be customised or personalised. Each part of the available personalisation options has to be evaluated. The co-creation process should not unnecessarily complicate the customer order process as too much choice can negatively influence the customer experience. The manufacturing capabilities have to be taken into account for the product requirements. A product recipe is created and translated into a producible product in the product factory based on the co-creation process and product requirements. Using Enterprise resource planning, the manufacturing of personalised products from procurement and order management to manufacturing and supply chain execution is covered.

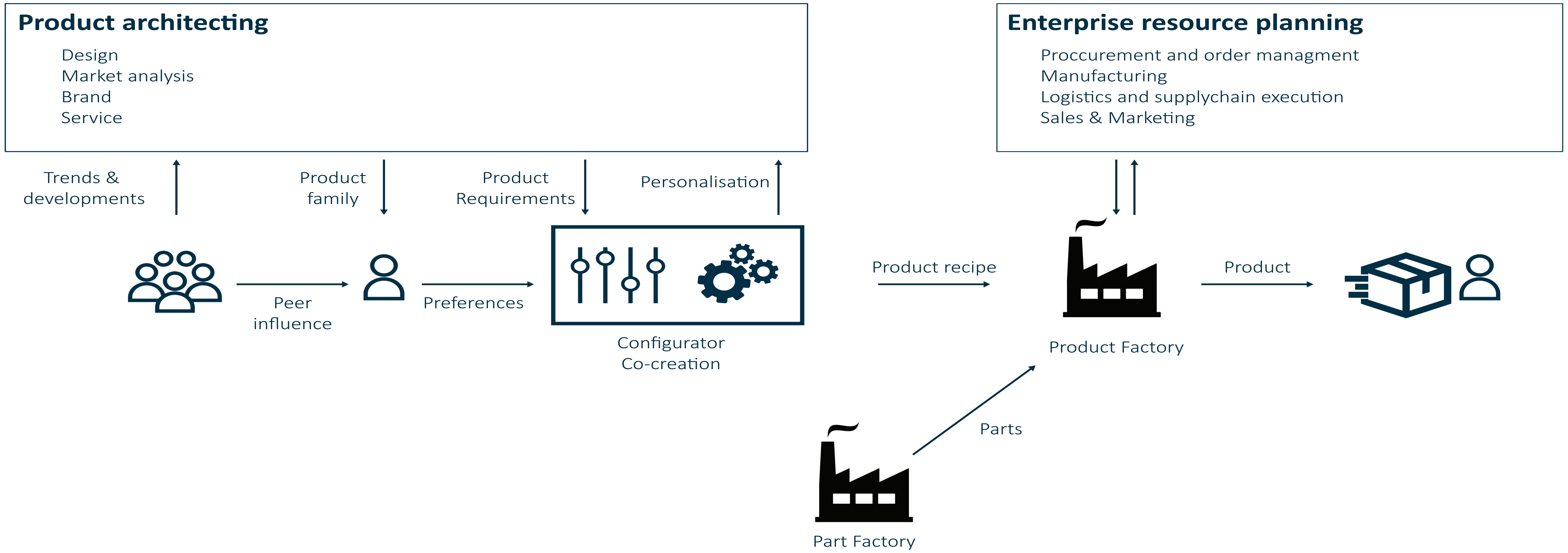


Figure 2.26 Transcended manufacturing process

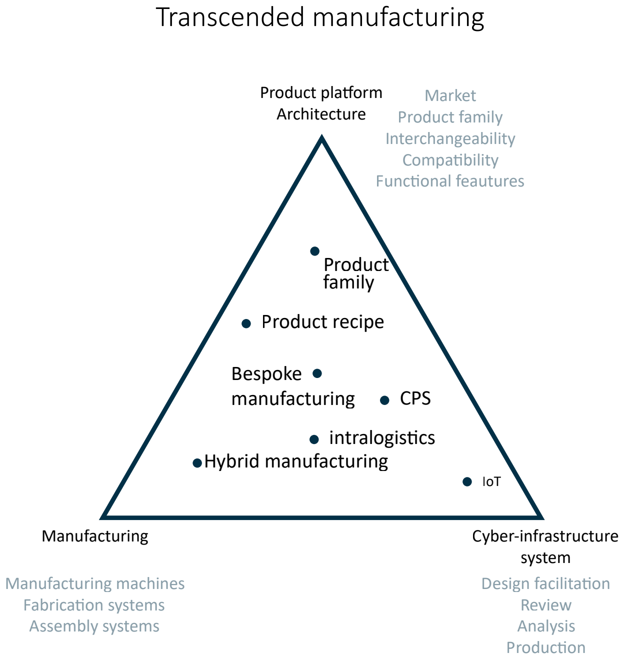


Figure 2.27 The field of transcened manufacturing

2.4.1 Manufacturing

Ultra-personalised product assembly and manufacturing is more complex than for standardised products. Due to the uniqueness of personalised products, all products are one of a kind making traditional manufacturing methods unsuitable. Conventional manufacturing methods like injection molding rely on high volumes of the same part to realise low manufacturing cost, which is impossible with ultra-personalised products. Digital manufacturing with flexible and reconfigurable systems using CNC driven systems are more expensive but can create unique parts required for personalised products.

Transcended manufacturing combines the innovative processes and techniques that gave rise to industry 4.0 in order to create one of a kind products based on the customer's preferences. The TM factory relies on process generality and flexibility to make products. Unlike standard linear product lines, similar parts are manufactured using the same machines and processes.

Product personalisation is inherently slower than mass manufacturing, in manufacturing processes must either fast or numerous. Transcended manufacturing counts on numbers and many process modules working in parallel to cope with demand and increase throughput. The need for countless modules makes factory real estate a premium. Machines need to be stackable and sized according to the product they produce. In his research on TM, Ben Kromhout devised an industry standard for stackable process modules, which promotes modularity and minimises the loss of resources (Kromhout, 2020).

2.4.3 Product platform architecture

The product platform architecture defines product compatibility/interchangeability and its functional features and components. It covers the market and individuals needs and considers the product family and the perceived value of the product family to the market. It is used to define the way the user is involved in the creation process and defines the freedom in which the user is able to personalise the product.

2.4.4 Cyber-infrastructure system

To support product personalisation and on demand production a cyber-infrastructure system needs to be in place that supports integration between the product platform architecture and manufacturing and covers the process from customer input to production and delivery of the product. Integration of smart systems and IoT are key components to facilitate the transcended manufacturing process. With the use of connected systems the user is able to give input to the manufacturing process which in turn produces the personalised product according to the user's input.

The transcended manufacturing process is a flexible manufacturing process that responds to different needs of the individual consumer. The manufacturing process is demand-driven and requires input from the consumer, TM uses MTO and CTO to create the products on demand. The manufacturing process is able to fabricate and assemble unique products within the same product family. However, the transcended manufacturing process sacrifices process speed to be able to manufacture complex one-of-a-kind products.

2.4.5 Conclusion

Transcended manufacturing is enabled by the convergence of developments in the areas of manufacturing, product platform architecture and cyberinfrastructure. Transcended manufacturing is an answer to the rising need for mass personalisation and ultra-personalised products. Transcended manufacturing employs automation and digital manufacturing to manufacture ultra-personalised and deal with the required complexity and flexibility.

Integration of smart systems and IoT are key components to facilitate the transcended manufacturing process. With the use of connected systems and defined by the product platform architecture, users can input their preferences into the automated manufacturing process.

The TM factory relies on process generality and flexibility with numerous process modules working in parallel to increase factory throughput.

To increase efficiency and minimise loss of resources, process modules in the TM factory should be modular and stackable, using an industry-standard dictating machine size and form.

Process modules size is selected according to the parts produced in the factory and modules should be as small as possible.

Process modules are product independent; similar parts are manufactured in the same process module.

2.5 Hybrid fabrication

Transcended manufacturing is achieved by linking multiple standalone digital fabrication stations together, using the flexibility and customizability provided by these digital fabrication stations. In addition to typical digital fabrication, hybrid fabrication could improve the field of transcended manufacturing and complement the manufacturing clusters and digital fabrication stations with hybrid manufacturing stations.

Hybrid manufacturing combines multiple digital fabrication methods in a single system to achieve new fabrication possibilities. In the industry hybrid manufacturing is used for combining additive and subtractive manufacturing processes; however, the field of hybrid manufacturing is still new and relatively unexplored. Therefore research is conducted in hybrid fabrication to look for opportunities that may benefit Transcended manufacturing. For this research, hybrid fabrication is defined as the fabrication process that combines multiple different fabrication processes and performs multiple process steps in a single system to create a new fabrication process.

This chapter explores the combination of fabrication techniques into hybrid fabrication and the opportunities it presents.

> *Hybrid fabrication **combines** multiple **different** fabrication **processes** and performs **multiple process steps** in a **single system** to create a new fabrication process.*

2.5.1 Fabrication Characteristics

Hybrid fabrication takes existing digital fabrication techniques and combines the advantages of both methods to create new manufacturing possibilities. Digital fabrication is a constantly developing and growing discipline. Depending on the characteristics of digital fabrication techniques, combining systems could be beneficial or could work adversely. Various digital fabrication systems are explored and ranked from 1 to 7, evaluating the suitability of digital fabrication methods for hybrid fabrication. Evaluating the following aspects: Cost, Process time, Adaptability, Cleanliness and robustness. A score of 7 indicating it is favourable for hybrid fabrication (Figure 2.28).

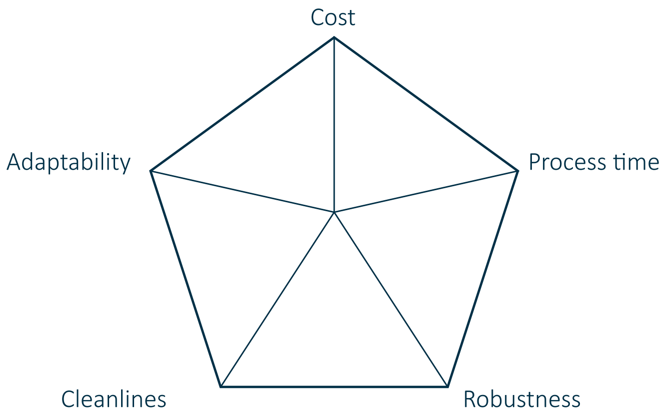


Figure 2.28 Digital fabrication aspects

Cost
Cost is the purchase price of the system.
Low-cost systems require less investment and are well suited for flexible hybrid systems. Expensive systems are less suitable for flexible hybrid systems. Expensive system can still benefit from additions to the system; however, it is harder to justify the investment cost when it is not the primary process.

Process time
Process time is the processing time required for the fabrication process.
Long process time creates an ineffective system, and it should be considered if separating the process is not more capital effective. Fast processes are good as additions to the system since they have less impact on overall processing time.

Adaptability
Adaptability covers how combinable the system is and how demanding it is of the CNC system. An adaptable system is a system that does not require specialised parts or has additional requirements on the system.

Robustness
Robustness covers the sensitivity of the system and the process. A robust process has general operating conditions, while a fragile process has sensitive operation conditions and is prone to pollution.

Cleanliness
Cleanliness is how clean the process is. A clean process does not create debris, while a dirty process operates in a dirty environment or creates waste.

Score	7 →	1
Cost	Good addition Cost effective to implement	Too expensive to combine Can benefit from additions with low cost and procces time
Process Time	Good addition Time effective process to combine	Ineffective to combine Can be combined with cost effective additions
Adaptability	Very combinable Easy to combine with other machines	Difficult to combine Does not fit modular hybrid fabrication
Robustness	Robust & Combinable Robust and easy to combine	Fragile Only combine with clean processes
Cleanliness	Clean process Can be combined with Fragile processes	Dirty process only combine with robust processes

2.5.2 Process evaluation

Over 30 processes are analysed, resulting in radar charts representing the characteristics of the fabrication techniques and the suitability for modular hybrid fabrication. The full results and charts can be found in appendix 6.3.

While the radar charts clearly visualise individual system characterics, it is hard to compare all of the fabrication methods together, thus the results need to be further categorised. The radar charts are used to plot the fabrication methods on a dual-axis comparison chart that compares compatibility and efficiency. (Figure 2.31)

The resulting chart from the analysis has clear clusters categorised as Add-ons, Base and Specialised. Analysing the clusers also creates a distinction between processes, of which primary and secondary processes are identified. A primary process defines the system's main operation; the primary process defines the system requirements and is the leading factor in system design and system boundaries. Secondary processes are more adaptable and have less influence on requirements for the system.

Efficiency

Efficienct techniques are processes that score high on cost, adaptability and process time. These systems are cheap to implement and do not negatively impact process time. Efficient processes are ideal for modular hybrid manufacturing. Figure 2.29 illustrates the characteristics of an efficient process.

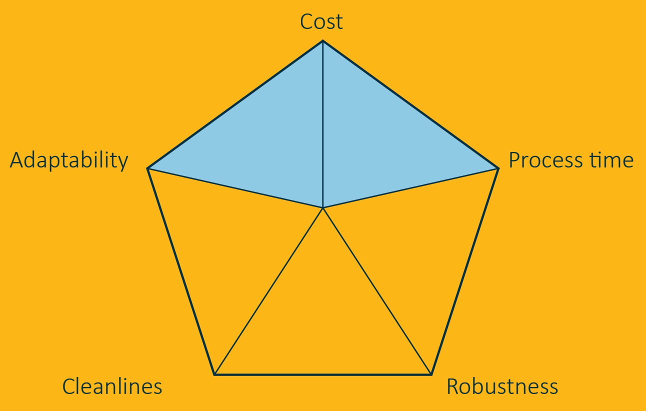


Figure 2.29 Efficient digital fabrication characteristics

Compatibility

Compatibility is the metric used for how suited the system is for combination with other techniques. These systems are characterised by high adaptability, Cleanliness and robustness. Figure 2.30 illustrate the characteristics of such systems.

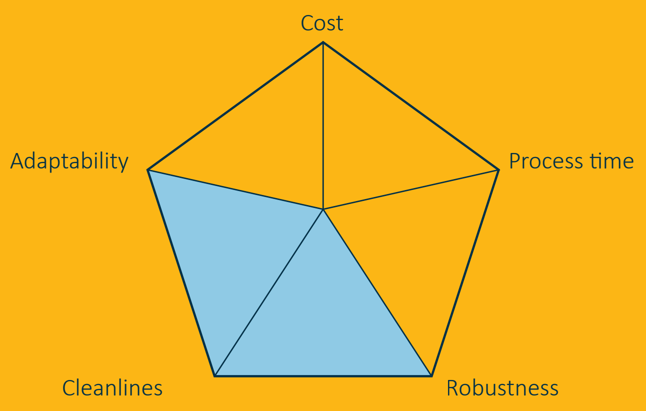


Figure 2.30 Highly compatible digital fabrication characteristics

Figure 2.31 Digital manufacturing compatability chart

Add-ons

Add-ons are ideal for hybrid manufacturing, tools in this category are very suited for combination with other fabrication processes, they are efficient and suit modularity. Adding these tools to a hybrid fabrication system could boost the capabilities with minimal complications. Add-ons can be used as secondary tools that support a primary process, or various add-ons can be combined in a single station, creating lots of possibilities.

Base

Tools that fall into the "Base" category are less compatible and efficient as add-ons. They have extra operational requirements or combining these processes negatively impacts the processing time. While it still possible to add these tools to hybrid systems, the fabrication techniques that fall in this category can be seen as primary tools of the fabrication system—benefiting from add-ons to increase fabrication possibilities. These tools can still be combined or interchanged with other primary processes, but practicality and productivity need to be considered. Base tools are suitable for modular hybrid fabrication.

Specialised

The last identified category is the specialised category. Systems that fall in this category are not very combinable. The process has extra requirements, is sensitive or is less efficient. Specialised systems can still benefit from the addition of other processes, but complications arise if the system has to be added onto other stations. Like Base systems, specialised tools fall into the primary process category. However, unlike base tools, specialised systems are ill-suited for modular hybrid fabrication, specialised tools dictate the requirements of the hybrid system. Reconfiguring of the main process of a specialised system is impractical and not advisable.

2.5.3 Hybrid fabrication opportunities

In the previous chapter, potential digital fabrication processes are analysed and categorised. This chapter covers the possibilities and opportunities that combining these digital fabrication methods enable. By looking at current research and solutions, opportunities and challenges are identified for hybrid fabrication in support of ultra-personalised product production with transcended manufacturing.

Hybrid fabrication can be used to increase the capabilities of a CNC system and it could be used to create new processes which are not possible without hybrid fabrication. Using the categorised fabrication techniques and existing hybrid fabrication examples, opportunities are explored. First a hybrid fabrication matrix from the previous analysis is created to help with the exploration. The matrix evaluates possible process pairs based on compatibility and indicates potential benefits. This chapter discusses the most promising combinations and opportunities. See appendix 6.4 for the full matrix.

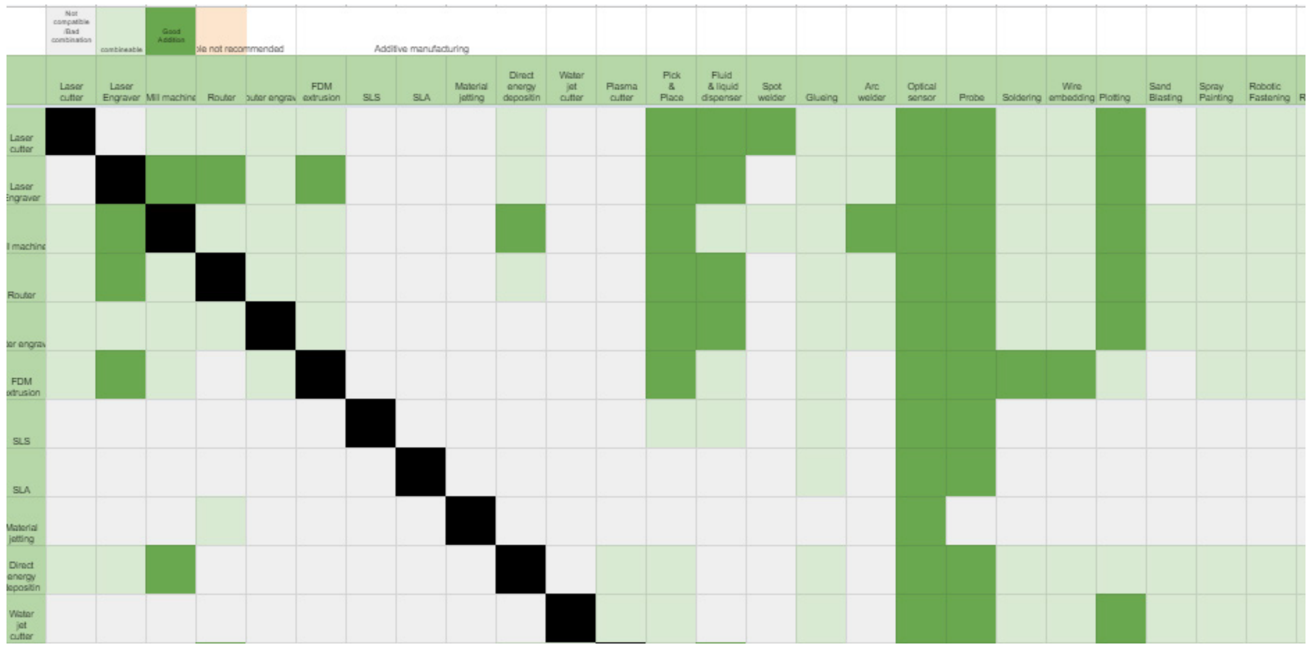


Figure 2.32 Digital fabrication combination matirx

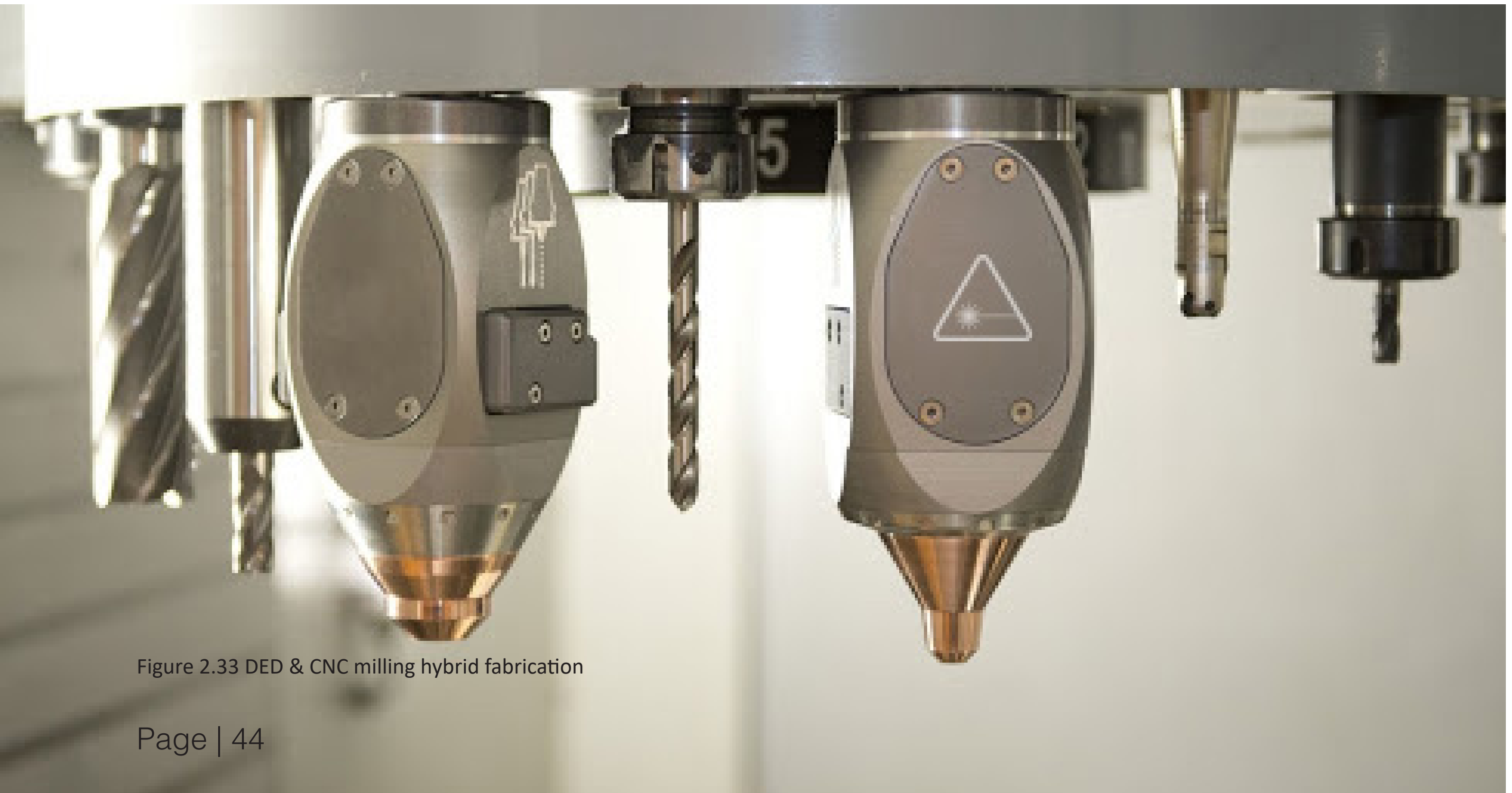


Figure 2.33 DED & CNC milling hybrid fabrication

2.5.3.1 Enhancing process tolerances

Combining processes can result in the usage best of both methods. Improving the tolerance of 3D printing while increasing the possible form complexity of CNC machining. Or adding laser cutting to machining to fabricate microscale features in machined parts. Hybrid metal 3D printing CNC machines already exists on the market, these machines are specialised systems that combine additive metal 3D printing techniques like DED (Direct energy deposition) with CNC milling (3DHybrid: AM for CNC, n.d.) They combine the form freedom of 3D printing that has poor finish and tolerances with the speed, accuracy and finish capabilities of CNC milling. This process can reduce material usage and increase form flexibility. Although, it is a time-intensive process (Lee et al., 2018).

For the same reasons as metal 3d printing, it is also possible to machine FDM printed plastic parts for which a CNC Mill or router is used. Although there is no commercial solution, multiple researchers have developed prototypes that offer these hybrid capabilities (Lee, Wei and Chung, 2014).

3D printing and CNC machining is mainly used for one-off specialised parts, that have high complexity and require high dimensional accuracy like parts for aviation. It is not jet used in a mass manufacturing context, but there are multiple advantages to this hybrid process (Benefits of CNC Machining FDM Parts | Stratasys Direct Manufacturing, n.d.)

Besides, having great opportunities combining the processes comes with a tradeoff. CNC mills and routers are more rigid systems with higher system requirements than 3D printers that need less stiff systems. In addition to the system requirements, both processes are time-intensive, creating a long process time of the part and long idle time of the more expensive tools.

Benefits FDM & CNC:
- Boring, drilling and reaming features for better accuracy
- Machining an entire part to specific dimensions
- Machining mating features to aid in increased fitment in assembly
- Circular machining for interior bores and exterior profiles
- Face milling for accurate, flat, and smooth surfaces
- Machining complimentary metals parts for assemblies
- Thread milling precision hole to hole accuracy for inserts installations
- Positional and alignment boring
- Surface enhancement and profile machining
- Precision machining for enhancing fixtures
- Tolerancing inside features

Combining 3D printing and CNC machining creates many possibilities. Depending on the product simplicity, it could be more beneficial to keep the process separated. For metal 3D printing DED systems, the DED laser is often an addition to the CNC milling machine while for FDM printing with long process time separate systems are mostly used with the exception of some research systems. Combining 3D printing and machining is best suited for specialised parts that have complex geometry need tight tollerances and have features that cannot be accessed by the milling machine when the process is separated. For example complex and expensive parts with incapsulated features like the cooling channels of an injection moul (Lee, Lee and Sung, 2014).

Takeaways
- Can improve tolerances
- Can create new possibilities
- System efficiency is a concern.
- Long process time, and different requirements.
- Creation of specialised complex parts
- Tools: Routing/milling, 3D printing

2.5.3.2Versatile manufacturing

Hybrid fabrication combines different processes and tools to provide a diverse toolset. The previous two chapters discussed combinations that could enhance manufacturing, creating new processes and manufacturing possibilities. The hybrid toolset can also create flexible workstations. Chapter 2.4.2 discussed the need for flexibility in bespoke manufacturing, and chapter 2.4.5 showed how versatile and flexible production cells benefit stochastic manufacturing systems.

Versatility
Hybrid workstation can provide high versatility in a single package, reducing the amount of machines needed in a production cell. Improving accuracy and limiting part movement between devices. In cellular manufacturing, a hybrid workstation can provide multiple processes to the production cell without requiring additional machinery, enhancing the operation and part flexibility of the cell. Cycle time, tool utilisation and part flow have to be considered for a versatile fabrication station. Processes with fast cycle times and high tool utilisation can not be combined with slower processes, restricting part flow and bottlenecking the system. When the tool utilisation is lower, meaning the tools are not operating at full capacity, tools can be combined, saving the cost of multiple machines. Tools in the add-ons category are most suited, like glueing, pick & place and probing/sensing.


Figure 2.34 Kuka matrix fabrication cell

Multifunctional systems
Numerous hybrid CNC systems are emerging in the hobby and maker market that provide multiple CNC operated tools in a single package. In that market cost and space are restricting the available toolset of users, while cycle time is less of a concern. A CNC motion system is expensive, adding reconfigurability to the system provides versatility without the cost of multiple CNC systems. The Creality CP-01 , Snapmaker, Makerarm and Dobot M1 are examples of such systems with prices ranging from $600 to $6000.

Product development
In product development and prototyping use of a versatile fabrication station can also be beneficial. Multi-process prototyping capabilities are helpful for developing ultra-personalised products with the transcended manufacturing method, providing a cost and space-effective solution for prototyping. In product development, tool utilisation and cycle time are less relevant. With product development, the toolset and reconfigurability are essential.

Matrix fabrication
Hybrid fabrication stations can also be used with the aforementioned matrix production method. Using a matrix of standardised hybrid workstations to provide operation flexibility, part flexibility and capacity flexibility to the production process. In the case of matrix fabrication it is important that production cells can be reconfigured and have multiple processes available.

Takeaways
- Good for product development
- Efficient use of space & machines
- Efficiency & bottle necking concerns
- Possibilities in matrix manufacturing


Figure 2.35 Snap maker, modular CNC system

2.5.3.3 New process capabilities

Integrated electronics, while still in development, is a promising area for hybrid fabrication and bespoke products. Adding electronics to products is a multi-step process. The product body is created, electronics are inserted and are connected. Currently, most products have multi-part injection moulded bodies with PCB's inserted and connected during assembly. Traditional manufacturing limits product geometry and process flexibility. Having a system able to create or layout electronics regardless of product shape, creates new possibilities overcoming design constraints in the geometry and performance of the product.

Integrated electronics combines 3D printing techniques like SLS and FDM with conductor dispensing like solder extrusion or ultrasonic wire embedding and adds pick & place electronics to create parts with integrated electronics.

Multiple integrated electronics solutions are emerging on the market and it is already possible to 3D print electronics circuits. Making it possible to create fully 3D printed electronic circuits inside the products. However, integrated electronics can be approached in multiple ways and does not necessarily have to be fully printed. Separate electronic components can be placed, printed and connected. The part can have embedded PCB components that are dynamically connected with conductive elements/wires, or the PCBs and hardware are connected before embedding the electronics into the product.

At the KECK center for 3D innovation they develop multi process 3D printing; this process can create parts with fully integrated electronic circuits. With multiprocess 3D printing at KECK they 3D print parts, add conductive traces and pick & place electronics, swapping between the process to realise an integrated part (MacDonald et al., 2014). Multiprocess 3D printing shows a gaming dice with integrated electronics. At KECK they are also working on ultrasonic wire embedding into 3D print, further advancing 3D printed electronics (Martinez, 2020).

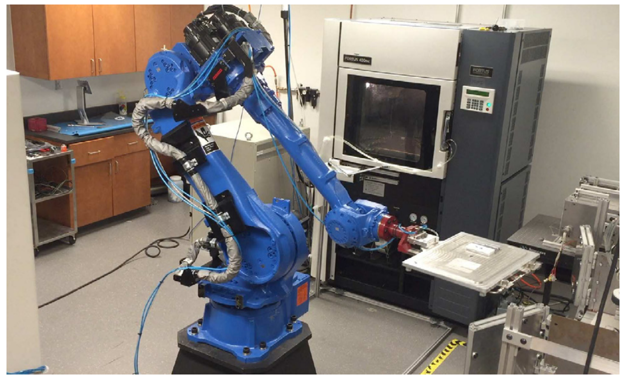


Figure 2.36 Keck multi process 3D printing

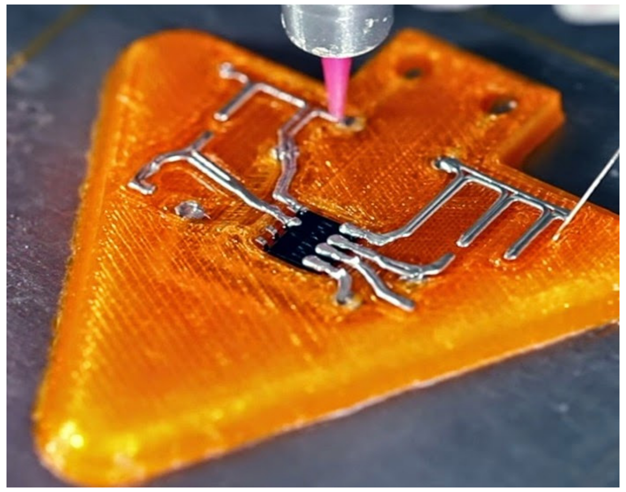


Figure 2.38 Voxel8 Integrated electronics printer


Figure 2.37 Voxel 3D printed drone

In his research on printing integrated electronics and in an attempt to a more affordable solution, Kasper also developed a method for printing conductive traces directly onto FDM printed parts, showing how electronic (PCB) components can be connected and inserted into 3D printed parts (Eekhout, 2020). Combining PCBs with flexible conductor placement can improve process speed and cost while not constraining the design. Using the free form of 3D printing conductors with the cost-effectiveness of PCBs.

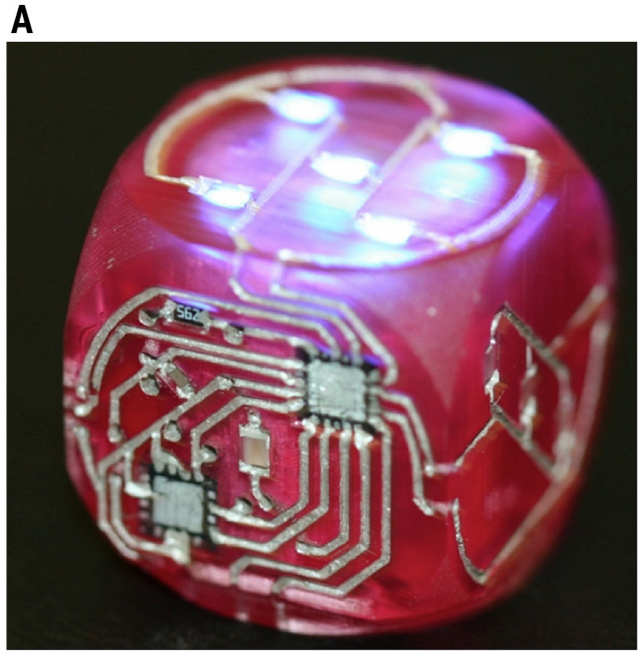


Figure 2.39 Dice with integrated electronics

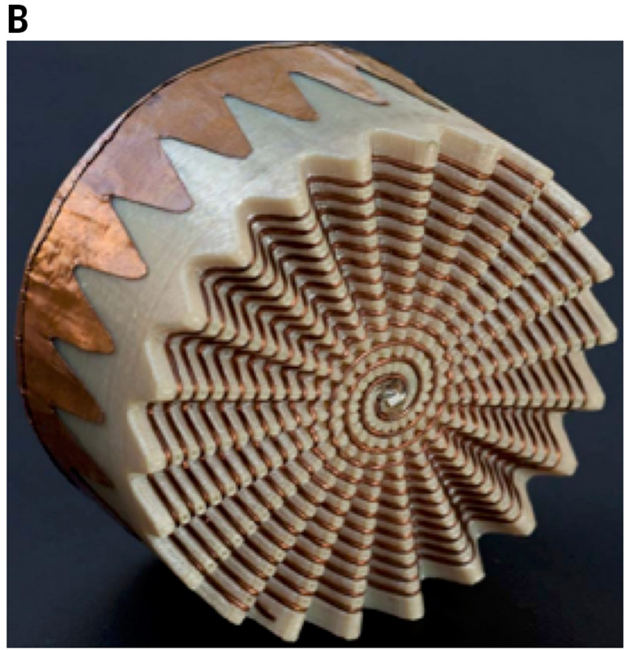


Figure 2.40 FDM with ultrasonic wire embedding

Integrated electronics can accelerate the development by speeding up the time to create a prototype with up to 4 times (MacDonald et al., 2014). Currently, integrated electronics is mostly used for rapid prototyping and is not jet used in a manufacturing context. Research and development of fully automated systems are underway. Before implementation into manufacturing, the systems have to be automated, and the process needs to mature.

Integrating 3D printing with other technologies always has an efficiency concern since 3D printing is a slow process. Therefore, it should be considered if it is not more beneficial to have a hybrid integrated electronics system with separate 3D printing, such as the multiprocess from the KECK centre. Integrating 3D printing into the system could be advantageous if design constraints are an issue.

Using PCBs along with conductor dispensing decreases product constraints while using the cost effectiveness of PCBs. (Figure 2.37 3d printed drone voxel8)

There are sustainability and repairability concerns with the usage of integrated electronics. Integrated electronics can make it harder or impossible to repair a product. Combining materials decreases the product's recyclability. The sustainability of electronics integration should be taken into account when designing products with integrated electronics.

Takeaways
- 3D printing, conductor dispensing, soldering and pick and place can be combined to create an automated system that can manufacture integrated electronics.
- Efficiency concerns when adding 3D printing
- Enables flexible electronic placement and lowers design constrains
- Fully printed electronics offer form freedom
- PCBs offer cost-effectiveness
- Repairability and sustainability concerns.
- Good for rapid product development
- Tools: 3D printing, conductor dispensing, wire embedding, (reflow) soldering, (Pick & place)

2.5.4 Summary

Hybrid fabrication is defined as the fabrication process that combines multiple different fabrication processes and performs multiple process steps in a single system to create a new fabrication process. By looking at current research and digital fabrication solutions, opportunities and challenges are identified for hybrid fabrication in support of ultra-personalised product production with transcended manufacturing.

Various digital fabrication systems are explored, evaluating the suitability of digital fabrication methods for hybrid fabrication. The fabrication methods were evaluated on: cost, process time, adaptability, robustness and cleanliness. Grouping the results from the first analysis and evaluating those on compatibility and efficiency returned three categories in which the digital fabrication methods can be categorised: base, specialised and add-ons. The three process categories are further classified in either primary or secondary processes.

Primary processes define the system's main operation and dictate the system design of the module. Secondary processes are more adaptable and have less influence on the overall system design.

Add-ons are ideal for hybrid manufacturing, tools in this category are very suited for combination with other fabrication processes, add-ons can be used as secondary tools that support a primary process, or can be combined to provide versatility to a system.

Tools that fall into the "Base" category are less compatible and efficient. Base tools can still be combined or interchanged with other primary processes but at the cost of tool productivity.

Specialised systems can benefit from the addition of other processes, but complications arise if the system has to be added onto other stations. Specialised systems dictate the hybrid system's requirements and reconfiguring the main process of a specialised system is impractical and not advisable.

After categorising and classifying the fabrication methods, opportunities are explored for the use of hybrid fabrication in support of ultra-personalised product production in transcended manufacturing. From the exploration three opportunities for TM are identified: enhancing processes tolerances, new process capabilities like integrated electronics, and versatile manufacturing.

2.5.5 Conclusion

There are multiple opportunities in hybrid fabrication for transcended manufacturing.
Hybrid fabrication modules can be used to enhance processes tolerances, create new process capabilities, and provide flexibility and versatility to the TM factory. More research is required on the implementation of hybrid fabrication, starting with the creation of more hybrid fabrication stations. Direct implementations of hybrid fabrication modules can be, integrated electronics modules, machining and 3D printing modules, and versatile manufacturing stations enabling matrix fabrication.

When designing for hybrid systems, the following points have to be considered:

- Hybrid systems can be modular or dedicated to a specific process.
- The primary process is the leading factor in the design of a hybrid module
- Add-on and base system can be used in a modular and flexible hybrid setup.
- Specialised systems are not suited for system reconfiguration of the primary system.
- System and tool efficiency have to be considered when combining processes.
- Efficiency is less a concern for product development and research.

2.6 List of requirements

Multiple opportunities have been found in support of hybrid fabrication workstations for transcended manufacturing. Through the synthesis of the analysis phase, a list of requirements is developed. The list of requirements is used for the ideation and validation of the hybrid workstation design.

 # Requirement

1 Compatability
1.1 The system must be scalable to accomdate the different industry standards
1.2 The system must be able to interface with different systems in the factory
1.3 The system is dust proof Compatability

2 Tools
2.1 The system must be applicable with multiple fabrication technologies
2.2 The system must be able to swap tool within 30 seconds
2.3 The system muust be able to support a minimum of 3 tools
2.4 The available toolset of the system must be changeable
2.5 The system is able to support tools with a volume of 15x15x30cm
2.6 The system must minimize the setup time when changing available toolset
2.7 The system must be rigid enough to support the selected range of techniques
2.8 The system must be able to support tools that weigh 10kg

3 Service
3.1 The system must allow for tool maintenanceService

4 Product
4.1 The system must be able to support products of different shapes and sizes
4.2 The system must be able to adapt to changes in the product family
4.3 The system must allow for both manual and automatic loading and unloading of parts

5 Production
5.1 The system must be able to accomodate line production
5.2 The system must be able to accomodate stochastic production

6 Intralogistics
6.1 The system must not hinder the intralogistics of the factory
6.2 The system can be used with AGV
6.3 The system can be used with Belt systems

 # Wish Category

1 Tools
1.1 The system is rigid enough for milling metals
1.2 The sytem is rigid enough for milling wood, plastics and soft metals (routing)

2 Production
2.1 The system can be used for dirty operations
2.2 The system can be used for wet operations

Ideation

During the analysis, opportunities are identified for the use of transcended manufacturing to create ultra-personalized products. Hybrid fabrication is a new manufacturing method that could be very usefull for the transcended manufacturing process. During the ideation phase hybrid fabrication for transcended manufacturing is explored and a design is created. This chapter will look into possible methods of realising a hybrid fabrication station, from the creation of a workstation to the use of that workstation in a manufacturing context and the product that can be created with such a system.

3

3.1 Design Vision

The Ultra-personalised product market is growing and the new manufacturing method, Transcended manufacturing, is emerging. Transcended manufacturing is not jet realised and requires development before full scale transcended manufacturing is adopted by the industry. It needs development and research in the product platform architecture, cyber-infrastructure system and manufacturing. This research explores the manufacturing opportunities that hybrid fabrication stations can provide to the transcended manufacturing process, creating new manufacturing possibilities and creating flexibility. The following design vision is formulated to guide the ideation process.

*Enable transcended manufacturing with a **hybrid fabrication** system that supports the production process. Creating a workstation that efficiently supports multiple control, assembly, and fabrication techniques in a single workstation to facilitate the production of **ultra-personalised products**.*

3.2 Hybrid fabrication scenario

Transcended manufacturing uses state of the art manufacturing to create ultra-personalised products. It takes advantages of the Industry 4.0 CPS factories, which efficiently automate the production process. Advanced manufacturing techniques like additive manufacturing are utilised to create bespoke products on demand. In chapter 2.6 it was found that hybrid manufacturings could benefit transcended manufacturing at multiple stages of the manufacturing process. A future transcended manufacturing vision is discussed, integrating hybrid fabrication stations throughout the transcended manufacturing process.

Product development
At the start of ultra-personalised product creation, hybrid fabrication stations facilitate product design.
Hybrid fabrication helps product development by providing rapid prototyping capabilities to designers. By providing similar process steps as the factory, hybrid fabrication stations can improve and accelerate product research and development. Reconfigurability of the system creates the possibility of researching new manufacturing methods and product design. The system is also adaptable to improvements and changes in the factory.

Product manufacturing
At the product manufacturing level, hybrid fabrication provides multiple possibilities. The use of hybrid stations provides hybrid fabrication capabilities to the manufacturing process, like enabling the creation and incorporation of integrated 3D printed electronics into products.

Hybrid fabrication stations also replace parts of dedicated manufacturing systems, providing operational and machine flexibility. The flexibility of the stations enable hybrid stations to deal with part complexity of ultra-personalised products. Hybrid fabrication stations are adaptable to product changes, making the system future proof and usable for numerous product life cycles.

Matrix manufacturing
Hybrid fabrications are used to improve the efficiency of the factory. Personalised product have to be created using the make-to-order model (MTO). MTO creates fluctuation in demand, a matrix of hybrid fabrication stations is deployed to handle order fluctuations in the system and provide factory load balancing. The matrix guarantees fast response time to the MTO strategy, while limiting the number of digital fabrication machines needed to cope with order fluctuations. The hybrid fabrication stations can perform a multitude of process steps and is able to handle a variety of parts in different stages of the manufacturing process.

While the illustrated scenario sketches a bright future for hybrid fabrication, such a scenario is not likely to be implemented in the near future. However, it does show how hybrid fabrication can contribute to the transcended manufacturing process. Early adoption of hybrid manufacturing will focus more around; personalised product development, the usage of hybrid fabrications processes like integrated electronics and the usage of hybrid fabrication stations as flexible manufacturing stations. The possibilities and capabilities of hybrid fabrication will improve as research on hybrid fabrication and advanced manufacturing continue and systems mature. In the meanwhile, the scenario is used for exploration and ideation of hybrid fabrication station design.

3.3 Exemplary product

The personalised production process offers multiple challenges, and a product has to be designed that creates value in product personalisation and takes into account the co-creation process and the manufacturing process. An exemplary product needs to be created showing features and the possibilities of hybrid fabrication and personalised products. The computer mouse is a suitable exemplary product due to the versatility in preferences of its consumers and the options to personalise a computer mouse on the areas discussed in chapter 2.2.4; fit, performance and aesthetics.

3.3.1 product characteristics

This chapter discusses how the personalisation areas influence a computer mouse. A wide range of computer mouses is already on the market, catering to their specific niche, from gaming mouses to ergonomic or productivity mouses. Gaming is the most represented mouse category, with product families featuring different performance, fit, and aesthetics options. In comparison, the standard office mouse, the most generic productivity mouse with few to no customisation options.

Figure 3.1 Logitech computer mouse variety

Performance

The preferred performance differs greatly. There are ergonomic mouses that focus on ergonomic postures, gaming mouses focused on hardware performance, productivity mouses that have features to improve your productivity and small portable mouses. Hardware is the primary influencer on the performance of the computer mouse. But weight and ergonomic posture are also functional features important to the consumer. Personalisation in the following parts can provide personalised performance to the user: cord/cordless, battery/charging, weight, movement resistance, sensor sensitivity, buttons, scroll wheel and posture.

Aesthetics

The aesthetics of mouses significantly differ between mouses, gaming mouses are often futuristics and feature led lighting, productivity mouses are more neutral and businesslike, and design mouses are featuring minimalistic designs. Personalised aesthetics can influence colour, material, lighting and shape.

Fit

Currently, most mouses have 3 different sizes to fit the mouse size to the customer. A few customisable mouses allow for customisation in product fit, offering small adjustments. But no mouses exist that precisely match fit to the hand of the user. There are mouses targeted on ergonomics. Ergonomic mouses primarily focus on improving the shape of the mouse to create a better posture for operating the mouse while offering different sizes to improve fit. Personalisation on fit influences: body shape, size, grip orientation and ergonomics.

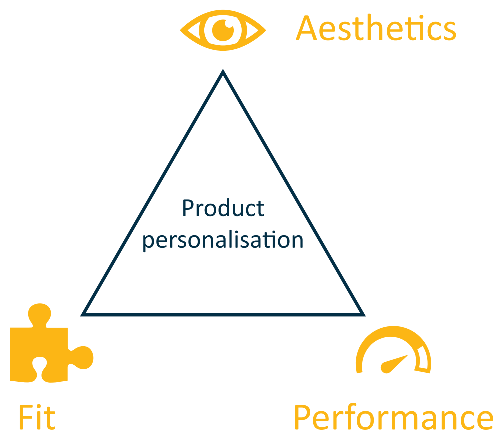


Figure 3.2 Personalisation areas

3.3.2 product breakdown

To understand how an ultra-personalised mouse can be created, the computer mouse is broken down into it's components. Analysing the elements and the posibilties for personalisation will give the areas that need customisation and personalisation, which dictate how the mouse is manufactured.
Disassembling and analysing a simple mouses the identiefied the following primary components: Top plate, Body, Button interface, scroll wheel, Hardware PCB and the base. An overview of the components and their personalisation options can be seen in Figure 3.3.

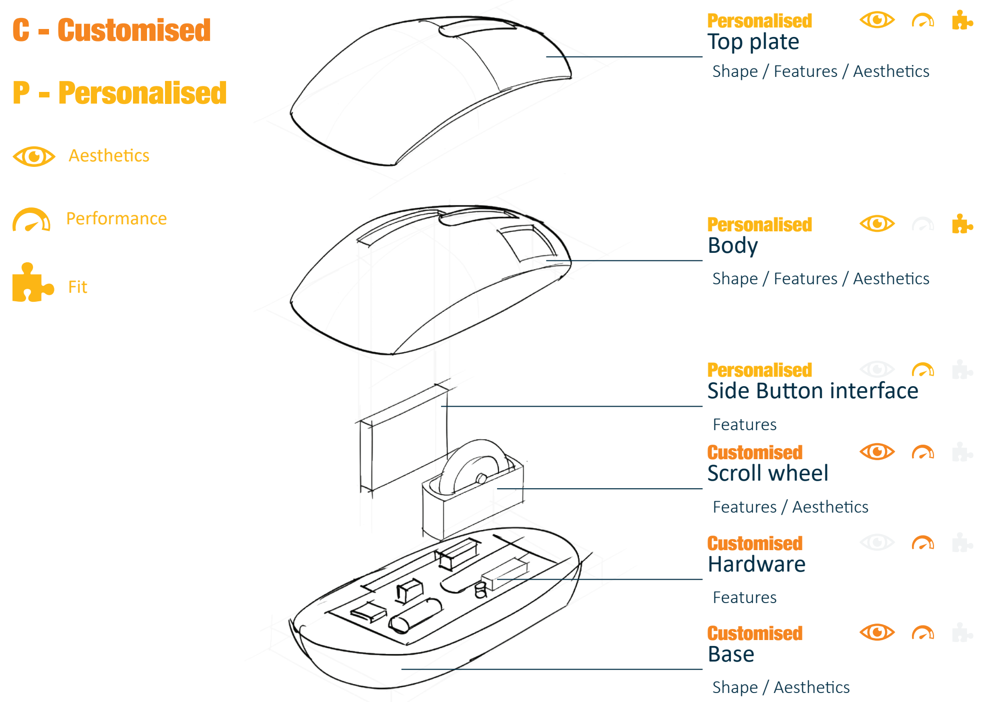


Figure 3.3 Computer mouse product breakdown

Top plate

The top plate interfaces with the hand of the user. To create an ultra-personalised mouse that fits the user, the top plate's geometry needs to be personalised.

Body

The body is the shell of the mouse and defines the main shape of the mouse.

Side Button interface

The side button interface is extra depending on the performance the user wants. The amount and kind of buttons can be customisable however since the side button interface also needs to be integrated into the personalised shape of the mouse this part needs personalisation.

Scroll wheel

The scroll wheel is a hardware part that can be customised based on the user's preference. While it is tactile, a selection of wheels could provide enough customisation to the user to provide aesthetic and performance choices, it does not need personalisation.

Hardware

Hardware is mainly influenced by the performance the user wants. Hardware is most cost-effective when it is on PCBs so it is best to provide standard hardware modules customised to user preference.

Base

The base of the mouse is the base to wich the other parts are attached to. The base holds the hardware components and brings the rest of the mouse together. For a bespoke mouse the base does not necessarly need to be personalised as long as it is customasiable to fit the personalised parts. However the base can be personalised depending if the base is a main feature instead of a bottom plate.

3.3.3 Bespoke mouse

A bespoke mouse has many personalisation areas. For demonstration, it is chosen to go for a full ultra-personalised mouse. Showcasing the possibilities of ultra-personalised products enabled by hybrid fabrication.

Shape
The shape of the mouse is based on the preferred grip of the user and the measurements of the user's hand. The top plate, body and mouse are fully 3D printed to fit the ultra-personalised shape and preferred aesthetics.

Electronics
Integrated electronics are used to create the complex button interface that is personalised on shape, fit and aesthics. Matching the shape to the hand of the user, having buttons depending on the required performance and incorporating personalised lighting. Using hybrid fabrication the buttons in the button interface can be 3D printed in place with the electronic switches. (Papp, 2021) 3d printed buttons

The hardware is split up into 3 PCBs that are later connected and integrated into the base, these are customisable features depending on the required performance. Combining the price benefits of PCBs with the possibility of customisable electronics and shape freedom.

Button PCB
The button, scroll wheel and connection PCB, with customisable scroll wheel.

Main PCB
The sensor and main hardware provide functionality to the mouse and integrate the hardware modules.

Power PCB
The power module provides battery, charging and wireless capabilities to the mouse.

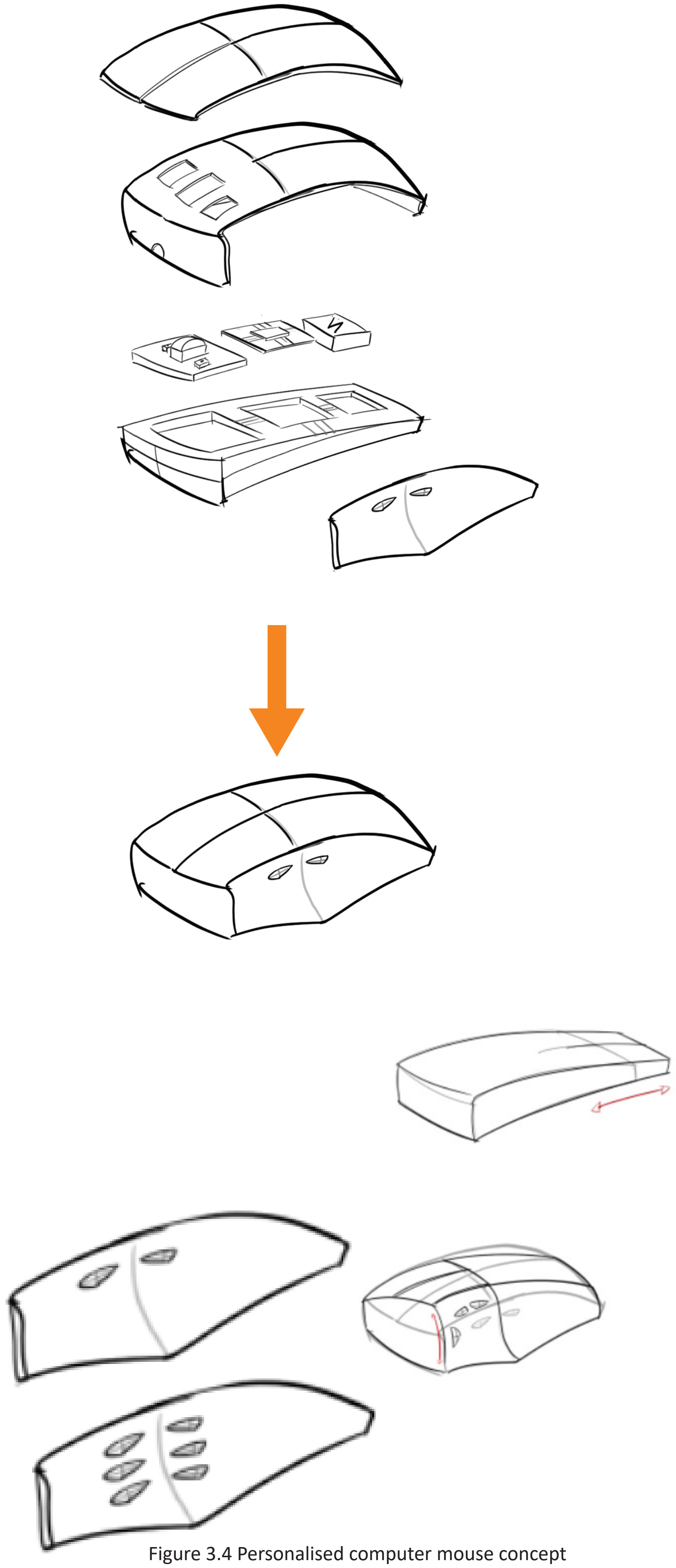


Figure 3.4 Personalised computer mouse concept

3.3.4 product scenario

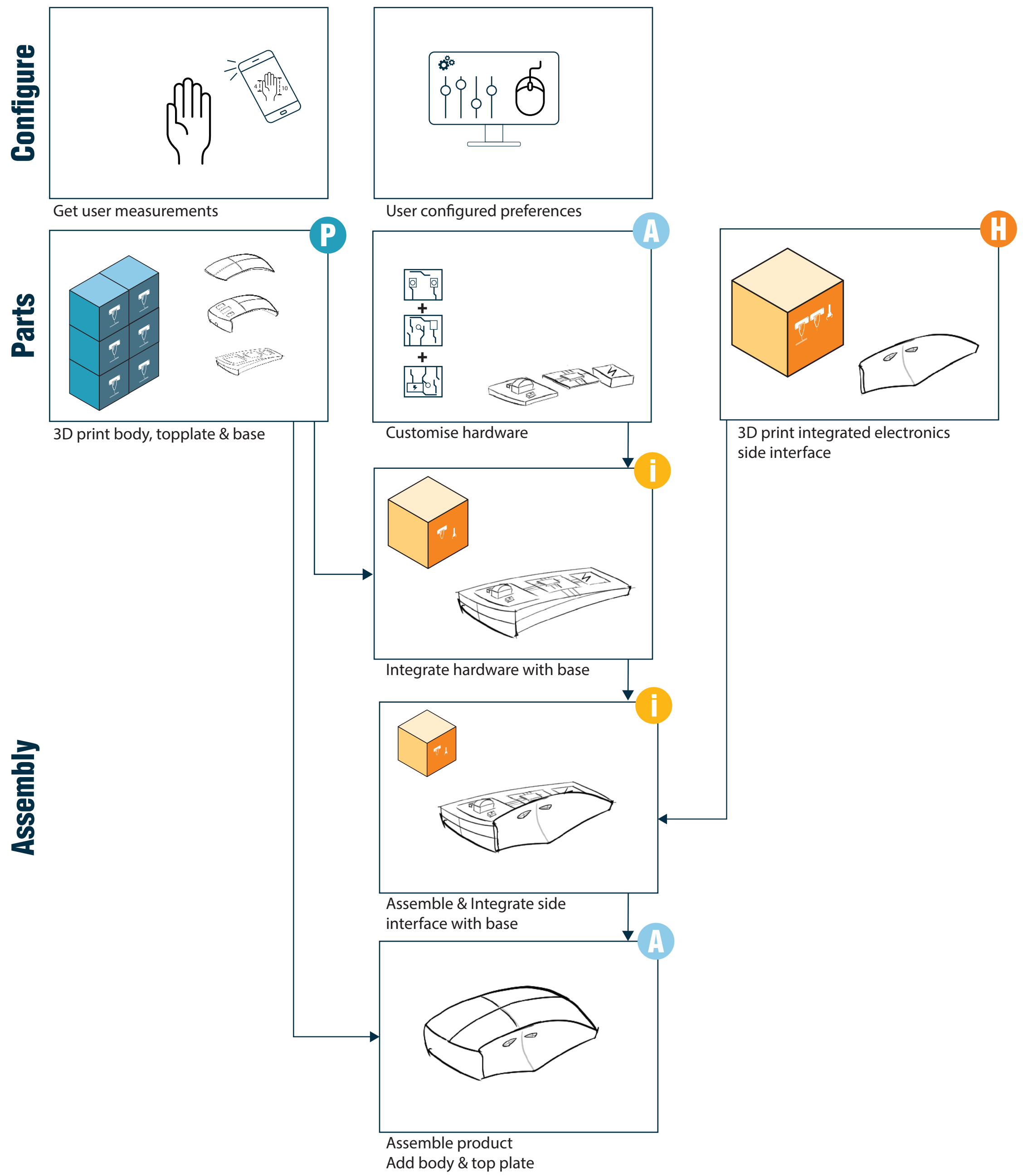


Figure 3.5 Exemplary production scenario

H **Hybrid fabrication cluster**
With hybrid fabrication and integrated electronics the button interface is created. The button interface uses multi-material 3d printing alongside integrated electronics to create a compact and personalised part.

i **Integrated electronics cluster**
To integrate the customised PCB's and other electronics an integrated electronics cluster is used. This cluster differs from the hybrid fabrication since it lacks 3D printing capabilities and is more assembly and electronics oriented.

P **3D printing cluster**
The bulk of the personalised shape is created with 3D printing clusters that manufacture components including the creation and finishing of the parts.

A **Assembly cluster**
The assembly clusters assemble parts and (sub) assemblies.

3.4 Hybrid workstation exploration

To enable transcended manufacturing and enable the envisioned scenario's a hybrid workstation needs to be created. Before designing the hybrid workstation, various features need to be considered. Through brainstorming and looking at existing (flexible) CNC systems, core system features are found. The core aspects are intralogistics, tool utilisation, available toolset and support hardware. These features are further explored and used for ideation of the hybrid workstation.

Figure 3.6 Suitable processes for hybrid fabrication

Intralogistics
In regards to workstation design, intralogistics is defined as how the workstation handles parts and products. The workstation is part of a complex manufacturing ecosystem, the interaction of the workstation and the ecosystem defines how the workstation is used. During the production process products and parts are interchanged between machines. The way products are handled define the possibilities and boundaries of the system.
There are multiple ways of transporting parts in a factory, all with advantages and disadvantages. Factories can deploy multiple systems for handling the intralogistics within the factory.

Tool utilisation
The key part of hybrid fabrication, combines multiple tools in a fabrication process in a system to create parts. There are multiple ways to use an available toolset, how the available tools are utilized and how the system changes between tools influence the functionality, the possibilities and the system boundries.

Available toolset
The hybrid fabrication station uses multiple tools to take advantage of multiple fabrication tecniques. The available toolset covers how changes to the toolset are made. Tools need maintenance or replacement. Depending on product demand or changes in the product, the functionality of the workstation might also need to be reconfigured. The available toolset needs to be flexible but, flexibility also comes with extra difficulties and an increased price.

Support hardware
CNC machines need electronic signals and power in order to operate. Different system require different hardware. The system's support hardware is the hardware required to operate the system and its tools. How the support hardware is configured influences the system flexibility and capabilities.

3.4.1 Intralogistics

Manual part handling
Parts and products can be manually transported and placed in machines. This is a labour-intensive method of handling parts since humans cannot handle many parts at the same time. A big advantage of manual part handling is the flexibility a human brings to the process. However introducing a human in the mix of an automated system also raises the chance of human error within the process. When introducing manual labour, the ethics of repeatable monotonous task should also be considered.

Conveyor/rail systems
When talking about factories, you will most likely also think of conveyors. Conveyers are deeply embedded in the industry and almost every factory has some sort of conveyor system in place to transport parts. There is a wide variety of possible solutions and with an industry that is increasingly interconnected, conveyors are also getting smarter. Parts can directly be transported on the conveyor, or carriers called pallets are used to transport parts on the conveyor. Conveyors have the benefit of being able to swiftly and efficiently transport parts from place to place.
The main benefit of conveyors is that it has a high throughput a disadvantage of conveyors is that it is a rigid system which is less flexible to change.

Automated guide vehicles
Since recent years Automated guided vehicles (AGV) are finding their way into the industry. AGV's are robotic vehicles that can autonomously transport parts. AGV's are used to automate and optimise intralogistics in factories. Current industry example use cases are in: assembly lines, order picking systems, warehousing and production plants. AGV's use standardised pallets to interface with the products or parts that are transported. Benefits of AGV's are the motion of freedom that AGV's provide while being optimised and efficient.


Figure 3.7 Assembly workers China

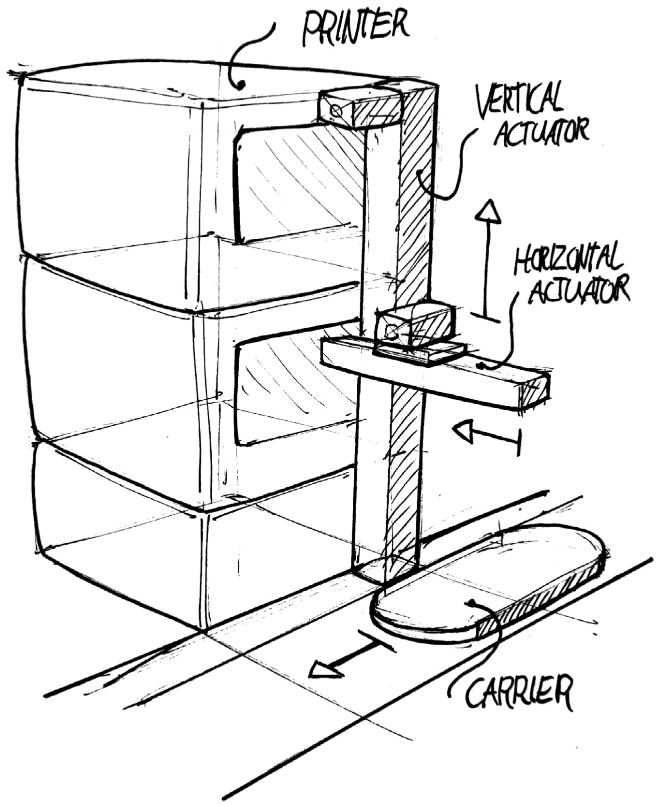


Figure 3.8 Intralogistics concept (Kromhout,2020)


Figure 3.9 Kuka AGV solution in automotive environment

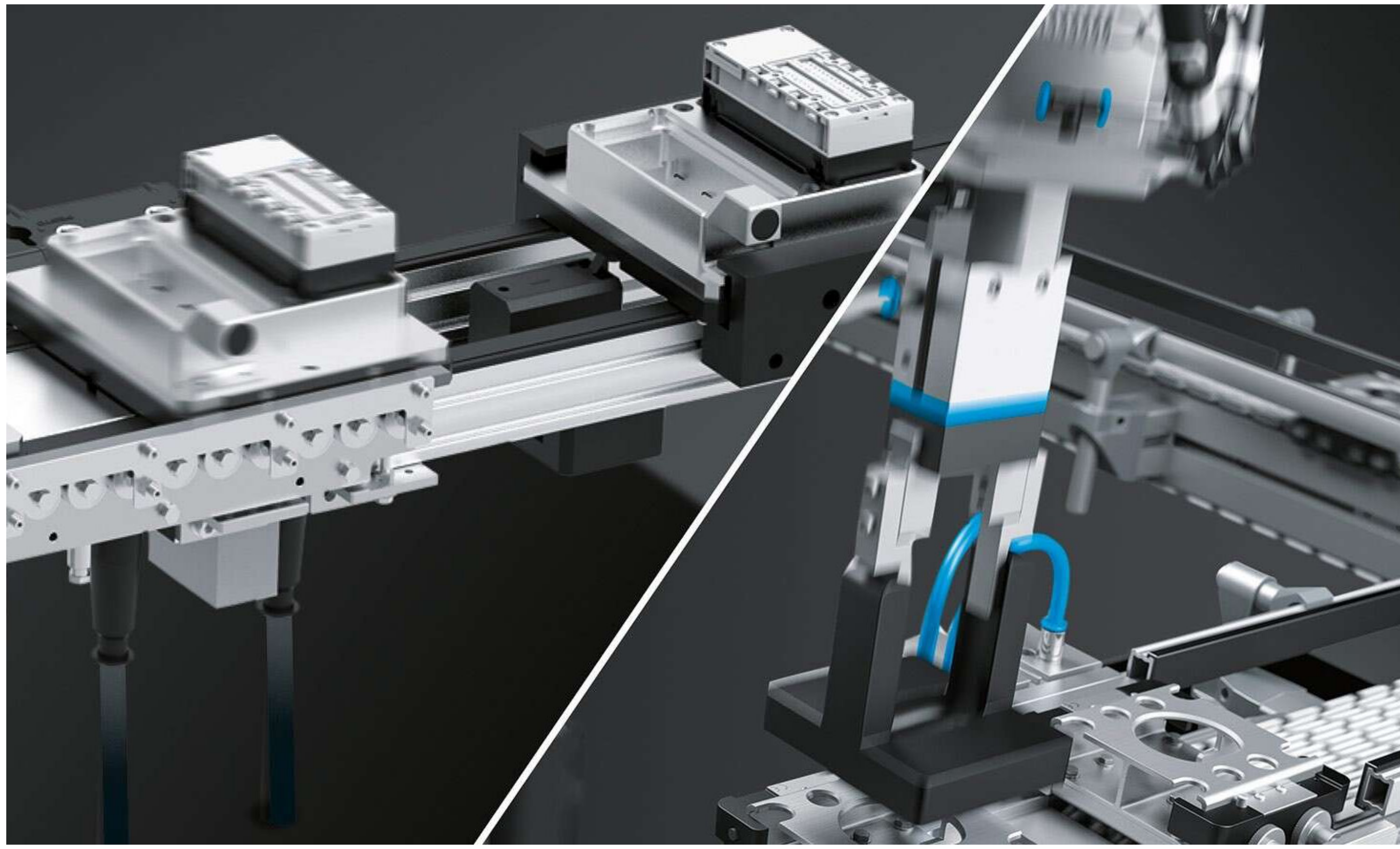


Figure 3.10 Festo Multi carier system

3.4.2 Tool utilisation

The system could swap tools for the required operation, the system could have all tools constantly operational, or the system could change the part/bed when the parts require a different operation.
From the brainstorming, three promising ways of utilising multiple tools in a single system are identified.

- Using the available tools by deploying a toolchanger which automaticly changes the current tool head for the required system.
- A fixed toolsystem that has all tools readily available and changes the part location within the machine to make use of the tools.
- A manufacturing system that has multiple tool stations and interchanges the part between these changes to change operation.


Figure 3.11 ATI robotics tool changer

Figure 3.12 ATC tool changer

3.4.2.1 Tool changer

Tool changers are already widely used by dedicated CNC systems to change the tool available tool to the system. For example, they are used in industrial robots which pick up tools from a tool rack, and CNC milling machines which have dedicated tool changers that hold tools and actively change the tool in the machine.

Tool change designs differ from application but most tool changing systems have a few core parts: A tool holder which holds the tool. A toolmount or coupler pairs the tool holder and the machine together, and a tool rack stores the toolholders when the tool is not in use. A toolrack can either be static rack or automated depending on the movement restrictions of the system, the speed of the tool change and the available space.

Metal milling requires a large set of expendable mills to facilitate different milling operations. Therefore automated toolchangers are often used to quickly change the active tool in the milling machine. When many tools are needed like in a milling machine an automated toolchanger is often used because this increases the capacity of the available tools without sacrificing tool changing speed. Tool changer alignment and tolerances have to be considered while designing a tool changer.

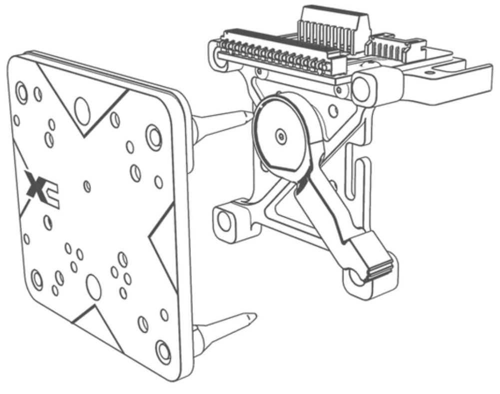


Figure 3.13 Xchange 3D printing tool changer

When using a tool changer, it should also be considered how the tool interfaces with the machine. Milling tools do not require an electrical connection but, many of the devices discussed earlier in the hybrid fabrication chaper require electrical signals. Multiple tool changers already exist and there are two main ways this is solved. The tool holder has an electrical connector that interfaces with the machine or the tool can always be connected to the machine.

Good examples are the FDM tool changers of E3D and the tool changer of XChange which showcase the different solutions. The benefit of having a toolholder with a connection is that it reduces the amount of wires in the signal. However, connections need to be standardised, which is more expensive for a flexible manufacturing system that requires tools that do not have similar power and signal requirements. Having the tools continuously connected negates the requirement of a universal connector, but wire routing and the connection to the system still have to be considered.

At last rigidity needs to be considered while choosing a tool changing system. Both rigid and non-rigid tool changers exist depending on the required rigidity of the operation. For example a milling machine requires very tool mounting while an FDM printer requires a lot less rigid system. When designing a tool changer and a hybrid fabrication system the operation that requires the highest rigidity determines the design. And this can greatly increase the tool changer cost because it is overbuild for most tools.

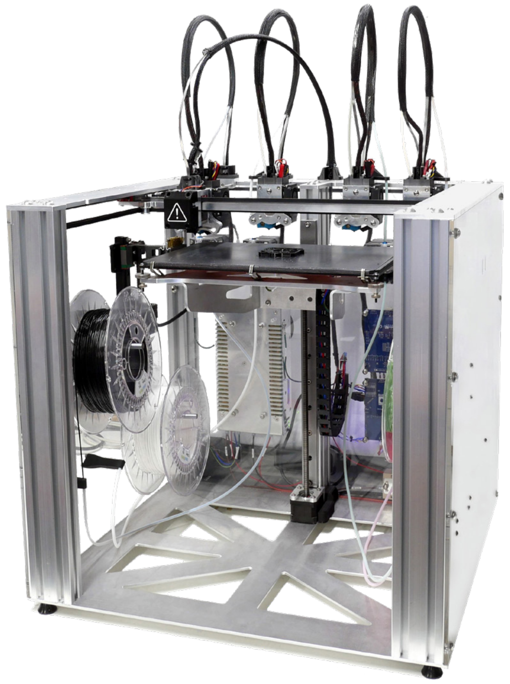


Figure 3.14 E3D, 3D printer with tool changer

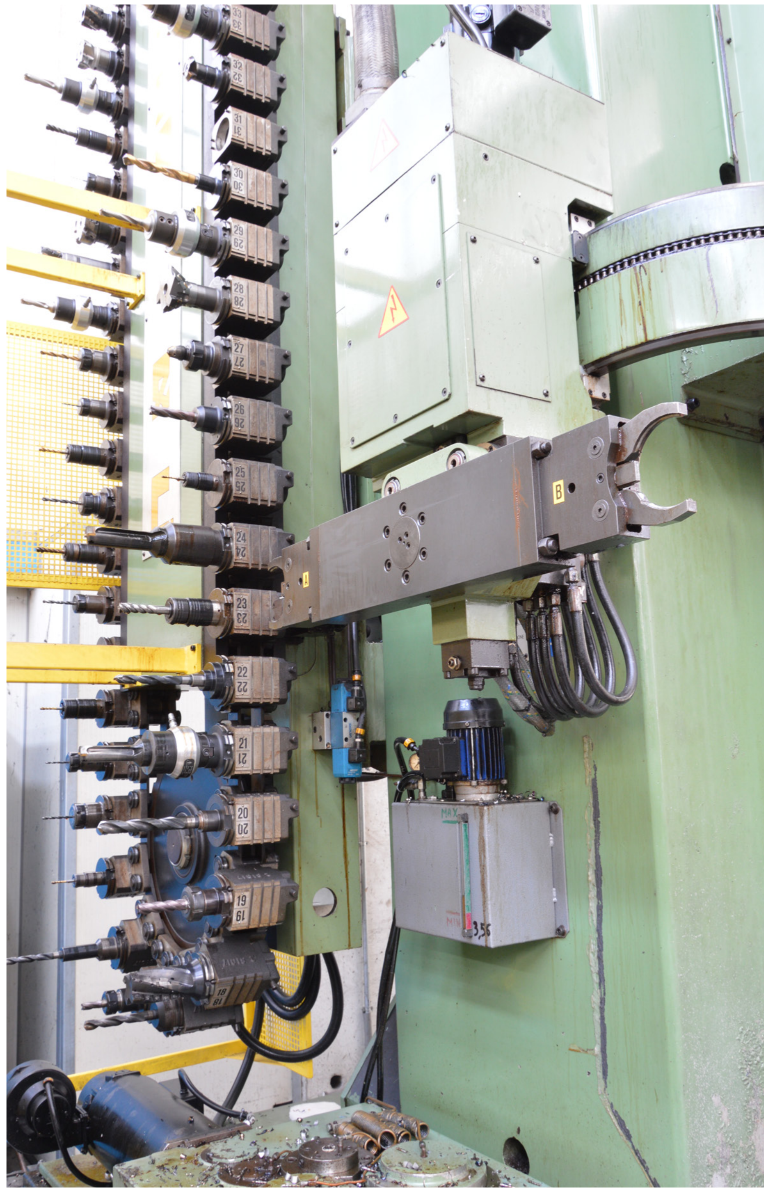


Figure 3.15 CNC mill belt tool changer

3.4.2.2 Fixed Tools

The fixed tool utilisation has all the required tools mounted on the system. To have multiple tools available to the system, it is possible to have a fixed amount of tools on the same carriage, and move in tandem. Similar to factories that use production lines to change the product to different operation stations, a fixed system has all tools for the various operations readily available. The part is moved within the machine to make use of the multiple tools. Unlike the traditional production line, a fixed system only uses a single tool at a time. Tool time has to be taken into consideration when combining slow processes with fast processes.

An advantage of fixed system is that attaching tools on the machine can be relatively simple. However, the tool's alignment and installation still have to be considered to provide a flexible system. An example of a CNC that has multiple tools fixed on that carriage is the stacker 3D. This 3D printer uses multiple print heads attached to the Y-axis to print multi-colour or print multiple identical parts at the same time.

The system has a limited capacity of tools depending on the size of the system and it's tools. Increasing the available toolset means increasing the carriage size. The build volume and thus the size of the product also influence the size and the available toolset. The tools need to be able to access the full build volume. Tool size and product size both determine how the configuration of the axis is set up. In cartesian based CNC systems the weight of the part and the tools determine on which axis the build plate is placed and which axes control the tools.

If the available toolset is relatively heavy and large compared to the product, it is best to have the build plate with the most degrees of freedom since this reduces the system size and price. When the toolset is small compared to the required build volume, it is recommended to have the toolset with the most degrees of freedom.

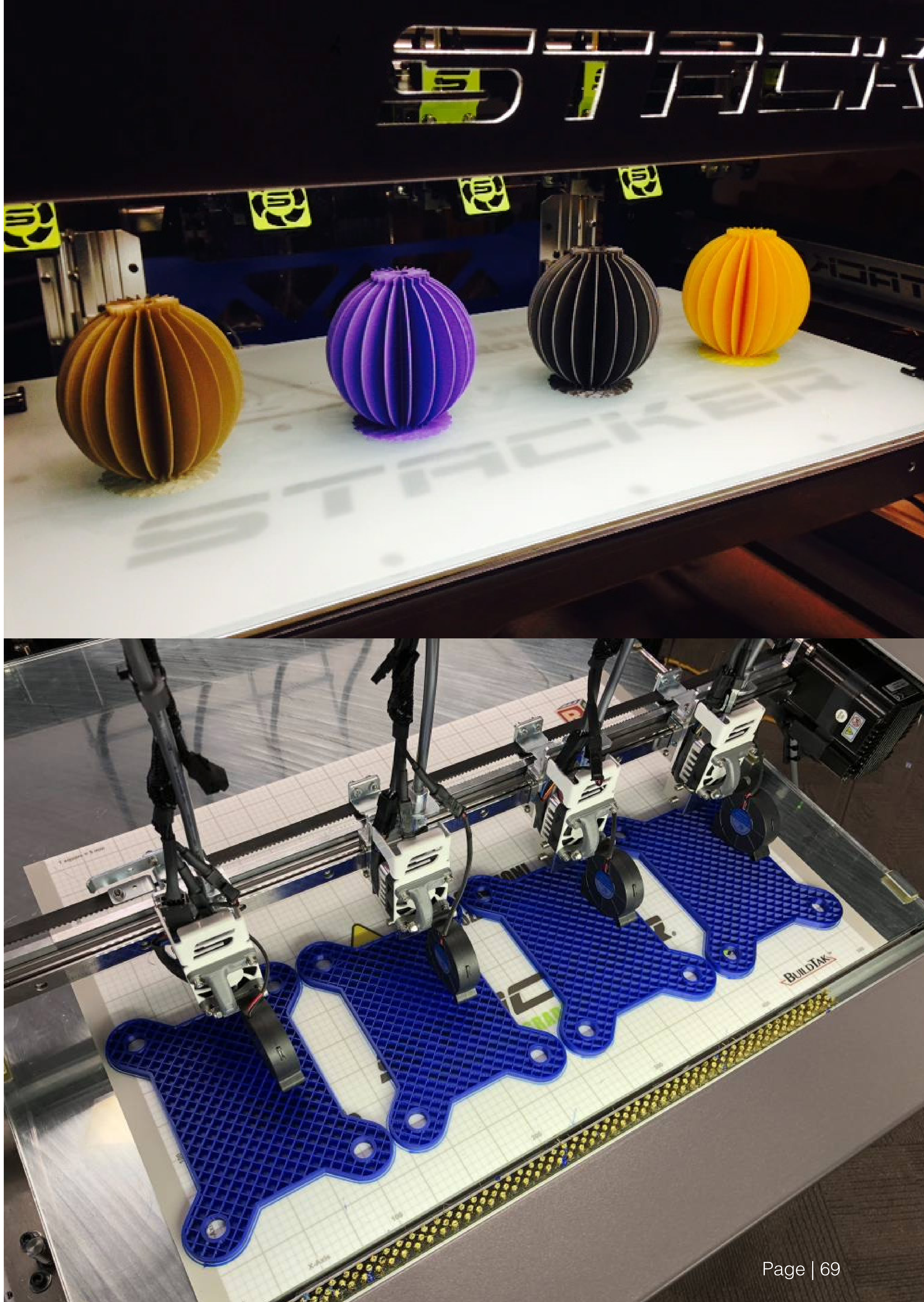


Figure 3.16 Stacker 3D simultanous 3D printing

3.4.2.3 Part changer:

In his research on transceded manufacturing, Ben Kromhout proposed a system which moves the products within a factory from machine to machine for each processing-step. Using pallets to transport the parts between machines. This can be used for a multi machine system or it could be combined in a dedicated hybrid fabrication station with multiple compartments.

The approach is good for Hybrid fabrication techniques with long process-steps that do not need frequent tool changes. Hybrid fabrication that requires repeated tool changes suffer loss in production speed due to the transit time required between machines.

A challenge with changing parts between machines is how to ensure correct part alignment within tolerance. More movement and replacing of parts in machines increase the difficulty of keeping tight tolerances.

Another example of such a system is researched by Keck Center for 3D innovation. Their project uses a robotic arm to transport a build plate with the product between multiple machines.

A big benefit of this method is that it is possible to have effective tool usage since the machines can process parts independently. This is great for operations that require expensive tools and processes that are time-consuming. However all tools need to operate and move independently and requires multiple expensive motion systems to have an operational system.

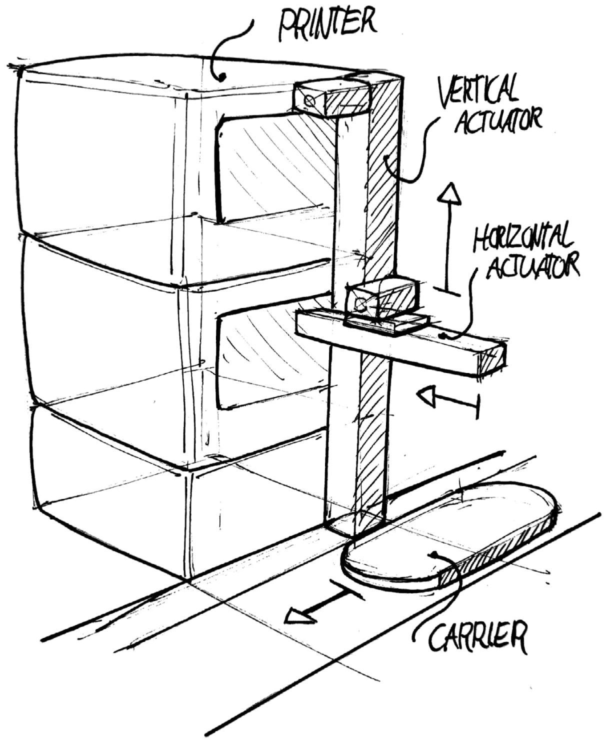


Figure 3.17 Intralogistics concept (Kromhout,2020)

Figure 3.18 Integrated electronics fabrication through part changing

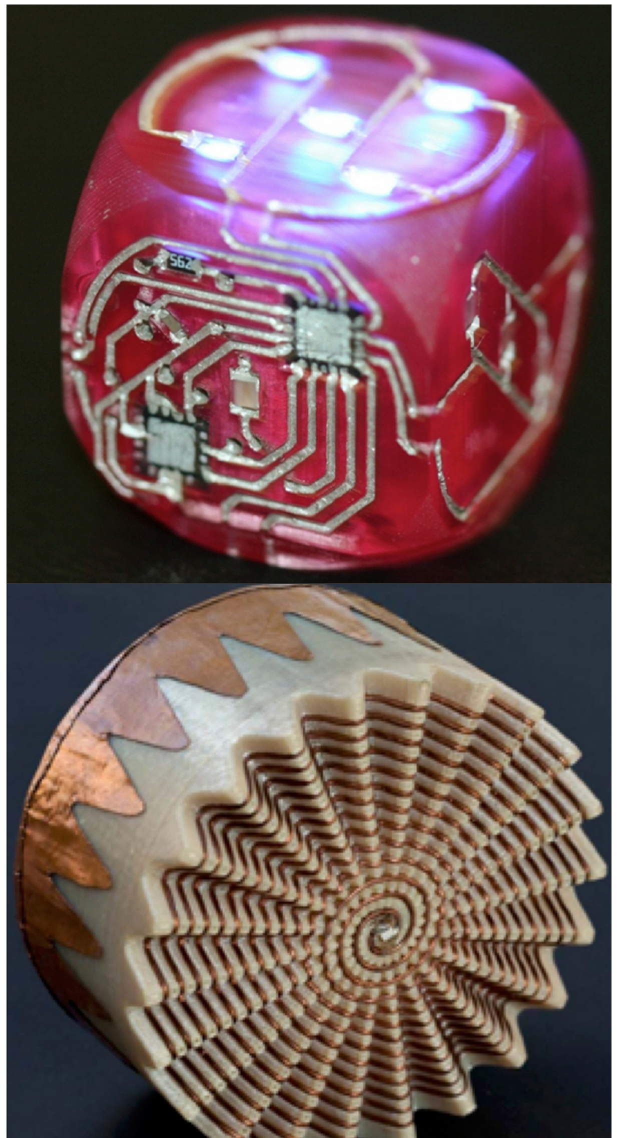


Figure 3.19 Factory CNC mill loading and unloading

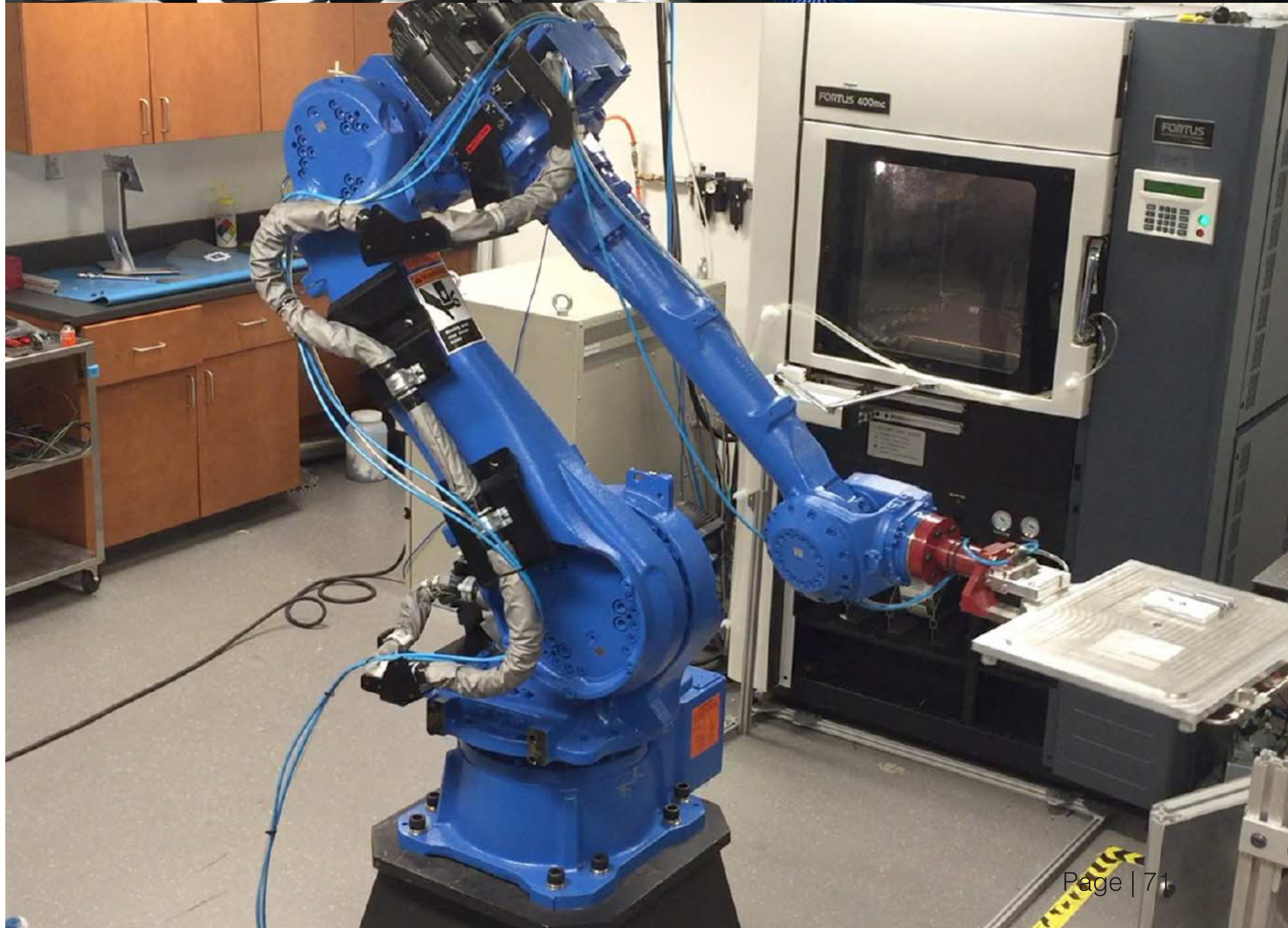


Figure 3.20 Factory CNC mill loading and unloading

3.4.3 Available toolset

There are multiple ways of approaching hybrid fabrication and numerous possibilities in configuring and installing tools available to the system. For this research, we hold to a reconfigurable manufacturing system that has a reconfigurable toolset. A hybrid system needs to use different tools available depending on the required processes needs. Furthermore, it needs to facilitate tool maintenance and the replacement of expendable tools . Replacing and reconfiguring the available toolset can be manual or automated.

Automated toolset

Having the correct tools available to the machine is vital to guarantee production productivity. By automating the process of changing the available tools, the system can efficiently use the tools available in the factory. Linking the machine's tool rack to tool storage the machine's tool expands its manufacturing capabilities while using the tool rack as a buffer. Furthermore tools can be shared between devices, decreasing the number of stored tools.

Adding automation to the toolset might look like a no brainer; nevertheless, adding increases logistic difficulties and vastly increases system cost. The extra cost for an automated system can be justified when; optimal productivity is required, a vast amount of tools is needed, often replacement of the tools is required or when the used tools are expensive and infrequently used.

Multiple automated solutions exist, tools could be transported by conveyors/rails or could be delivered with an AVG.

As an illustration, FASTEMS provides a central tool storage for milling CNCs, a toolset solution that stores tools in central storage and delivers the tools to the machine's tool rack when required.

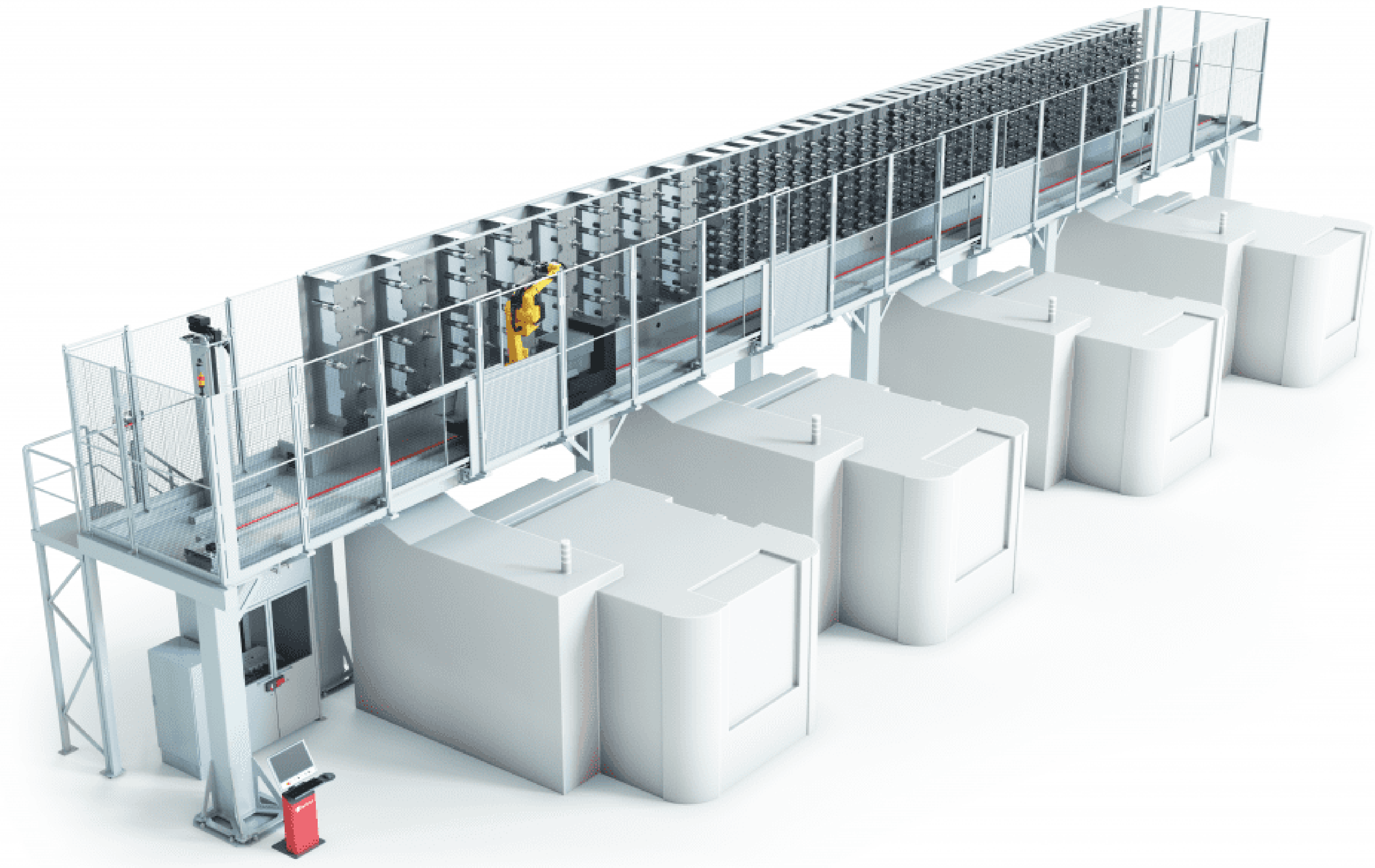


Figure 3.21 Fastems tool storage and delivery system

Manual tool reconfiguration

When there is an automated solution to a problem, there is often also a manual solution. With manual tool replacement, a worker needs to replace or reconfigure the available toolset. Manual tool replacement and reconfiguration has low investment costs and circumvents the complexity that system automation adds. Manual replacement of tools is labour intensive and is slower than an automated solution, and can decrease productivity. Tool size and weight also need to be taken into account since it needs to be handleable. However, manual tool replacement is still widely used because of the lower required cost and the flexibility a human adds to the process.

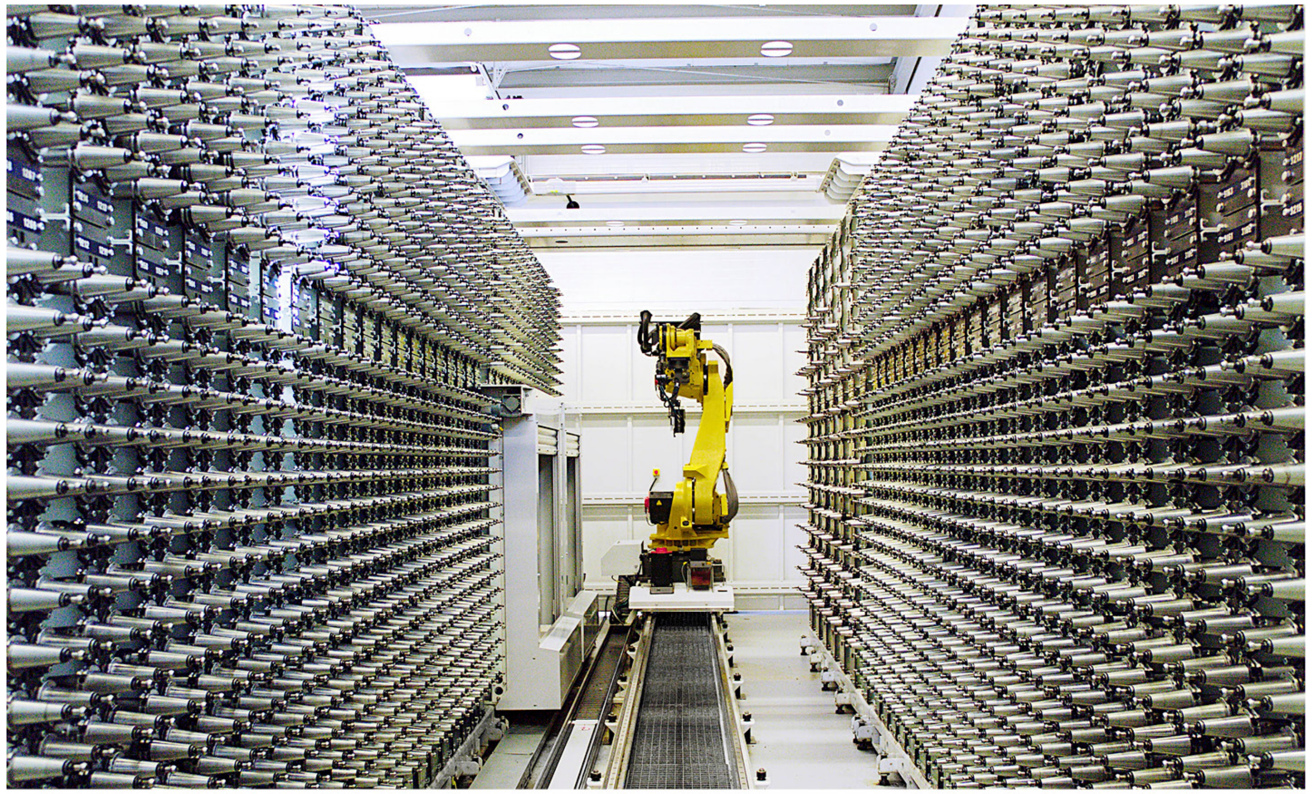


Figure 3.22 Fastems tool storage

3.4.4 Support hardware

CNC systems are complex electronic systems that need hardware to run the system and its tools. A flexible manufacturing system also needs to be flexible in the way it interfaces with the tools. Combining multiple different tools into a system creates challenges in data and power transmission. As always there are multiple solutions to this problem. The hardware can be reconfigurable, meaning reconfiguration of tools requires reconfiguration of hardware, the system hardware can be flexible, meaning it has multiple ways of interfacing with tools. Or the hardware can be fixed, requiring the tools to be generalised to interface with the system.

Modular hardware
Modular hardware can be reconfigured depending on tool requirements, adding or removing modules to the primary system. This increases the adaptability of the system since it can be modified to fit the process needs. Allowing for specialised tools requiring specialised hardware which can interface with the system through add-ons. Expanding the capabilities of the system. How the core system is linked does have to be considered when designing the core hardware, allowing for expandability through add-ons. The usage of add-ons benefits starting investment cost since it can limit the hardware to only the required hardware. An excellent example of reconfigurable hardware is how desktop computers deal with constant developments in computer hardware. A computer has a motherboard that links all computer components together. When additional functionality is required the computer can be upgraded accordingly. For example if the user wants more computer monitors, components like graphicscards can be added. Working with add-ons increase the relevance and longevity of a system, while keeping cost low.

Flexible Hardware
Flexible hardware is hardware that can be for multiple situations. The benefit of flexible hardware is that it has full system capabilities from the start without requiring additions. The hardware has multiple standardised ways of interfacing with tools and is built to accommodate these tools' different requirements. Flexible systems are overbuilt to handle numerous scenarios; however, this redundancy requires additional investment in hardware. Furthermore, the hardware could limit system upgradability if not accounted for. Staying with computer examples, flexible hardware can be seen as a laptop. Often laptops have limited upgradability; however, laptops still provide a set of connections to attach USB peripherals or computer monitors.

Tool hardware
With tool hardware, the systems hardware is predefined like in flexible hardware. However it is the tools job provide interface with the system. The CNC hardware is not made to accommodate different tool requirements, connections are provided however this is universal and provides both data and power, additional tool hardware is required when the tool cannot directly interface to the system. For this system the tools adapt to the system instead of the system to the various tools. This could limit the tool availability, increase the tool size and increase tool cost. However, this does guarantee all systems can use the same tools. In computers, this can be compared to connecting displays to your computer, monitors have onboard hardware to translate the computer signal and if the monitor cable does not fit the computer, an adapter cable is needed.

Modular hardware
Pros:
- low investment cost
- Expendable, System can grow and adapt to the needs of the factory

Cons:
- Limited barebones functionality
- Tool addition could require hardware addition

Flexible hardware
Pros:
- Has a wide range of tools available from the start
- Plug and play
- Generalised connection
- All systems can use the same tools

Cons:
- increased investment cost
- Limited expandability and upgradability

Tool hardware
Pros:
- Wide range of tools available from the start
- No redundant hardware
- low starting cost
- All systems can use the same tools

Cons:
- Increased tool price
- Increased tool size
- Limits total tool availability

Figure 3.23 USB adapter

Figure 3.24 Din rail electronics modules

3.4.5 Workstation features summary

3.3.1 Intralogistics

Manual part handling

Pros:
- Flexible

Cons:
- Labour intensive
- Introduces human error

Conveyor/rail systems

Pros:
- Fast
- High throughput

Cons:
- Rigid

Automated guide vehicles

Pros:
- Flexible
- Optimizable

Cons:
- Complex
- Expensive

3.3.2 Tool utilisation

Tool changing

Pros
- Increased productivity
- High tool capacity

Cons
- Complex
- Tooladapter requires high stifness
- Idle tool storage

Fixed

Pros:
- simple design and tool attachment
- Tools can activate independently
- No need for tool changing

Cons:
- Idle tool time
- Limited tool capacity
- Limited build volume
- No large tools

Change part

Pros:
- Effective tool usage
- Parallel process
- Able to use specialised machines

Cons
- Transportation time between process-steps
- Expensive, Requires multiple machines or motion system

3.3.3 available toolset

Automated toolset

Pros:
- Increased productivity
- Increased process flexibility
- Shared tools

Cons:
- requires costly investment

Manual reconfiguration

Pros:
- Increased tool flexibility
- Low complexity
- Low investment cost

Cons:
- Decreased productivity
- Limited tool size and weight

Change part

Pros:
- Effective tool usage
- Parallel process
- Able to use specialised machines

Cons
- Transportation time between process-steps
- Expensive, Requires multiple machines or motion system

3.3.3 Support hardware

Modular hardware

Pros:
- low investment cost
- Expendable, System can grow and adapt to the needs of the factory

Cons:
- Limited barebones functionality
- Tool addition could require hardware addition

Flexible hardware

Pros:
- Has a wide range of tools available from the start
- Plug and play
- Generalised connection
- All systems can use the same tools

Cons:
- increased investment cost
- Limited expandability and upgradability

Tool hardware

Pros:
- Wide range of tools available from the start
- No redundant hardware
- low starting cost
- All systems can use the same tools

Cons:
- Increased tool price
- Increased tool size
- Limits total tool availability

3.4.6 conlusion

There are various possible solutions to creating hybrid fabrication workstations, and each feature has its pros and cons depending on the toolset and manufacturing setting.

Intralogistics
Intralogistics is defined as how the workstation handles parts and products.
The flexibility of manual intralogistics is great for small fabrication scenario's, but in large scale production, automation can be more efficient.

Conveyors and rails are great for mass production lines, providing high throughput. Conveyors are rigid systems defined beforehand; Conveyors are less flexible, and reconfiguring conveyor lines is a more involved process.

Automated guide vehicles provide great flexibility and are ideal for flexible manufacturing scenario's. However, AGV swarms are expensive and complex systems making them less suited for small operations.

Intralogistics needs to be considered during ideation. However, intralogistics must not be the leading element. Intralogistics is essential to factories, but system could be adapted after the fact.

Hardware
Modular hardware is way of providing large flexibility while keeping upfront cost low. Modular hardware is great for systems with future expansion in mind. Modular hardware is less beneficial when the system boundaries do not change.

Flexible hardware has a wide range of tools available from the start. With flexible hardware, the system is plug and play. Flexible hardware is suitable when all the processes are predefined and there is no need for future expansion.

Tool hardware is for scenario's when tools are specialised and require specific incompatible hardware. Tool hardware keeps initial costs low but increases tool price and size. Tool hardware is suitable for systems with future expansion in mind.

Tool utilisation
Tool utilisation defines how tools within the system are used and dictates how efficiently tools are used.

Tool changers are widely used in machines to provide a range of tools to the system, and tool changers are a great way of providing more functionality to a system. Tool changers are complex and tools within a toolset have long idle time. Tool changers are good for a system that needs a (expendable) toolset where tools are small and often need to be changed.

Fixed tools is a simple way to provide a multi toolset to a system without increasing the complexity. Fixed tools can be used simultaneously and are useful when tools do not wear much and tools don't often need tool replacement. Fixed tools are great when the tooling is comparatively small in respect to the part.

Part changing is most useful in scenario's where specialised machines are required. The advantage of part changing is that multiple machines can work in parallel; however, it requires more machines and multiple expensive motion systems. Part changing is well suited for long processes with infrequent switching between the fabrication methods.

Ideation
Through the exploration of the mentioned workstation features it can be found that each has it's advantages. The discussed features will be used and combined to create hybrid workstation designs.

3.5 Workstation design

This chapter covers the design process of the hybrid workstation for transcended manufacturing. At first, brainstorming with Howto's was used to create ideas and solutions to individual challenges like the previous workstation aspects. After the ideation of separate solutions, the aspects were grouped in a morphological chart.

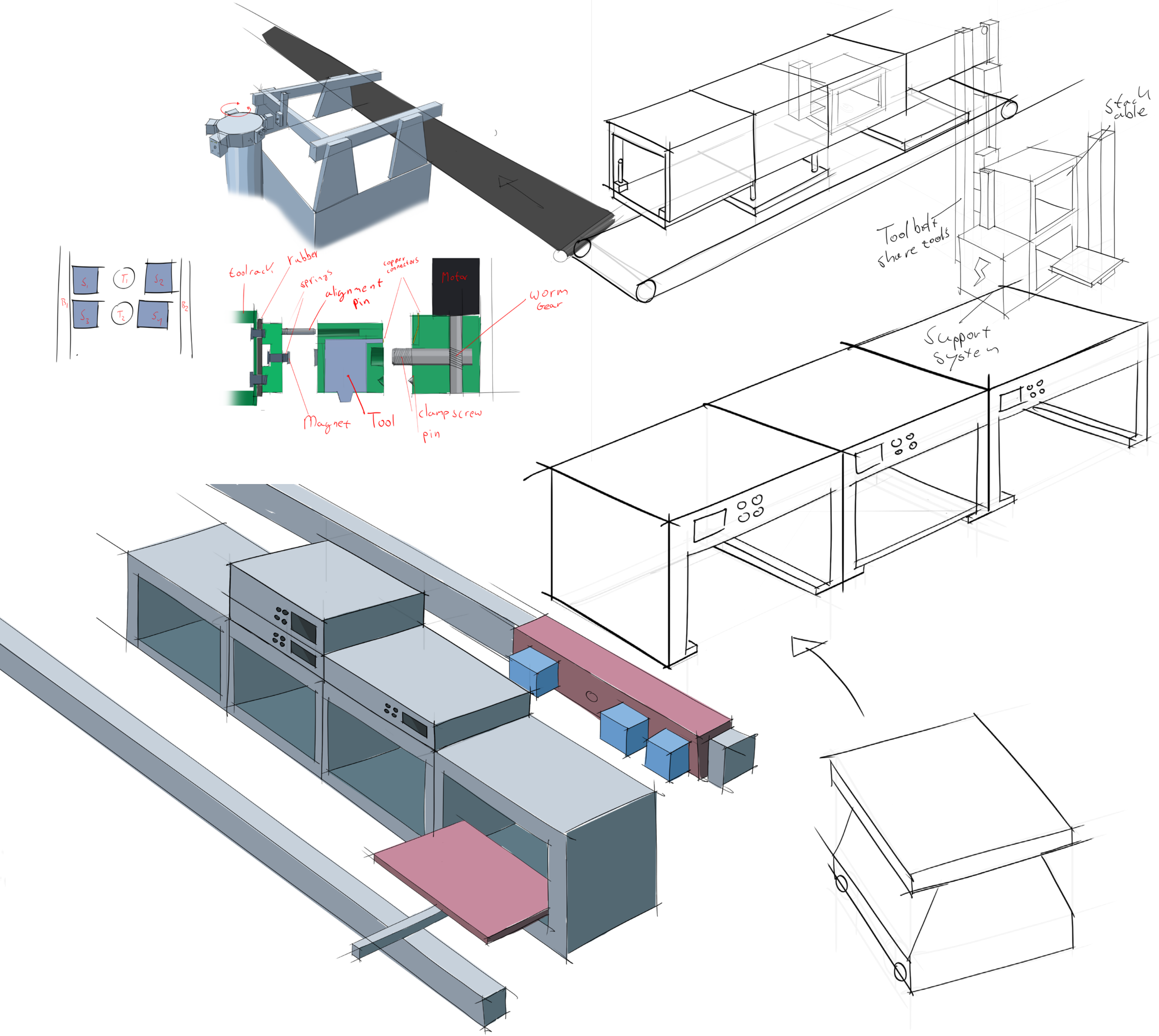
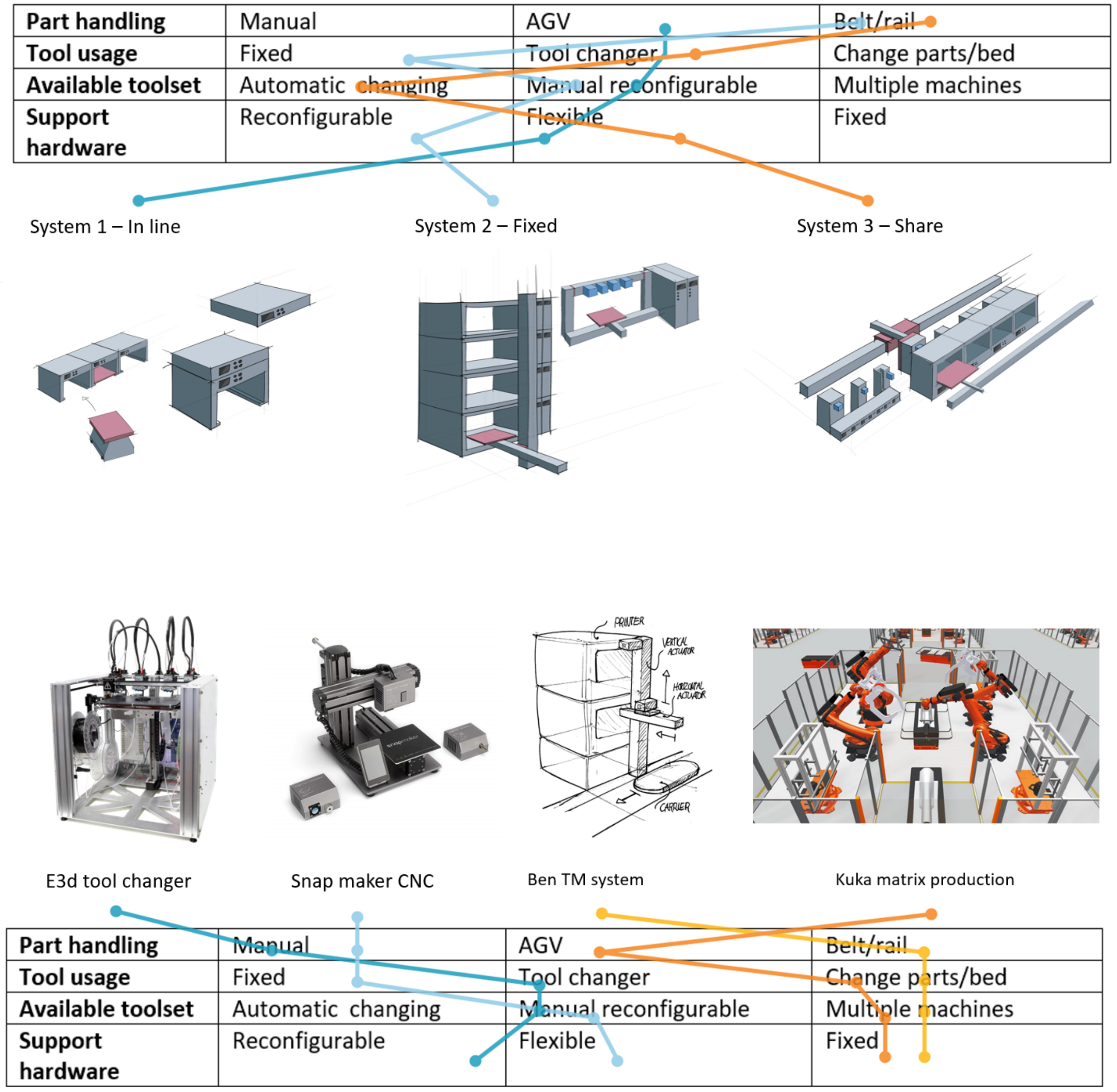


Figure 3.25 Ideation

The morphological chart was then used to support the ideation of the workstation designs. Figure 3.26 shows how the morphological chart was used to develop solutions and shows how similar existing machines solved the multi-tool problem. The ideation resulted in 3 promosing solutions which were refined into workstation concepts. After the concepts are evaluated, a single design direction is chosen to be further embodied in the embodiment stage. The three concepts are all drawn with intralogistics to provide context. However, intralogistics are not considered during evaluation because the factory determines the intralogistics, and the concepts can be adapted to fit the factory.



Part handling	Manual	AGV	Belt/rail
Tool usage	Fixed	Tool changer	Change parts/bed
Available toolset	Automatic changing	Manual reconfigurable	Multiple machines
Support hardware	Reconfigurable	Flexible	Fixed

Part handling	Manual	AGV	Belt/rail
Tool usage	Fixed	Tool changer	Change parts/bed
Available toolset	Automatic changing	Manual reconfigurable	Multiple machines
Support hardware	Reconfigurable	Flexible	Fixed

Figure 3.26 Morphological chart

3.5.1 Inline hybrid manufacturing

The inline manufacturing station uses tool changers and reconfigurable hardware to provide a versatile toolset. Tools are stored in on a toolrack and the native CNC motion system performs the tool changes. The reconfigurable hardware makes the system adaptable to the toolset. Opening the toolrack at the back of the system allows for rapid toolset reconfiguration. This system is great when tool replacement is regular.

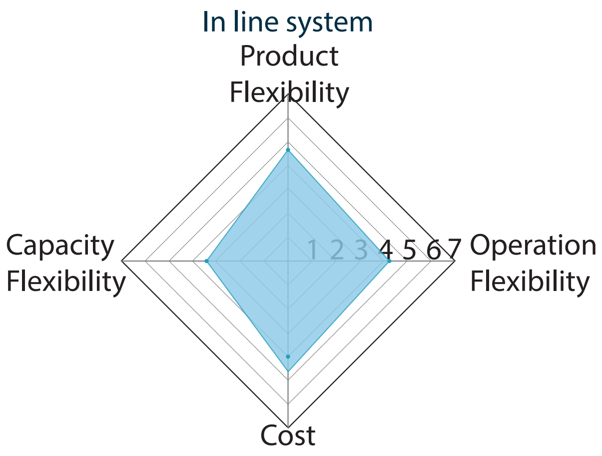


Figure 3.27 In line system characteristics

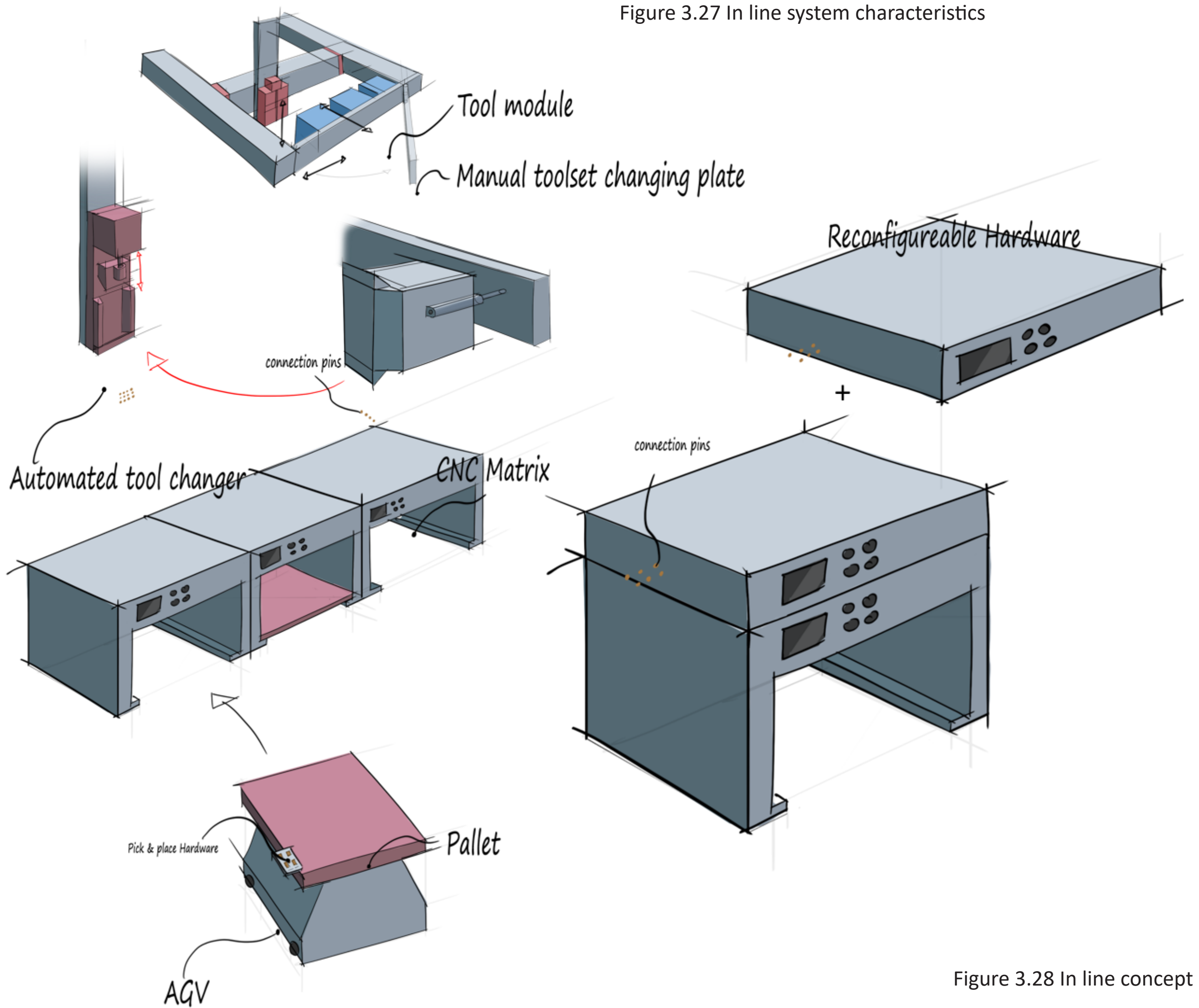


Figure 3.28 In line concept

Features:

- Manual reconfig toolset
- Tool changer
- Manual reconfig hardware
- Automatic connect tools

Pros:

- Fast manual reconfig
- Small scale efficiency
- Easy to add hardware modules

Cons:

- Tool holderComplexity
- Toolset capacity
- Cost

3.5.2 Fixed hybrid manufacturing

The fixed workstation has a fixed toolset attached to the system. The tool attachment is simple and tools can be screwed on to the system to rigidly attached them. The toolset is manually reconfigurable but a bit more involved to keep tool attachment simple. The modular hardware makes upgrades to the system convenient. This system is great when a flexible toolset is required, but tool reconfiguration is uncommon. The part does most of the movement for tool pathing, making large & heavy products less suited.

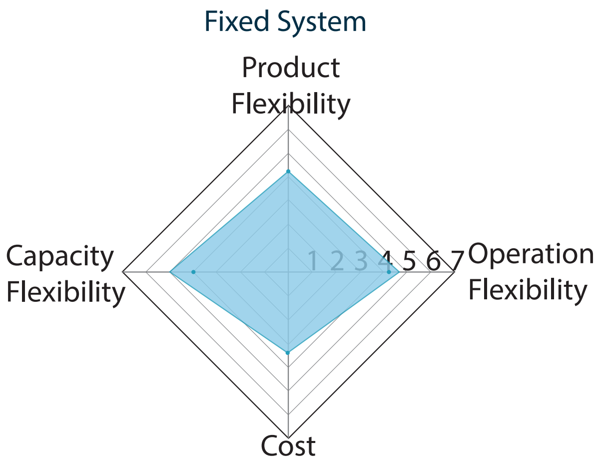


Figure 3.29 In line system characteristics

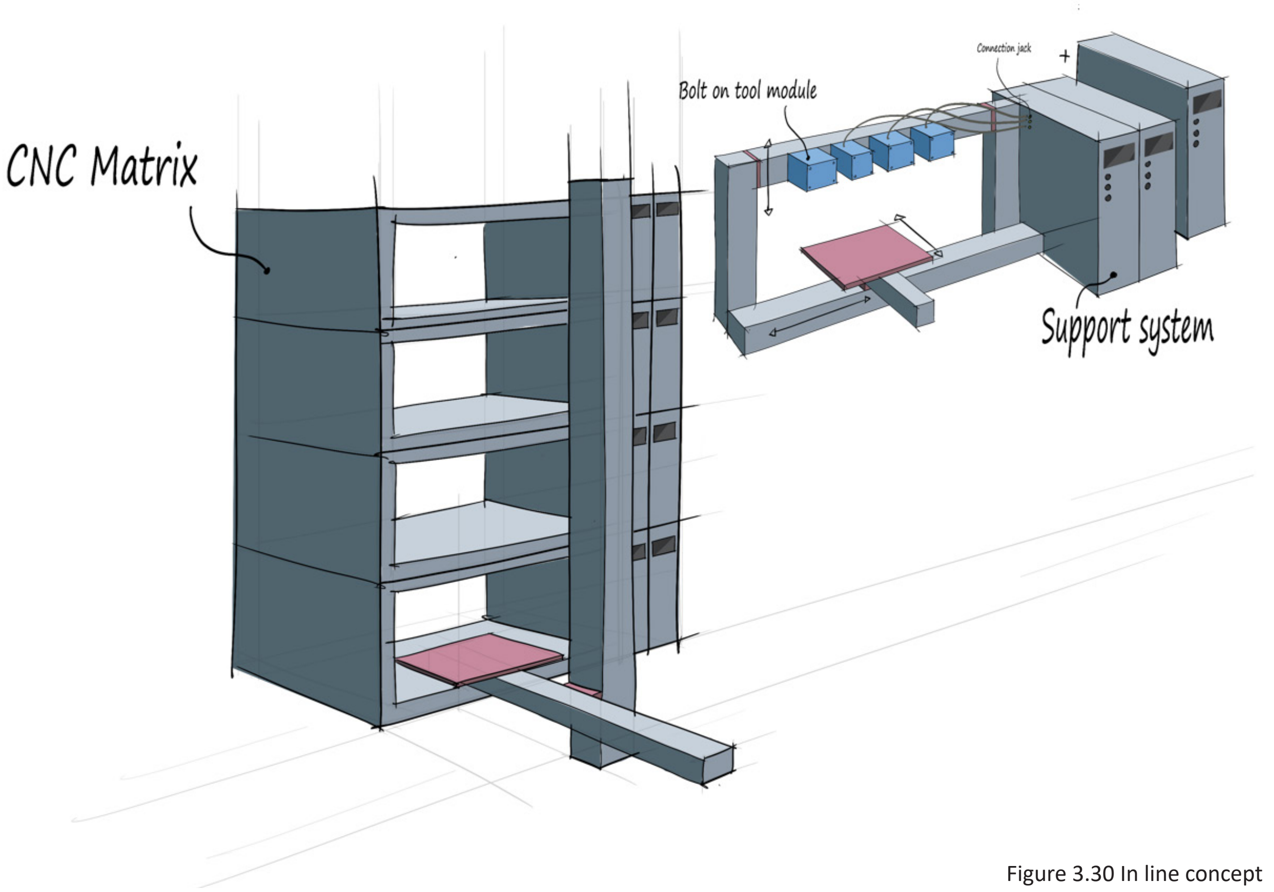


Figure 3.30 In line concept

Features:

- Manual reconfig toolset
- Fixed toolset
- Part moves

Pros:

- Fast manual reconfig
- Small scale efficiency
- Easy to add hardware modules
- Simultanous tool usage
- Simplicity

Cons:

- No large heavy products
- Toolset capacity

3.5.3 shared hybrid manufacturing

The shared hybrid system is an advanced system that automatically swaps tools and can share tools with other workstations. The system is versatile and flexible and toolset can quickly be changed to meet production demands. Tool modules have their own hardware and support material and maintenance to the toolset does not interrupt the workstation. The flexible hardware in the workstation and the specialised tool hardware give the system great flexibility. This system is viable when tools often need maintenance or replacement. However, the automation of changing tool modules and tools makes the system complex and expensive.

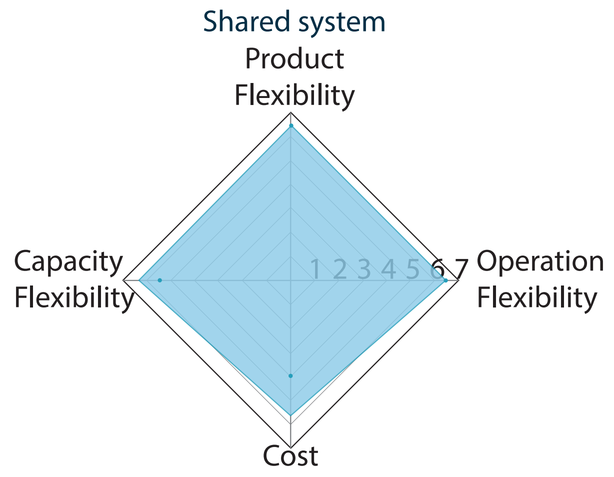


Figure 3.31 In line system characteristics

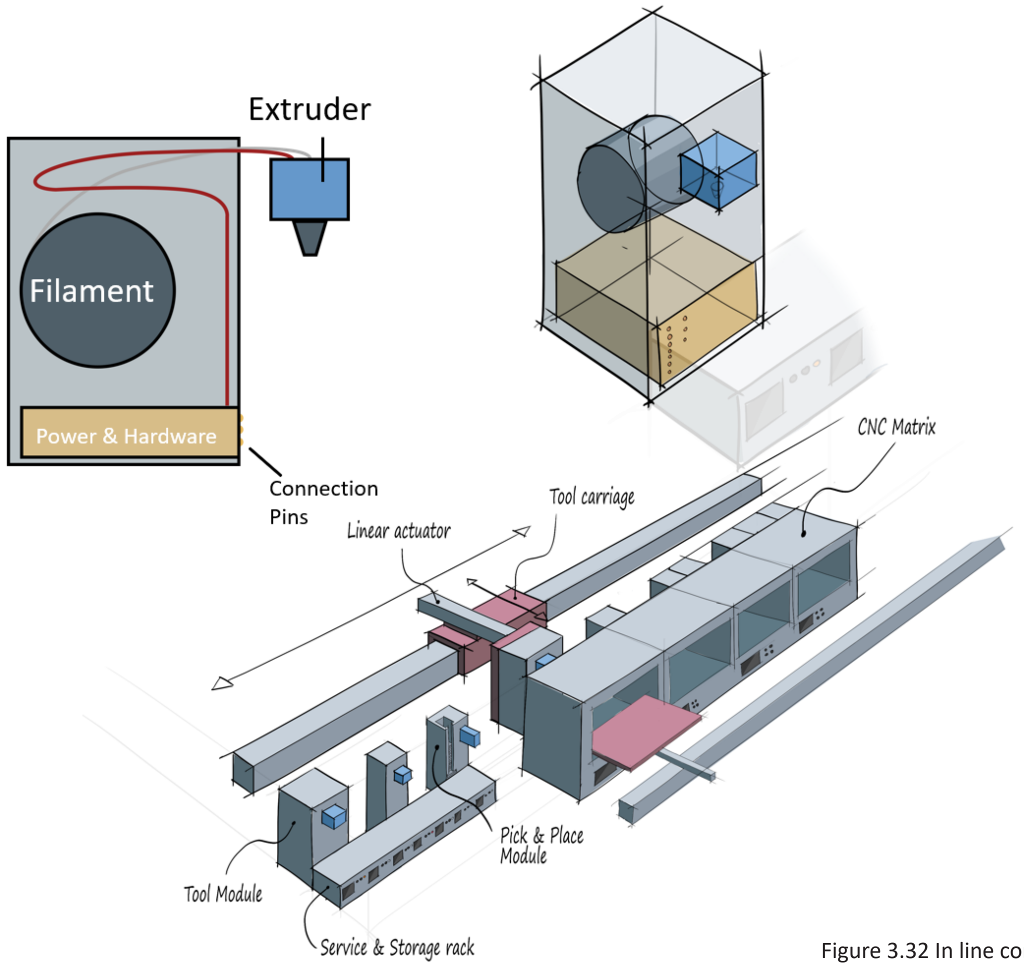


Figure 3.32 In line concept

Features:
- Tool sharing
- Automatic tool switching
- Uninterrupted tool maintenance
- Separate tool storage

Pros:
- Automated reconfiguration
- Flexible
- Large tooling capacity
- Scales well with more stations

Cons:
- Very expensive
- Very complex

3.4.4 Concept evaluation

The concepts were evaluated on the 4 atributes important to personalised product manufacturing: product flexibility, capacity flexibility, operation flexibility and cost (Chapter 2.3.6). The cost was estimated on the envisioned exemplary product manufacturing scenario. In-depth grading of the four attributes can be found in appendix 6.5.

A target system was created based on the hybrid fabrication scenario and the exemplary product scenario (Chapter 3.2 & 3.3). The fixed system is to be further developed after comparing the target system with the other concepts. The fixed system has enough flexibility for the first implementation of Hybrid fabrication into Transcended manufacturing without over complicating the system and increasing system costs. In the following stage the system will be further developed with the hybrid fabrication scenario and the exemplary product scenario in mind. Since early adoption of hybrid fabrication stations will be in product development and flexible manufacturing stations, the embodied workstation will use an integrated electronics toolset as an exemplary toolset.

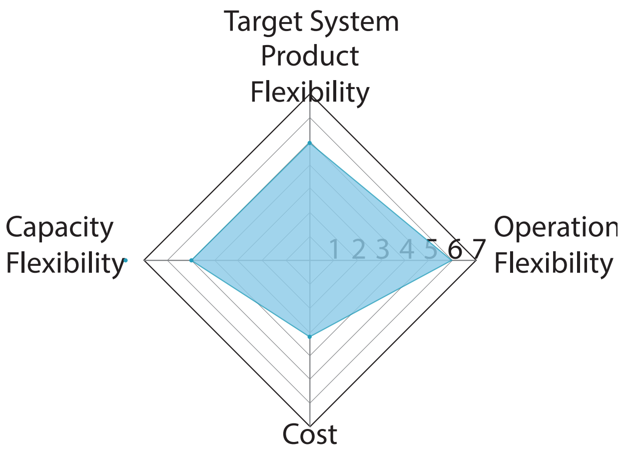


Figure 3.34 Target system characteristics

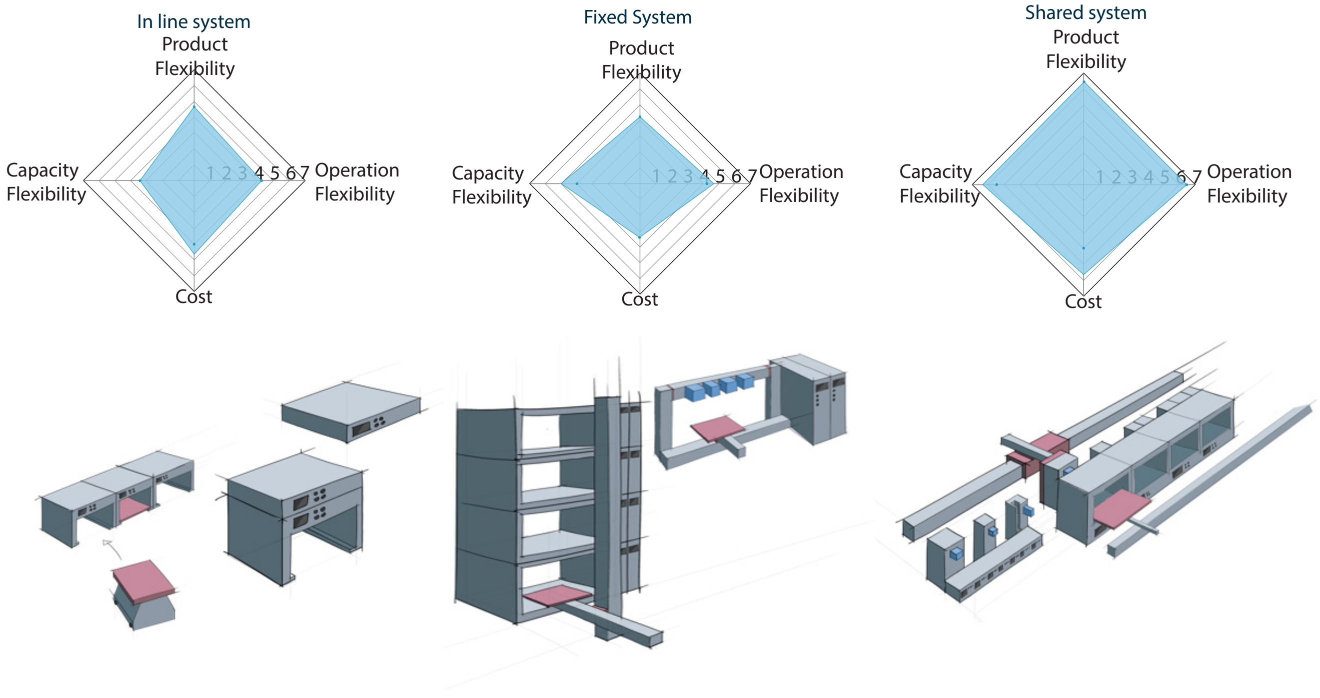


Figure 3.33 Concept evaluation

3.6 Summary

Vision
The ideation of a hybrid fabrication station was started using the following vision:
Enable transcended manufacturing with a hybrid fabrication system that supports the production process. Creating a workstation that efficiently supports multiple control, assembly, and fabrication techniques in a single workstation to facilitate the production of ultra-personalised products.

Transcended manufacturing
The analysis stage was used to create develop a future transcended manufacturing vision with a hybrid fabrication scenario, this scenario shows how hybrid fabrication can be used in transcended manufacturing. Hybrid fabrication is integrated in various parts of the Transcended manufacturing process: Product development, product manufacturing, and factory optimisation through matrix manufacturing.

Exemplary product
A concept for an ultra-personalised computer mouse is created, the mouse is personalised on shape, fit & performance. The production scenario uses hybrid manufacturing and the integration of electronics to fabricate the personalised parts. Hybrid manufacturing enables the creation of components that are personalised on all the personalisation areas.

A production scenario was created to shows how the exemplary product could is produced using digital manufacturing and hybrid fabrication workstations.

Workstation conceptualisation
Through exploration and ideation, three concept hybrid workstation are designed. The three concepts are evaluated on the four attributes important to personalised product manufacturing: product flexibility, capacity flexibility, operation flexibility and cost. The fixed hybrid workstation scored best. Therefore the fixed concept will be further developed.

3.7 Conclusion

Hybrid manufacturing can be used in multiple stages of the Transcended manufacturing process, more development of both Transcended manufacturing, ultra-personalised product design and hybrid fabrication is needed before hybrid can reach it’s full potential.

A simple, affordable, versatile and, flexible hybrid fabrication is most beneficial in the early stages of development. As the industry and hybrid fabrication mature, more complex fully automated and dedicated system can be developed.

For product development & research, the functionality of the workstation is reconfigured depending on current research and prototypes.

For product manufacturing, the workstation needs to be able to adapt to the addition of new products and changes in the product family.

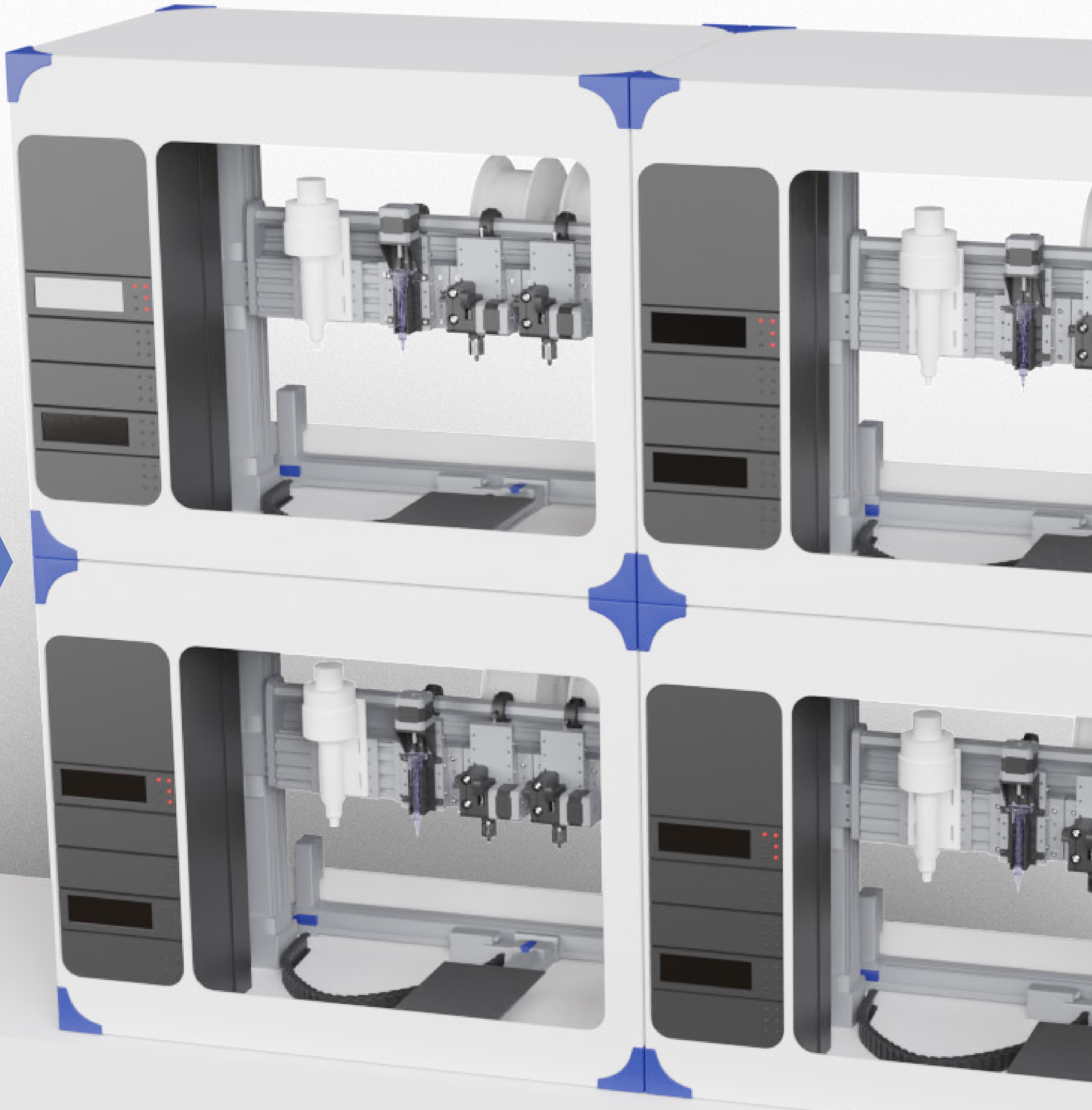
Development of the hybrid manufacturing concept will focus on the early adoption of hybrid manufacturing: personalised product development and flexible fabrication stations. The example toolset for the hybrid manufacturing station will be aimed at the tools required for the fabrication of the ultra-personalised computer mouse.

The fixed workstation concept will be further developed since it is best for the early stages of hybrid fabrication.

Embodiment

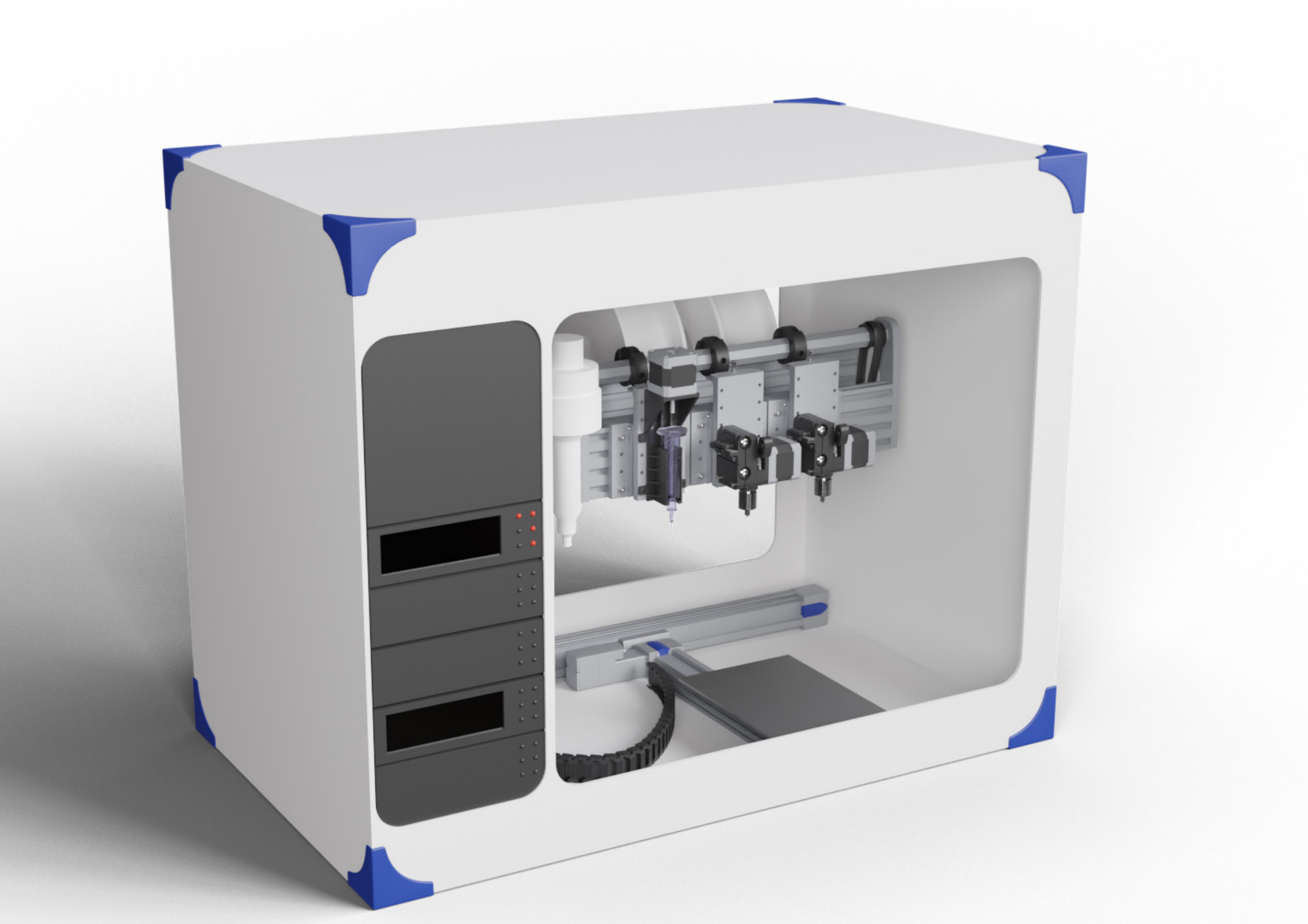
After choosing the fixed concept as a feasible design solution, the concept needs more development. Focusing on the early stages of hybrid fabrication and with the help of rapid iterative prototyping, the following workstation embodiment was created and validated. First the new design will be discussed after which the development of this design and validation through prototyping will be covered.

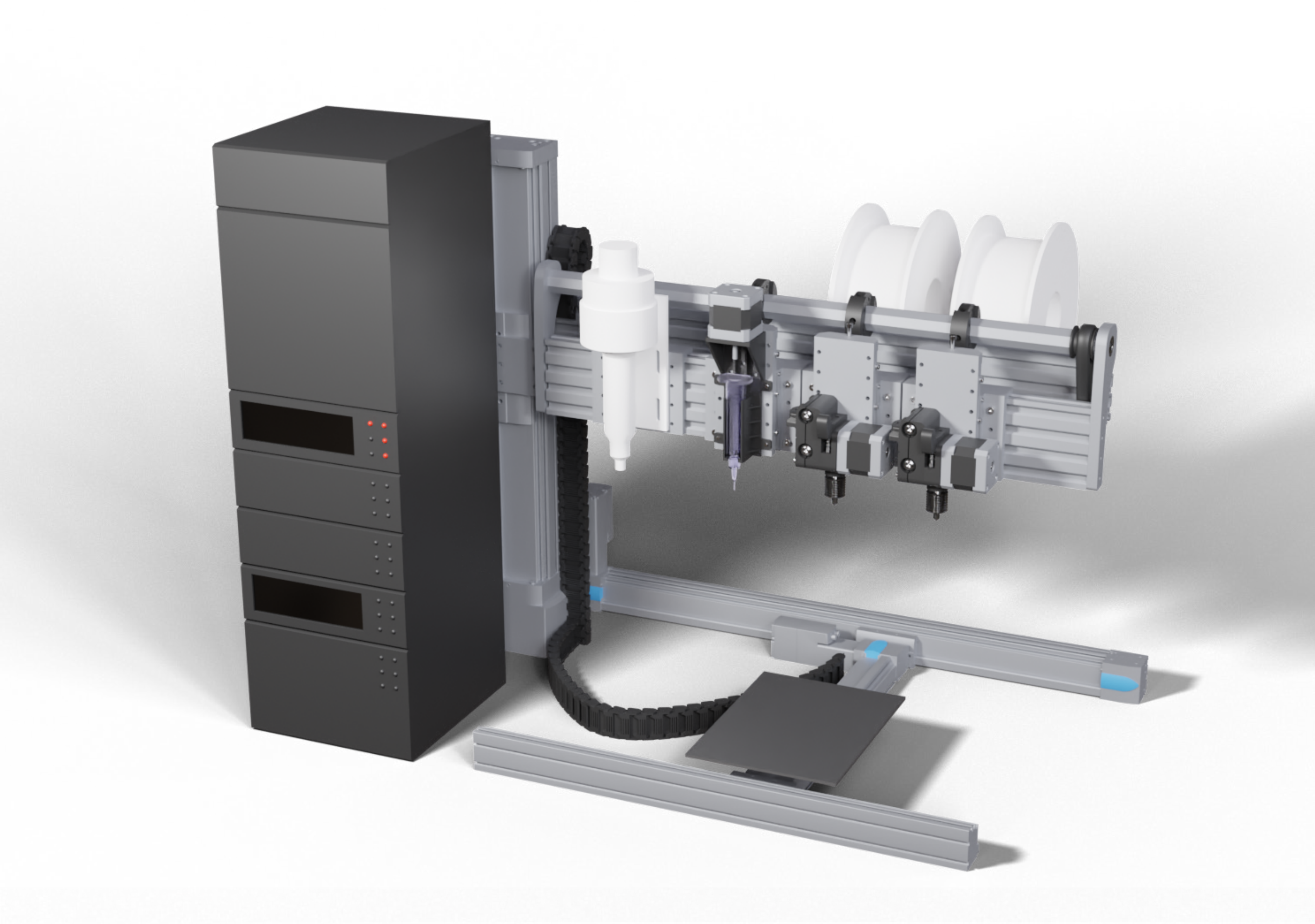
4



4.1 Workstation embodiment

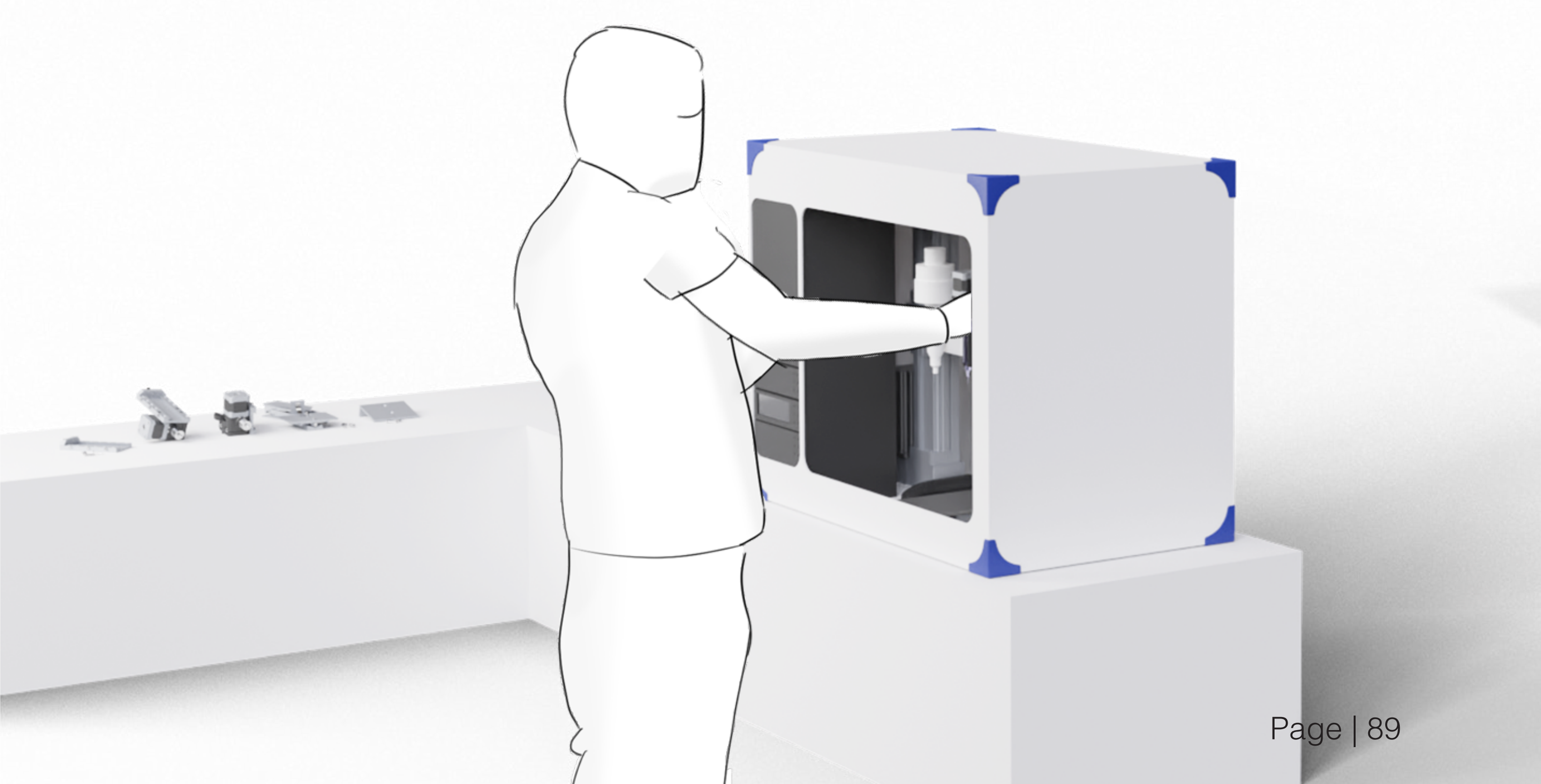
The hybrid fixed workstation for the early implementation of hybrid fabrication is further developed and embodied, the embodiment of the system focused on the usage and reconfigurability of the diverse toolset.





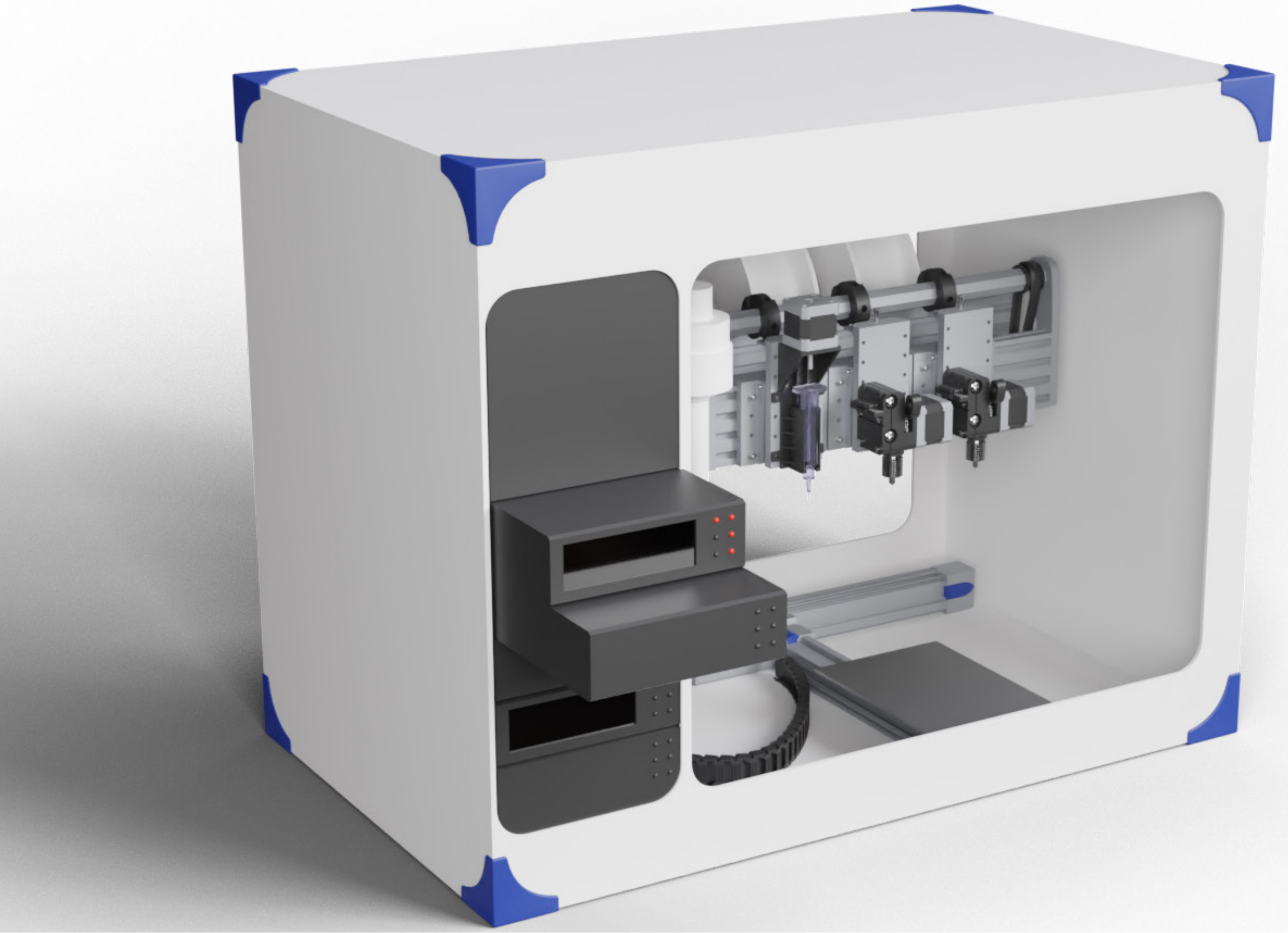
Features

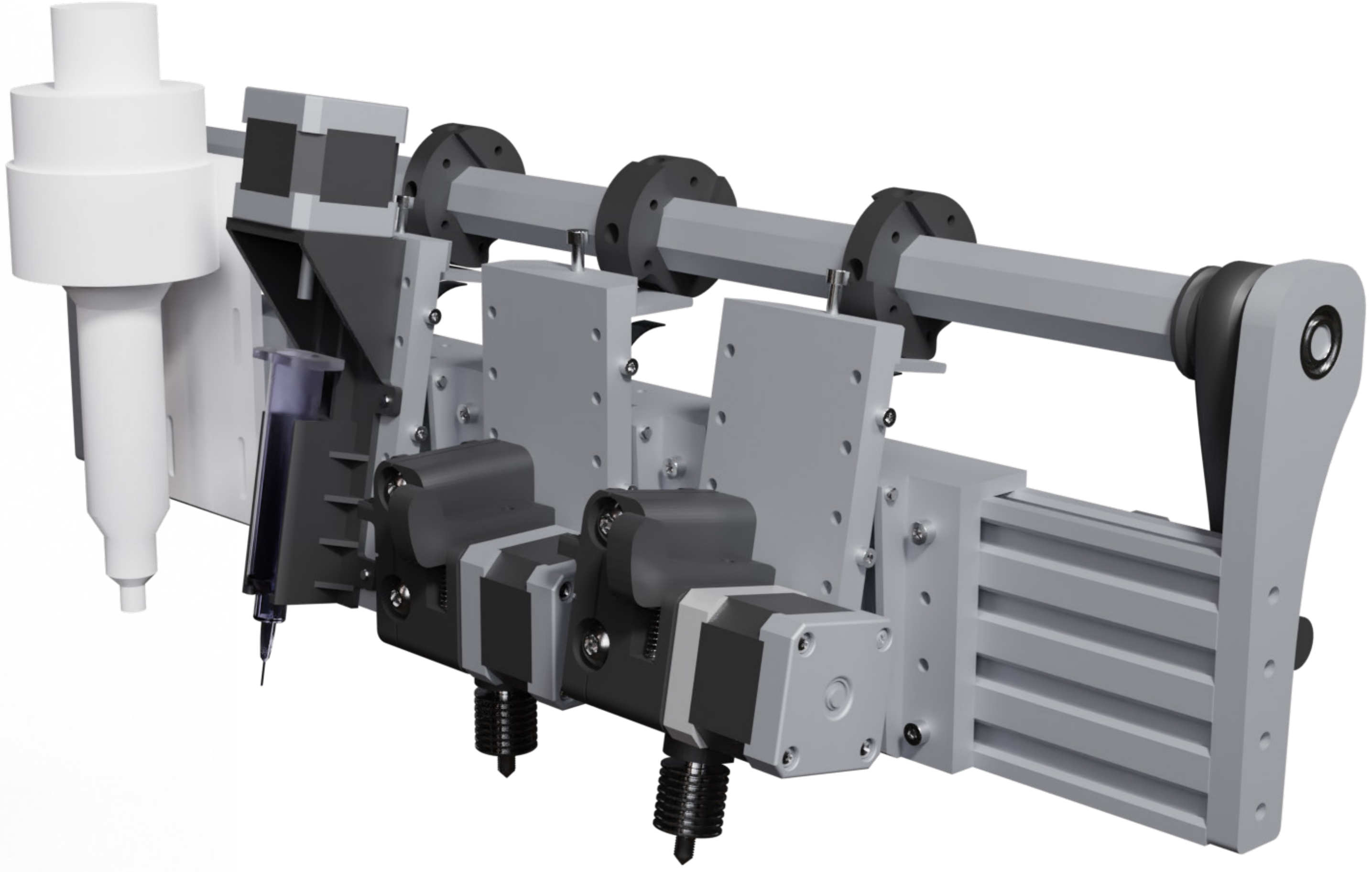
- The system can facilitate the usage of multiple tools and is able to facilitate rapid reconfiguration of the toolset. The system can use tools separate or simultaneous. The toolset can be reconfigured to accommodate the specific needs of multiple product families.
- The workstation has a tool rack that holds static and dynamic tool mounts. The tool mounts allow for accurate and repeatable manual tool (re)placement and reconfiguration of the available toolset.
- The system's hardware is expandable, allowing for a smooth installation of additional tools and adding functionality tailored to the product's production.
- The system can be used as a standalone unit in prototyping and research context. With the addition of an intralogistics system the system can be automated and used in manufacturing context.
- The system has a frame size of A1 and can produce small to medium-sized products.



4.1.2 Tool utilisation

Effectively using the available tools and reconfiguring the toolset is achieved with a flexible tool mount system that can support a variety of tools. The solution addresses several design challenges ensuring proper tool reconfigurability, tool rigidity, tool positioning, tool alignment, tool activation and preventing tool interference.





Tool rack

Having reconfigurable tools is advantageous but also creates challenges. While reconfiguring the toolset is a manual process, working with special mounting plates ensures quick placement and reconfiguration.

There are 2 types of mounting plates available, static and dynamic mounting plates. Rigid mounting plates have the advantage of being rigidly mounted to the system, but tools must be offset from the working plane. In contrast, dynamic mounting plates are not rigidly mounted but have a pivot that allows tools to move into an operating position.

Tools can be swapped fast and reliable, requiring minimal recalibration or alignment and dovetails on the toolholders make sliding tools in and out effortless. While set screws and a precision ball groove ensure tool alignment.

More intrusive adjustments to the toolset are also possible. Toolmounts are flexibly attached to the tool rack and can be rearranged. This allows the placement of many small tools or several larger tools on the tool rack.

Together with adjustable tool mounts and tool holders the tool reconfiguration is fast and flexible. Tools can be quickly swapped, but more drastic changes to the toolset are also possible. Toolholders provide fast reconfiguration, while the adjustable tool mounts offer extra flexibility. Changing tools with tool holders requires minimal calibration; however, adjusting the tool mounts does require recalibration and realignment.

Tool support

Tools require drivers/hardware and can also require extra support materials. The support materials and hardware are modular and reconfigurable just like the toolset.

The system’s tool support is expandable and reconfigurable, allowing for a smooth installation of additional tools and functionality. Having expandable hardware allows the system to achieve flexibility and modularity while managing redundancy and cost.

Support materials

In the back of the machine, there is room for support materials and extra hardware. With the use of DIN-rails, support materials can be installed and reconfigured with ease.

Support Hardware

The system has allocated hardware racks in which support hardware can be slotted. Aside from the standard electronics, tool-specific modules can be installed to expand the system’s capabilities. This can include hardware to support extra sensors and measuring equipment, hardware to drive incompatible and new tools or additional hardware to increase the number of tool slots available.

The cables and connectors are standardised, managing compatibility with the tools and keeping the rerouting of cables and wires to a minimum, making reconfiguration convenient.

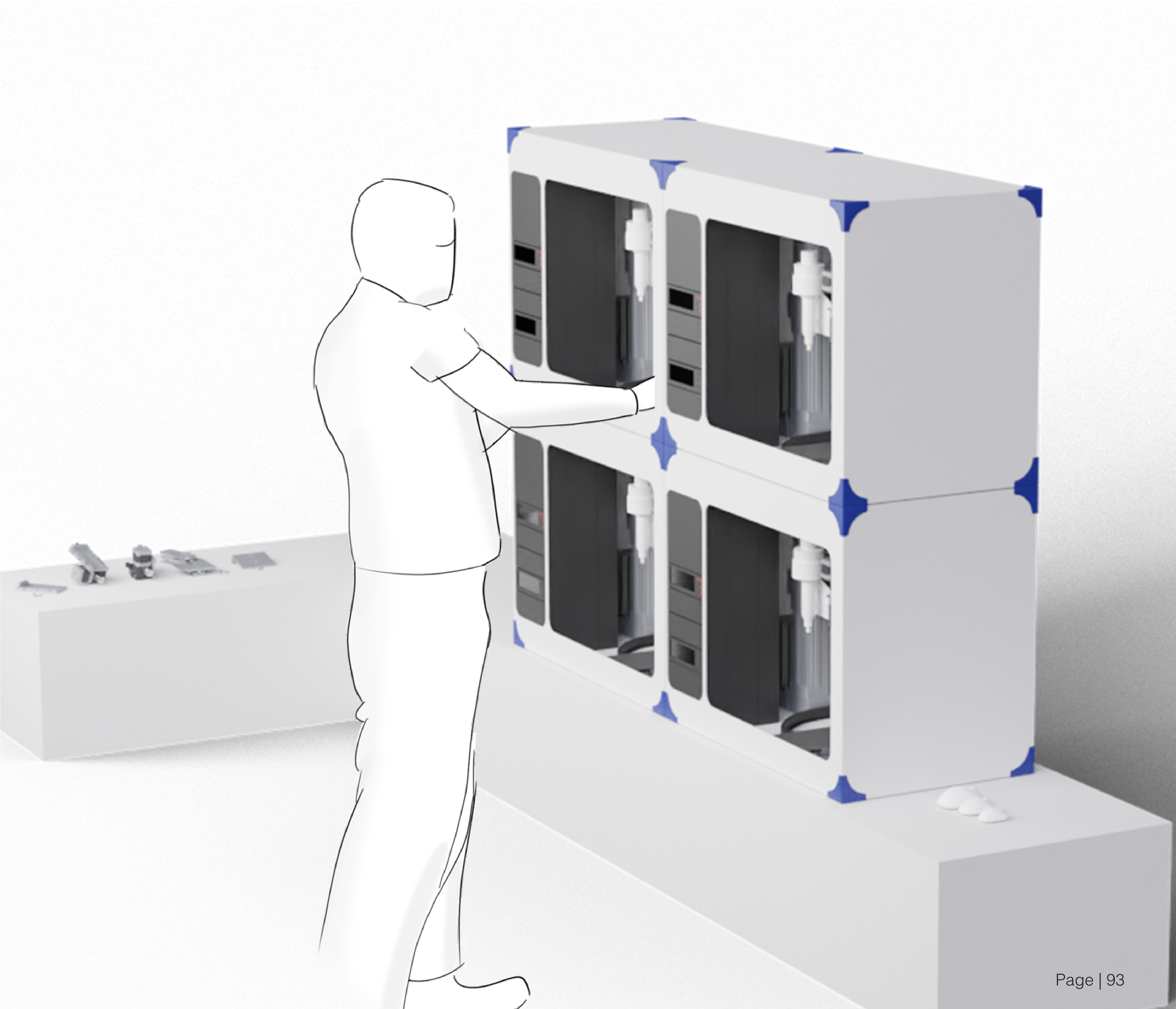
4.1.2 Fabrication

Fabrication
With multiple tools in the toolset the workstation can use and combine these tools to create new fabrication and manufacturing possibilities.
The system can use the toolset for hybrid fabrication, making otherwise difficult to produce parts easier. It can combine its tools to increase productivity by either swapping efficiently between tools or having multiple tools copying and working in tandem. And in a more traditional way, the workstation can provide multiple fabrication possibilities to the factory or workspace as a multifunctional reconfigurable machine.

Part handling & intralogistics
In smaller fabrication environments like R&D the workstation is manually operated while providing a wide range of capabilities. The system focuses on combining different fabrications techniques and requires external automation to be used in a moure automated factory setting. With the use of carrier pallets, the system can be integrated with the factory's intralogistics.

4.1.3 System design

Formfactor
While the featured processes are product independent, the formfactor and size of the system are influenced by the product. The part size dictates the required build volume which determines the form-factor of the system. Machines follow an industrial standard , to provide scalability and modularity to the factory. The exemplary product requires a machine size A1, with outer dimensions of 841mm x 505mm x 667mm. Accommodating up to 4 tools and a part build volume of 150mm x 200mm x 150mm.



4.2.1 Development System Design

The hybrid fabrication station is based on CNC controlled XYZ cartesian systems. However there are many possible configurations to achieve this motion. System requirements dictate what kind of configuration is used to actuate the tools. As mentioned in chapter 2.5.2 the fabrication process influences the system requirements. The target production process is defined based on the manufacturing requirements of the exemplary product.

System configuration

To quickly test and define the configuration rapid prototyping with cardboard was used. The cardboard mockup helped to rapidly test different configurations based on the linear actuators from Festo.

The format of the system will follow the industrial standard defined by Ben to ensure that the fabrication station can be incorporated in the transcended manufacturing process. All required components are able to fit in a system that conforms to the A1 format, making the outer dimension of the system 841mm x 505mm x 667mm. Accommodating atleast 4 tools and a part build volume of 150mm x 200mm x 150mm.

Evaluating the possible configurations results in a configuration shown in Figure 4.1This configuration maximises the available space in the system. It is to be noted that the system uses a single actuator for the Z-axis with a free-floavting toolrack. This configuration limits the possible tools used by the system due to tool weight and rigidity limitations. An increased build volume was chosen instead of extra rigidity. Referring to chapter 2.4.2, part flexibility was chosen over operational flexibility. This demonstrates how the process and the product influence the system design and shows that trade-offs need to be made when designing flexible manufacturing systems. The full exploration and evaluation can be seen in Appendix 6.6.

Figure 4.1 Configuration prototyping

Formfactor

Buildvolume, machine size and toolset are interdependent factors that determine the possibilities and size of the system. The correlation between the these factors can be formulated illustrated with the formula:

$Ms = (Buildvolume + Ntools \times (Toolsize + c))/cc$

The formula roughly shows the correlation and trade off between Buildvolume, tools and machine size.

Configuration

As mentioned earlier, the product influences the size of the system but this also influences the system design. In future scenaries multiple machines following the same system but with different configurations can be used in the same factory. In a factory setting it is important to manage floor realestate and the systems are sized according to the parts they produce. When the toolset is larger and heavier than the product/build volume systems it is most beneficial to move the part like in the proposed system but without the cantilever configuration. In this case the tools are stationary and the system moves the product. When the product/build volume is larger than the toolset, it is more efficient to move the toolset instead of the product. The latter requires a minor redesign of the tool rack to accommodate for a moving toolset. Using the industrial standard, workstations in the factory are modular and efficient and can work together.

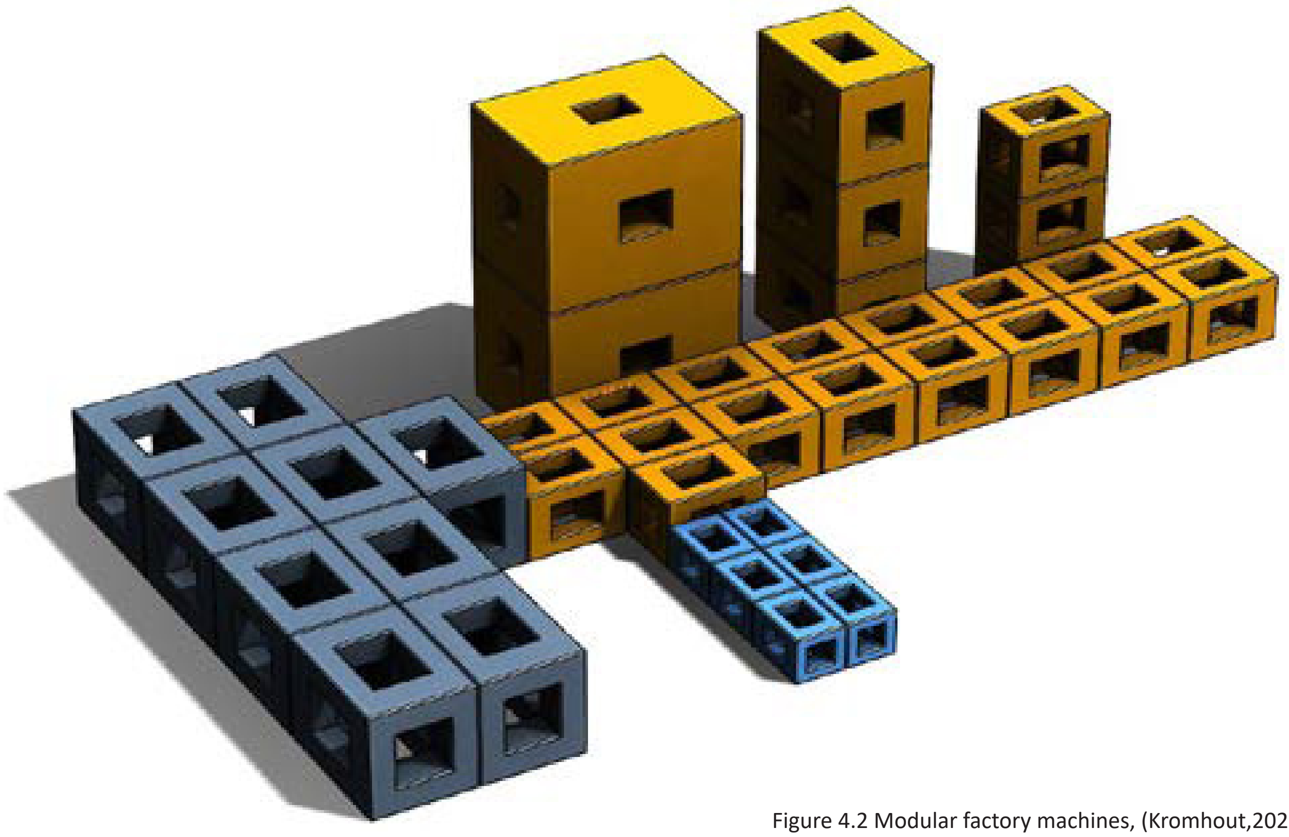


Figure 4.2 Modular factory machines, (Kromhout,2020)

4.2.2 Tool Development

The previous chapters covered the overall embodied system. The system can be devided in several parts the tool utilisation. This chapter covers the embodiment process and the design decisions corresponding to the tool utilisation, including the ideation and design of the tool rack and mounts, creating a flexible solution that enables multiple tools while also providing reconfigurability.

4.2.2.1 Problem definition

Tool utilisation is how the system utilises the tool rack and support system to provide a flexible toolset to use. Designing a flexible system comes with multiple challenges and components that must be considered while designing the tool rack. The goal of the tool rack is to enable the system to hold and use various tools the tools also have different requiremts in tollerenaces, offset, size and mounting rigidity see figure Figure 4.3. In order to use various tools the system needs to be able to swap out its tools and also needs to be able to offer full reconfiguration of the toolset. The swapping and reconfiguring of tools should require minimal maintenance and time to perform. The toolset also needs to be flexible and reconfigurable while managing cost and complexity. A flexible and reconfigurable system has its challenges in regard to repeatable and accurate alignment and adjustment since a quick swap of tools should not require lots of recallibartion. Furthermore reconfiguration of the toolset the system should also require minimal calibration and realignment.

4.2.2.2 Ideation

To solve the challenge, the toolrack is separated in its main components which can be ideated individually. Import parts of the toolrack are, the rack, the mount and the tool holder. The toolrack holds the tool assembly, the mount holds the tool & tool holders, the tool holder hold the tool. After the separate ideations, the solutions can be combined in tool rack design with a reconfigurable toolset.

For a flexible and reconfigurable tool rack the following challenges are identified: tool placement, mounting style, Y offset, mount alignment, install access, alignment adjustments.

The ideation process is started by creating individual Howtos for each component, after which a morphological chart is used to combine the solutions in a new tool mount designs for the toolrack.

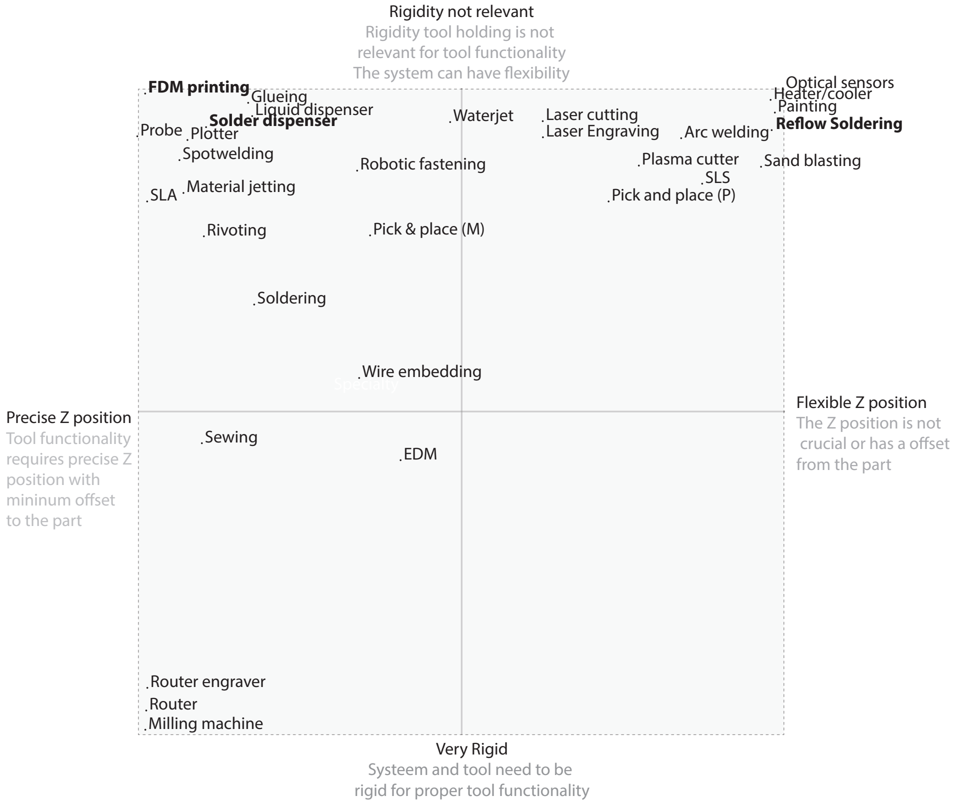


Figure 4.3 Z-rigidy chart

Tool placement

Tool placement covers the positioning of tools on the tool rack.

The tool placement needs to provide a flexible placement of tools, allowing for tools of different sizes on the tool rack.

The biggest challenge is in keeping recalibration and realignment minimal while providing high flexibility for various toolsets.

Tool mounting

Tool mounting is the way the tools attach to the tool rack. The way tools are placed on the toolrack influences the flexibility and reconfigurability of the machine. The way tools are placed on the toolrack influences the flexibility of tools that can be installed and also influences the ease of reconfigiurability in the means that alignment and recalibration is required.

Active Z-offset

A disadvantage of having multiple tools on the same rack means that the tools could interfere with the workpiece if the tools don't have the the exact same distance from the XY plane. Therefore a way is needed to keep the tools out of the working area. Moving the tools out of the working plane when not in use solves the problem of interference.

Alignment

For a CNC machine to function the machine need to be accurate. In order to keep a machine accurate the machine tools need to be accurately installed. Having a flexible toolset means that when tools are swapped or reconfigured, there needs to be a way to ensure all tools are aligned properly. However tool alignment and recalibration time should be kept to a minimum.

Mounting access

Mounting access should also be accounted for while designing the tool utilisation. Mounting access is how the worker accesses the machine to mount and reconfigure the toolset. Only needing to access a single side of the machine to mount tools is most favourable.

Placement / position The tool position on the tool rack.	Fixed/(adjustable) Fixed tool mounts which can be adjusted • Little calibration required • High repeatability • Less flexibility in tool placement	Modular Modular placement of tools following a layout. • Little calibration required • High repeatability • Flexible in tool placement	Free Freely placed tools on the tool rack • Every tool change requires new calibration • Low repeatability • Very flexible tool placement
Mount What kind of system is used to mount & swap tools	Tool holder Tool holders have brackets which mate with brackets on the tool rack • High repeatability • Increased complexity	Direct mount Tools are directly mounted on the tool rack • Low complexity	Clamp mount Tool holders have clamps that clamp onto the tool rack • Medium complexity
Z active offset How to offset the inactive tools and active tools in x-y plane	Actuate Z Linear actuate the tool Z position • Decrease Z-build height • High complexity	Rotate Rotate the tool out of position • High complexity	Tool spacing Space between tools is larger than the print bed • Low complexity • Increased machine size
Alignment How to adjust tool alignment	Adjustable mount Adjust at the mount • Requires accuracte mounting • Can be adjusted before installment	Adjustable holder Adjust at the tool holder • Can be done before tool installment	Adjustable rack placement Adjust the rack placement • Has to be adjusted at the machine
Mounting Access Where does the operator need to access the machine in order to install tools	Front Easily accessible	Back Harder to access	Front & back Needs to be accessed from multiple sides

Figure 4.4 Morphological chart

4.2.2.3 Tool holders prototyping

Using the previous mentioned morphological chart, multiple solutions were created. Since tools have different requirements it was decided with two mounting designs an rigid static design and a less rigid dynamic design, one tool mount for rigid tools and a tool dynamic mount for tools that need to be actuated in the Z-direction. The combination of both keep the possible tools large while reducing cost and complexity of the system. It was chosen to go with a modular bracket based system to increase the repeatability and accuracy for changes to the toolset.

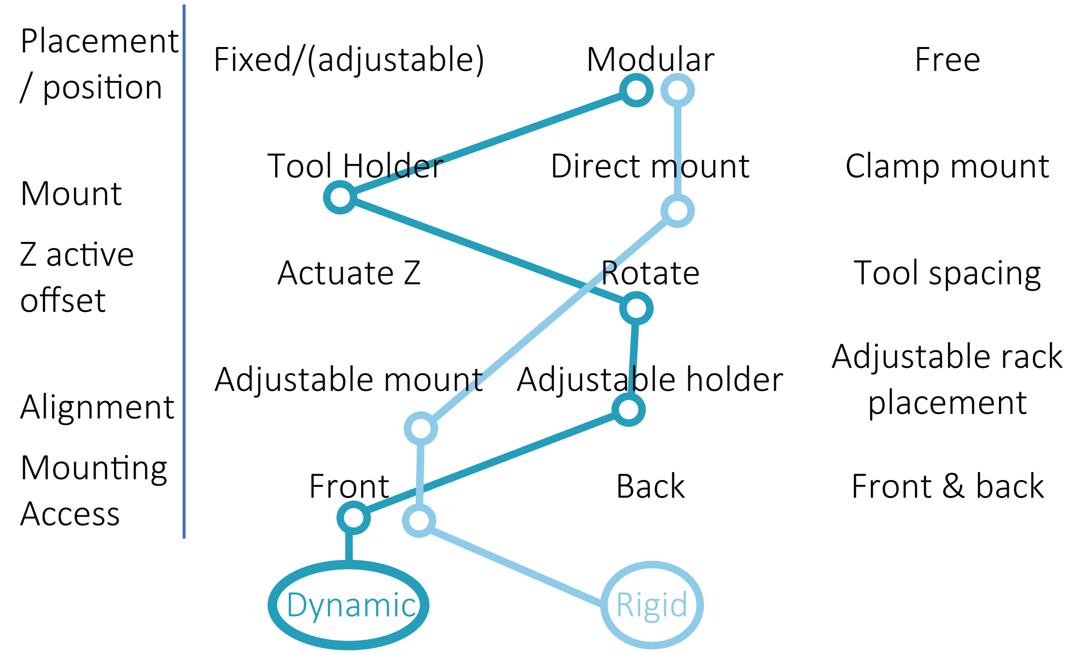


Figure 4.5 Morphological chart choices

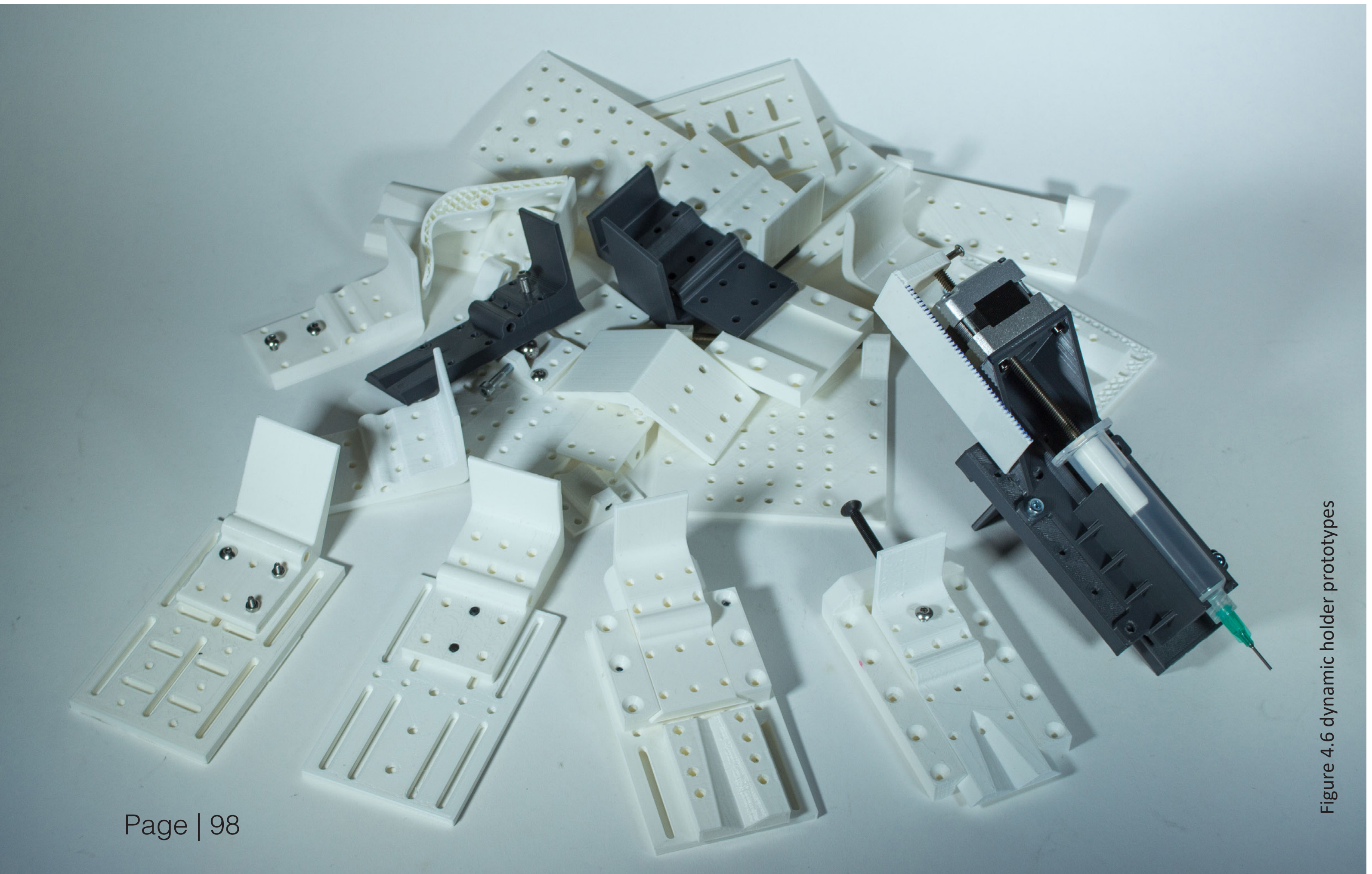


Figure 4.6 dynamic holder prototypes

Dynamic tool mount
Through rapid prototyping the toolmounts were designed created and improved. Most time was spend on the design of the dynamic tool holder since this was the most complex part of the machine. The modular design was chosen since this provides plenty of flexibility in tool placement while also keeping the repeatability high and complexity low. Z-offset rotation is most beneficial because it does not limit the Z-height, enables tool drip pouches, and makes use of the empty space at the front of the machine. To fine-adjust tool alignment the tools can be adjusted at the holder to reduce tool change time and increase repeatability.

Static tool mount
The static tools are directly mounted to the tool mount mounting the tools directly to the tool mounts ensure maximum rigidity while keeping the complexity of the tool mount low. However, it does come with its implications since the static mounted tools cannot prevent tool interference. The rigid mount is suited for tools that are offset from the work surface, or extra care is required in the tool configuration by alternating static in dynamic tools.

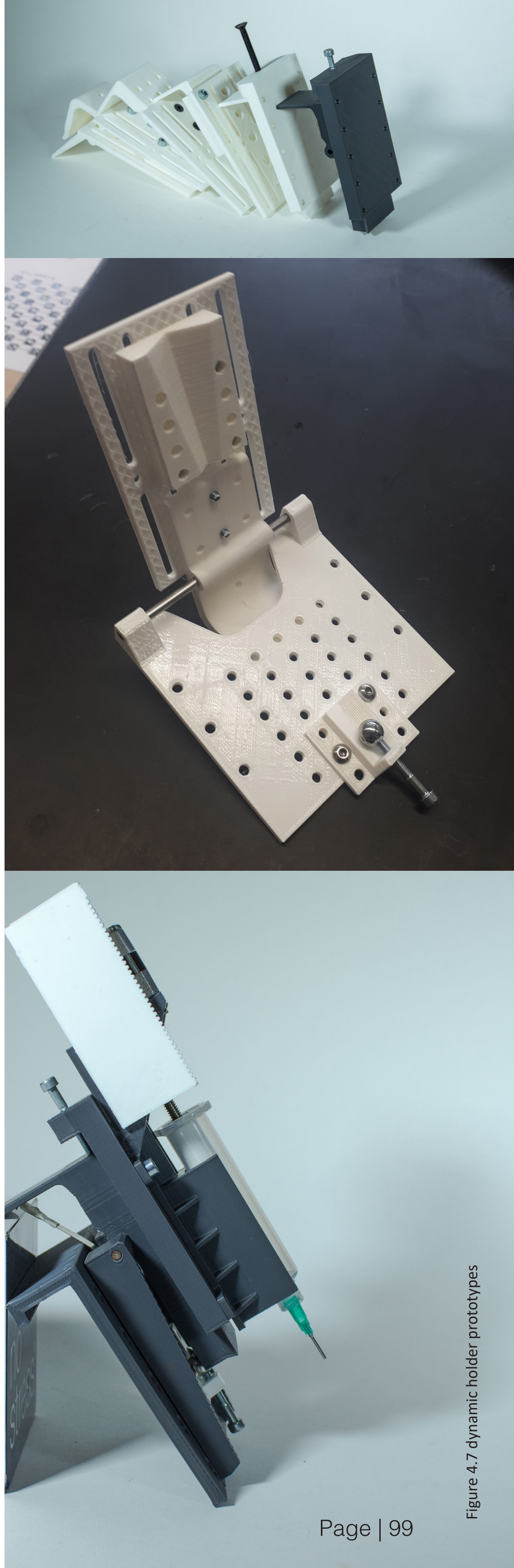


Figure 4.7 dynamic holder prototypes

4.2.2.4 Tool Actuation

The following design followed from the rapid prototyping. Each iteration got improved and tackled new challenges until the last prototype followed. In this prototype a cam is turned which actuates the rotation of the toolholder. This results in a tool that is rotated out of position until the cam is in the right position.

Static tool mount
The static toolmounts are directly mounted onto the tool rack using bolts and t-nut. The T-nuts provide great flexibility of the tool mount placement and tool mounts can be freely placed onto the toolrack. Mount alignment is simplified with the use of guide pins, which help align the tool mounts in set intervals. Either Static tools or Dynamic tool mounts can be attached to the Static tool mount, two guide holes help to attach the parts in the right place.

Dynamic tool mount
As mentioned, dynamic tool mounts are directly attached to the static tool mounts, making it easy to swap between static or dynamic tools. Alternating between different dynamic tools is also made effortless with the dove tail tool holder that slides onto the dynamic tool mount.

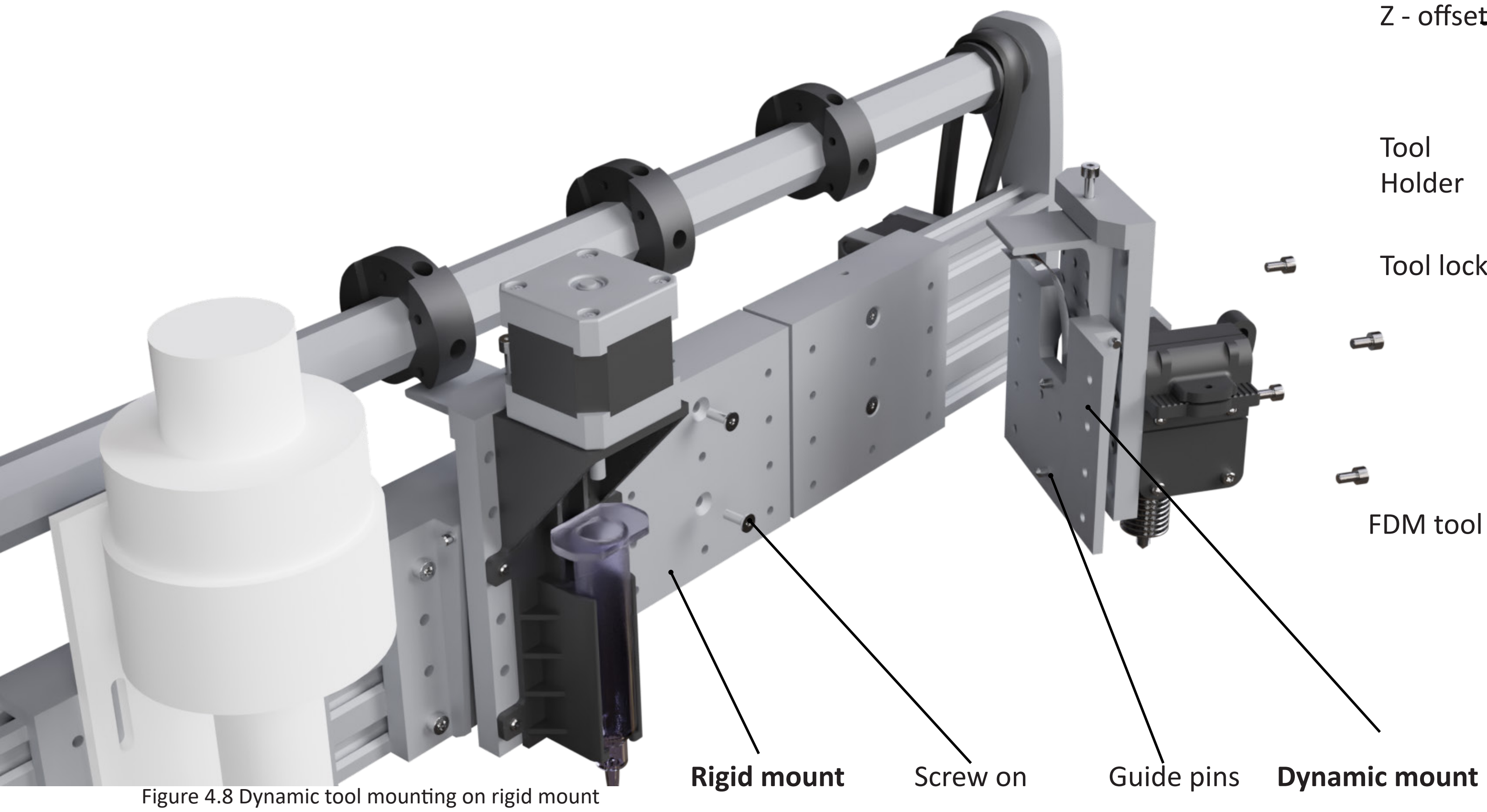
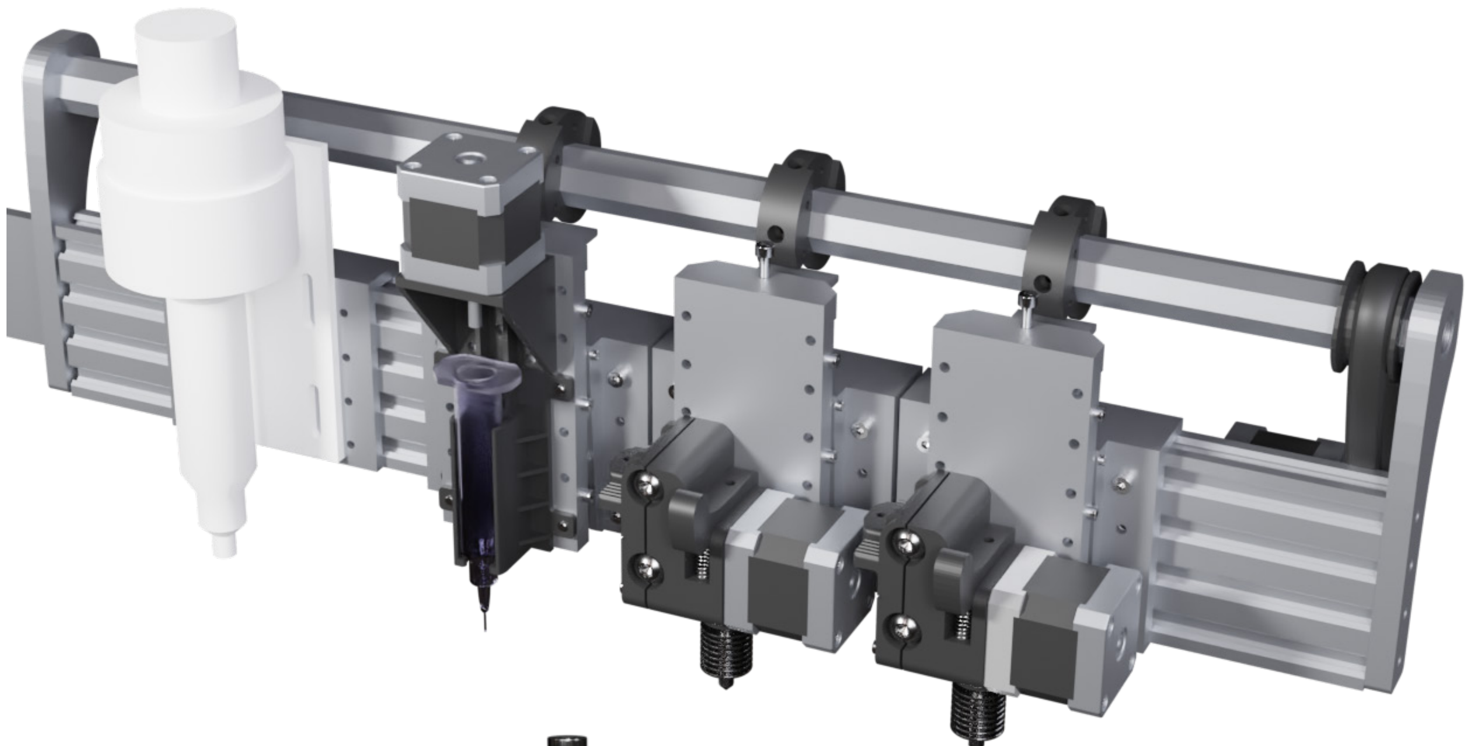


Figure 4.8 Dynamic tool mounting on rigid mount

Figure 4.9 Tool rack



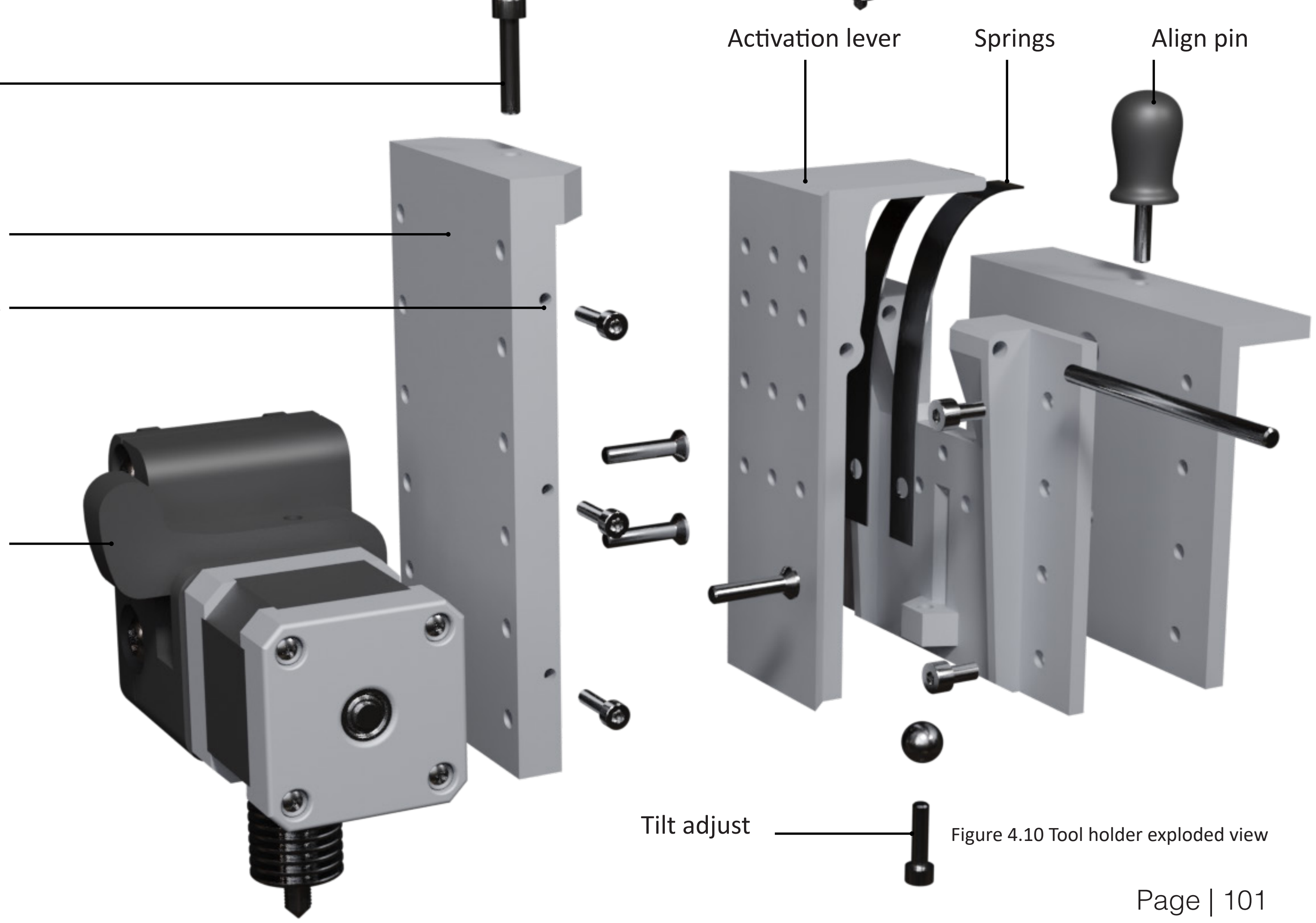


Figure 4.10 Tool holder exploded view

Alignment
When the tool is in the active position the tool is resting in a V groove matching with an adjustable ballbearing. Together with a spring this ensure the tool is accurately positioned creating a repeatable and accurate motion. The tool holder can slide in and out to get the a precise and adjustable Z-offset from the XY-plane, the offset can be set with the machine screw at the top.

Tool holder
Tools are installed on the tool holder, the toolholder has a dovetail groove that keeps tools slotted, the toolholder can be fastened to the tool mount by tightening the screw on the side. Tool can be installed on the tool holder with slotted bolts, either directly attached to the tool or by using bolts and nuts. Having the bolts inserted from the back ensures that tools can always be attached to the holder.

Cam actuation
A motor drives the cam axel that actuate the dynamic tools when rotated. The cams are located on an octagonal axel, with the octagonal rod the cams can be configured in 8 different positions. The shape octagonal shape ensures easy alignment while providing configuration flexibility. The cams are built out of two parts and slotted onto the axel. The cams are shaped in such a way that when the tool is activated, the cam does not touch the tool lever letting the tool mounts align the tools.(Figure 3.13)

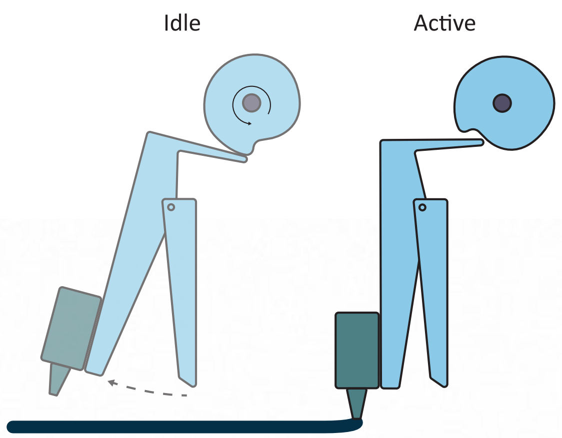
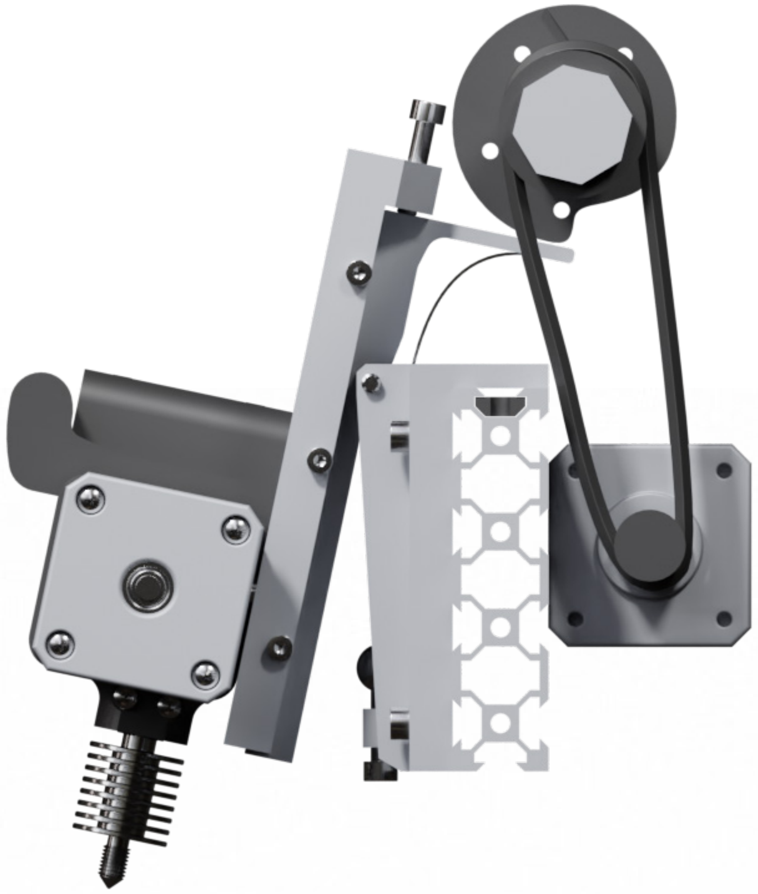


Figure 4.13 Dynamic tool cam actuation



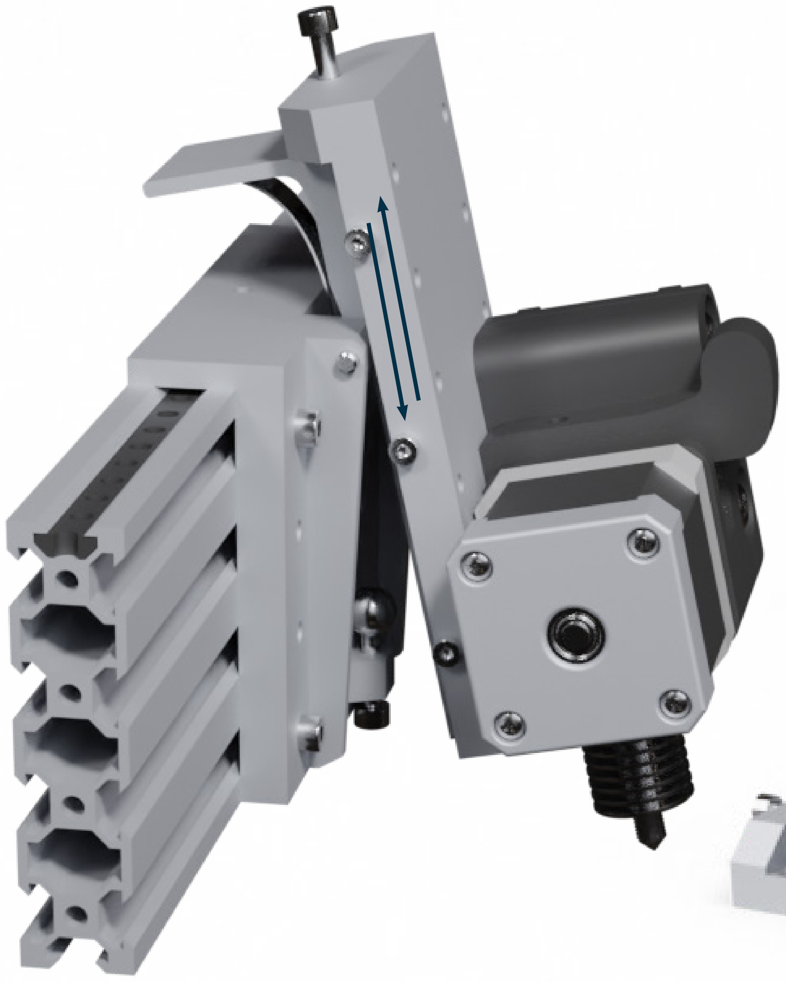


Figure 4.11 Offset adjustmen

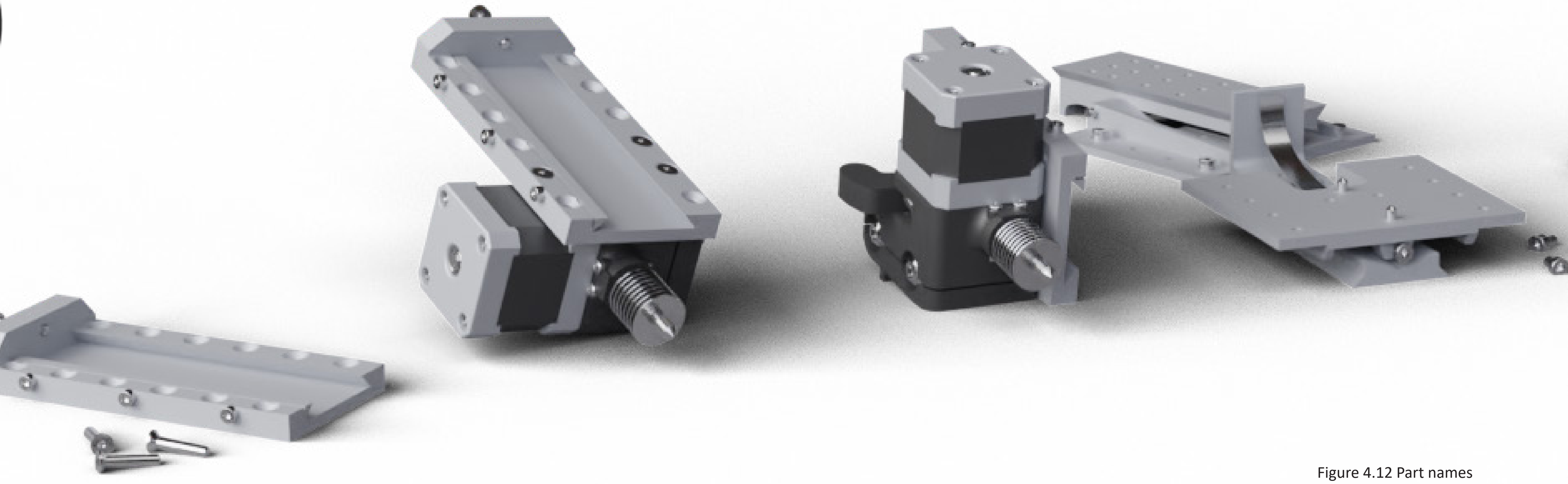


Figure 4.12 Part names

4.3 Fabrication

The system is a versatile platform for hybrid fabrication aimed at the early adoption of hybrid manufacturing. The toolset is manually reconfigurable to test and prototype the combination of digital fabrication processes. The exemplary toolset is the integrated electronics toolset that combines FDM printing with electronics soldering. With this system, further development of the integrated electronics research is possible. The other tools that the hybrid fabrication supports is tools in the add-on category and most of the tools from in the base class as defined in chapter 2.6.2. The full list of supported tools can be found in Appendix 6.11. Besides developing new hybrid fabrication processes the station can also combine the supported tools as a versatile manufacturing station and test and establish versatile fabrication and the early development of matrix manufacturing.

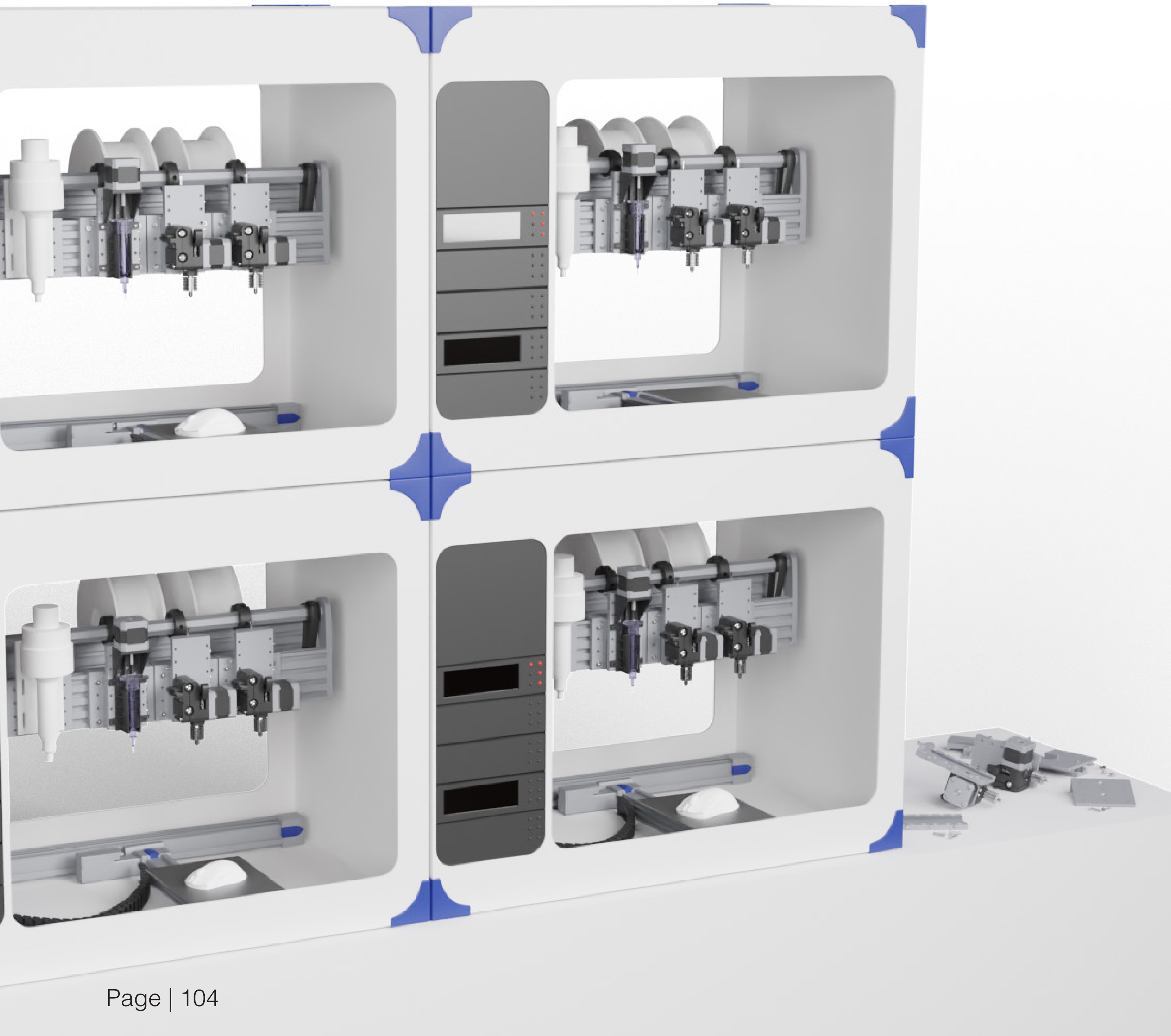


Figure 4.14 Printed Integrated electronics with pick & place

Figure 4.17 Ultra sonic wire embedding, soldering, pick & place

Figure 4.15 Simultanous 3D printing

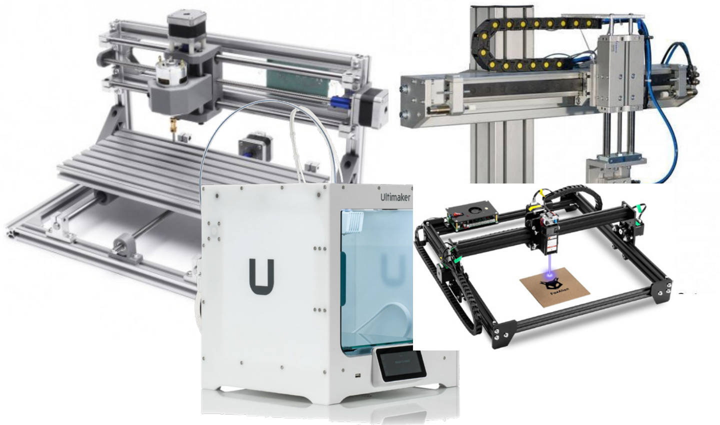


Figure 4.18 Versatile fabrication system

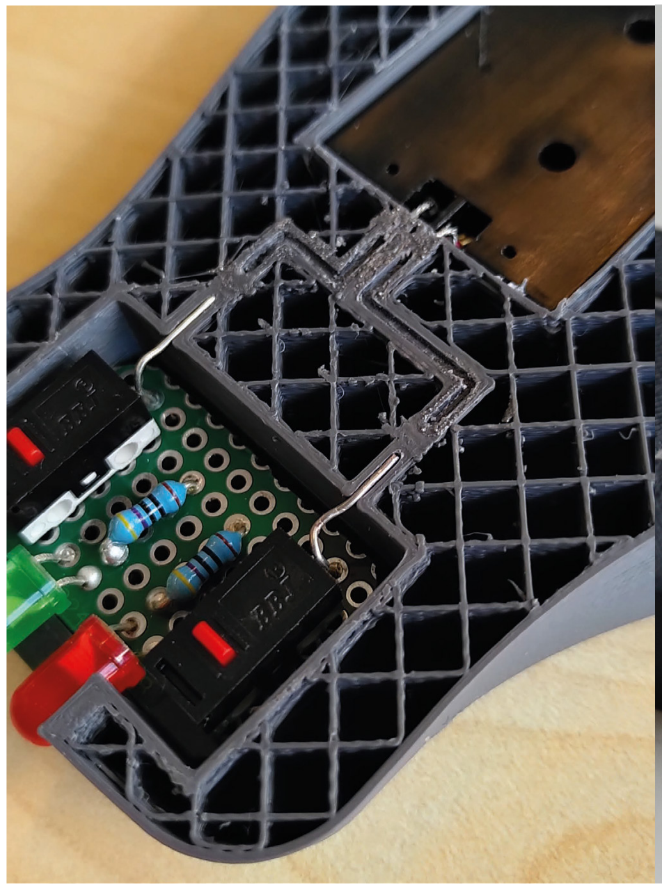


Figure 4.16 Integrated elecetronics using fdm and solder paste extrusion by Eekhout, K.

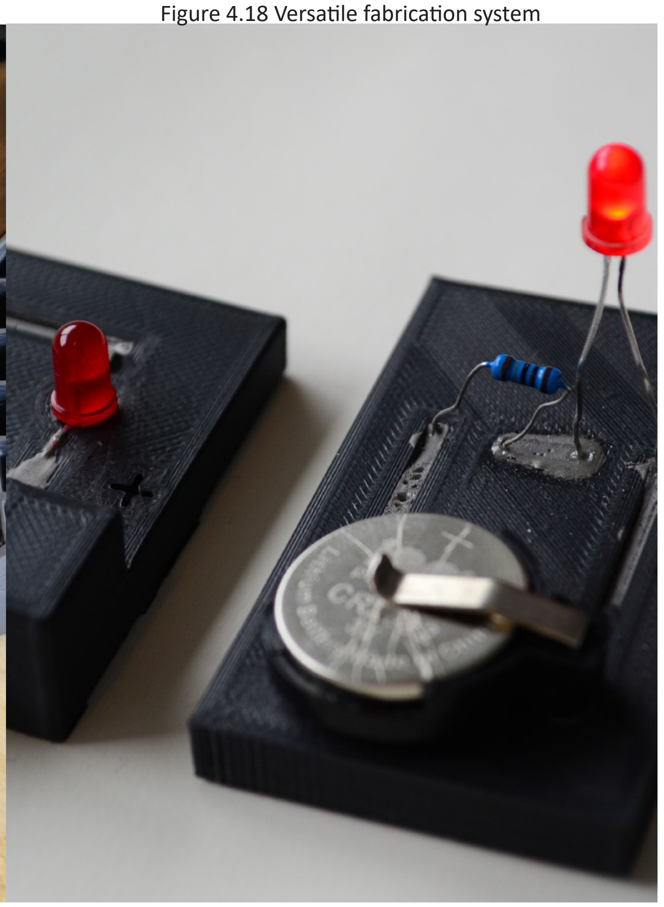


Figure 4.19 Integrated electronics using fdm and solder paste extrusion by Bon, M.

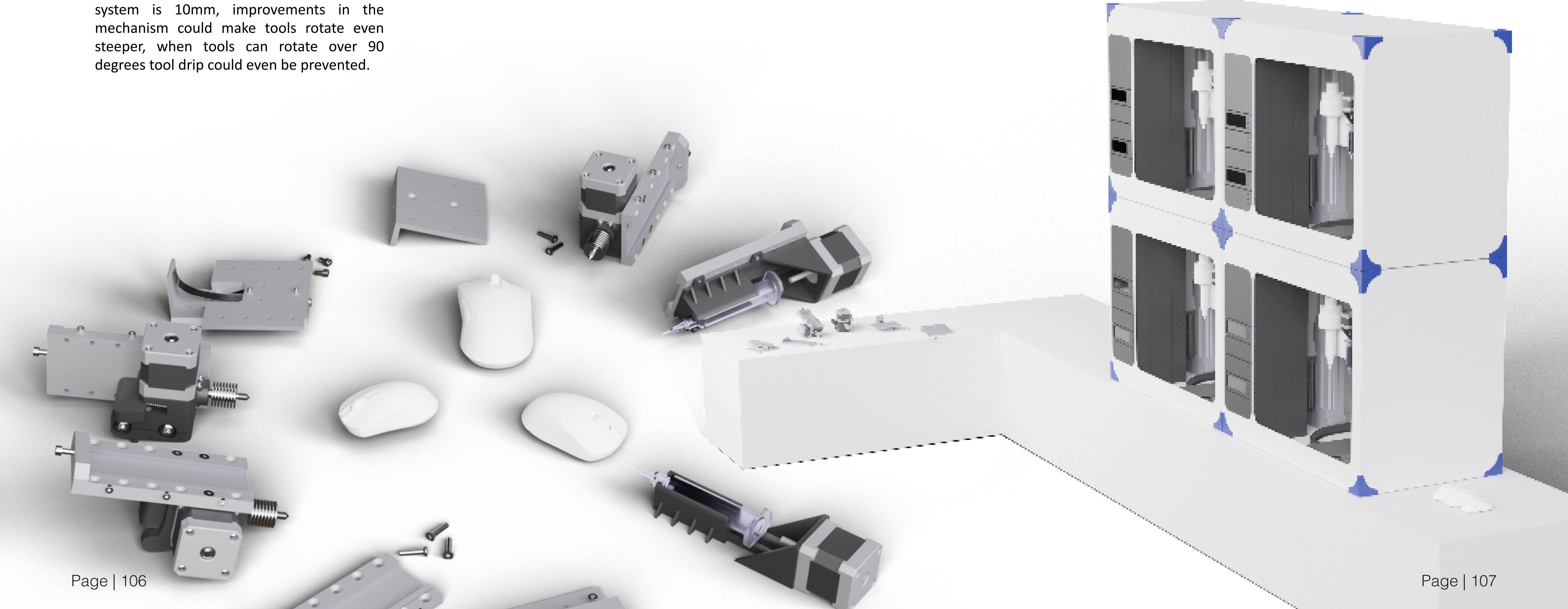
4.4 Future improvements

Limitations:

- The system is not jet suitable for tools that require rigidity and plunge deep into the part like drills or routers. For these tools, a special mount should be created that is rigid and can move tools up and down.
- When using custom tools, drilling extra holes or fabricating a custom intermediate plate, is required because tool holes don't align with the holder.
- The tool rack lacks rigidity, and tools that put strain on the rack during usage should not be used. Improving the tool rack profile and changing the cantilever configuration can make the system more rigid.
- Wiring can get tangled up into the cams, along with further embodiment of the hardware, a wiring shield should be created.
- The tool clearance created by the current system is 10mm, improvements in the mechanism could make tools rotate even steeper, when tools can rotate over 90 degrees tool drip could even be prevented.

Future development:

- The parts need to be optimised for manufacturing.
- The cams need to be redesigned the cam profiles need to be further optimised. The tool path of the cam is too large making the activation too gradual. The cams should be redesigned to make cam installation less involved.
- A standardised bolt hole arrangement has to be created for installing tools on the mounts and holders.
- The dynamic tool mount ballbearing is currently adjustable to fine adjust the tilt in the mechanism and enable maintenance to make up for potential wear. The ballbearing could potentially be attached rigidly, simplifying the system.



4.5 Prototype

Through the use of rapid prototyping, the individual components were designed and created. To test and show the feasibility of the whole system a prototype system was created testing the most important parts of the concept. The prototype is created with linear actuators provided by Festo and the focus is on designing, testing and validating the tool rack design.

Prototype system

The prototype system is build for a possible integrated electronics workstation, the test toolset is FDM 3D printing and 3D printing electronics using the solder paste extrusion method. Showcasing the use of the dynamic tool mounts with the FDM & paste extrusion tools and showcasing a rigid mount using the heat gun tool. The system is build in barebones setup without enclosure, using readily available parts. Using these parts makes the system different than the designed system, since the goal is to test and showcase the toolrack and the tool utilisation, this is not a problem since those systems can still be tested and evaluated using this prototype. A full overview of the parts can be found in Appendix 6.8

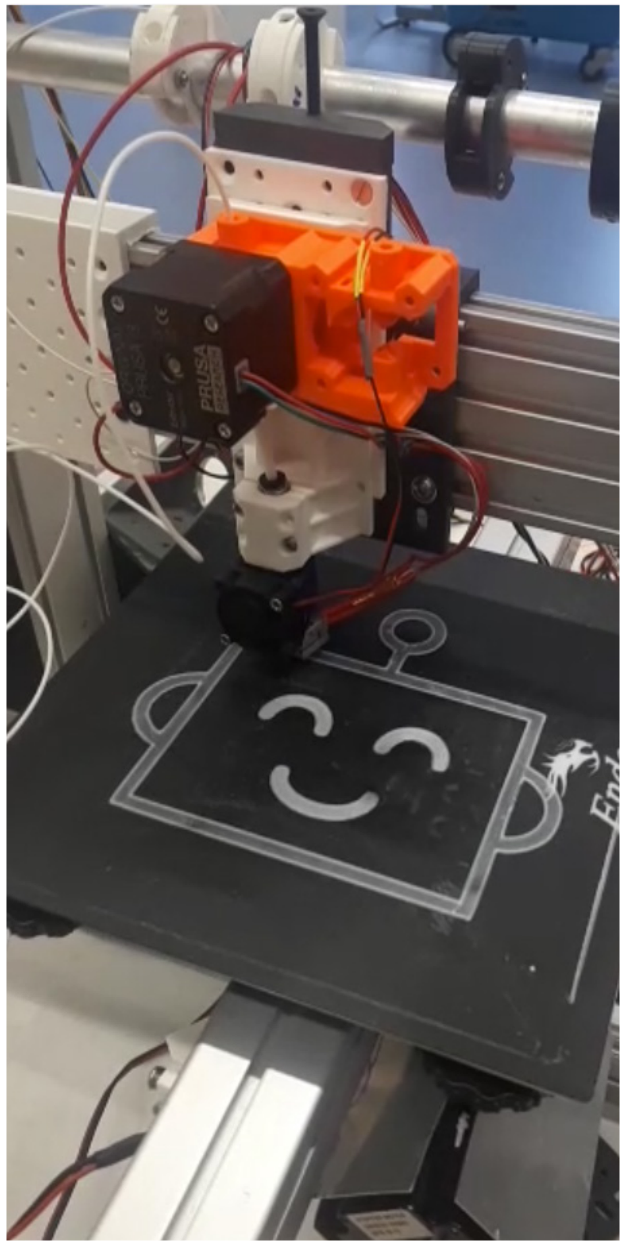


Figure 4.20 Prototype testing

Linear axis

The motion of the machine is provided by the linear actuators from Festo, the linear actuators are larger than in the design but still follow the same configuration as the worksation concept. The Z-axis and the tool rack are actuated by an EGC-80-700-BS. The advantage of using this actuator is that it is plenty strong and rigid, while still using the same cantilever design as in the concept.

The X-axis is actuated by an EGC-80-1250-TB-KF and the Y-axis is actuated by a DGEA-18-240-ZR-GVL. While the linear axes are oversized for the protype use case, the prototype can be upgraded to test the different configurations and machine sizes in the future.

Tool rack

At the base of the tool rack is an 2080 T-slot aluminium extrusion profile. The advantage of the extrusion is that it accepts various T-nuts which makes installing parts on the profile convenient. The flexibility in attaching parts made protototyping the toolrack easy and made tool mount installation effortless. Most custom parts of the tool rack are 3D printed. The tool rack is sufficient for the current toolset, although the machine does vibrate and lacks rigidity.

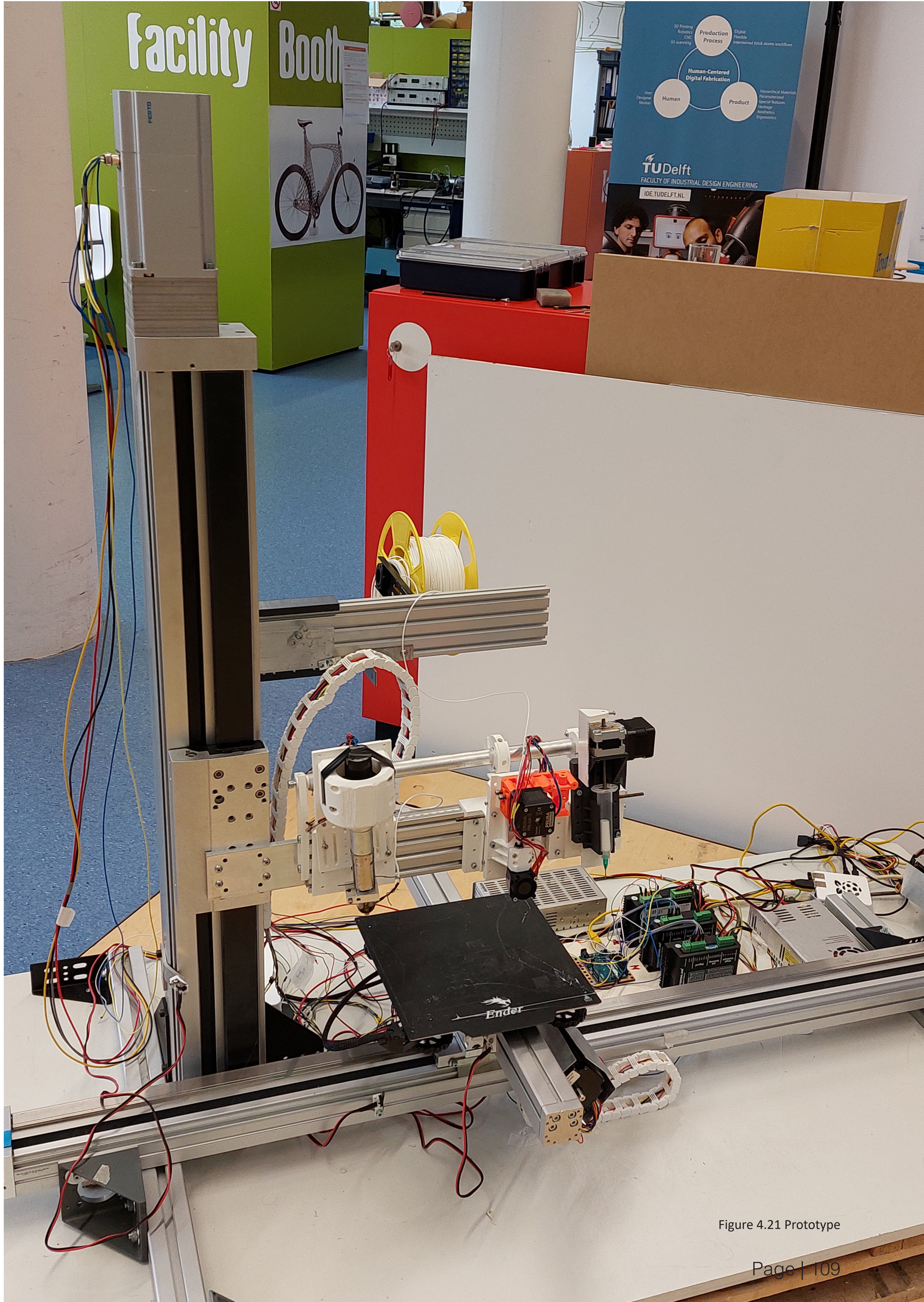


Figure 4.21 Prototype

Hardware
The prototype's hardware is similar to the proposed modular hardware. The central controller is a raspberry pi with Klipper firmware installed. The raspberry pi sends instructions to the other modules controlling the additional Arduinos and other microcontrollers. The use of the Klipper firmware showcases how a modular hardware setup could be used and also helped with prototyping making hardware expansion simple. Figure 3.22, shows a simplified control overview, Figure 3.23 to Figure 3.25 show the full electronics diagram of the respective modules. For the controls, two controllers are used, an Arduino to drive the main axes and a 3D printer motherboard to control the toolset. Since the prototype is focused on electronics printing, the 3d printing board provided most of the required hardware to the toolset. Only the heat gun requires extra hardware such as an Arduino, to convert the signal and send it to the dimmer module controlling the heating element.

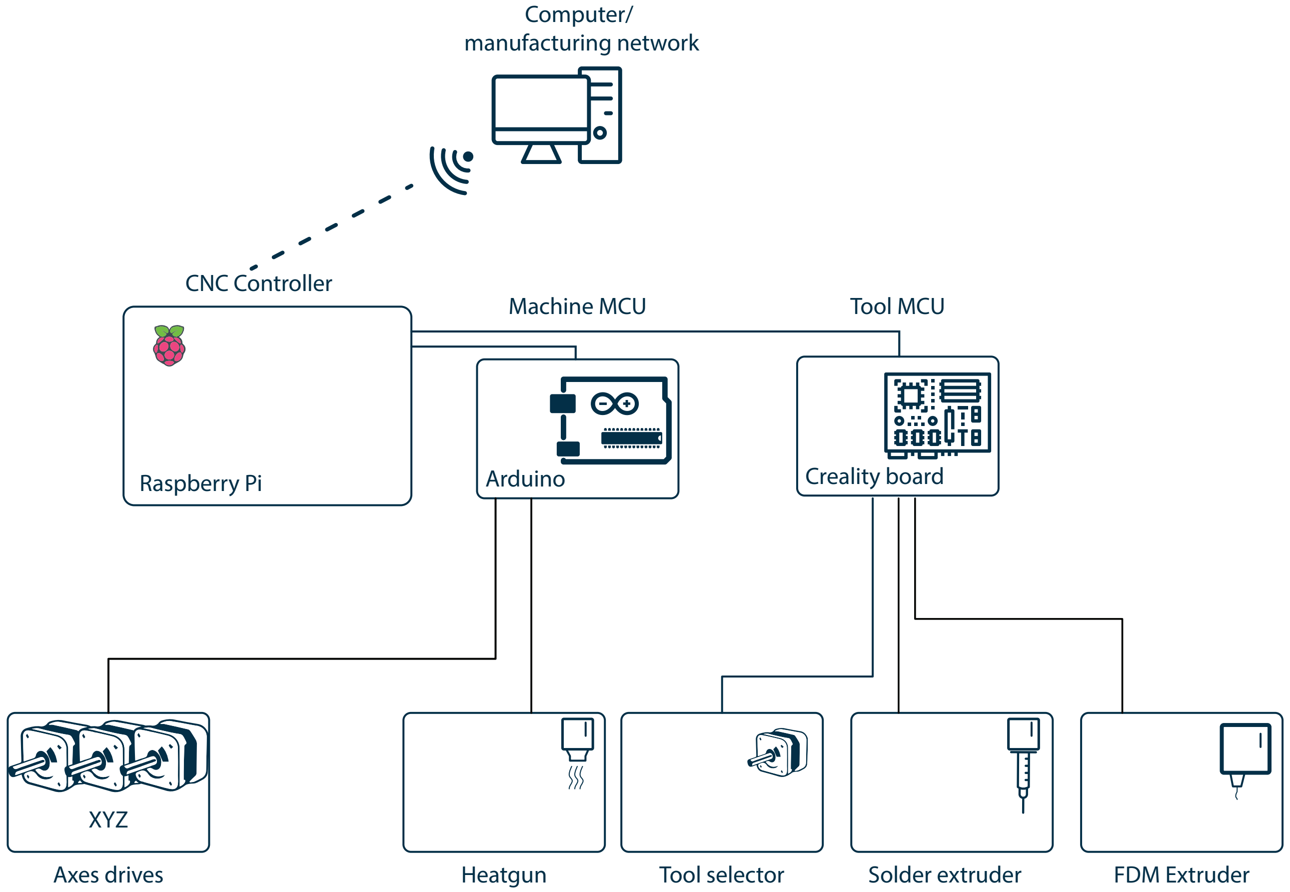


Figure 4.22 Hardware overview

Software
As mentioned, the prototype is controlled by a raspberry pi running Klipper firmware and OctoPi. The used software is open source and build for 3D printers but can be modified and configured to run extra tools. The configuration and modifications to run it can be found in Appendix 6.9 software configuration. Because the system is running on a 3D printer platform, it can interpret gcode and common slicers can create the toolpaths. For the project, a custom configuration of Cura is used. Toolpath creating is fairly straight forward, the gcode is generated with Cura and requires a small amount of post-processing. (Appendix 6.10)

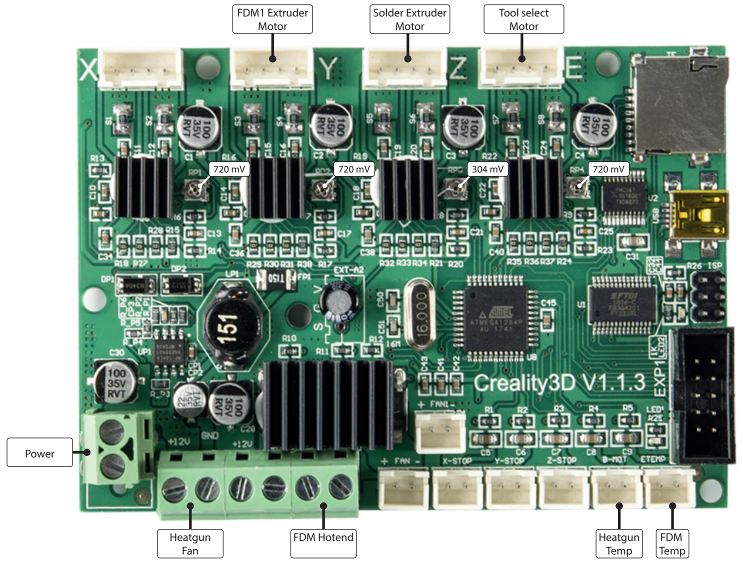
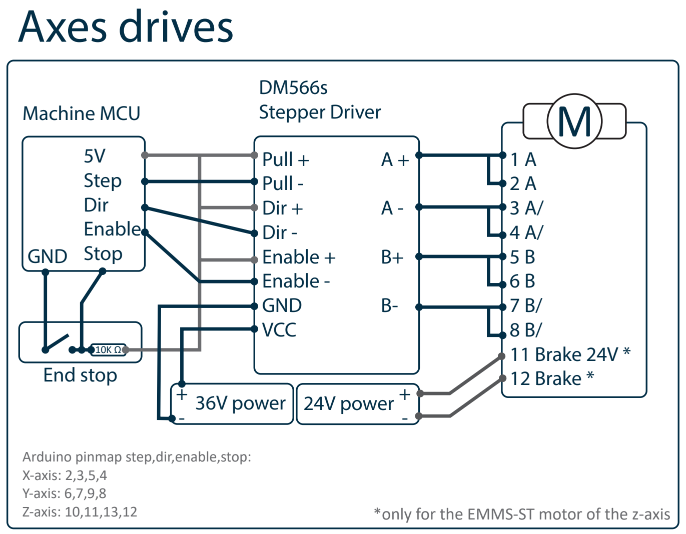


Figure 4.23 Tool MCU configuration



Arduino pinmap step,dir,enable,stop:
X-axis: 2,3,5,4
Y-axis: 6,7,9,8
Z-axis: 10,11,13,12

*only for the EMMS-ST motor of the z-axis

Figure 4.24 Drive axes wiring

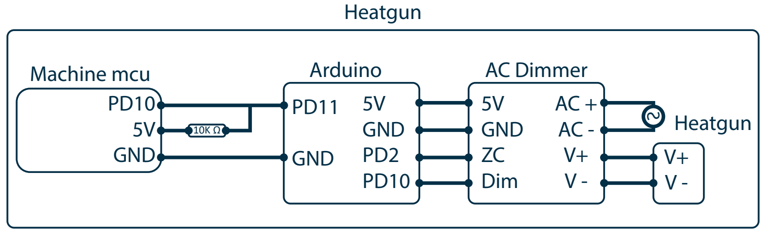


Figure 4.25 Heatgun wiring

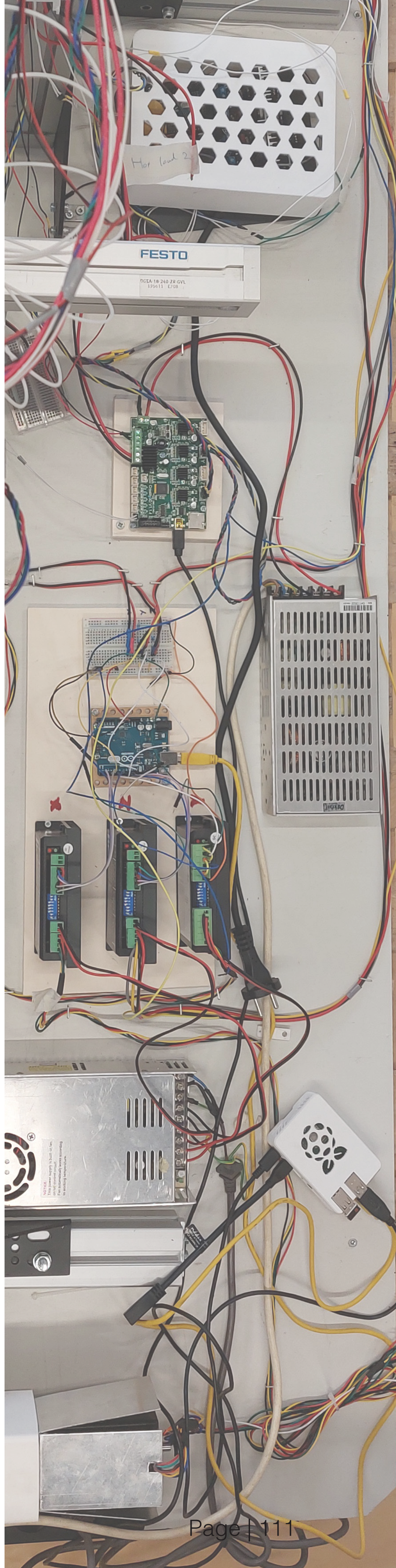


Figure 4.26 Protype hardware

4.6 Validation

The system uses an unproven method to switch tools and prevent tool-part interference. The prototype is used to validate the design and perform repeatability and accuracy tests. The dynamic tool design is proven and deemed viable when tools are actuated in and out of working position with minimal deviation to tool head position.

Testing setup

Dynamic tool repeatability tests consist out of multiple test prints performed using an FDM printing setup. The 3D printing setup consists out of a single FDM printing head installed in the middle toolslot on the machine.(Figure 4.28) The printhead is installed on a dynamic tool plate, and repeatability actuated during printing.

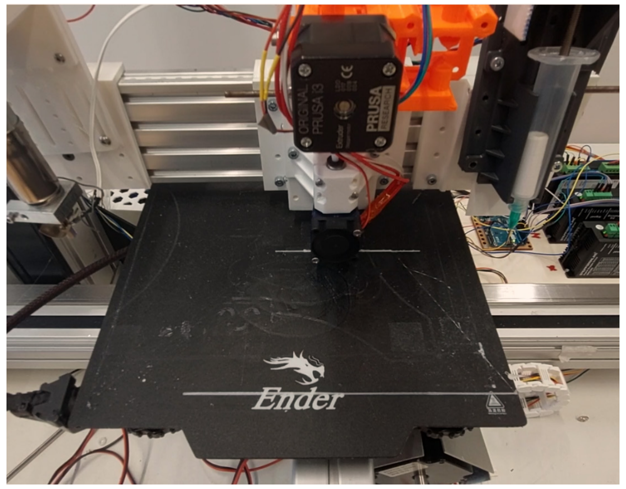


Figure 4.27 Printing setup

Test prints

Two kind of test prints were performed, a line test which is interrupted by a toolchange and hollow test rectangles. The interrupted line tests single layer accuracy, during the test the printer will try to print a line while performing a tool change in intervals of 20mm (Figure 4.31). Multi layer accuracy and repeatability is tested by printing rectangles, during the test the printer performs a toolchange every 6 layers. (Figure 4.29)

Print cycle

Printing cycle

The printing cycle is repeated multiple times throughout the test prints. The cycle has two stages, the printing and the simulated tool change. (Figure 4.29) For the simulated tool change, the tool rack cams are rotated an entire revolution moving the tool head into an idle position and returning to the working position. During testing, the printing cycle repeats multiple times. Preliminary tests had stringing and drooping issues. Adding filament retraction and Z retraction during tool changes remedied the issues.

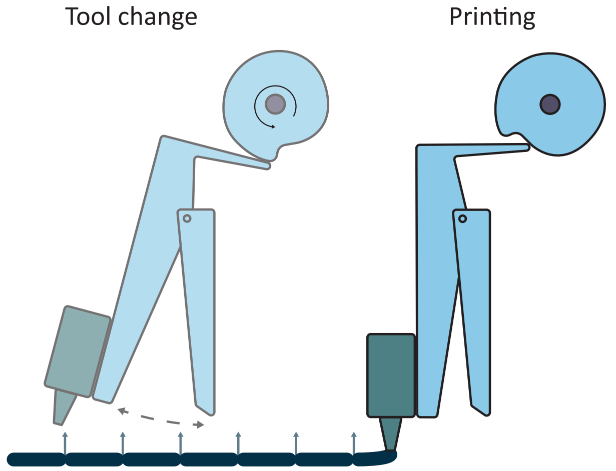


Figure 4.28 Printing cycle line test

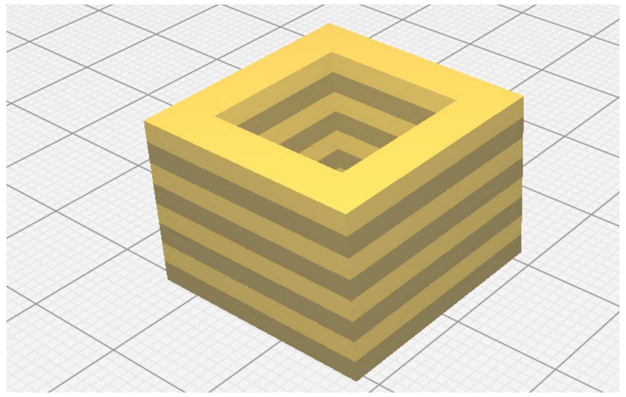


Figure 4.29 Rectangle test pattern


Figure 4.30 Line test pattern

Results

Both the line and rectangles tests were successful, as can be seen in figure Figure 4.32. The consistency of the printed line during the single layer test is uniform, and there is no noticeable deviation in the rectangles. Some test prints are far from perfect and many artifacts can be seen (Figure 4.32). The artifacts show right after tool changes and are caused by tool change settings instead of the system's inaccuracy. Further finetuning of the print settings resulted in improved print quality and elimination of the artefacts. The final test prints are compared to a stock ultimaker S2+ print with similar print settings but without tool changes. Comparing the final test prints shows that the system achieves desired accuracy and repeatability. Tool changes are almost unnoticeable and both systems achieve similar printing quality. (Figure 4.32)

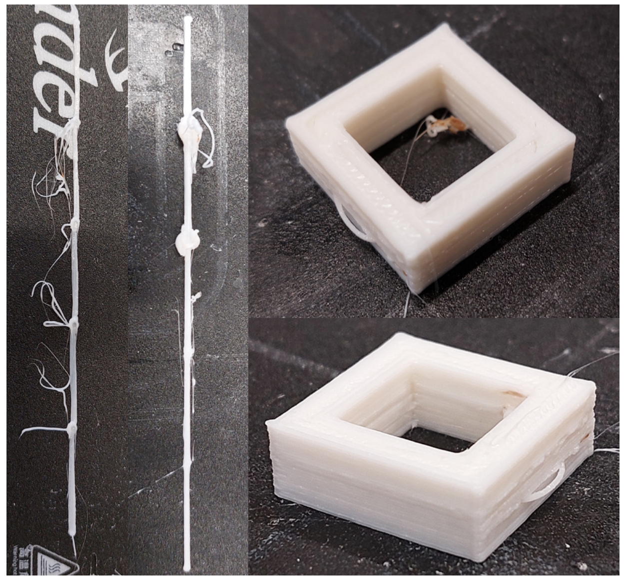


Figure 4.31 Preliminary test prints

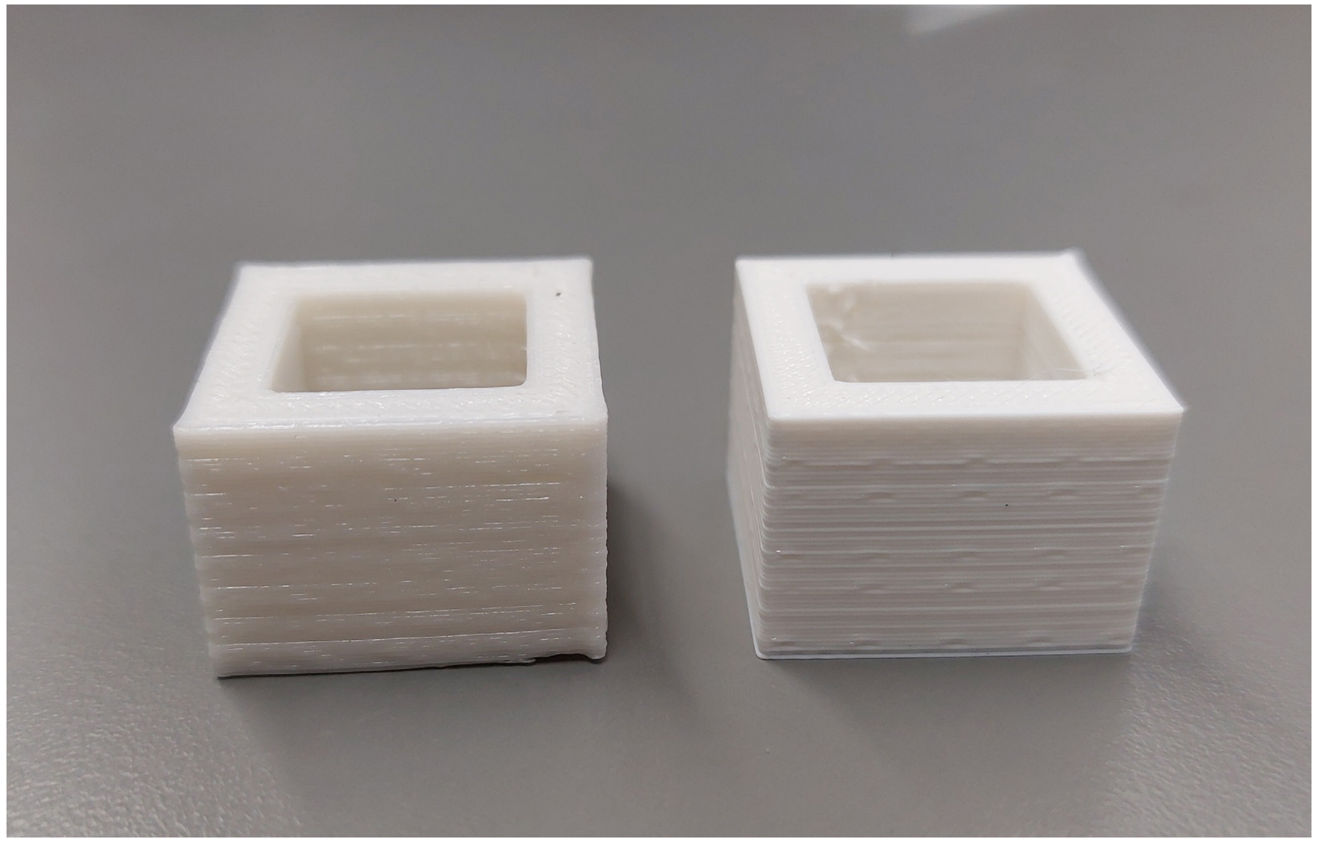


Figure 4.32 Testprint comparison, (Protype left, Ultimaker right)

4.6 Summary

A hybrid workstation for the early adoption of hybrid fabrication in transcended manufacturing was created. The workstation is aimed at product research and development, and a exemplary toolset for integrated electronics was used to test and prove the system.

Development of the system was focused on the tool utilisation of fixed hybrid machines, with the use of rapid prototyping the tool rack and toolmounts were developed and tested.

- The hybrid workstation facilitates the use of multiple tools. The toolset is reconfigurable and rapid manual reconfiguration of the toolset is possible.
- Depending on the tools, tools for the the hybrid fabrication can be placed on static or dynamic tool mounts.
- The systems hardware is modular and expendable, making it possible to expand the hardware according to new tool acquisitions and developments in digital manufacturnig.
- The system follow an industry standard with integration into the TM factory in mind.
- The system can produce small to medium-sized products.

The flexible tool concept was validated by test prints using FDM. The system is capable of using multiple tools while staying accurate.

The proposed hybrid workstation needs further embodiment before it is a comprehensive system but core concepts have been validated and tool usage is accurate, reconfigurable and flexible.

The next steps in hybrid fabrication for TM will be to further research and explore the hybrid fabrication processes enabled by such a system. The created prototype can be used in further development of the hybrid fabrication for transcended manufacturing field.

4.7 Conclusion

The hybrid fabrication workstation concept is viable for prototyping context and for research of hybrid fabrication. With the embodiment of the concept hybrid fabrication techniques can be tested. The hybrid fabrication workstation opens een new approach of creating personalised products, the hybrid fabrication workstation enables research on how hybrid fabrication is used in product design.

The hybrid fabrication workstation is still in it's concept phase and requires further development before it is a complete system. Development should be concentrated on the tool utilisation and implementation of hybrid fabrication. The rest of the workstation can be embodied later.

Tool utilisation
Tool holders are created to provide the versatile toolset to the system, the concept of the toolholders has been proven but they need further development before they can be manufactured.

Multiple sizes of tool holders should be made to maximise the number of tools fitted on a system and increase effective build volume.

Toolholder should be futher developed to accommodate both dedicated tools and off-brand tools. The tool mounts and holders should be embodied and redesigned for manufacturability.

Implementation hybrid fabrication
Hybrid fabrication for personalised product fabrication is an under developed field, with the creation of hybrid workstation the implementation of hybrid fabrication can be further developed.

Hybrid fabrication opens a new way of manufacturing products and therefore it has to be researched how hybrid fabrication facilitates personalised product production. Hybrid fabrication can change the way products are designed but architecting personalised products needs to be explored.

When hybrid fabrication station are more common the use of hybrid fabrication stations as versatile manufacturing machines in matrix fabrication can be researched and proven.

Conclusion

5

5.1 Conclusion

Transcended manufacturing is an emerging manufacturing paradigm that is being developed. Transcended manufacturing is an answer to the rising need for mass personalisation and ultra-personalised products. Ultra-personalised products are unique in fit, aesthetics and performance, the one-off a kind nature of ultra-personalised make them hard to manufacture with traditional fabrication methods. Transcended manufacturing uses automation and digital manufacturing to manufacture ultra-personalised products, the factory relies on process generality and flexibility to make the products. Hybrid fabrication can add value to the transcended manufacturing process with its advantages over traditional digital manufacturing.

Hybrid fabrication
Hybrid fabrication workstations combine multiple fabrication techniques in a single system, a hybrid system offers multiple opportunities to transcended manufacturing. The identified opportunities are process enhancements and improving tolerances of additive manufacturing; versatile manufacturing with a multi-purpose workstation; and integrated electronics printing. Before the integration of hybrid fabrication for manufacturing, these opportunities require more research and development. More hybrid systems need to be created and hybrid fabrication needs to be tested to unlock the potential of hybrid fabrication. When the hybrid fabrication space is more mature, development can be shifted towards implementing hybrid systems into the transcended manufacturing process. To kickstart the development, a hybrid workstation is developed as a platform for hybrid fabrication to enable research of its implementation.

Transcended manufacturing
Hybrid fabrication systems can be useful in multiple stages of the transcended manufacturing process. Hybrid stations can be used to accelerate product development by providing rapid prototyping capabilities to product designers. The flexibility and reconfigurability of hybrid systems allow these systems to perform similar operations as the factory. The new possibilities of hybrid fabrication can be deployed during manufacturing to deal with the shape complexity and uniqueness of personalised products. Hybrid machines can be used to create new factory processes like integrating electronics into products. The versatility of hybrid fabrication stations can also increase the factory's flexibility and versatility, allowing the factory to be more efficient and faster respond to consumer demand.

Hybrid workstation
A prototype workstation is created to showcase hybrid fabrication and research it's possible implementation. The workstation is built for flexibility and reconfigurability with a 3D printing integrated electronics toolset. The platform provides a development framework for hybrid manufacturing with a manually reconfigurable toolset. The prototype addresses reconfigurability and flexibility in hybrid systems but needs further improvement before it is a comprehensive system for researching and testing hybrid fabrication techniques.

The future of hybrid manufacturing and transcended manufacturing looks promising. The earliest adoption of hybrid manufacturing will be in product research and development. As the industry 4.0 grows and transcended manufacturing, hybrid fabrication and CPSs mature, the new way of manufacturing ultra-personalised products can include hybrid fabrication systems.

5.2 Recommendations

The first steps towards hybrid fabrication for transcended manufacturing have been made but it will take time and development before the full potential of hybrid fabrication and transcended manufacturing are unlocked.

The proposed workstation is a good development platform for hybrid fabrication and its multitude of implementations. There for it should be used to further research in the field of hybrid fabrication and product personalisation.

At first the hybrid fabrication station should be used to further develop hybrid fabrication techniques like integrating electronics printing with pick and place hardware or enhancing the process tolerances of FDM 3D printing. Further research should also be done in new combination, base and add-on tool combinations should be combined and tested to see if their potential can be improved.

With the new process possibilities come new design possibilities, the domain of product personalisation design and it's added value should be further explored using hybrid and digital manufacturing.

When hybrid fabrication is further developed, dedicated hybrid machines can be created that are optimised for specific tasks, like integrated electronics machines or matrix manufacturing stations.

Transcended manufacturing itself also needs further development with research in product platform architecture, manufacturing and Cyber-infrastucture systems.

5.3 References

3D HYBRID: AM FOR CNC. n.d. Applications. [online] Available at: <https://www.3dhybridsolutions.com/applications.html> [Accessed 13 September 2021].

3D Printing Media Network - The Pulse of the AM Industry. n.d. The 3dpbm interactive map of commercially available AM technologies. [online] Available at: <https://www.3dprintingmedia.network/map-of-additive-manufacturing-technologies/> [Accessed 12 September 2021].

Bányai, Á. et al. (2019) 'Smart cyber-physical manufacturing: Extended and real-time optimization of logistics resources in matrix production', Applied Sciences (Switzerland), 9(7). doi: 10.3390/app9071287.

Bayless, J., Chen, M. and Dai, B. (2010) 'Wire Embedding 3D Printer', Engineering Physics Department, p. 39. Available at: http://reprap.org/mediawiki/images/archive/2/25/20100412224301!SpoolHead_FinalReport.pdf.

Berry, C., Wang, H. and Hu, S. J. (2013) 'Product architecting for personalization', Journal of Manufacturing Systems, 32(3), pp. 404–411. doi: 10.1016/j.jmsy.2013.04.012.

Bortolini, M. et al. (2017) 'Assembly system design in the Industry 4.0 era: a general framework', IFAC-PapersOnLine, 50(1), pp. 5700–5705. doi: 10.1016/j.ifacol.2017.08.1121.

Cheng, F. et al. (2002) 'Inventory-service optimization in configure-to-order systems', Manufacturing and Service Operations Management, 4(2), pp. 114–132. doi: 10.1287/msom.4.2.114.282.

Childs, T. H. C., Dalgarno, K. W. and McKy, A. (2005) 'Delivering mass-produced bespoke and appealing products', LEM 2005 - 3rd International Conference on Leading Edge Manufacturing in 21st Century, 49(1), pp. 11–18. doi: 10.1299/jsmelem.2005.1.11.

Choi, J., Lee, D. H. and Taylor, C. R. (2016) 'The influence of purchasing context and reversibility of choice on consumer responses toward personalized products and standardized products', Psychological Reports, 118(2), pp. 510–526. doi: 10.1177/0033294116637730.

Configurator Database. n.d. [online] Available at: <https://www.configurator-database.com/> [Accessed 12 September 2021].

Coronel, J. L. et al. (2020) 'Hybrid manufacturing with FDM technology for enabling power electronics component fabrication', Solid Freeform Fabrication 2018: Proceedings of the 29th Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference, SFF 2018, pp. 357–364.

Davies, R. (2015) 'Industry 4.0. Digitalisation for productivity and growth', European Parliamentary Research Service, (September).

El Maraghy, H. A. (2006) 'Flexible and reconfigurable manufacturing systems paradigms', Flexible Services and Manufacturing Journal, 17(4 SPECIAL ISSUE), pp. 261–276. doi: 10.1007/s10696-006-9028-7.

Esmaeilian, B., Behdad, S. and Wang, B. (2016) 'The evolution and future of manufacturing: A review', Journal of Manufacturing Systems, 39, pp. 79–100. doi: 10.1016/j.jmsy.2016.03.001.

Grant, K. E. et al. (2013) 'The search for individualism: Self-expression through product personalisation', International Journal of Designed Objects, 6(1), pp. 17–29. doi: 10.18848/2325-1379/cgp/v06i01/38694.

Hu, S. J. (2013) 'From mass production to mass customization and personalization', Procedia CIRP, 7, pp. 3–8. doi: 10.1016/j.procir.2013.05.002.

Hu, S. J. et al. (2011) 'Assembly system design and operations for product variety', CIRP Annals - Manufacturing Technology, 60(2). doi: 10.1016/j.cirp.2011.05.004.

Jordan, P. W. (2000) 'Future trends and product design', Proceedings of the XIVth Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Association, 'Ergonomics for the New Millennium', pp. 1–4. doi: 10.1177/154193120004403201.

Katana. 2021. How Bespoke and Custom Manufacturing Works - Katana. [online] Available at: <https://katanamrp.com/blog/bespoke-manufacturing/> [Accessed 12 September 2021].

Kia, R. et al. (2014) 'Solving a multi-floor layout design model of a dynamic cellular manufacturing system by an efficient genetic algorithm', Journal of Manufacturing Systems, 33(1), pp. 218–232. doi: 10.1016/j.jmsy.2013.12.005.

Kromhout, B. (2020) 'TRANSCENDED MANUFACTURING'.

Lee, J. et al. (2018) 'Industrial Artificial Intelligence for industry 4.0-based manufacturing systems', Manufacturing Letters, 18, pp. 20–23. doi: 10.1016/j.mfglet.2018.09.002.

Lee, J., Lee, S. and Sung, J. H. (2014) 'Effects and Application Cases of Injection Molds by using DED type Additive Manufacturing Process', 32(4), pp. 10–14.

Lee, W. C., Wei, C. C. and Chung, S. C. (2014) 'Development of a hybrid rapid prototyping system using low-cost fused deposition modeling and five-axis machining', Journal of Materials Processing Technology, 214(11), pp. 2366–2374. doi: 10.1016/j.jmatprotec.2014.05.004.

Maagdenberg, D. (no date) 'FDM Printing', Hot Mess 3D print Shop. Available at: http://hotmess3d.com/iimg/265/950x/i.png.

MacDonald, E. et al. (2014) '3D printing for the rapid prototyping of structural electronics', IEEE Access, 2, pp. 234–242. doi: 10.1109/ACCESS.2014.2311810.

Martinez, N. L. (2020) 'ScholarWorks @ UTEP Development of an Automated Ultrasonic Wire Embedding Process for use with Material Extrusion Additive Manufacturing and Rapid Electronics Fabrication Master ' s Program in Mechanical Engineering'.

Monostori, L. et al. (2016) 'Cyber-physical systems in manufacturing', CIRP Annals, 65(2), pp. 621–641. doi: 10.1016/j.cirp.2016.06.005.

Papp, D., 2021. 3D Printed Buttons, Printed As A Single Unit. [online] Hackaday. Available at: <https://hackaday.com/2019/07/06/3d-printed-buttons-printed-as-a-single-unit/> [Accessed 13 September 2021].

Rajagopalan, S. (2002) 'Make to order or make to stock: Model and application', Management Science, 48(2), pp. 241–256. doi: 10.1287/mnsc.48.2.241.255.

Stratasys. n.d. Benefits of CNC Machining FDM Parts | Stratasys Direct Manufacturing. [online] Available at: <https://www.stratasysdirect.com/technologies/cnc-machining/benefits-cnc-machining-fdm-parts> [Accessed 13 September 2021].

Toni DE, Tonchia S (1998) Manufacturing flexibility: a literature review. Int J Prod Res 36(6):587–1617

Ustundag, A. and Cevikcan, E. (2017) Managing The Digital Transformation, Industry 4.0: Managing The Digital Transformation.

Välimäki, M. K. et al. (2020) 'Printed and hybrid integrated electronics using bio-based and recycled materials—increasing sustainability with greener materials and technologies', International Journal of Advanced Manufacturing Technology, 111(1–2), pp. 325–339. doi: 10.1007/s00170-020-06029-8.

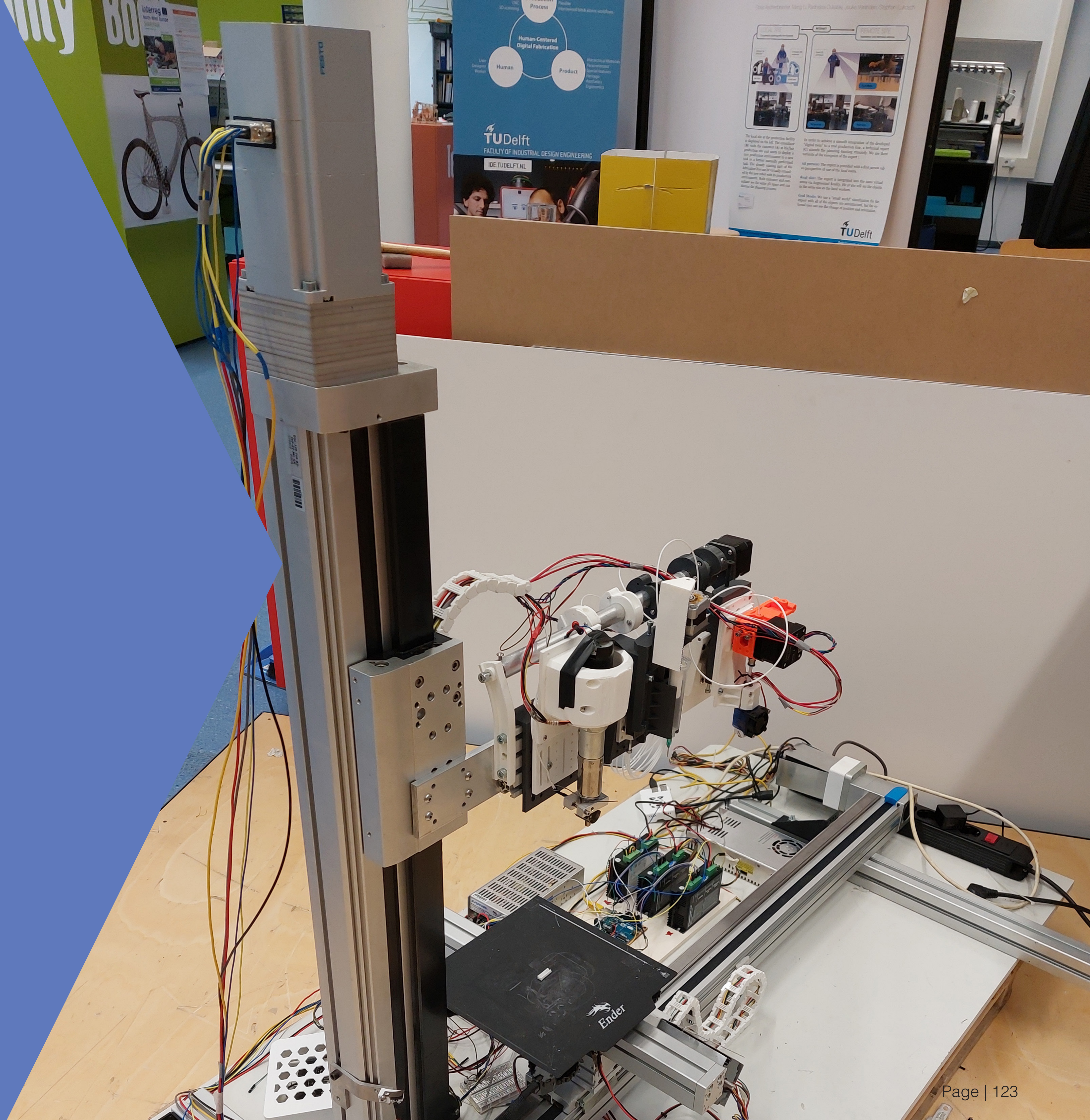
Wiendahl, H. P. et al. (2007) 'Changeable Manufacturing - Classification, Design and Operation', CIRP Annals - Manufacturing Technology, 56(2), pp. 783–809. doi: 10.1016/j.cirp.2007.10.003.

Yan, J., Zhang, M. and Fu, Z. (2019) 'An intralogistics-oriented Cyber-Physical System for workshop in the context of Industry 4.0', Procedia Manufacturing, 35, pp. 1178–1183. doi: 10.1016/j.promfg.2019.06.074.

Zheng, P. et al. (2017) 'User-experience Based Product Development for Mass Personalization: A Case Study', Procedia CIRP, 63, pp. 2–7. doi: 10.1016/j.procir.2017.03.122.

Appendix

6


Human-Centered Digital Fabrication
Human
Product
Process
TUDelft
FACULTY OF INDUSTRIAL DESIGN ENGINEERING
IDE.TUDELFT.NL
FESTO
Ender

DESIGN FOR our future

Appendix 6.1 - Design brief

IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy". Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name Berden

initials F J given name Freek

student number 4283031

street & no.

zipcode & city

country

phone

email

Your master programme (only select the options that apply to you):

IDE master(s): ● IPD ○ DfI ○ SPD

2nd non-IDE master:

individual programme: - - (give date of approval)

honours programme: ○ Honours Programme Master

specialisation / annotation: ○ Medisign

○ Tech. in Sustainable Design

○ Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair A.L.M. Minnoye dept. / section: SDE/MM

** mentor J.J.F. van Dam dept. / section: SDE

2nd mentor

organisation:

city: country:

comments (optional) The expertise complement each other. Sander's expertise is at Mechanics, embodiment design and Agile manufacturing. While Joris can lend his expertise on 3D printing, robotics and Industry 4.0.

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair A.L.M. Minnoye date - - signature

CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair. The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: ______ EC

Of which, taking the conditional requirements into account, can be part of the exam programme ______ EC

List of electives obtained before the third semester without approval of the BoE

○ YES all 1st year master courses passed

○ NO missing 1st year master courses are:

name date - - signature

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **. Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: ○ APPROVED ○ NOT APPROVED

Procedure: ○ APPROVED ○ NOT APPROVED

comments

name date - - signature

Initials & Name F J Berden Student number 4283031

Title of Project Hybrid fabrication for transcended manufacturing

Hybrid fabrication for transcended manufacturing project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 08 - 09 - 2020

end date 11 - 03 - 2021

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

We are at the start of a new industrial revolution. Based on technological advances in adaptive robotics, data analytics and artificial intelligence (big data analytics), simulation, embedded systems, communication and networking such as Industrial Internet, cloud systems, advanced manufacturing and virtualization technologies. The current industry 3.0 is transcending into the Industry 4.0. The connection and integration of manufacturing and service systems are used to increase product quality and diversity, optimize processes and decrease the costs with smart systems. With as goals of Industry 4.0 to achieve smart factories and cyber-physical systems (CPSs).

Along with the realization of smart factories and CPSs the mass customization and personalization of products is trending. The Configurator Database Project shows how widespread mass customization has become, providing links to over 1350 companies across 17 industries that are offering individualized products to the consumer. With this new demand a new manufacturing method is emerging; transcended manufacturing, the manufacturing method that uses product independent process steps to make one-of-a-kind products at a mass-production output capacity.
Digital manufacturing technologies are increasing in relevance with the rise of the industry 4.0. 3d printing and many other CNC based systems are becoming a standard in the development or manufacturing of products due to the flexibility and adaptiveness these systems provide.

The Center of Design for Advanced Manufacturing (CDAM) is at the front of these developments and is researching advanced manufacturing including transcended manufacturing.

Transcended manufacturing can be achieved by linking multiple standalone digital fabrication stations together making use of the flexibility and customizability provided by these digital fabrication stations. In addition to normal digital fabrication, hybrid fabrication could improve the field of transcended manufacturing and complement the digital fabrication stations with hybrid manufacturing stations.

Hybrid manufacturing combines multiple digital fabrication methods in a single system in order to achieve new fabrication possibilities.

A good example is the research on printing integrated electronics where CDAM has combined the usage of FDM printing and solder paste printing to achieve 3d printed integrated electronics. While the printing of integrated electronics is still performed manually with two separate machines, this technique could be combined into a single hybrid fabrication system.

CDAM is interested in the possibilities of a hybrid fabrication system and the possibilities of hybrid fabrication to support the transcended manufacturing process.

Festo, a leader in industrial automation will be supporting this project with their expertise in motion and control systems.

space available for images / figures on next page

Initials & Name F J Berden Student number 4283031

Title of Project Hybrid fabrication for transcended manufacturing

introduction (continued): space for images

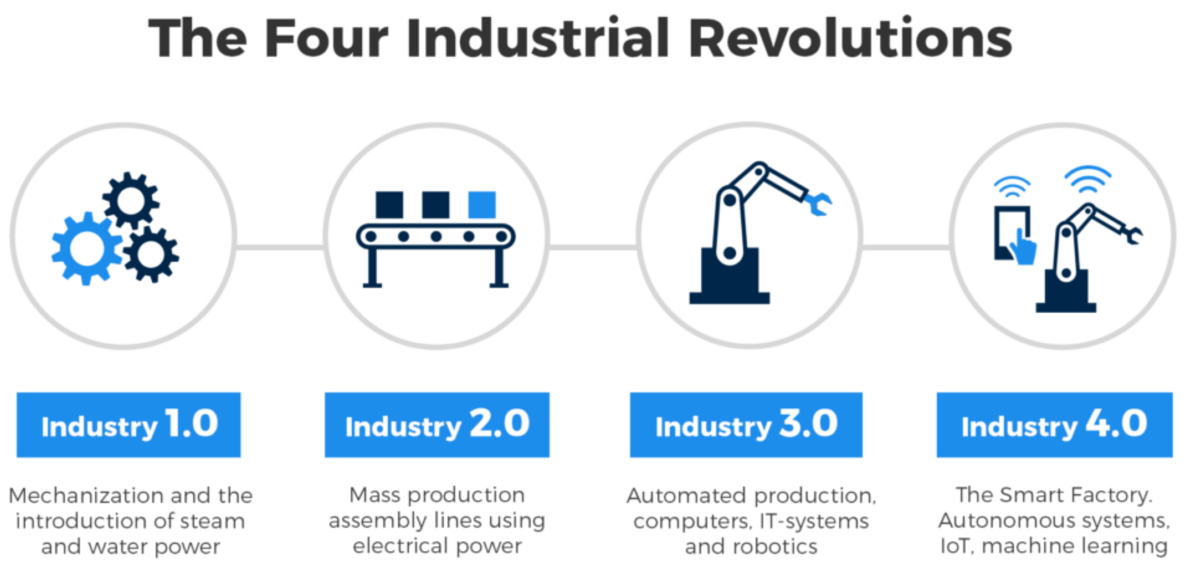


image / figure 1: industry 4.0 the new industrial revolution

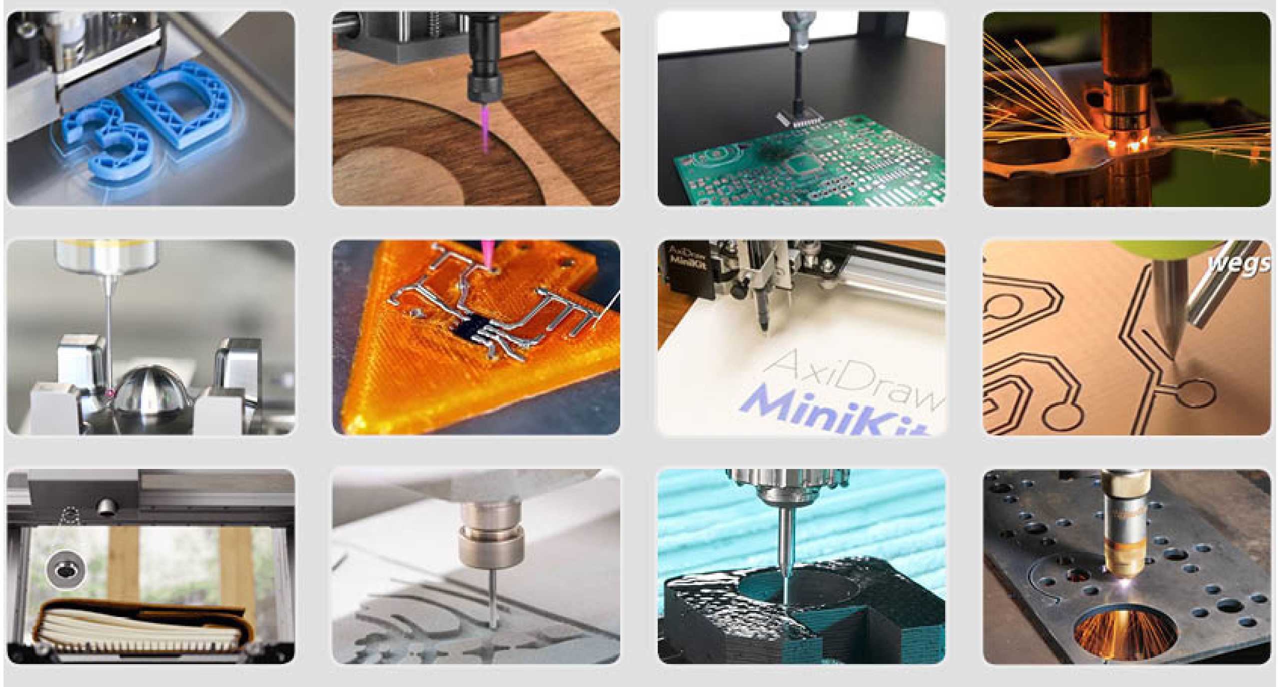


image / figure 2: Digital fabrication techniques

Initials & Name F J Berden Student number 4283031

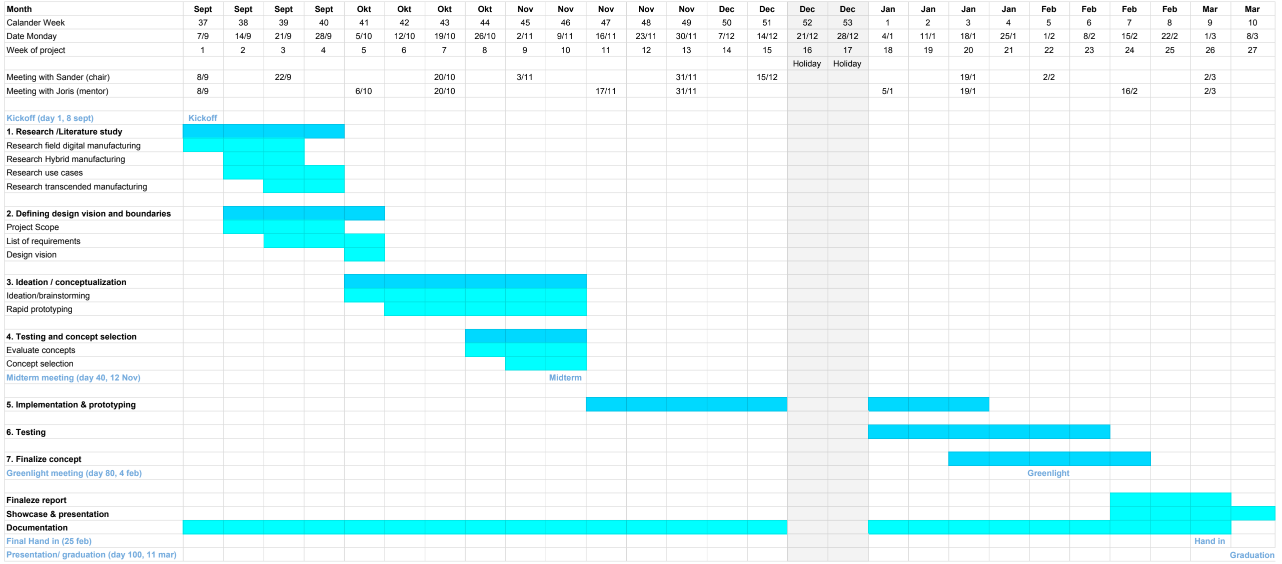
Title of Project Hybrid fabrication for transcended manufacturing

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 8 - 9 - 2020

11 - 3 - 2021 end date



Month	Sept	Sept	Sept	Sept	Okt	Okt	Okt	Okt	Nov	Nov	Nov	Nov	Nov	Dec	Dec	Dec	Dec	Jan	Jan	Jan	Jan	Feb	Feb	Feb	Feb	Mar	Mar
Calander Week	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	1	2	3	4	5	6	7	8	9	10
Date Monday	7/9	14/9	21/9	28/9	5/10	12/10	19/10	26/10	2/11	9/11	16/11	23/11	30/11	7/12	14/12	21/12	28/12	4/1	11/1	18/1	25/1	1/2	8/2	15/2	22/2	1/3	8/3
Week of project	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
																Holiday	Holiday										
Meeting with Sander (chair)	8/9		22/9				20/10		3/11				31/11		15/12					19/1		2/2				2/3	
Meeting with Joris (mentor)	8/9				6/10		20/10				17/11		31/11					5/1		19/1				16/2		2/3	
Kickoff (day 1, 8 sept)	Kickoff																										
1. Research /Literature study	▨	▨	▨	▨																							
Research field digital manufacturing	▨	▨	▨																								
Research Hybrid manufacturing		▨	▨																								
Research use cases		▨	▨	▨																							
Research transcended manufacturing			▨	▨																							
2. Defining design vision and boundaries		▨	▨	▨	▨																						
Project Scope		▨	▨	▨																							
List of requirements			▨	▨	▨																						
Design vision					▨																						
3. Ideation / conceptualization					▨	▨	▨	▨	▨	▨																	
Ideation/brainstorming					▨	▨	▨	▨	▨	▨																	
Rapid prototyping						▨	▨	▨	▨	▨																	
4. Testing and concept selection								▨	▨	▨																	
Evaluate concepts								▨	▨	▨																	
Concept selection									▨	▨																	
Midterm meeting (day 40, 12 Nov)										Midterm																	
5. Implementation & prototyping											▨	▨	▨	▨	▨			▨	▨	▨							
6. Testing																		▨	▨	▨	▨	▨	▨				
7. Finalize concept																				▨	▨	▨	▨	▨			
Greenlight meeting (day 80, 4 feb)																						Greenlight					
Finaleze report																								▨	▨	▨	
Showcase & presentation																								▨	▨	▨	▨
Documentation	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨			▨	▨	▨	▨	▨	▨	▨	▨	▨	
Final Hand in (25 feb)																										Hand in	
Presentation/ graduation (day 100, 11 mar)																											Graduation

The project will start with an research phase where the current industry and situation will be analyzed. Mapping out the current fabrication methods and the needs of the stakeholders. From this research a design direction and vision will be created after which the Ideation phase will start.

During the Ideation phase concepts will be created and quickly tested with rapid prototyping.

The second half of the project will be dedicated of the implementation of the concept. Improving and embodying the final concept. A final prototype will be created in order to test the system with an use case.

The planning follows a part time schedule of 4 work days a week for 25 weeks following the 100 day graduation schedule. This allows for one day a week which is not spend on this project and enables me to do my job next to graduating.

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

I started with my studies because I have a passion for creating things and love to invent new interesting ways to solve problems. I am fascinated with the inventive ways designers solve (technical) problems and love how simple mechanisms are often very thoroughly designed. During my years at the TU Delft I developed my interest for design embodiment, production, manufacturing, AI, machine learning, IT , connected products and electronics. I can regularly be found in the PMB workspace working on my own projects and really like to expand my knowledge in the regard to fabrication and manufacturing. I also have experience with multiple digital fabrication machines like FDM printers, laser cutters, CNC Router and and since recently also waterjet cutting.

I have always had an interest in mechatronics however until now I did not have the chance to incorporate this into one of my projects. Therefor I really appreciate the chance this project gives me to elaborate on this interest.
As mentioned before I perceive myself as competent in regard of fabrication. This enables me to easily prototype designs and there for I like to improve my rapid prototyping skills during this project. Making short design cycles to quickly improve the product.

I also have a range of software knowledge to my exposal throughout the years I managed to become familiar with Solidworks, Maya, Illustrator, Photoshop, Premier Pro, After Effects and Indesign. These tools are a means to an end which is enabling me as designer to communicate my ideas to the world. Although I have the technical understanding I still believe I can greatly improve on my visual presentation and will try improve my visual presentation during my graduation project.

As with many students I sometimes have trouble following my planning and keeping up with documentation, this often leads to long nights shortly before the deadlines. For this project I plan to improve on this and keep extra attention to my planning and documentation.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

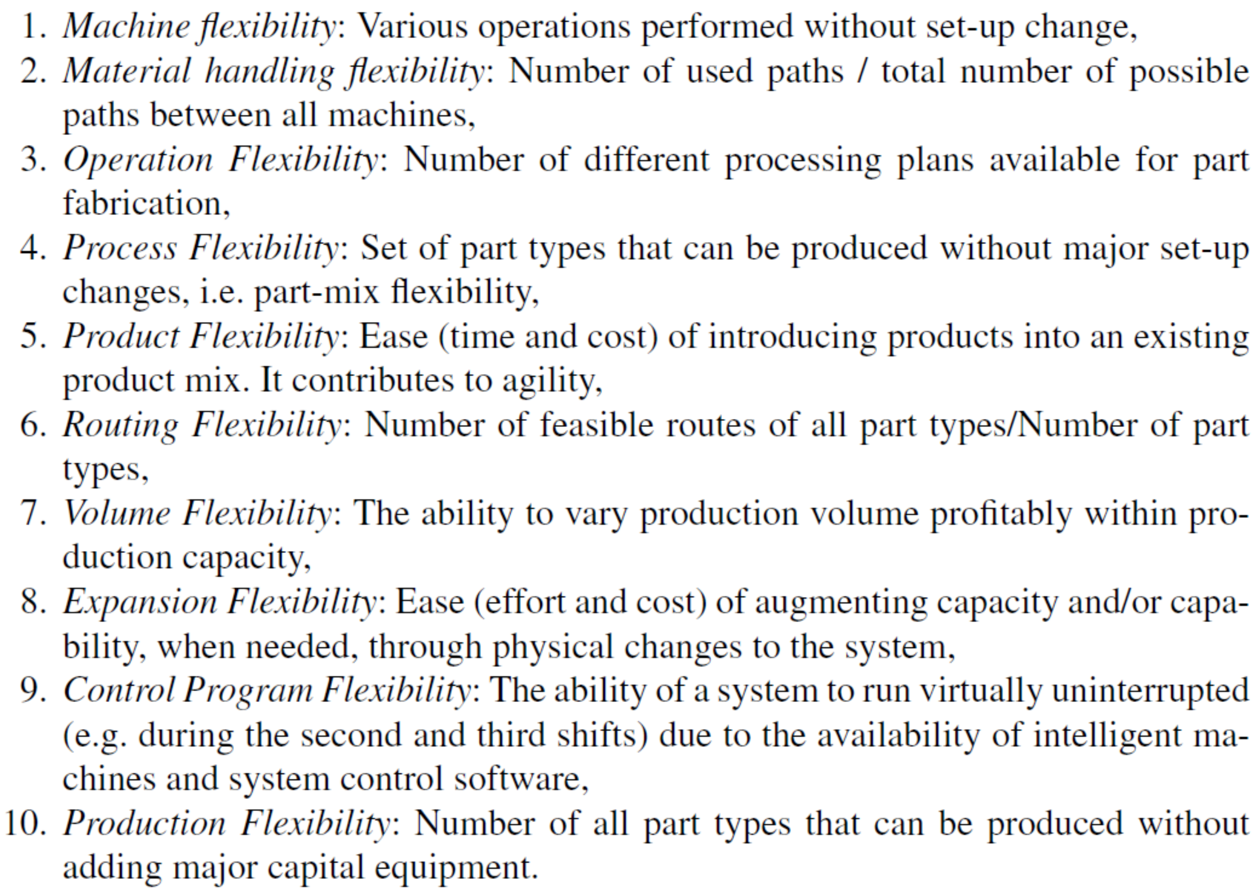
Appendix 6.2 - Manufacturing flexibility areas

Manufacturing flexibility areas as defined by (El Maraghy, 2006)

Product Flexibility
The ability of a manufacturing system to make a variety of part types. The ability of the system to adapt to changing demands for various products. Including machine flexibility, process flexibility, production flexibility and part flexibility.

Capacity flexibility
The ability of the manufacturing system to vary the production volume of products and the ability to contract or expand. Including Volume flexibility and expansion flexibility.

Operation Flexibility
The ability of a system to produce a set of products using different machines, materials and sequence of operations. Including operation flexibility, material handling flexibility, routing flexibility and control program flexibility.

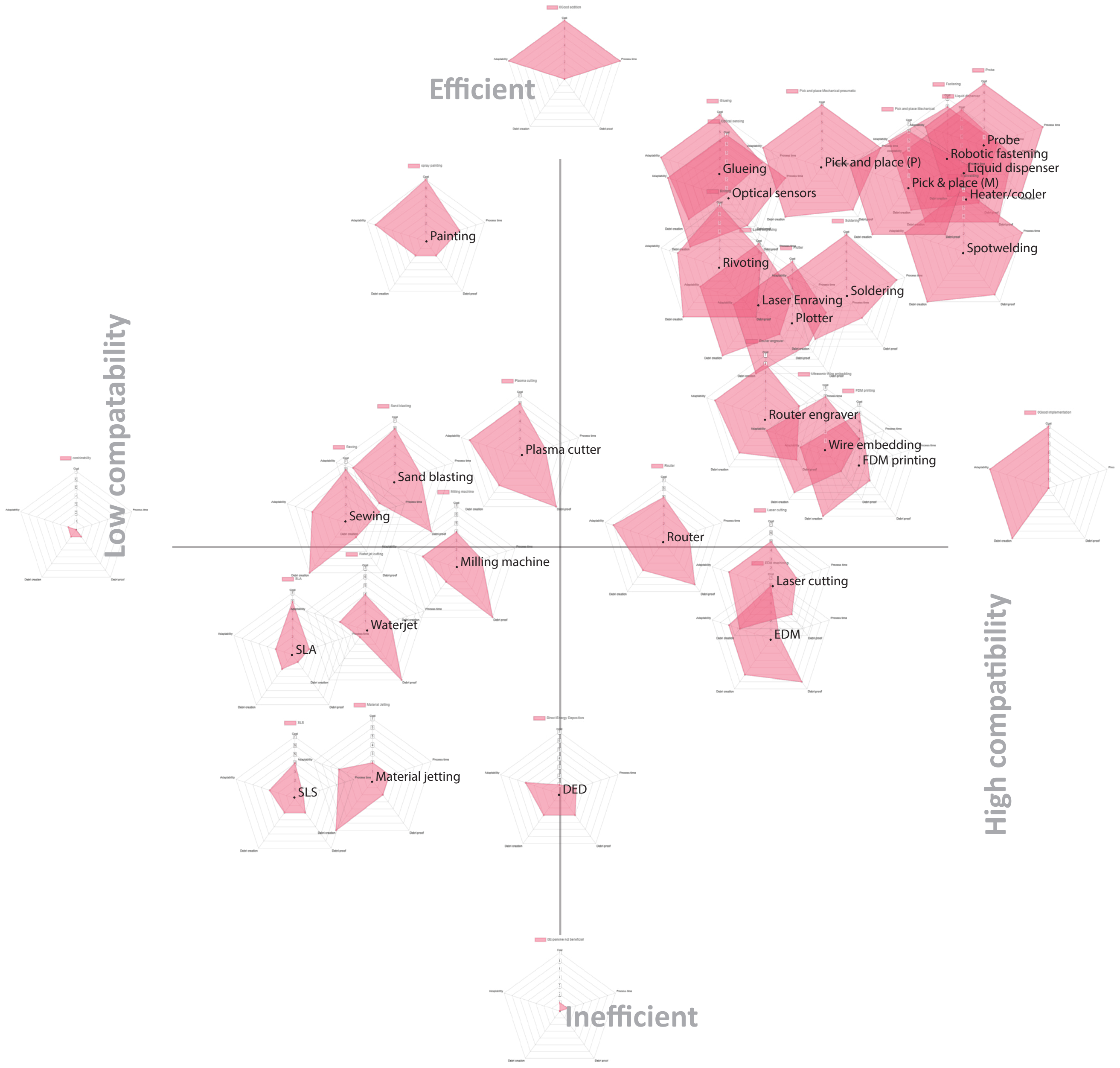


1. *Machine flexibility*: Various operations performed without set-up change,
2. *Material handling flexibility*: Number of used paths / total number of possible paths between all machines,
3. *Operation Flexibility*: Number of different processing plans available for part fabrication,
4. *Process Flexibility*: Set of part types that can be produced without major set-up changes, i.e. part-mix flexibility,
5. *Product Flexibility*: Ease (time and cost) of introducing products into an existing product mix. It contributes to agility,
6. *Routing Flexibility*: Number of feasible routes of all part types/Number of part types,
7. *Volume Flexibility*: The ability to vary production volume profitably within production capacity,
8. *Expansion Flexibility*: Ease (effort and cost) of augmenting capacity and/or capability, when needed, through physical changes to the system,
9. *Control Program Flexibility*: The ability of a system to run virtually uninterrupted (e.g. during the second and third shifts) due to the availability of intelligent machines and system control software,
10. *Production Flexibility*: Number of all part types that can be produced without adding major capital equipment.

Appendix 6.3 - Digital fabrication evaluation

Score	7 →	1
Cost	Good addition Cost effective to implement	Too expensive to combine Can benefit from additions with low cost and procces time
Process Time	Good addition Time effective process to combine	Ineffective to combine Can be combined with cost effective additions
Adaptability	Very combinable Easy to combine with other machines	Difficult to combine Does not fit modular hybrid fabrication
Debri Proof	Robust & Combinable Robust and easy to combine	Fragile Only combine with clean processes
Dirt creation	Clean process Can be combined with Fragile processes	Dirty process only combine with robust processes

Efficient
Support process
Good addition
Ideal for hybrid fabrication



Appendix 6.4 - Digital fabrication combination matrix

	⬜ Not compatible /Bad combination	░ little benefit	🟩 Good Combination		Additive manufacturing											
	Laser cutter	Laser Engraver	Mill	Router	Material extrusion	Light polymerized	Powder bed	Material jetting	Direct energy depositin	Water jet cutter	Plasma cutter	Pick & Place	Dispenser	Spot welder	Arc welder	Sensor	Solder Iron
Laser cutter	⬜	🟩	░	░	░	⬜	⬜	░	░	⬜	⬜	🟩	🟩	🟩	░	🟩	░
Laser Engraver	🟩	⬜	🟩	🟩	🟩	⬜	⬜	░	░	⬜	⬜	🟩	🟩	⬜	⬜	🟩	░
Mill	░	🟩	⬜	░	░	⬜	⬜	⬜	🟩	⬜	⬜	🟩	░	░	🟩	🟩	░
Router	░	🟩	░	⬜	░	⬜	⬜	⬜	░	⬜	⬜	🟩	░	⬜	⬜	🟩	░
Material extrusion	░	🟩	░	░	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟩	🟩	⬜	⬜	🟩	░
Light polymerized	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	░	░	⬜	⬜	🟩	⬜
Powder bed	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	░	░	⬜	⬜	🟩	░
Material jetting	░	░	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟩	░
Direct energy depositin	░	░	🟩	░	⬜	⬜	⬜	⬜	⬜	⬜	░	░	░	🟩	░	🟩	░
Water jet cutter	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	░	⬜	⬜	⬜	⬜	🟩	⬜
Plasma cutter	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	░	⬜	░	⬜	⬜	⬜	⬜	🟩	░
Pick & Place	🟩	🟩	🟩	🟩	🟩	░	░	⬜	░	⬜	⬜	⬜	🟩	⬜	⬜	🟩	🟩
Dispenser	🟩	🟩	░	░	🟩	░	░	⬜	░	⬜	⬜	🟩	⬜	⬜	⬜	🟩	🟩
Spot welder	🟩	⬜	░	⬜	⬜	⬜	⬜	⬜	🟩	⬜	⬜	⬜	⬜	⬜	⬜	🟩	░
Arc welder	░	⬜	🟩	⬜	⬜	⬜	⬜	⬜	░	⬜	⬜	⬜	⬜	⬜	⬜	🟩	⬜
Sensor	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	⬜	🟩	🟩	🟩	🟩	🟩	⬜	🟩
Solder Iron	░	░	░	░	░	⬜	░	⬜	░	⬜	░	🟩	🟩	░	⬜	🟩	⬜

Appendix 6.5 - Concept evaluation

Based on the product scenario I estimated a production time for both Ben's TM system (seperate TM) and using hybrid manufacturing.

I have kept the printing time the same, only I have included the loading/unloading of the pallets in the calculation + the separate or joint assembly in the machine.

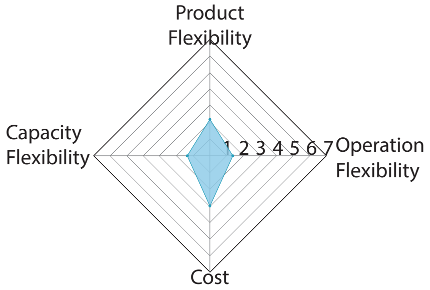
This brought me to 16,000 seconds for Hybrid and 15,980 seconds for TM. The difference lies in the fact that TM has to load more often, but Hybrid assembles on the same system.

This allowed me to estimate the number of products that can be produced with 100 Modules. Then I made a rough price estimate of the systems based on the sales price of a premium mouse. The price estimate is based on a factory that runs 24/7 and is constantly producing.

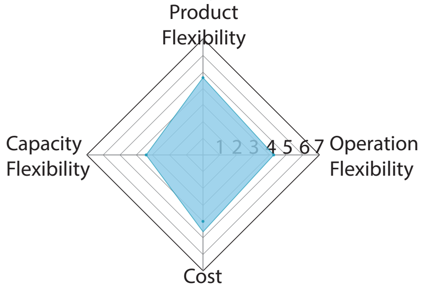
I've added a rough system efficiency to the equation. It also takes into account the maintenance and changing of fillament of the modules. This also clearly shows the difference in maintenance of the systems, but I still have to look more closely at the service & maintenance costs.

Finally, I compare the investment costs with the annual turnover of the system. For example, you can see that the investment costs are also higher relative to the turnover, but that automation does provide extra turnover.

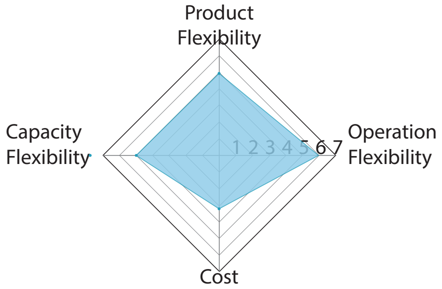
Dedicated manufacturing system



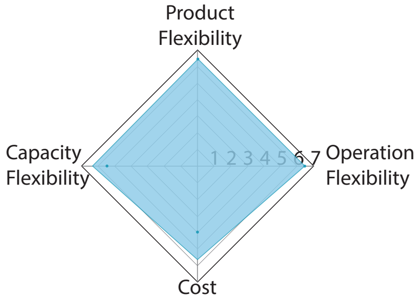
In line system



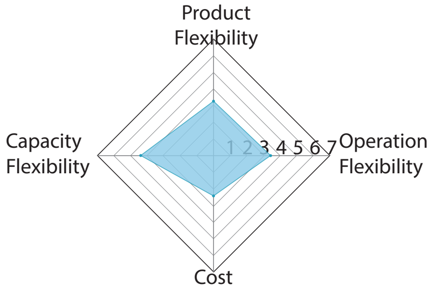
Target System



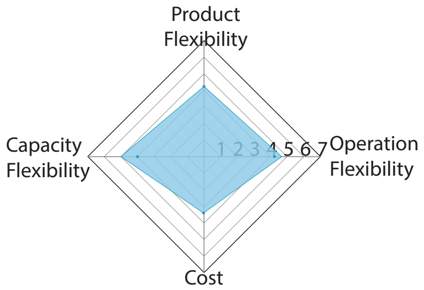
Shared system

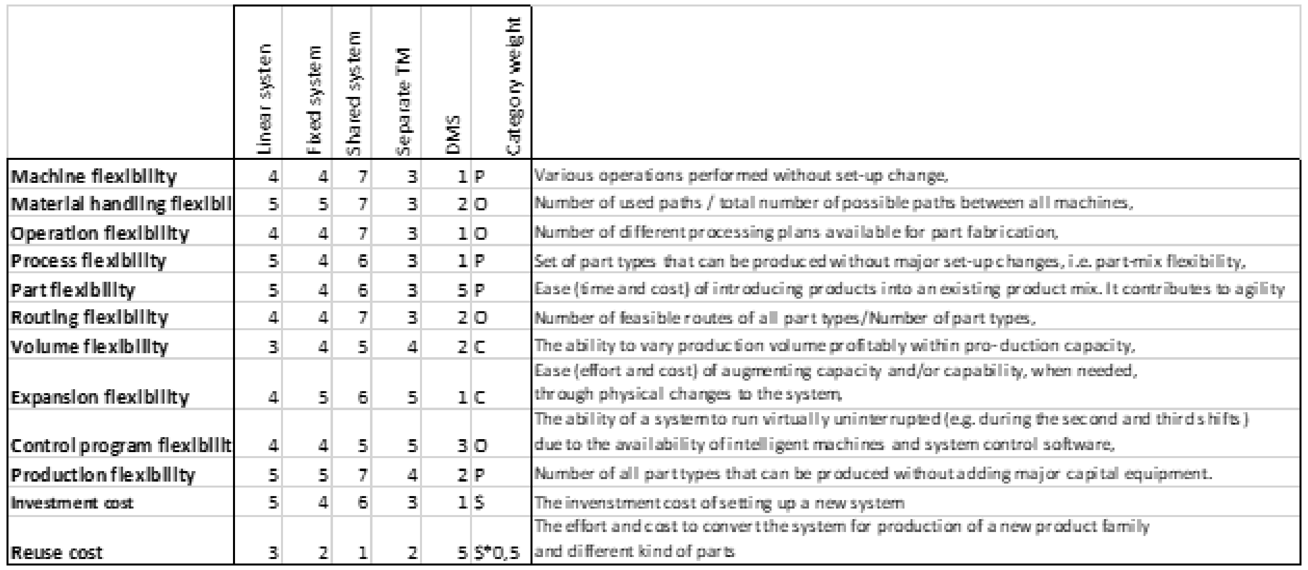


Seperate TM

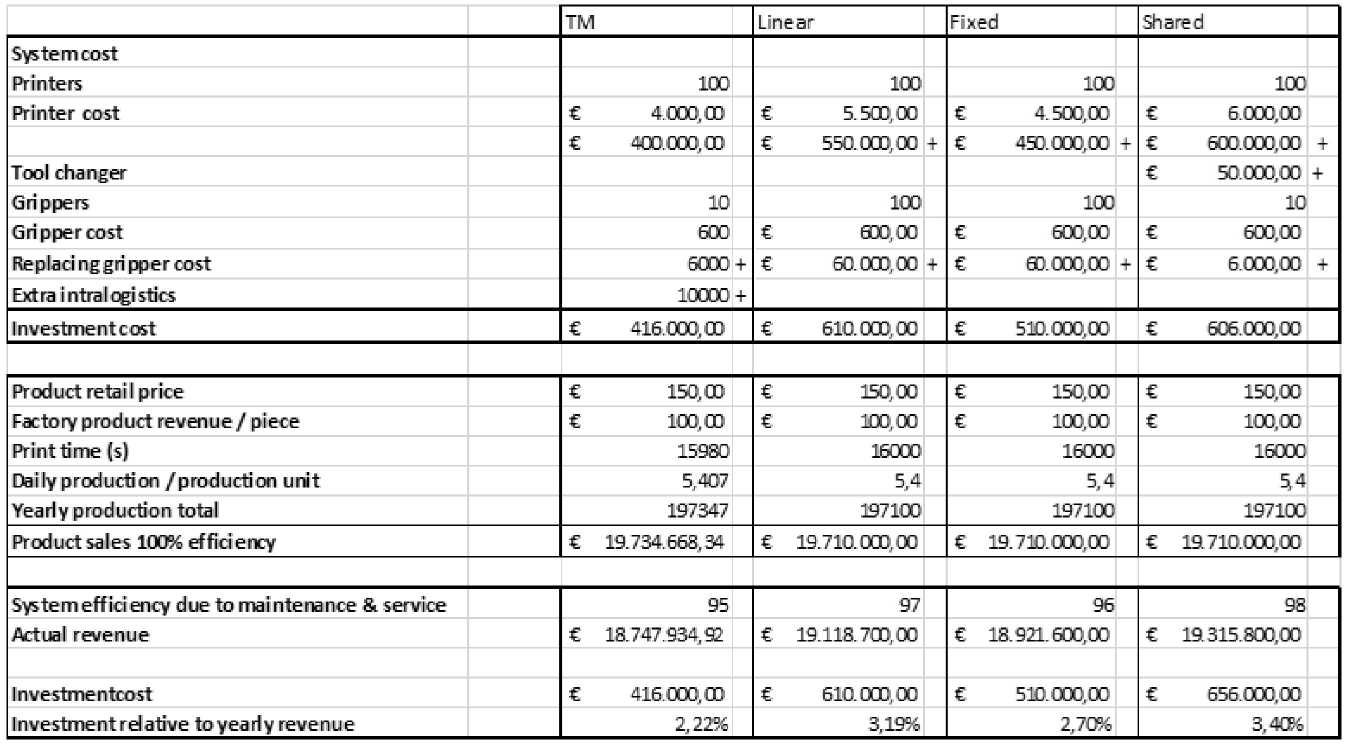


Fixed System



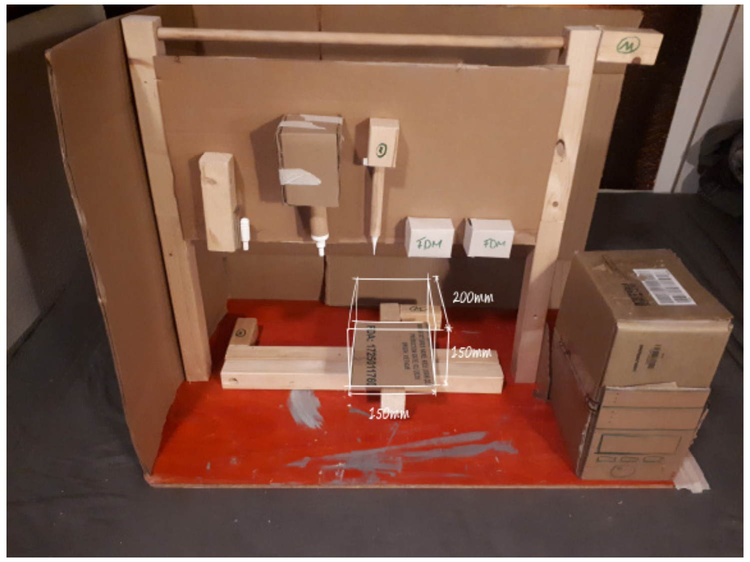


	Linear systen	Fixed system	Shared system	Separate TM	DMS	Category weight	
Machine flexibility	4	4	7	3	1	P	Various operations performed without set-up change,
Material handling flexibil	5	5	7	3	2	O	Number of used paths / total number of possible paths between all machines,
Operation flexibility	4	4	7	3	1	O	Number of different processing plans available for part fabrication,
Process flexibility	5	4	6	3	1	P	Set of part types that can be produced without major set-up changes, i.e. part-mix flexibility,
Part flexibility	5	4	6	3	5	P	Ease (time and cost) of introducing products into an existing product mix. It contributes to agility
Routing flexibility	4	4	7	3	2	O	Number of feasible routes of all part types/Number of part types,
Volume flexibility	3	4	5	4	2	C	The ability to vary production volume profitably within pro-duction capacity,
Expansion flexibility	4	5	6	5	1	C	Ease (effort and cost) of augmenting capacity and/or capability, when needed, through physical changes to the system,
Control program flexibilit	4	4	5	5	3	O	The ability of a system to run virtually uninterrupted (e.g. during the second and third shifts) due to the availability of intelligent machines and system control software,
Production flexibility	5	5	7	4	2	P	Number of all part types that can be produced without adding major capital equipment.
Investment cost	5	4	6	3	1	S	The invenstment cost of setting up a new system
Reuse cost	3	2	1	2	5	S*0,5	The effort and cost to convert the system for production of a new product family and different kind of parts

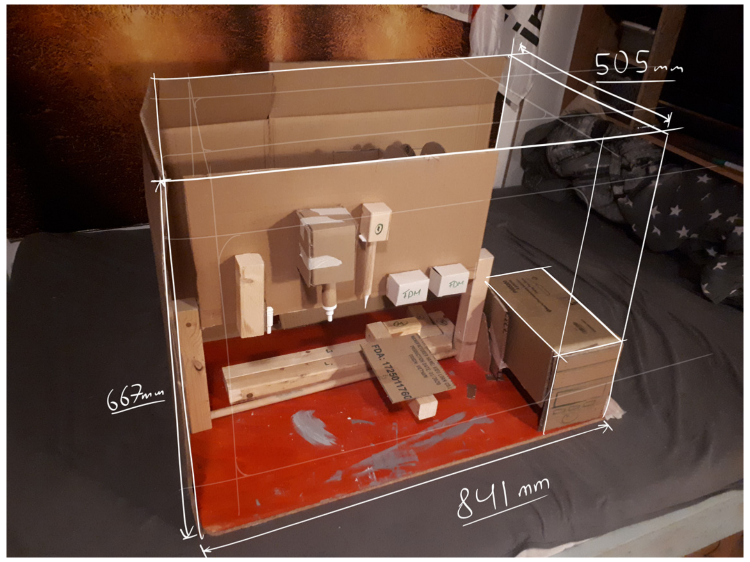


	TM		Linear		Fixed		Shared	
System cost								
Printers	100		100		100		100	
Printer cost	€ 4.000,00		€ 5.500,00		€ 4.500,00		€ 6.000,00	
	€ 400.000,00		€ 550.000,00	+	€ 450.000,00	+	€ 600.000,00	+
Tool changer							€ 50.000,00	+
Grippers	10		100		100		10	
Gripper cost	600		€ 600,00		€ 600,00		€ 600,00	
Replacing gripper cost	6000	+	€ 60.000,00	+	€ 60.000,00	+	€ 6.000,00	+
Extra intralogistics	10000	+						
Investment cost	€ 416.000,00		€ 610.000,00		€ 510.000,00		€ 606.000,00	
Product retail price	€ 150,00		€ 150,00		€ 150,00		€ 150,00	
Factory product revenue / piece	€ 100,00		€ 100,00		€ 100,00		€ 100,00	
Print time (s)	15980		16000		16000		16000	
Daily production / production unit	5,407		5,4		5,4		5,4	
Yearly production total	197347		197100		197100		197100	
Product sales 100% efficiency	€ 19.734.668,34		€ 19.710.000,00		€ 19.710.000,00		€ 19.710.000,00	
System efficiency due to maintenance & service	95		97		96		98	
Actual revenue	€ 18.747.934,92		€ 19.118.700,00		€ 18.921.600,00		€ 19.315.800,00	
Investmentcost	€ 416.000,00		€ 610.000,00		€ 510.000,00		€ 656.000,00	
Investment relative to yearly revenue	2,22%		3,19%		2,70%		3,40%	

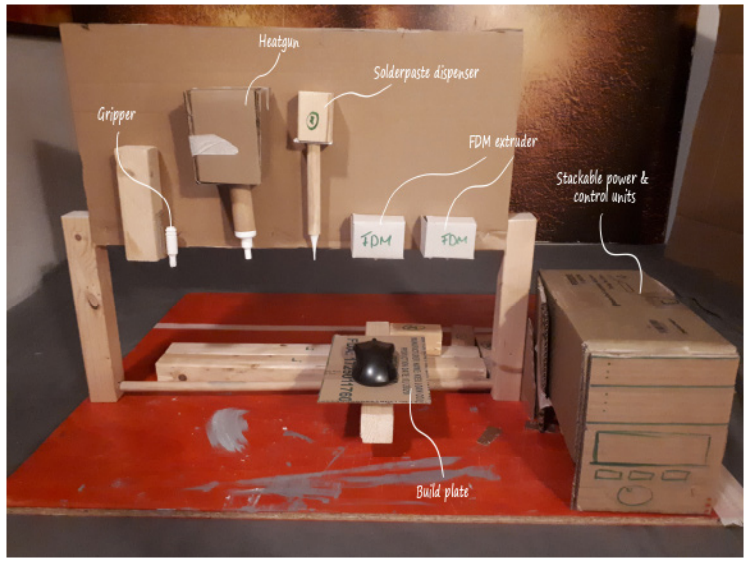
Appendix 6.6 - Workstation configuration prototyping



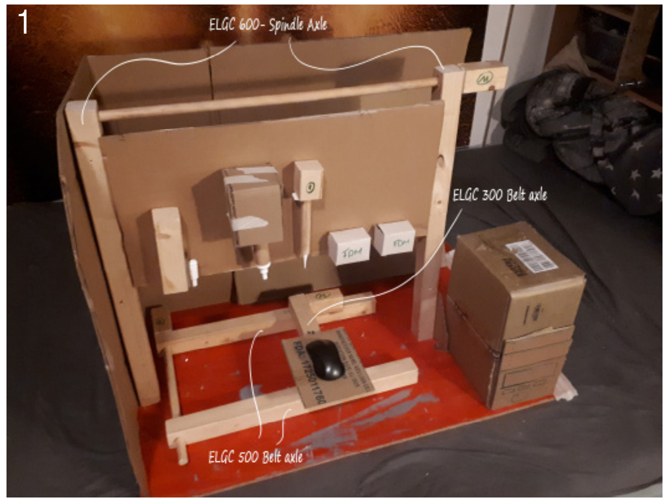
Prototyping:
I have started to blockout and create the system. For this I created a prototype from cardboard and wood. This allowed me to quickly get hold of the required size and possible arrangements.For the build volume I determined the required build volume to be 150mm x 200mm x 150mm.This is baed on the size of controllers and computer mouses. I also determined that the system need to hold atleast 4 tools with the size of 100mm x 100mm x 300mm.



Format:
The modules are following the industrial standard as proposed by Ben Kromhout.This industrial standard is build so machines can be efficiently be stacked. For the size ofthe hybrid stations I will keep to A1 which is 841mm x 505mm x 667mm. While prototyping it was possible to fit the system within this frame.



Toolset:
The toolset that I used for the prototype is a toolset that is able to print integrated electronics into the part. It includes two extruders for multi material printing, a solder paste dispenser, a heatgun and a pneumatic gripper.



Using double guides for the x-axis. For the Y-axis 600mm linear actuators are used which are connected on the top with an shaft.

Instead of using double guides a bigger linear actuator is used for the X movement. For the Y-axis 600mm linear actuators are used.

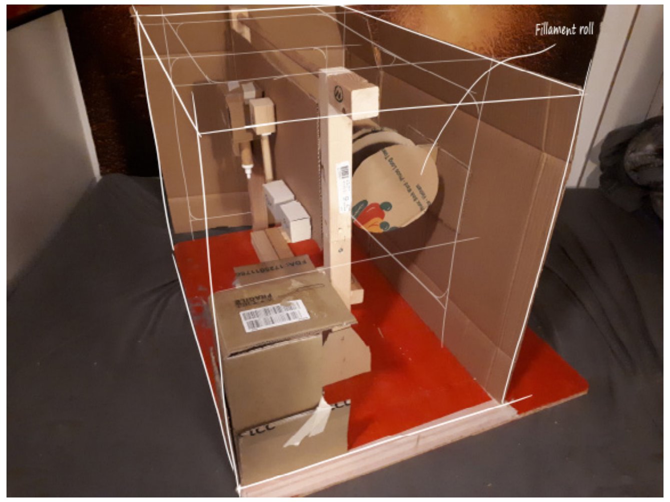
Setup with multiple drive axles and both the X and Y axis have double guides. The actuator and guides are placed so the axles won't interfere. Therefore longer x axis actuators are needed.

Instead of using double guides a bigger linear actuator is used for the X movement.

For this setup the Z axis is inplane with the X axis which gives extra build volume in the Y direction.

This setup also has the Z-axis in plane but uses a single bigger actuator for the Y-axis

Out of the 6 configurations 2,5&6 are the most promising solutions.



Behind the tool rack there is space for extra materials that might be required by the tools. Like fillament for fdm printing. Next up I will be working on designing a toolrack that makes it easy to place and allign tools and I will also work on a solution that enables easy installment of the extra materials required by the tools.

Appendix 6.7 - Workstation components list

Component	**Comp. number.**	**1st level Part**	**Part. number.**	**2nd level Part**	**Part. number**
Total	CNC21_00.000.000_C				
ToolArm	CNC21_01.000.000_D				
		Z actuator	CNC21_01.010.000_D		
				EGC-80-700-BS	CNC21_01.010.010_A
				80 BS slider	CNC21_01.010.011_A
				EMMS-ST-87-M-SB-G2	CNC21_01.010.020_A
				Shaft adapter	CNC21_01.010.030_A
				Motor mount	CNC21_01.010.040_AA
				Motor Mount Top plate (M)	CNC21_01.010.040_A
				Motor Mount 1 (M)	CNC21_01.010.041_A
		Z arm	CNC21_01.020.000_B		
				Allu 20x80 profile	CNC21_01.020.010_A
				Index plate	CNC21_01.020.015_A
				Coupling plate	CNC21_01.020.020_C
				Nema 17 motor	CNC21_01.020.030_A
				Shaft motor adapter	CNC21_01.020.031_C
				Motor mount plate	CNC21_01.020.032_A
				Shaft mount plate	CNC21_01.020.035_C
				Shaft mount Bearing	CNC21_01.020.036_A
				Shaft mount adapter	CNC21_01.020.037_A
				Tool select shaft	CNC21_01.020.040_A
				Tool select Cam Core	CNC21_01.020.041_F
				Tool select Cam sides	CNC21_01.020.042_F
				Tool select Cam Assembly	CNC21_01.020.049_F
		Dynamic Toolplate	CNC21_01.030.000_A		
				Hinge plate	CNC21_01.030.020_E
				Hinge shaft	CNC21_01.030.021_A
				Hinge Spring	CNC21_01.030.022_A
				Hinge plate guide pins	CNC21_01.030.023_A
				Tool lever	CNC21_01.030.025_M
				Tool dovetail	CNC21_01.030.026_A
				Tool plate D	CNC21_01.030.040_E
				Plate spring	CNC21_01.030.050_A
				Micro adjustment plate	CNC21_01.030.070_A
				Micro adjustment ball	CNC21_01.030.071_B
				Micro adjustment slider	CNC21_01.030.072_D
				Ender mount	CNC21_01.030.080_A
		Static Toolplate	CNC21_01.040.000_C		
				Guide knob	CNC21_01.040.010_A
		Universal plate	CNC21_01.050.000_A		
		FDM Print Tool	CNC21_01.100.000_A		
				Extruder toolbracket bottom	CNC21_01.100.010_A
				Extruder toolbracket Top	CNC21_01.100.011_A
				Hotend	CNC21_01.100.020_A
				Extruder	CNC21_01.100.030_A
		Syringe tool	CNC21_01.110.000_A		
				Solder Tool holder Back	CNC21_01.110.010_A
				Solder Tool holder Front	CNC21_01.110.011_A
				Solder syringe	CNC21_01.110.020_A
				Plunger	CNC21_01.110.021_A
				Plunger spacer	CNC21_01.110.022_A
				Measuring plate	CNC21_01.110.030_A
				Motor	CNC21_01.110.040_A
				Nema 16 Syringe motor	CNC21_01.110.090_A

Component	**Comp. number.**	**1st level Part**	**Part. number.**	**2nd level Part**	**Part. number**
		Heatgun tool	CNC21_01.120.000_A		
				Heatgun holder back	CNC21_01.120.010_A
				Heatgun holder front	CNC21_01.120.011_A
				Heatgun	CNC21_01.120.020_A
				Thermo resistor	CNC21_01.120.030_A
				Thermo resistor block	CNC21_01.120.031_A
				Electronics case	CNC21_01.120.090_A
		Tool plates	CNC21_01.030.000_A		
Printbed	CNC21_02.000.000_A				
		X actuator	CNC21_02.010.000_A		
				Limit switch bracket X	CNC21_02.010.010_C
		Y actuator	CNC21_02.020.000_A		
				Limit switch bracket Y	CNC21_02.020.010_C
		XY adapter	CNC21_02.030.000_B		
		Printbed			
Electronics	CNC21_03.000.000_A				
		Heatgun electronics	CNC21_03.010.000_A		
				Heatgun bottom case	CNC21_03.010.010_A
				Heatgun top case	CNC21_03.010.011_A
				Dimmer	CNC21_03.010.020_A
				arduino	CNC21_03.010.030_A
				heatgun board	CNC21_03.010.040_A
Support system	CNC21_04.000.000_A				
				Din rail	CNC21_04.000.010_A
				Fillament roll	CNC21_04.000.020_A
				Spool holder	CNC21_04.000.021_A
Chassis	CNC21_05.000.000_C				
		Corners	CNC21_05.000.001_A		
		Hardware	CNC21_05.010.000_A		
				Elecetronics leds	CNC21_05.010.010_B
				Electronics	CNC21_05.010.011_A

Appendix 6.8 - Prototyping parts

Component	Part name	Count #
Y Rail	DGEA-18-240-ZR-GVL	1
X Rail	EGC-80-1250-TB-KF	1
Z Rail	EGC-80-700-BS	1
Stepper Z	EMMS-ST-87-M-SB-G2	1
Stepper driver	DM556s	3
Stepper XY	24hs39-3008d	2
AC Dimmer	RobotDyn AC Dimmer 3.3-5V - 4C	1
Solder Extruder stepper	16HSL3404	1
Nema 17 Stepper	42-40	2
Toolrack Profile	2080 T-Slot aluminium 400mm	1
Arduino Uno	Arduino Uno	2
Raspberry Pi	Raspberry pi 4	1
Hotend	Hotend V6 - Bowden - 1.75mm - 12V	1
Thermoresister Heatgun	NTC 100K 3950	1
Ender motherboard	Ender V21.1.4	1

Appendix 6.9 - Klipper configuration

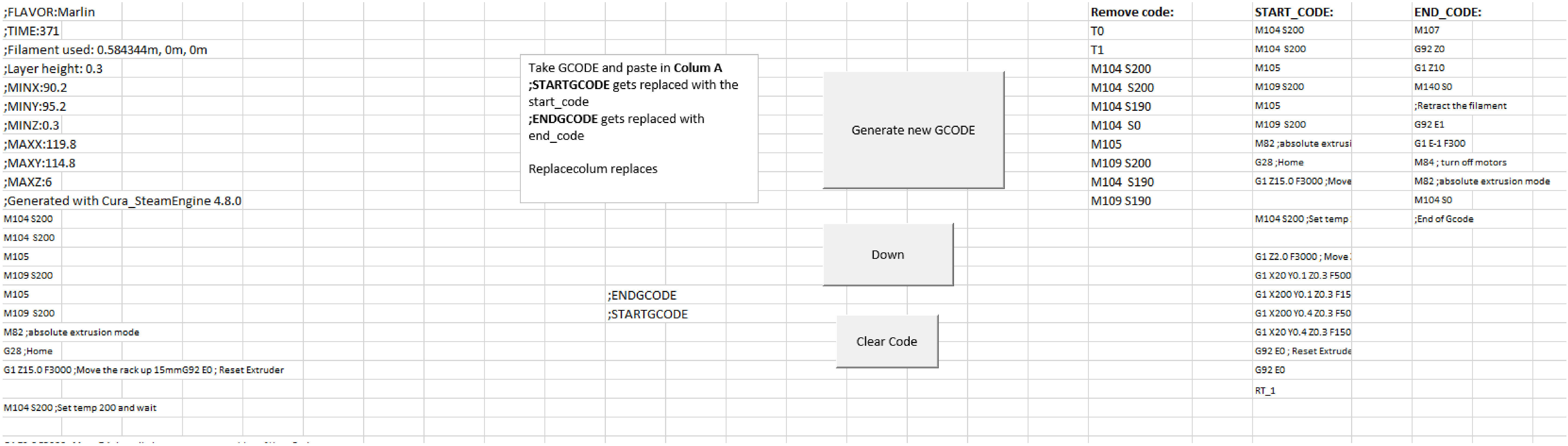
Important: during the flashing of the drive mcu, the pulse length of the motor signal has to be lengthend otherwise the stepper motors will not work. The pulse length has to be greater then 3mili seconds.

```
[mcu E3]
serial: /dev/serial/by-id/usb-1a86_USB_Serial-
if00-port0
[fan]
pin: E3:PB4

[mcu]
serial: /dev/serial/by-id/usb-Arduino__www.
arduino.cc__0043_754353530353517090B1-
if00
pin_map: arduino

[mcu hot]
serial: /dev/serial/by-id/usb-Arduino__www.
arduino.cc__0043_95233353131351415162-
if00
pin_map: arduino

############Arduino
[stepper_x]
step_pin: ar2
dir_pin: !ar3
endstop_pin: !ar4
microsteps: 400
rotation_distance: 4500
position_endstop: 0
position_max: 400

[stepper_y]
step_pin: ar6
dir_pin: ar7
endstop_pin: !ar8
microsteps: 400
rotation_distance: 1350
position_endstop: 0
position_max: 300

[stepper_z]
step_pin: ar10
dir_pin: ar11
endstop_pin: !ar12
microsteps: 400
rotation_distance: 1250
position_endstop: 0
position_max: 300

[extruder] #ender Y as > FDM extruder
step_pin: E3:PC6
dir_pin: E3:PC7
enable_pin: !E3:PD6
microsteps: 16
rotation_distance: 22.5
nozzle_diameter: 0.400
filament_diameter: 1.750
heater_pin: E3:PD5
sensor_pin: E3:PA7
sensor_type: NTC 100K beta 3950


control: pid
pid_Kp: 21.527
pid_Ki: 1.063
pid_Kd: 108.982
min_temp: -46.9
max_temp: 250


# Secondary extruder
[extruder1]
step_pin: E3:PD7
dir_pin: !E3:PC5
enable_pin: !E3:PD6
microsteps: 16
rotation_distance: 33.500
```

```
nozzle_diameter: 0.500
filament_diameter: 1.75

heater_pin: E3:PD4
sensor_pin: E3:PA6
sensor_type: EPCOS 100K B57560G104F

control: pid
pid_Kp: 21.527
pid_Ki: 1.063
pid_Kd: 108.982
min_temp: 0
max_temp: 250

[extruder2] #arduino hot
max_extrude_only_distance: 100.0
step_pin: E3:PB3
dir_pin: E3:PB2
enable_pin: !E3:PA5
microsteps: 16
rotation_distance: 2.15

nozzle_diameter: 0.400
filament_diameter: 1.750
heater_pin: hot:ar4
sensor_type: NTC 100K beta 3950
sensor_pin: hot:PC0

control: pid
#tuned for stock hardware with 200 degree
Celsius target
pid_Kp: 21.527
pid_Ki: 1.063
pid_Kd: 108.982
min_temp: -200
max_temp: 999
min_extrude_temp: -199

# hot air gun
[extruder3]
step_pin: hot:ar6
dir_pin: hot:ar7
#enable_pin: !E3:PD6
microsteps: 16
rotation_distance: 33.500
nozzle_diameter: 0.500
filament_diameter: 1.75

sensor_pin: hot:PC1
heater_pin: !hot:ar10

sensor_type: EPCOS 100K B57560G104F

control: pid
pid_Kp: 21.527
pid_Ki: 1.063
pid_Kd: 108.982
min_temp: -200
max_temp: 250

[manual_stepper toolSelect] #Ender E
connection
step_pin: E3:PB1
dir_pin: E3:PB0
enable_pin: !E3:PD6
microsteps: 16
rotation_distance:120
velocity: 200
accel: 100


#[static_digital_output my_output_pins]
#pins: !hot:ar10

#[heater_bed]
#heater_pin:  !ar13 #E3:PD4
#sensor_type: NTC 100K beta 3950
#sensor_pin: E3:PA6
#control: pid
# tuned for stock hardware with 50 degree
Celsius target
#pid_Kp: 54.027
#pid_Ki: 0.770
#pid_Kd: 948.182
#min_temp: 0
#max_temp: 500

[printer]
kinematics: cartesian
max_velocity: 3000
max_accel: 500
max_z_velocity: 1000
max_z_accel: 200

#rotate toolselect full circle
[gcode_macro T000]
gcode:
   ACTIVATE_EXTRUDER EXTRUDER=extruder
          MANUAL_STEPPER STEPPER=toolSelect
ENABLE=1 SET_POSITION=0 SPEED=300
ACCEL=100 MOVE=60 #rotate toolselect
   SET_GCODE_OFFSET Z=0 MOVE=1                #
Adjust z-height
   SET_GCODE_OFFSET X=0                       # Clear
X offset

#rotate toolselect full circle
[gcode_macro RT_1]
gcode:
          SAVE_GCODE_STATE
          G92 Z0
          G92 E0
          G1 E-6
          G1 Z10 F2000

          MANUAL_STEPPER STEPPER=toolSelect
ENABLE=1 SET_POSITION=0 SPEED=300
ACCEL=100 MOVE=160
          M400

          G1 Z0 F2000
          ;G1 E3
          G92 E0
          RESTORE_GCODE_STATE

# Script to activate second extruder
```

Appendix 6.10 - Toolpath creation

A custom excel script was made to replace and inject custom gcode in the generated gcode from Cura This prevents the long wait cycles that Cura creates and prevents dripping. This could also be done by hand however with long gcode files this would be unreasonable.



```
;FLAVOR:Marlin
;TIME:371
;Filament used: 0.584344m, 0m, 0m
;Layer height: 0.3
;MINX:90.2
;MINY:95.2
;MINZ:0.3
;MAXX:119.8
;MAXY:114.8
;MAXZ:6
;Generated with Cura_SteamEngine 4.8.0
M104 S200
M104  S200
M105
M109 S200
M105
M109  S200
M82 ;absolute extrusion mode
G28 ;Home
G1 Z15.0 F3000 ;Move the rack up 15mmG92 E0 ; Reset Extruder

M104 S200 ;Set temp 200 and wait
```

Take GCODE and paste in **Colum A**
;STARTGCODE gets replaced with the start_code
;ENDGCODE gets replaced with end_code

Replacecolum replaces

```
;ENDGCODE
;STARTGCODE
```

Remove code:	START_CODE:	END_CODE:
T0	M104 S200	M107
T1	M104 S200	G92 Z0
M104 S200	M105	G1 Z10
M104 S200	M109 S200	M140 S0
M104 S190	M105	;Retract the filament
M104 S0	M109 S200	G92 E1
M105	M82 ;absolute extrusi	G1 E-1 F300
M109 S200	G28 ;Home	M84 ; turn off motors
M104 S190	G1 Z15.0 F3000 ;Move	M82 ;absolute extrusion mode
M109 S190		M104 S0
	M104 S200 ;Set temp	;End of Gcode
	G1 Z2.0 F3000 ; Move	
	G1 X20 Y0.1 Z0.3 F500	
	G1 X200 Y0.1 Z0.3 F15	
	G1 X200 Y0.4 Z0.3 F50	
	G1 X20 Y0.4 Z0.3 F150	
	G92 E0 ; Reset Extrude	
	G92 E0	
	RT_1	

Appendix 6.11 - Supported tools

The following tools could be mounted on the system, individual considuration of each addition to the toolset should be evaluated depending on the compatibilty from Appendix 6.4.

Base

Router engraver
Wire embedding
FDM printing
LAser cutting

Addons

Probe
Robot fastening
Liquid dispenser
Pick & place (mechanical)
Heater
Cooler
Spotwelder
Reflow soldering
Laser engraver
Soldering
PLotter
Rivoting
Optical sensors
Glueing
Pick & place (pneumatic)