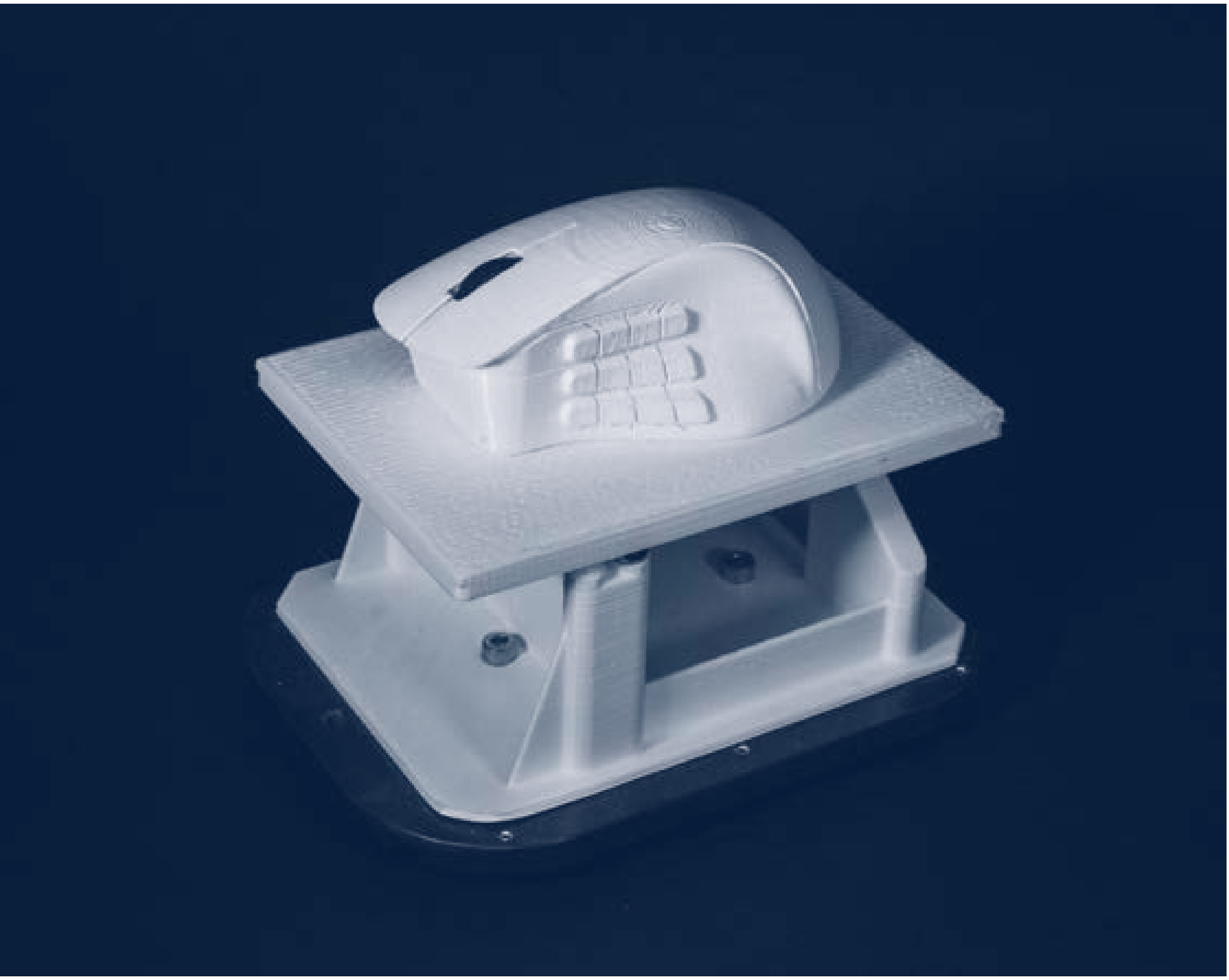

TRANSCENDED MANUFACTURING

THE MASS-PRODUCTION OF ONE-OF-A-KIND PRODUCTS

DELFT UNIVERSITY OF TECHNOLOGY

INDUSTRIAL DESIGN ENGINEERING
MECHANICAL ENGINEERING

CONTENT

PARTS, CHAPTERS, AND SUB-CHAPTERS

Title: Transcended Manufacturing: The mass-production of one-of-a-kind products
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1. INTRODUCTION

Within this part of the report the context of the project is described and the problems within this context elaborated. The design challenge and assignment are discussed as well as the role of the stakeholders. Then the approach that is used to tackle the assignment is elaborated. This information is used to envision a solution to described problems in the phase after Introduction.

1.1. SUMMARY

OVERVIEW OF THE REPORT

INTRODUCTION

Within this part of the report the context of the project is described and the problems within this context elaborated. The design challenge and assignment are discussed as well as the role of the stakeholders. Then the approach that is used to tackle the assignment is elaborated. This information is used to envision a solution to described problems in the phase after the Introduction phase.

ASSIGNMENT

The project is divided into three sub-assignments:

- A future manufacturing context must be envisioned and the most important requirements synthesized.
- An implementation of this envisioned manufacturing system must be developed and validated.
- An exemplary-product producible by this system must be designed, showcasing the benefits of the envisioned manufacturing method.

ENVISION

Following the problem definition and assignment defined in the Introduction phase, the current state of manufacturing and how we got there is analyzed. A future context around a complete product-life-cycle is envisioned. Within this vision both the product as well as the factory are explored. The design tasks were performed in parallel, but they will be described in sequence. First the factory will be discussed: a manufacturing concept is synthesized, the underlying principles are analyzed, and a factory classification is done. Then the exemplary-product will be discussed: the underlying principles of product personalization are explored, and the principles of a product within the developed future context are described. The acquired knowledge gets integrated in a design brief and a list of directing requirements. These form together with the future vision, a starting point to design an actual realization of both product and factory in the phase after the Envision phase.

ACTUALIZATION

Following the design brief defined in the Envision phase, the conceptualization of both product and production need to go hand in hand. A realizable future production system must be accompanied by a product that showcases this manufacturing method and the other way around: the personalizable product-family requires a production system that is capable of producing these one-off-products at a high production-capacity. Both design tasks were performed in parallel, but they will be described in sequence in this part of the report. First the exemplary-product will be discussed: the choice, the conceptualization, and the embodiment. Then the Transcended production system will be discussed: the required standardization, the proposed production cluster, conceptualization of the production framework and embodiment of the initial prototype. This prototype can then be used for validation of the propped framework in the phase after the Actualization phase.

VALIDATION

In the Actualization phase a framework is proposed for the full, so called, pick-and-place on-printing process. This framework should be able to produce the designed computer mouse discussed in the 3.1. The Exemplary product. And a prototype is developed solving the most important FDM-Cabinet embodiment challenges, resulting in a working system.

The goals for this prototype are, firstly to demonstrate an initial framework that is able to produce a personalized consumer electronics product from start to finish at a mass-production output capacity (theoretically). And secondly to validate the pick-and-place on-printing process as a feasible method to produce multi-component parts.

The Core Functional Requirements for this prototype are discussed and validated in each of following sub-chapters. The last subchapter validates the Core Functional Requirements for the exemplary-product itself described in the 2.5.2. Product-family Requirements chapter (at the end of the Envision phase). The research findings will then be used for evaluation in the phase after the Validation phase.

EVALUATION

In the Validation phase the developed framework is analyzed on different axes, and the resulting findings discussed and validated. In this final chapters the achievements of the project: the developed future context, the exemplary-product and the production-framework are evaluated in terms of the original problem definition. Recommendations for the next step in research and development are described in terms of the original design brief. And finally a personal reflection is given.

1.1.1. GLOSSARY

In this chapter the most important definition used in this report are described. Both, definitions described in literature, as well as self-formulated definitions.

AGILE MANUFACTURING:
"Responding to, and taking advantage of changes through strategic utilisation of managerial and manufacturing methods and tools are the pivotal concepts of agile manufacturing." (Sharifi. H, & Zhang, Z. 2001).

CO-CREATION LEVELS:
"The methodology of including the consumer in the product design process is called co-design or co-creation." (Sanders, E. B., et.al. 2008).

COMPUTER AIDED MANUFACTURING (CAM):
The definition used in this report is the process of turning digital design files into workable production files useable by production equipment.

CUSTOMER ORDER DECOUPLING POINT: (CODP):
"The CODP is the point in the material flow where the product is tied to a specific customer order; the basic choices being make-to-stock, assemble- to-order, make-to-order, and engineer-to-order." (Olhager, J. 2010).

CUSTOMIZATION:
The definition used in this report is the adaptation of a product aspect during personalization process.

CUSTOMIZATION-CATEGORIES:
Defined in this report as clusters of personalization aspects that are different in term of experience. These are: personalization in terms of: Identity (perception), Fit (presence), and Capabilities (features).

CYBER-PHYSICAL SYSTEM (CPS):
"The systems where physical and software components are deeply intertwined, each operating on different spatial and temporal scales, exhibiting multiple and distinct behavioral modalities, and interacting with each other in a myriad of ways that change with context." (Khaitan, S. K., & Mccalley, J. D. 2014).

DIGITAL TWIN:
"A near-real-time digital image of a physical object or process that helps optimize business performance." (Parrott, A., & Lane, W. 2017).

DIRECT-DIGITAL-MANUFACTURING (DDM):
The definition used in this report is the ability of a production process to dirtily produce parts from digital files, without equipment setup-time.

EXEMPLARY-PRODUCT:
Defined in this report as a product-family direction or business-case that helps to demonstrate or show off certain aspects. In the case of this report: Mass-customization and the developed future context.

FUSED DEPOSITION MODELING (FDM):
The definition used in this report is a 3D-printng process that melts a plastic string into layers that build up a part from the bottom up.

INDUSTRY 4.0 (I4.0):
The so called fourth revolution defined by the German Industry 4.0 Working Group (Kagermann, et.al. 2013). It represents the digitalization of all manufacturing industries in the last decades.

LEAN MANUFACTURING:
"Lean is defined as a strategy for achieving significant continuous improvement in performance through the elimination of all wastes of resources and time in the total business process." (Gobinath, S. et.al. 2015).

MASS-CUSTOMIZATION:
"Mass customization aims to provide customer satisfaction with increasing variety and customization without a corresponding increase in cost and lead time". (Tseng, M. et. Al. 1996).

ON-PRINTING:
Defined in this report as the process of continuing with FDM-printing on a part that has sub-components placed inside.

PERSONALIZATION:
The definition used in this report is the act of adapting product aspects to match personal needs or wishes.

PERSONALIZATION LEVEL:
Defined in this report as the customization complexity of a product aspect, resulting from the number possible realizations due to a applied customization resolution range.

PROCESS-GENERALITY:
Is defined in this report as an attribute of a production system or aspect, in which it is standardized and able to handle a multitude of variations within a defined framework.

PROCESS-MODULE:
Defined in the report as modular piece of process equipment.

PRODUCTION-CLUSTER:

Defined in this report as cluster of process modules comparable in characterization and capabilities.

PRODUCT-FAMILY:
"A product-family is simply defined as the set of all possible end-products from which the customer can make his selection." (Asbjørn, K., & Ditlev, T. 2011).

PRODUCT-FAMILY-MODEL:
"A model of a product-family, termed the product-family model, is then defined as a single model from which models of all end-products of the family can be derived." (Asbjørn, K., & Ditlev, T. 2011).

TRANSCENDED MANUFACTURING:
Defined in this report as the manufacturing method that uses product independent process steps to make one-of-a-kind products at a mass-production output capacity (it is a subset within mass-customization).

1.2. INTRODUCTION

WHAT STARTED THIS PROJECT

Until around 1760 agriculture was the most prominent industrial sector providing the primary human need; food. Other sectors contributed by providing the required tools and products to support this agricultural society. These products were made by artisans that were able to make highly personalisable build-to- order items, matching the customer's needs perfectly.

Fast forward to 2020, two industrial revolutions have gone by and we are currently in the third, bringing the world's economic output to unprecedented levels as well as the average standard of living. This leaves the population with more time and money to fulfill their needs and express themselves through consumerism, buying ever more personal products, creating more economic demand, activity, and growth; repeating the cycle.

The increased demand and expectations in consumer products results in short product-life-spans and volatile markets, increasing the pressure on existing supply-lines. Companies must keep providing novel products and make profit on shrinking margins.

The current lean-manufacturing mentality of optimizing productivity and reducing cost

is not enough (Sharifi & Zhang 2001). Having warehouses in low wage-countries full of the same mass-produced goods does not coincide with fast changing markets and the increasing need for mass-customized products; products that permit customized manufacturing on a mass basis (Davis, 1989).

As a society we try to keep up with this production-output, but invention and development seem to go faster than our ability to change our mindset and reflect on the implications locally, but also on a global scale. Resulting the depletion of natural materials and enormous amount of waste both on land and in the ocean.

With the information-age knowledge and technologies we have the world supply-system could already be improved. Developments such as Industry 4.0 by

the German Industry 4.0 Working Group (Kagermann, et.al. 2013), are already trying

to push a paradigm-shift in society, towards a more efficient, valuable, but mostly sustainable supply-chain and product-lifecycle. The smart-factory technologies that used to do this,

also enable mass-customization. Making the supply-chain capable of responding quickly to customer demand and enabling personalized products; closely matching consumer wishes and generating a better product-experience.

In this project the above described context is explored, a future scenario is envisioned, and an initial development step is proposed and demonstrated.

1.2.1. PROBLEM DEFINITION

The problem that this project deals with is threefold:

UNSATISFIED CONSUMERS

The world's population has more time and money to fulfill their personal needs and express themselves; with high expectations on consumer products that cannot be met with traditional mass-production methods.

PRESSURED SUPPLY-CHAINS

Short product-life-spans and volatile markets make it hard for companies to adapt their existing efficient supply-chains and keep delivering novel products.

GLOBAL IMPLICATIONS

Production and development seems to go faster than our ability to change our mindset and reflect on the implications resulting in an unsustainable global ecosystem.

These societal problems are the reason for a need paradigm-shift within manufacturing, which is still under-explored in terms of research and development. This report takes a step in solving this.

1.3. ASSIGNMENT

THE SCOPE OF THE PROJECT

This project is carried out as a final examination of the MSc Integrated Product Design and MSc Mechanical Engineering at Delft University of Technology. Both master directions require different competences that needed to be applied to the same project, giving it the dual character of both Industrial Design as well as Mechanical Engineering; each moving to the forefront at different stages of the process.

The project is executed for the department of Sustainable Design Engineering at the faculty of Industrial Design Engineering. It consists of an internal project and an internship. One external company was prominently involved, namely the operational company of Festo in the Netherlands. They were a supporting partner during this project and helped by bringing knowledge and insight at regular meetings and physical support by providing needed prototyping materials.

The project proposal was written as a part of ongoing research in the context of Agile Manufacturing and Industrial Design with Festo as partner. Festo observed that within their Industry 4.0 'CP Factory' the need for mass-customizable production was growing. To enable this they have asked to research and develop an agile manufacturing method to enable mass-customization within the Cyber-Physical Factory. The factory setup is then able to produce custom one-of-a-kind products on a mass-produced scale and clearly demonstrate cyber-physical-system principles (J. Koudijzer, personal communication, 25-10-2018).

This original assignment slowly evolved towards solving the societal problems described in the problem definition, trying to push the needed paradigm-shift within manufacturing and taking a first step. The project therefore revolves around research and demonstration, and was divided into three sub-assignments:

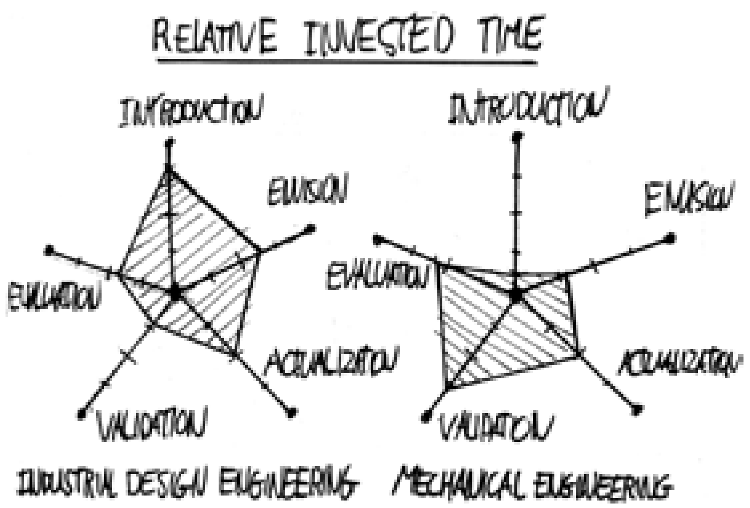
- A future manufacturing context must be envisioned and the most important requirements synthesized.
- An implementation of this envisioned manufacturing system must be developed and validated.
- An exemplary-product producible by this system must be designed, showcasing the benefits of the envisioned manufacturing method.

1.3.1. FESTO

Festo is a multinational company based in Germany and located in 61 countries worldwide. It was founded in 1925 and till this day it remains a family company. It transitioned from a manufacturer of wood cutting tools to an industrial control and automation company. The wood cutting branch separated into a new company Festool ("Company History", n.d.). Festo is a high-tech engineering company, specialized in pneumatic, mechatronic control and drive technology for factory automation. They are 'The engineers of productivity' ("Why Festo?", n.d.).

Festo Didactic is a part of the company. They are specialized in technical education and providing the required equipment. They have training solutions on multiple education levels, not only in factory automation but also on topics that are not in their own portfolio; for example; solar power ("Technical Education Solutions", n.d.). Also they provide local consultancy at the operational company for implementing Festo automation in the client's factory.

Festo spends eight percent of their annual revenues in innovation. They do research in bionics, superconductivity, automation movement and last but not least Industry 4.0 ("Innovation and technology", n.d.). They have a cyber-physical production setup which forms the framework that this project is developed in. This production setup is called the CP Factory and will be discussed in the 2.1.3. Festo CP Factory chapter.



1.3.2. APPROACH

The assignment was originally initiated following the basic design cycle of: analysis, synthesis, simulation, and evaluation (N.F.M. Roozenburg; J. Eekels. 1998), or in other terms: analysis, ideation, conceptualization and embodiment. Within this cycle, intermittent results such as, 'criteria' and 'provisional design' are assumed. These results can either be accepted to go to the next stage or be rejected for another design iteration.

Because of the dual character of the project, due to the two different master directions as well as designing both a production-system and an exemplary-product, it was not possible to follow one basic design cycle. Each separate assignment required its own cycle with decisions influencing each other.

To deal with these cross-dependencies a different overarching design cycle was applied. This developed design cycle has the following phases: Introduction, Envision, Actualization, Validation, and Evaluation. Within each of the phases some analysis, conceptualization, and embodiment is performed. The production system, and exemplary-product are developed step-wise in parallel. Each phase required different competences and therefore an unequal amount of work per master direction. The structure of the used design cycle, is also implemented to linearly document the report with minimal continuity errors. In the Envision part the factory is discussed followed by the product. In the Actualization part first the product and then the factory and in the Validation part, again, first the factory then the product.

The documented process goes from a broad abstract context to a very specific design. Insights are translated into requirements, which get transformed into design decisions. These pose research questions, that in turn get validated to get findings, that are used to give recommendations for further research.

2. ENVISION

state of manufacturing and how we got there is analyzed. A future context around a complete product-life-cycle is envisioned. Within this vision both the product as well as the factory are explored. The design tasks were performed in parallel, but they will be described in sequence. First the factory will be discussed: a manufacturing concept is synthesized, the underlying principles are analyzed, and a factory classification is done. Then the exemplary-product will be discussed: the underlying principles of product personalization are explored, and the principles of a product within the developed future context are described. The acquired knowledge gets integrated in a design brief and a list of directing requirements. These form together with the future vision, a starting point to design an actual realization of both product and factory in the phase after the Envision phase.

2.1. PRESENT MANUFACTURING

WHERE ARE WE AND HOW DID WE GET HERE

In the introduction a description is given from the current global supply-chain, and all the problems society faces as result of the existing consumerism and manufacturing mentality.

But how did we get to this point, this is discussed in the following chapter. The chapters thereafter go into current manufacturing developments and possible solutions to the defined problems.

2.1.1. HISTORY OF MANUFACTURING

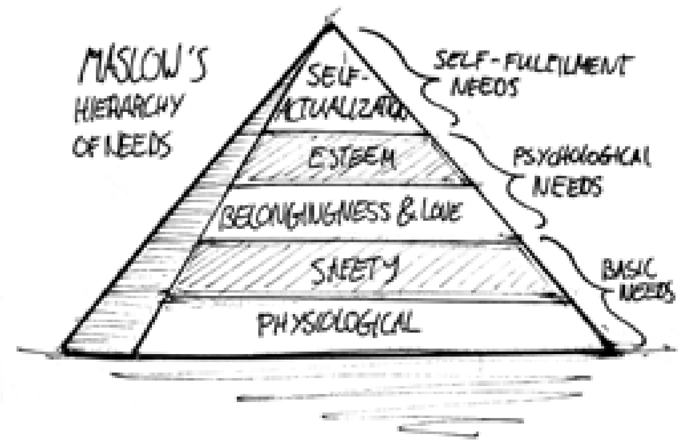
The world population not only grows but becomes more connected, therefore consumer interests change at an increasing rate while product performance must meet ever higher expectations. In these markets, products come and go, faster and faster, putting pressure on traditional supply lines.

To deliver and keep performing manufacturers change tactics, on the one hand, reducing their costs by making their process more streamlined or adaptable, and on the other, generating more value from products by letting consumers configure their own products.

These tactics and methods require state-of-the-art technology and rethinking the whole value-chain. This rethinking resulted in what is called Industry 4.0, or in other words the fourth industrial revolution by the German Industry 4.0 Working Group (Kagermann, et.al. 2013). But is it actually a revolution?

A. Maslow expressed in his 1954 book Motivation and Personality his theory on the hierarchy of needs, he described how humans intrinsically partake in behavioral motivation climbing the ladder from basic-needs, to psychological-needs, to self-fulfillment-needs.

This becomes relevant in the following part of the chapter. Here the industrial revolutions, and manufacturing methods that have been used up until that time are examined. Why these methods where relevant and how they shaped economic progression. The standard of living of the population, the climb towards self-actualization and the increased consumer product expectations are linked to these developments.



- Self-actualization needs: achieving one's full potential, including creative activities
- Esteem Needs: prestige and feeling of accomplishment
- Belongingness and love needs: intimate relationships, friends
- Safety needs: security, safety
- Physiological needs: food, water, warmth, rest

PROTO-INDUSTRIALIZATION

Before industrialization there was a time until 1760 called the proto-industrialization. This was a time where agriculture was the most important and large sector delivering on the most primary physiological needs namely food.

The required tools and products to support this agricultural society where made by artisans able to produce and repair custom products. These craftsman were connected to a guild that provided fair competition, protected trade secrets, and educated apprentices.

At the end of the 17th century a process started where production labor was diverted as sideline-activity during down-time of agricultural work, this provided more security for the population. As a result, the always policing guild-system, slowly collapsed and with it the closed-off crafts, which in turn generates more work and market value. This resulted in a growing population, more labor but also more demands from the population and this circle continued.

CRAFT/JOB-PRODUCTION:

Artisans where were able to make highly personalisable build-to-order products, matching the customer's needs. This was of course a slow process, depending on the expertise of the craftsman able to design and optimize the product.

This can, in certain fields, still be seen today, for example in the production personal inlay soles or earplugs. Here the minimal efficiency is compensated by the increased price of the products, which is possible due to the high generated personal value.

BATCH-PRODUCTION:

In this production method the products are made as specified groups of set amounts, within a set time frame. By implementing setups and manufacturing schedules it is possible to make the process more efficient and faster. The determined, or ordered amount is produced and delivered. And for the next batch the process can be optimized or adapted to fit new customer needs. Making the business approach flexible and agile.

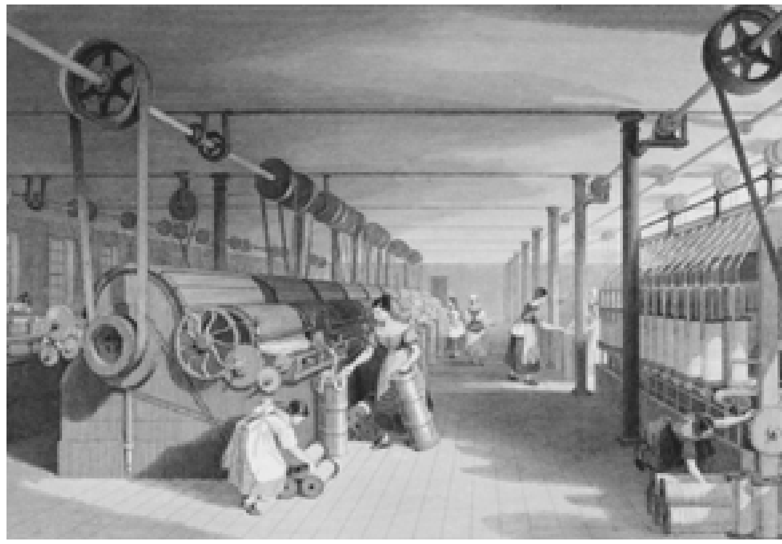
THE INDUSTRIAL REVOLUTION

The developments in the proto-industrialization and the change in manufacturing processes resulted in an extreme increase in productivity, which is called the first Industrial Revolution from 1760 until 1830. Creating new manufacturing needs which led to key developments such as the invention of the steam engine and the screw cutting lathe. This in turn enabled production of standardization of interchangeable parts and mechanization of bulk material processing (iron, coal and textile) into continuous-production. Labor become centralized in factories full of specialized workers turning standardized-parts and processed-material into batch-production goods, these developments led to enormous economic growth. The population started to earn more money and have more time for psychological needs such as belonging and connection. The cheap processed materials were also used by craftsmen to cater these needs, by producing personal products (job production).

This growth continued until the primary markets of the revolution matured and started an economic recession.

CONTINUOUS-PRODUCTION:

This production method, also called flow-production, enables bulk materials to be manufactured, produced, or processed into useful materials without interruption in a continuous flow. The products are measured in units, not in discrete quantities. The benefit is that these materials get transformed as fast and efficiently as possible. These general processed materials can then be used to make other products. Another benefit is that a lot of the mass and unwanted byproducts can be removed, before being transport thereby reducing costs.



DISCRETE-PRODUCTION:

This method is the opposite of continuous-production and refers to manufacturing resulting in individually identifiable products. Both job-production and batch-production are forms of discrete-production.

THE TECHNICAL REVOLUTION

The economic and scientific growth picked up at the start of the second industrial revolution from 1870 until 1914. Key development in metallurgy, chemistry, and physics led to the invention of the combustion engine, the screw propeller, the steam turbine and commercial dynamo. The world became more connected by railroads, steam-boats, automobiles and the telegraphs.

This led in the first place to more production and a higher demand for labor and therefore better salaries and working conditions. The populace had more time and money to supply their increasing psychological needs on belonging and accomplishment. They were able to buy the goods they produced.

Taylor developed the first approach at scientific management to optimize manufacturing tasks and Ford popularize the assembly-line factory, goods were produced at such a scale that the workers could buy the goods they made. This led to the first instance of consumerism and mass-production of standardized products. The growth continued until the First World War started.

MASS-PRODUCTION:

Assembly-line mass-production uses fully scheduled production steps, with specialized labor, and standardized parts to transform discrete batch production into a continuous flow of product output. By following strict, process dependent design requirements, large quantities of exactly the same product can be produced. This results in an extremely efficient system, reducing production costs and waste, while creating a lot of jobs. Due to the investment in both education and equipment, when demand declines or new products are introduced, it can be cumbersome to adapt the system and cope with the required changes.

THE DIGITAL REVOLUTION

After the Second World War, the current industrial revolution started in 1947 with the invention of the transistor and the first computers. This led in combination with photographic-processing of silicon-crystal-slices to the mass-production of integrated circuits. Gordon Moore predicted that the number of Transistors on an integrated circuit would double every two years, which holds to this very day.

Further developments led to: the first full computer processor and home-computer, the digital image sensor and digital camera, the first interconnected network of computers and the World Wide Web.

This exponential growth of digital storage and computing power accelerated invention, software tools such as Computer-aided Engineering for modeling and optimization were invented and pushed invention even more, resulting in a positive feedback loop. (Including: CAD, CAM, FEA, CFE, CDM, EDA, MBD)

Parallel to this computational revolution developments in chemistry in the early 20th century, led to the invention of synthesized plastics and later the screw injection molding machine. After the Second World War there was a high demand for cheap mass-produced products and plastics provided the answer and as a result plastic overtook steel production in 1979. Programmable Logic Controllers (PLC's) were implemented to automate most production processes, and robotic-manufacturing became a reality, performing repetitive complex tasks fast.

But human labor for assembly or machine operation remained necessary, and cheap overseas options where the competitive answer. The transport sector grew and grew, and the modern mass-production value-chain became a reality.

With the growth of the world population, the manufacturing-, and the transport industry, the material and energy demand increased as well, putting an ever increasing pressure on the existing supply lines, manufacturing chains, and the world itself. To reduce waste and costs, the production systems needed rethinking. This resulted in Just-in-time Manufacturing, what later became Lean Manufacturing.

The world economy grew and with it the average standards of living, leaving the population with more time and money for needs such esteem and self-actualization, in other words a higher demand and expectation of consumer products; resulting in volatile markets and short product-lifespans. To deal with these sudden changes, an agile-manufacturing business approaches needed to be applied, redeveloping the supply-chain constantly to follow consumer trends.

ROBOT-PRODUCTION:

Also called automation, this manufacturing method implements process-controlled mechanisms to take over the simple tasks within the assembly line that were originally performed by the human worker. As a result, the outcome is more efficient, cost effective and there are almost no mistakes. This solution takes simple repetitive tasks out of the hands of the human work force and generating more creative problem-solving tasks.

LEAN-MANUFACTURING:

Originally called Just-in-time manufacturing, this approach tries to streamline the supply-chain by removing all non-value adding activities, eliminating waste, and by using a build-to-order pulling strategy for each process step, as opposed to a traditional build-to-stock pushing strategy; where every component and sub-assembly gets stored until needed (this where the term just-in-time comes from). This streamlined manufacturing system reduces production costs, makes the system more efficient, and able to learn from small mistakes. It is able to produce large quantities of the same standardized parts or products, but is harshly affected by suddenly changing markets.

AGILE-MANUFACTURING:

This approach tries to make its cost-effective supply-chain responsive in competitive and volatile markets, being able to adapt production systems quickly to accommodate new products. This requires strong supplier networks to reduce lead time for getting supplies and to correct quality issues as early as possible. It also requires reconfigurable production facilities, to construct different assembly-line layouts.

The focus must remain on meeting consumer needs, keeping in mind the time they are willing to wait. This must be achieved while maintaining high standards of quality and controlling the overall cost.

THE DIGITAL EVOLUTION

The current revolution is still in full-force and big setbacks such as a world war or economic collapse have not yet arrived. As a society we try to keep up, but invention and development seem to go faster than our ability to change our mindset and reflect on the implications locally, but also on a global scale. With the information-age knowledge and technologies we already have, without new discoveries and further advancement, the world supply-system could already be improved, but a lot remains unexplored. Computer Aided Design for example, existed already in the 60's but become more prevalent in Small and Medium Enterprises at the end of the century. Another example is the paperless office principle, driven by digital-interface technology, this was already described in 1975, but only recently started to become accepted; this is seen in the sales of office photocopy machines (Em. Prof. Dr. Ir. J.M.P. Geraedts, personal communication, 15-11-2019).

Some of these explorations towards improvement result in movements such as Industry 4.0 (and even 5.0), trying to push a paradigm-shift in society, towards a more efficient, valuable, but mostly sustainable supply-chain and product-lifecycle. The resulting technologies, in areas such as direct-digital-manufacturing, algorithm-aided-design, cyber-physical systems, the industrial-internet-of-things, and 3D-printing, make it possible to make configurable products in a mass-production output capacity. This manufacturing method, called mass-customization, makes it possible to produce personalized products closely matching consumer wishes. Giving consumers the opportunity to achieve the highest form of motivational needs as described by Maslow (1954), namely self-actualization.

MASS-CUSTOMIZATION

Mass-customization is defined as producing goods and services to meet individual customer's needs with near mass production efficiency (Tseng et al. 1996).

In the book Operations, Logistics and Supply Chain Management Henk Zijm (2018) states that the basic strategy in mass-customization sectors is that of postponement, similar to the make to stock, assemble to order philosophy; producing a product or its constituting parts with all the functionality desired, but leaving it to the customer to select the final combination of parts, or to choose a personalized outlook (e.g. a print on a shirt, to be delivered by that customer).

In short mass-customization combines: the high-value personalization of artisan-production, with the streamlined low-cost output capacity of lean-manufacturing.

This manufacturing method requires firstly a framework for integrating customer wished into a personalized design; a co-creation service. And the supply-chain must be setup to deliver products with a reasonably short customer-order-cycle. This requires no- or minimal upstream and downstream warehousing and production facilities; which can reduce costs. It also requires direct-digital-manufacturing (DDM) based on automated computer systems control, such as computer-numerical-control (CNC) and additive-manufacturing (AM). This allows direct conversion of digital products from bulk-materials directly into rather complex parts and products. These process-methods are still relatively expensive, require much energy and are relatively slow. Before the advantages of process-generality and flexibility can be utilized, the disadvantages must be overcome.

The advantages and disadvantages are further discussed in the 2.1.4. Why Mass Customization chapter.

CUSTOMER ORDER DECOUPLING POINT

An important parameter in the described manufacturing methods is the customer-order-decoupling-point (CODP) as described by Olhager (2010). And will be used throughout the report to denote how specialized or general the supply chain is. The different CODP levels are described below:

- **Digital copy (DC):** Where products are digital and inventory is maintained with a single digital master. Copies are made on demand in real time and instantly delivered to customers.

- **Build-to-stock (BTS):** Where products are built and stocked in anticipation of demand. Most products for the consumer would fall into this category

- **Build-to-order (BTO):** Where products are built based on orders received. This is most prevalent for custom parts where the designs are known beforehand.

- **Configure-to-order (CTO):** Where products are configured or assembled to meet unique customer requirements, e.g. computers

- **Engineer-to-order (ETO):** Where some amount of product design work is done after receiving the order

Within mass-customization there are different subtypes related to the customer order decoupling point which fall within this manufacturing method. Technologies such as direct-digital-manufacturing make it feasible to manufacture individual products just as artisan-production but with a mass-production output capacity (CTO or ETO); further use of term mass-customization will refer to this type.

Relevant Insights:

2.1.1.1 The CTO/ETO mass-customization factory must postpone manufacturing of materials and part into a product until product is configured and ordered.

2.1.1.2 The CTO/ETO mass-customization factory must accommodate a short customer-order-cycle.

2.1.1.3 The CTO/ETO mass-customization factory must use direct-digital-manufacturing techniques to integrate process-generality and make engineer-to-order products.

2.1.1.4 The CTO/ETO mass-customization factory must overcome the direct-digital-manufacturing disadvantages of being relatively expensive, requiring more energy, and being relatively slow.

2.1.1.5 The CTO/ETO mass-customization factory must be able to produce one-off products.

2.1.1.6 The CTO/ETO mass-customization factory must be capable of a high output-capacity.

2.1.1.7 The personalized product must have an increased emotional value and customer satisfaction.

2.1.2. INDUSTRY 4.0

In the previous chapter it was made clear that the Digital Revolution is still in evolution to this day. The movement towards utilizing this information age technologies for revolutionary changes in the existing manufacturing system is called Industry 4.0 by the German Working Group (Kagermann, et.al. 2013).

The fourth industrial revolution comes from the digitalization of all manufacturing industries in the last decades. Production gets more automated, more intelligent, and more connected requiring us to rethink industrial production as a whole. The fourth industrial revolution is different than the previous, in the sense that we see it coming allowing us to prepare and transition into it, say Drath & Horch (2014)

Hermann et al. (2016) identified four design principles to implement Industry 4.0 scenarios in industry, through these four principles the concept of Industry 4.0 is explained:

INTERCONNECTION:

In Industry 4.0 people, production-machines and products are connected through the Internet of Everything (IoE). This requires communication standards, to enable different people and modular machines of different vendors to talk to each other productively.

The result is a Cyber-physical system consisting of a smart and modular factory, the digital world, and people all interacting with each other.

Interconnection is not only prevalent within a factory but also between factories, allocating production streams to reduce manufacturing time or product transport distances.

INFORMATION TRANSPARENCY:

The interconnection in Industry 4.0 results in a large amount of data from every participant, from factory sensor data, product drawing data, process simulation data, factory worker interruptions, and management decisions. This enormous amount of information need to be made transparent for each participant in the Cyber-physical System. To enable cooperation of system participants, to create optimal process sequencing, and to identify failing or underachieving parts within the system. To do this a model must be embedded in the digital world, this virtual representation of the system must include all interconnected physical persons, parts, and process systems. These virtual representations are called Digital Twins. Products can have a Digital Twin even after production, product and their digital counterpart go through their product lifecycle in parallel.

This model makes it possible to cluster lower-level information, evaluated it, and share it in an informative way to the appropriate system-participant; enhancing communication and transparency. The system is then able to relocate production streams, allocate maintenance to reach just-in-time maintenance, gain near-zero downtime within the factory, and is able to transform the factory, adapting fast to changing markets and enabling Agile Manufacturing. Due to specific-product-tracking within the manufacturing process, it also possible to make one-off personalized products at a high production rate thus enabling mass-customization.

DECENTRALIZED DECISIONS:

For the system to function efficiently each participant in the Cyber-physical System must be able to act autonomously on his acquired data, only interacting with each other for exceptions and interferences, delegating tasks to a higher level. The global Cyber-physical System then monitors progress and intervenes when necessary.

TECHNICAL ASSISTANCE:

The fourth design principle involves the augmentation needed for each participant in the Cyber-physical System. Information needs to be visualized at a moment's notice, for the human participants to make decisions and act appropriately within the system. The human participant then in turn provides technical assistance within the system and solves problems locally. To do this robotic assistance and support might be needed, especially if the tasks are physically challenging or unpleasant for the human participant.

FESTO 4 I

To be compatible with Industry 4.0 Festo sets goals for their Cyber-physical Factory modules which are autonomously functioning mechatronic assemblies called intelligent components. These goals are the 4 i properties (Industry 4.0 - Intelligent components, n.d.):

- **Intuitive** to operate. Festo does not simply sell products, they deliver a full service of setup, maintenance, and warranty. It is therefore important that the system can be handled intuitively both physically as digitally, this is in line with the 'Technical assistance' design principle identified by Hermann et al. (2016).

- **Intelligent** thanks to functional integration: for example with a programmable logic controller or the ability to communicate. This means that individual components themselves are able to provide information about which order they belong to or about processing instructions. This is in line with the very characteristic 'Decentralized decisions' design principle of implementing Industry 4.0 scenarios in the industry, as defined by Hermann et al. (2016).

- **Internet-capable** and locally networked, e.g. thanks to WLAN or industrial Ethernet This is the current practical solution enables the 'Interconnection' design principle, as defined by Hermann et al. (2016).

- **Integrating:** Modules log on to the master computer, communicate their capabilities and are then scheduled into the production process.

Their vision is that of a standardized adaptable interface for the system modules, comparable with the USB interface, enabling modules to log in to the production facility independently, resulting in 'plug and produce' capability. The use of the Digital Twin principle for automatic initialization of system participants and their representation in the digital model is in line with the 'Information transparency' design principle identified by Hermann et al. (2016).

Relevant Insights:

2.1.2.1 Communication standards will be required for inter and intra factory communication between digital and physical participants.

2.1.2.2 The Digital Twin principle must be implemented for every part/participant in the manufacturing system.

2.1.2.3 A real time digital model will be required to make the complex process observable, transparent and understandable for every system-participant.

2.1.2.4 Every factory system-participant (product, module, employee, etc.) must be able to act autonomously on the available operations data.

2.1.2.5 The human worker must have a managing or creative problem solving role in the factory.

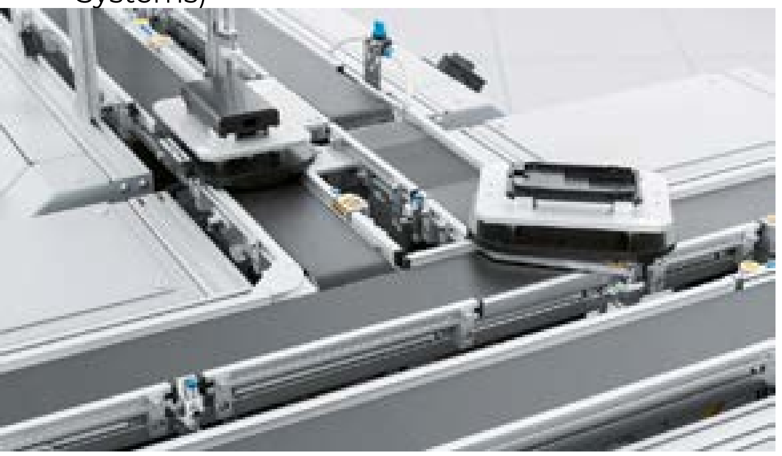
2.1.2.6 The factory process-modules need to have a digital but also physical interface (USB) to log into the system and connect to each other.

2.1.3. FESTO CP FACTORY

In Industry 4.0, production and manufacturing systems are capable of self-monitoring, are interconnected by the Internet of Things and are connected to the cloud and the Internet of People (Kagermann, et al., 2013). These smart factories make it possible to adapt instantly to demand, maintenance, and the implementation of new designs. This results in an agile manufacturing approach capable of responding quickly to customer needs and enabling personalized products.

These integrated systems consisting of computer networks and physical processes are called Cyber-physical systems (CPS) (Khaitan, & Mccalley, 2014). And this is where the company Festo's Cyber-physical Factory comes in. They have built a modular factory with building-block style manufacturing machines that can be connected to each other in different arrangements to form a conveyor belt course. This course can include pick-and-place, drill, press and control-stops. The CP factory is promoted as a learning system for training and research purposes, to enable innovation and developments in the fourth industrial revolution ("Learning Systems for Industry 4.0", n.d.).

The Festo CP Factory was initiated at the Hannover Messe trade fair in 2015, where companies got the chance to design a version of Festo's 'factory' to produce their own products. Festo's CP Factory has a presence at the Hannover Messe till this day. One of the CP Factories was chosen and is now for sale by Festo Didactic (J. Koudijzer, personal communication, 6-12-2018). (Festo Didactic currently has three Industry 4.0 training systems see Appendix: 7.1.1. Festo Learning Systems)



PHONE PRODUCTION SEQUENCE

Festo currently sells one exemplary product that their CP factory can produce. The product resembles a phone, but without a screen. It consist of an upper and lower shell and a PCB with two glass tube-fuses that can be locked into it. Below the production sequence, including each required application module, is explained. Between each process step the carrier is transported by the transport-tracks integrated above each basic-module.

1. The carrier with an empty pallet is initialized for production.
2. The shell magazine module places the front shell on the pallet.
3. The distance measuring module retrieves the orientation of the shell.
4. The drilling module performs order related workpiece machining.
5. The pick-and-place robot-arm module puts the PCB in the front shell and places the fuses on the PCB.
6. A second shell magazine module places the back shell on the top shell.
7. The muscle press module presses both shell pieces together.
8. The camera inspection module validates the product.
9. The tunnel furnace module keeps the product at constant temperature (resembling glue curing).
10. The product handling module rotates the front side of the product upwards on the pallet.
11. The warehouse module stores the pallet with product.
12. The product output module displays the product for operator removal.

Two existing modules that are not used in this setup are:

- The CNC mill module, including a pick-and-place robot-arm.
- The transport dock for the mobile robotics system.

THE CP FACTORY

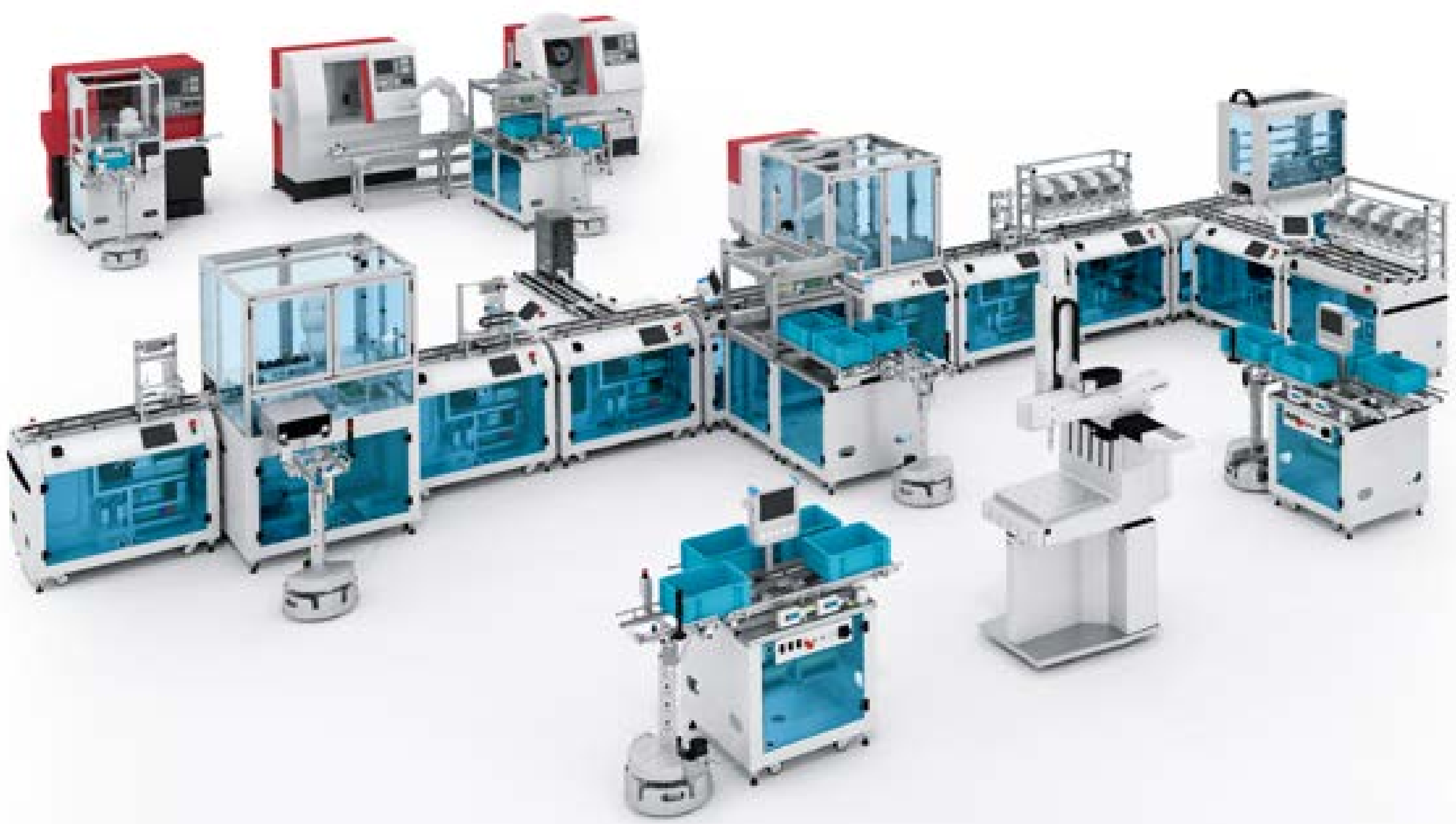
Festo's Cyber-physical Factory is used for trade fairs to promote developments in Industry 4.0. It is also sold to education institutions for research in cyber-physical system technologies and as a learning tool to prepare students for an Industry 4.0 related carrier.

The factory consists of modules both for production-steps as well as for transport, the system is therefore able to switch quickly to different production layout and build completely new products in minimal setup time. This enables an agile-manufacturing business approach.

The products that the current system can produce, are limited to the workpiece-carrier dimensions (100 x 160 mm) and maximum weight requirement (3 Kg) and the conveyor belt width (80 mm). A completely new system will be needed if a different size product must be produced. It is currently not scalable for different product- and part sizes.

Each basic transport module is designed to be handled by a human operator in standing position, it has room for at least two application modules on top of it, and is made to house all necessary conduits and equipment. This setup takes up a lot of floor space, this makes each part of the system readily accessible and visible, which is beneficial for demonstration on trade fairs. This makes the system on the other hand also slow, there are only so much production-steps taking place within the system. The system is therefore not scalable for actual high-volume production; not unless the factory hall is really big.

When looking at the existing application modules the only material-process module to make custom individual parts is a metal CNC milling module, with a robotic arm for part pick-and-placement. And this module is not used in Festo's exemplary-product production setup. The system consists mostly of assembly type production modules and its mass-customization capabilities are therefore minimal.



THE EXEMPLARY-PRODUCT

The example of a phone was chosen because it is a highly recognizable product that exist in different forms and capabilities, it can therefore be highly configurable in terms of specifications. The customer dependent orders would require the need for the cyber-physical factory they demonstrate.

A benefit for using the exemplary-phone is that the production and assembly of this product type, namely electronic devises, is clean; no dust, chips, waste, lubricants, post-processing and spoiling ingredients (e.g. food or pharmaceutical industry). The exemplary-phone is also easy to disassemble, the parts can therefore easily be reused for new test or demonstration runs within the CP Factory.

These aspects are important for the current CP Factory research and demonstration objectives. Because the operators can focus on the system itself, requiring almost no extra general operation tasks.

The exemplary-phone and factory implement the principle of the digital twin, being part of the Internet of things. This digital counterparts supports the, design, order, production, and use-phase of each individual product; for the CP Factory the design and production are most important. This principle is already found in the digital tracking of the RFID chip and the QR code on the workpiece carrier. The RFID chip is used to synchronize digital and physical world's ant the QR code can be used by the human operator to check on production.

The system already shows off Industry 4.0 principles, the problem is that it does not clearly show the uniqueness of each separate product that is defined in its digital twin. Each exemplary-phone looks the same and it would be beneficial to show this uniqueness in the form or functionalities of the product. This is a big challenge in the example of phone, since developments transform this product to an interactive display, without space for visible individuality.

The phone is a clearly recognizable personal consumer product, dependent on the specific consumer's wishes, it will eventually be a good business-case to produce with such a cyber-physical factory. But a commercially working phone requires components that are extremely small and complex, and the technological developments within this mass-producing industry progress quickly each year. That makes this business-case a bit to much as a first exemplary-product. And the final goal of developing a commercially viable cyber-physical product far out of reach. It will be beneficial to work towards an economically viable product business-case, only that way it is possible to encounter the hurdles required for cyber-physical production.

DEVELOPMENT

Although Festo's modular assembly-line provides an initial throw towards a Cyber-physical Factory of the fourth industrial revolution it is only a start, implementing important general ideas but lacking a further development direction. In this project the existing framework will be further researched and build upon. And one of the most important additions that must be implemented is that of mass-customization, bringing the capability of making unique parts and products to the CP Factory.

Aspects that can be applied from Festo's CP Factory system such as: the software framework, the carrier tracking system, the transport system, and their developed modules can be used or assumed in the design.

Relevant Insights:

2.1.3.1 The cyber-physical factory and exemplary-product must promote and enable further research, integrating aspects of: Industry 4.0, Cyber-physical Systems and Mass-customization.

2.1.3.2 The cyber-physical factory must consist of a modular setup to be able to change the production-setup quickly.

2.1.3.3 The cyber-physical factory framework must be scalable for different product sizes.

2.1.3.4 The cyber-physical factory must integrate mass-customization in its modular production setup, to make individually different parts and products.

2.1.3.5 The exemplary-product must be recognizable as a clear personal consumer product.

2.1.3.6 The exemplary-product production process must be clean, in terms of dust, chips, waste, lubricants, post-processing, spoiling ingredients, etc.

2.1.3.7 The exemplary-product must be disassemblable to reuse the materials for new test or demonstration runs of the production system.

2.1.3.8 The exemplary-product must demonstrate unique cyber-physical product aspects through form and functionality.

2.1.3.9 The exemplary-product must be designed in both a commercial business-case, as well as a research and demonstration context.

2.1.4. WHY MASS CUSTOMIZATION

Industry 4.0 technologies can already make manufacturing an agile business approach, what purpose has mass-customization then? Most products are not meant to be as unique that these modern production capabilities are required. These products are fine just being produced in large quantities in a couple of batches, to cater the varying population; in other words mass-production. And for the people still requiring personal solutions, there are skilled workers that are happy to learn your wishes and make something perfect and on demand; in other words artisan and job-shop manufacturing. Between these two, the options a company can choose are enormous.

Then why should a product brand company choose for mass-customization? Answering why, is about analyzing the benefits that it brings and if they outweigh the drawbacks that are associated with it. To elaborate this choice, the benefits that modern mass-customization brings and the associated drawbacks are discussed below:

MASS-CUSTOMIZATION PROVIDES INCREASED PROFIT MARGIN

The company's most clear reason, and probably the reason they wanted to implement mass-customization, is that of personalization. By producing customer specific products they are able to provide benefits that were otherwise impractical or impossible. This provides new customer value and therefore more company value. This is further elaborated in the 2.2. Future Life-cycle Concept.

Due to the technological developments it is possible to connect the manufacturing chain and make all activities transparent. This is required because of the configure-to-order and engineer-to-order nature of mass-customization. This requires a certain process-generality (such as DDM) in the design of the production setup and a platform focused business approach to create the necessary ecosystem. This in turn results in very low supplier dependencies, reduced warehousing of stock, and reduced transport distances between production steps, low repetitive human labor, and low losses due to production errors. In other words reduced overhead costs per product and therefore a higher profit margin.

The personalized products require an advanced smart manufacturing setup to keep track of individual product differences. This makes it some product business cases also possible to track how the product is used by the consumer, by giving feedback to the company through the integrated Digital Twin principle. This enables them to learn from this knowledge and make better products and adapt their business case, to gain a competitive advantage.

MASS-CUSTOMIZATION PROVIDES AN AGILE BUSINESS PLAN

The above described reduced stock and supplier dependencies result not only in reduced cost of manufacturing but have the added benefit of enabling fast initiation of, and switching between manufacturing chains. With this minimal time-to-market, the company is able to adapt quickly in a volatile market; automatically using an agile business plan.

As an example, the company Amazone produces their paperback books with digital printers at the closest of multiple facilities, after the customer order comes in. This results 100.000 different products get produced in one production stream and shipped within 24 hours; if one facility stops another takes over (Em. Prof. Dr. Ir. J.M.P. Geraedts, personal communication, 15-11-2019).

Starting a mass-customization business-plan is therefore relatively fast, since the needed manufacturing chain is short. This value chain requires also low venture capital, especially if existing manufacturing facilities are used or adapted to fit their new product. These two aspects result a fast return of investment and a lower associated risk level resulting in a high net present value (NPV), which makes this agile business plan an attractive opportunity.

The process-generality of the mass-customization production setup provides, after initial development, the possibility to increase and decrease capacity dependent on market demand. And also make it possible to add and subtract product production form the manufacturing chain quickly. Reducing the risk associated with the initial investment even more.

Net present value (NPV): Is a measure of the difference between the present value of cash inflows and the present value of cash outflows over a period of time, for a possible investment as compared to other activities (for example stocks of a comparable risk level). It therefore provides insight on the investment's delay of return. To clarify: A dollar today is worth more than a dollar in a year, because that dollar could have been invested; NPV is in this case negative. NPV would be positive for some value higher than one dollar; dependent to the other possible activities.

MASS-CUSTOMIZATION PROVIDES SOCIETAL BENEFITS

Another reason companies would use mass-customization as a manufacturing method are the societal benefits it provides. Due to the reduced manufacturing chain complexity, reduced supplier dependency, and the process-generality of the mass-customization setup; it is possible to have more but smaller production facilities. These can be placed locally which can be a societal benefit in itself by providing jobs.

The reduced complexity of the manufacturing chain and the required technological requirements for personalization result in, minimal stock, warehousing and intermediate waste during production. This in combination with local production also result in reduced transport distances. Which minimizes fossil fuel consumption, and pollution. This is in the first place better for the world, but provides also subsidized societal benefits.

The personalized products which are one of the main reasons for mass-customization require advanced smart manufacturing to keep track of individual differences. This makes it also possible to track what goes into a product and in which way, enabling designs with an integrated recycling plan for their end-of-life. Which further extract value from a product, and reduces loss of, for example, rare earth metals.

MASS-CUSTOMIZATION DRAWBACKS

Smart mass-customization is still starting up and a lot of developments are still required. Developments on a technical level, such as Cyber-physical systems and direct-digital-manufacturing research; on a commercial level, such as connecting partners and services to streamline the value chain; and on a regulatory level, such as developing standards and regulations to stimulate integration of local smart and personalized manufacturing. Including standards for digital intercompany communication and digital product and part specification and design. In the 2.2 Future lifecycle Concept chapter a platform is proposed to structure the required mass-customization product life-cycle.

As of today the population's expectations for products, and how personalisable they must be, is in most product-cases still not high enough that mass-customization is required. Traditional manufacturing will be sufficient for most products; because standard items (microchips, fastners, etc.) with no personal user-investment form the majority of manufactured goods, traditional mass-production will therefore remain the prominent manufacturing method even after global adoption of mass-customization

Also competing with traditional high-volume-mass-production on factory speed, capacity and efficiency is not possible, resulting in a higher production cost per product.

Relevant Insights:

2.1.4.1 The mass-customization factory products must generate high customer value through personalization.

2.1.4.2 The mass-customization factory's production systems and processes must be 'general' to produce varying build-to-order products.

2.1.4.3 The mass-customization factory requires low dependencies and overhead costs.

2.1.4.4 The mass-customization factory must keep track of each part and product during manufacturing.

2.1.4.5 To improve future mass-customization products they must be designed with a method to keep track of their use.

2.1.4.6 The mass-customization factory must be able to increase and decrease production capacity continuously.

2.1.4.7 The mass-customization factory must be able to quickly add new, and subtract products from production.

2.1.4.8 There must be a lot of (relatively small) mass-customization factories to provide local production and reduce transport and warehousing.

2.1.4.9 The mass-customization business-case must make up for a higher per-product production-cost; compared to traditional mass-production methods.

2.1.5. CONCLUSION

When the Industry 4.0 evolution continues, smart manufacturing becomes more advanced and the population's product-expectations increase. The advantages and value that highly personalized-products bring will drive initial development towards the mass-customization manufacturing method. This is seen in the question from Festo for adding mass-customization into their CP Factory system.

It must be stated that traditional continuous- and mass-production will always exist for general products but mostly for bulk materials and standardized generic components, because of the efficiency and cost benefits. Even mass-customization production processes will require bulk-materials and standard components. It is for a product-design company therefore extremely important that their planned business-case lends itself perfectly for mass-customization and makes use of the benefits. If not, traditional mass-production or artisan-production will be the better choice.

Eventually after this initial phase where mass-customization becomes more common and the infrastructure is in place, the benefit of shorter time-to-market, lower risk, and smaller overhead costs is what will drive companies to further adoption of mass-customization (The Amazon example in the previous sub-chapter), the drawbacks slowly decrease and even new traditional mass-production goods will locally be made with this method (that is: until the risks are clear and mass-production supply lines are installed).

The configure-to-order and Engineer to Order mass-customization method will form the core of the research described in this report. In the next chapter a Concept discussed that elaborates wat the required product value-chain might look like.

The focus will be on product development within mass-customization, not necessarily product design and methodology. Another important aspect of Industry 4.0, is the roll of the human worker and designing interesting jobs into the system, this aspect will be left unexplored because this requires a further developed understanding of a specific production value chain.

2.2. FUTURE LIFE-CYCLE CONCEPT

A CIRCULAR FUTURE VISION

Assuming Industry 4.0 supported mass-customization, what will society's product-life-cycle and value-chain look like? And what will be required to sustainably manufacture these custom products.

This chapter gives an abstract representation of the manufacturing system required to produce personalized, configure-to-order products at a mass-production scale. Abstract because no specific industry or product type is defined. When looking at society, there exist complex value networks, multiple products being produced by even more corporations in complex production chains. This chapter has a single product centered view, showing the required players in a single product life-cycle.

The Industry 4.0 Working Group (Kagermann, et.al., 2013) describes three levels of integration which are the key feature of the so called 'Dual Strategy' of deploying and marketing Cyber-physical Systems in Germany's manufacturing Industry and thereby preparing the country for Industry 4.0. The integration levels are:

Development of inter-company value chains and networks through horizontal integration: Horizontal Integration is to find, introduce, and connect corporations to set up intercompany value networks. Enable value chain partners to exchange knowledge, finances and assets and create new business opportunities. This while protecting intellectual property and know-how.

Digital end-to-end engineering across the entire value chain of both the product and the associated manufacturing system: End-to-end integration is to synchronize the value chain partners to work optimally towards the same product centric goal. Optimize business execution to bring perfect products with minimal losses and create a high combined value margin.

Development, implementation and vertical integration of flexible and reconfigurable manufacturing systems within businesses: Vertical Integration is to connect a corporation's smart assets and departments, and make all value chain activities transparent. Departments therefore can act continuously and change the system accordingly. This does require the implementation of flexible and reconfigurable manufacturing operations.

These integration levels are in this chapter used to develop and describe the mass-customization manufacturing system; but the used scope is broader than just the value chain and the whole product-life-cycle as described by Porter, M. (1985) product inception to end-of-life is used. These same integration levels are also used and explained by Whang et al. (2016) in their paper describing the implementation of an industry 4.0 Smart Factory.

2.2.1. MASS-CUSTOMIZATION PRODUCT LIFE-CYCLE

In this subchapter an overview is given of the envisioned mass-customization product life-cycle and its participants. It consists of both the value chain and the product-use-phase. Through value networks this chain is set up and connected, both digitally and physically.

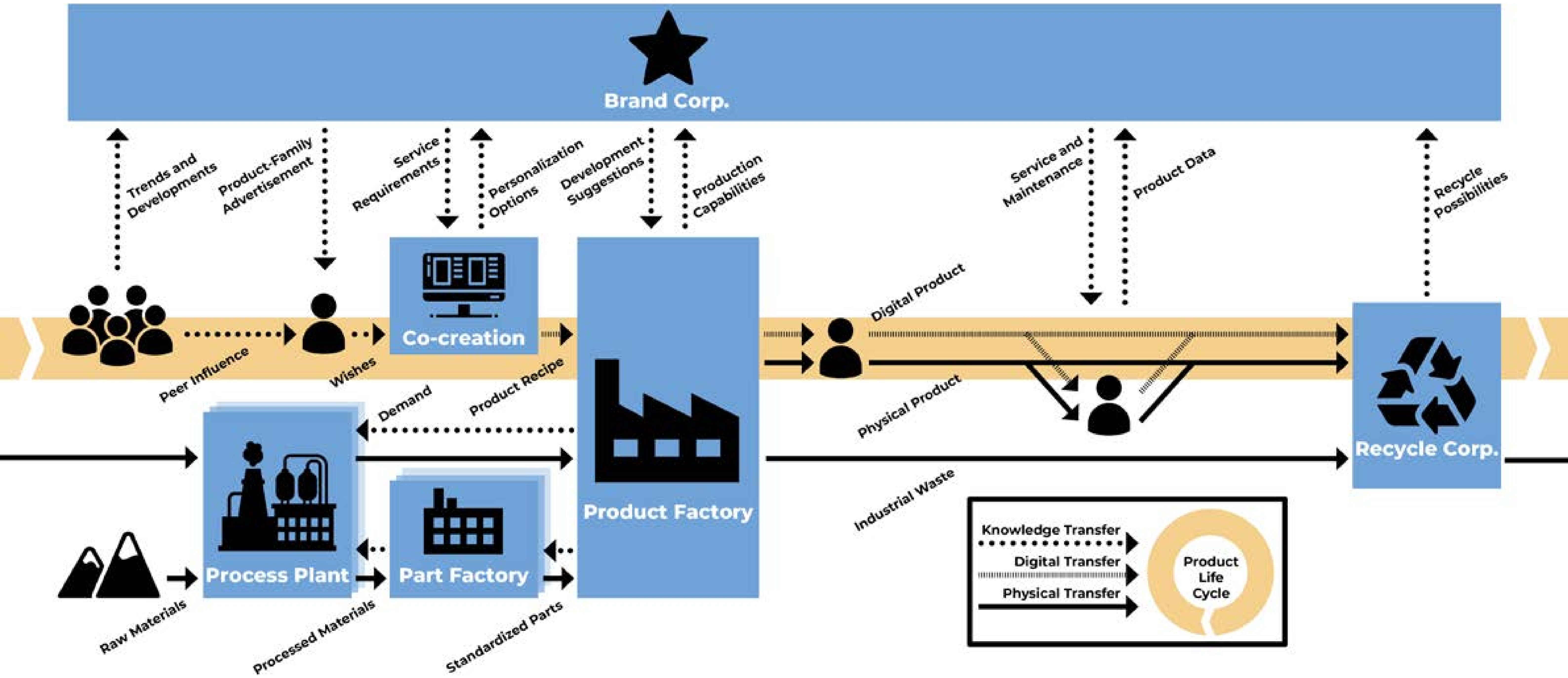
The goal of a value-chain is firstly, to create, deliver and capture as much value in a product-service as possible. And secondly, to reduce the cost of creating this value. The profit margin is then the final product value, minus the cost of adding this value. To increase the captured value, personalized products are build that fit user-wishes perfectly. This requires a mass-customization production system. The consumer eventually trades value in terms of money for expected value in product-use hoping to make his or her own theoretical profit margin.

To deliver a configure-to-order product in a reasonable time to a customer, the mass-customization value chain middle-layers must be reduced to a minimum. As a result the middle layer profit margins are removed and the required cost to make this product will be reduced. This minimal manufacturing value chain and product life-cycle is represented in this chapter centered around a single factory and the value chain links are described as separate 'corporations' (Corp.); this is also done by Whang et al. (2016).

Theoretically these corporations might be owned by one company, the links would be between departments or subsidiary companies instead of corporations. Really big brand companies for example, would fully design the value chain from raw materials up to service (even when they outsource some business), and the corp. blocks in the visual on the next page would overlap (The 'Development Suggestions' arrow to the Product Factory would instead be a 'Development Requirement' arrow to the operations department).

In contradiction, to reduce risk and to find flexibility, it has become common for companies to outsource departments such as production and even R&D (ATKearney, 2015) increasing the number of middle layers. Every middle layer takes away from the final profit and control over a big part of the value chain, it becomes harder for the company to navigate and adapt in volatile markets and to overcome disruptions. To keep a competitive edge the product companies must adopt a true end-to-end perspective on the value chain, from raw materials to finished product, to recycling (ATKearney, 2015). In the product-life-cycle the brand corporation has the role as 'orchestrator', and the task of finding the right partners to develop their product-family (see definition), synchronizing these companies. Creating trust, transparency, and communication to work toward the same product centric goals of production performance, resource efficiency and quality.

A product-family is simply defined as the set of all possible end-products from which the customer can make his selection. A model of a product-family, termed the product-family model, is then defined as a single model from which models of all end-products of the family can be derived. A model of a product-family, termed the product-family model, is then defined as a single model from which models of all end-products of the family can be derived. The product-family model can serve as a foundation for the configuration process and, in order to secure that only legal configurations are selected, the model should contain restrictions about what is possible and not possible. (Asbjørn, K., & Ditlev, T. 2011) .



In envisioned mass-customization product-life-cycle, there are enough outsourced middle layers to reduce company risk, but at a minimum to successfully implement a mass-customization business-plan able to deliver configure-to-order personal products.

In addition to the value chain, there is the use phase, the goal of this phase in the product life-cycle, is to convert as much value into consumer satisfaction and to reduce value dissipation by implementing the right service and maintenance. The end-of-use remaining value can then be retrieved by reselling or recycling the product, and the user has evaluated the acquired value margin and brand loyalty has increased or decreased.

The product-life-cycle overview consists of six corporation types, this will be the minimum in a single factory view. The benefits of keeping separate corporations as input-output systems after removing middle layers are:

- Their respective responsibility and legal accountability for delivering acceptable outputs; as opposed to integrating all into one factory.
- The reduced risks for business-plan initiators; especially in the investment and market-introduction phases.
- The output of a corporation can be used as inputs further in the value chain by multiple other corporations.
- The other way around: one corporation can also use outputs from multiple corporations earlier in the value chain.
- The last important reason to keep these corporations separate, is for their required location dependent activities thereby reducing transportation distances and thus costs and emissions.

All the links in the Cyber-physical product life-cycle and their function are described below:

BRAND CORPORATION:

The brand corporation is responsible for the product in both its design and use phase. It responds to trends in changing markets and knowledge acquired from previous products and the other corporations by designing and advertising new product-families. The design must be personalisable by the customer, producible by the factory and disassemblable by the recycle corporation. The Brand provides the required product service and maintenance if necessary, thereby increasing value or inhibiting value dissipation. The brand is in return able to track how the product is used, which enables them to learn from this knowledge and make better products and adapt their business case, and innovate their products.

The main challenge is to keep finding and developing successful product-family ideas. The brand corporation forms a source of product demand for the product factory. The second challenge is to provide the required product-user service and if necessary maintenance.

CO-CREATION CORPORATION:

The co-creation corporation is responsible for providing a configuration service that enables a customer to convert his or her wishes and requirements into a final design that is producible by the factory. This service is set up to fit the Brands vision for the product-family and the needed personalization. This software service is incorporated in the personalization service the brand corporation wants for the customer.

The main challenge is to integrate knowledge about personalization requirements and production capabilities into a service and software system that converts intangible user wishes into a file format that is usable by the product factory; this format is called the product-recipe.

PRODUCT FACTORY:

The product factory is responsible for converting materials into the final product following the provided design. The main challenge is producing highly personalized one-off or small batch products. The product design is only available after order and production only starts at this moment. To deliver in a reasonably fast time frame the factory must be able to convert materials directly in the finished product without the need of ordering parts specific parts for a specific product. The dependency on pre-production sub-assemblies must be reduced as much as possible.

For the product factory to compete with traditional mass-production it is important to make up for the loss in efficiency. This is done by increasing the value of the produced products and decreasing the costs of production; most importantly costs in warehousing of stock, transport and pre-production suppliers. The product factory must therefore strive to reduce dependency on the Standardized Part Factories as much as possible.

MATERIAL PROCESS PLANT:

The material process plant is responsible for continuous conversion of raw material resources into processed materials usable by the product factory.

The main challenge is controlling production flow following a pull strategy depended on the product factories material demands.

STANDARDIZED PART FACTORY:

The Standardize Part Factory is responsible for mass-producing standard parts or sub-assemblies that can directly be implemented in different product-family designs that are producible by the product-factories. This part must be made with an extremely high output volume to reduce the costs of the final products.

The first challenge is keeping up with demand from the product factory. The second challenge is to keep up with technological developments and adapt accordingly.

RECYCLE CORPORATION:

When the products are designed with disassembly in mind the recycle corporation is able to retrieve material value from the products. The Recycle Corporation can retrieve information about the bill of materials, the original design and the implemented recycle plan from the brand corporation to use in the recycle process. This can also be beneficial for the user. The parts and materials can then be reused for new product production.

THE USER:

Ultimately the user determines the value extracted from the product and what it is worth during the course of the product life-time. The user can resell the product to a different user when product appreciation drops for the first user. The product can also be transferred to the recycle corporation to retrieve material value.

PHYSICAL TRANSPORT:

Al physical transport of materials, parts and product costs energy time and therefore money. The system must be setup to reduce this as much as possible meaning, material process plants close to the natural resources to reduce the transportable mass early on. Standardized part factory optimally positioned between material process plants and product factories to minimize transport mass, volume, and distances. And product factories and recycle corporations close to the final consumers to reduce delivery time and the number of vehicles.

In the envisioned life-cycle the value-chain partners are for abstraction described as corporations, but as stated these could also be departments of a big corporation. For certain industries it can be advantageous to merge certain corporations under one business. For example:

- A brand owning a dedicated factory, which is possible when the demand is high enough.
- A product factory owning the co-creation corporation this way the capabilities of the Factory are directly translated in the software.
- The local product factory integrates the recycle corporation to retrieve materials to be used in production and minimizing transport.

The primary and support value adding activities described by Porter (1980) which are centered on the customer, are divided over all the de value chain partners. This division gives the corporation focus to do their part as optimally as possible thereby increasing quality and reducing costs. It gives them also legal accountability when they deliver wrong or harmful output. By following the steps in the product life-cycle the corporation roles and required digital and physical interactions are explained below (the arrows in the visual):

1. A brand corporation has a marketing department that keeps track of trends, developments, and their existing products in use. Their research and development department discusses possible capabilities with the marketing department of the co-creation corporation, the product factory and the recycle corporations; and develop a product-family design. They implement their product-family design in the personalization service and software to convert customer wishes into the design.
2. The customer is convinced through personal investment, peer influence and advertising to obtain a personalized product. The customer conveys its wishes through the personalization service into a design. The co-creation corporation converts this design into a product recipe, which include a process sequencing overview and computer aided manufacturing (CAM) files per process step. The product recipe is sent to the sales department of the product factory together with work order.
3. The product factory accepts the work order and adds it to the production list. The procurement department updates the stock demand and puts out a purchase order for the suppliers, which in turn produce more stock for the inbound logistics department. The operations department starts production and the product gets made following the product recipe, general maintenance is performed to keep the process going. Eventually the product is finished, packaged and stored at the outbound logistics department. The finished product is sent to the customer together with a sales order.
4. The customer receives ownership over the product and the accompanying service, both physically and digitally. He uses the product until he either transfer ownership to another person or the recycle corporation.
5. The recycle corporations gains knowledge about the product through digital ownership and is able to disassemble the product into raw materials. The remaining use and end-of-life data gets sent to the brand and the digital product gets deleted and the raw materials transported to the respective process plant.

To synchronize the value chain partners their needs to be a clear understanding about each other's capabilities, this requires a system of overarching industry standards. Also a solid digital framework is required to keep companies connected and enable intercompany synchronization. This framework consists of and order management system (OMS) which is required to keep track of: product-recipe files, work-orders, sales-orders, stock-purchase-orders, and digital-product-ownership. A connected database is also required to store information such as the available recycle-capabilities, production-capabilities, personalization-capabilities, available materials, pre-produced part designs, product-family designs, customer product designs, product-recipes files, and product use data. Other synchronized activities that require a digital platform are the following:

- Brand and Production Factory discusses implementation of a new production process.
- Brand and Production Factory and the Standardized Part Factory discusses implementation of a new part and fit in the value chain.
- Brand and Co-creation Corporation discusses new possible customization capabilities.
- The co-creation corporation and the product factory discusses Computer Aided Manufacturing software for new production processes.
- The product factory and suppliers discuss demand and stock requirements.

Relevant Insights:

2.2.1.1 The mass-customization factory must reduce supplier dependencies and incorporate as much manufacturing steps as possible (this is called vertical integration).

2.2.1.2 The product factory must be able to convert stocked materials directly into personalized product without waiting on suppliers.

2.2.1.3 The mass-customization product must be designed to retrieve remaining end-of-life value through recycling.

2.2.1.4 The mass-customization factory requires an influx of customer orders in the form of product-recipe files to operate and therefore brands that keep designing and promoting the product-families.

2.2.1.5 Product-family models must be designed with the potential users, factory production capabilities, co-creation-system capabilities, and recycle capabilities in mind.

2.2.1.6 The supplier parts must be standardized to be used in different products by multiple factories.

2.2.1.7 The physical location of the mass-customization value chain links must be optimized to reduce transport costs.

2.2.1.8 The mass-customization business-case must make up for the loss in efficiency (as compared to traditional manufacturing), by generating more user-value and minimizing, supplier, transport, and warehousing costs.

2.2.1.9 Minimal supplier dependencies will be important for the product factory in order to change production quickly in volatile markets.

2.2.1.10 The mass-customization factory must automatically recognize when stock runs low and put out purchase orders to suppliers.

2.2.1.11 The mass-customization factory must automatically initiates packaging and transport to the customer when products are finished.

2.2.1.12 Industry standards will be required to synchronize value chain partners streamline their interaction.

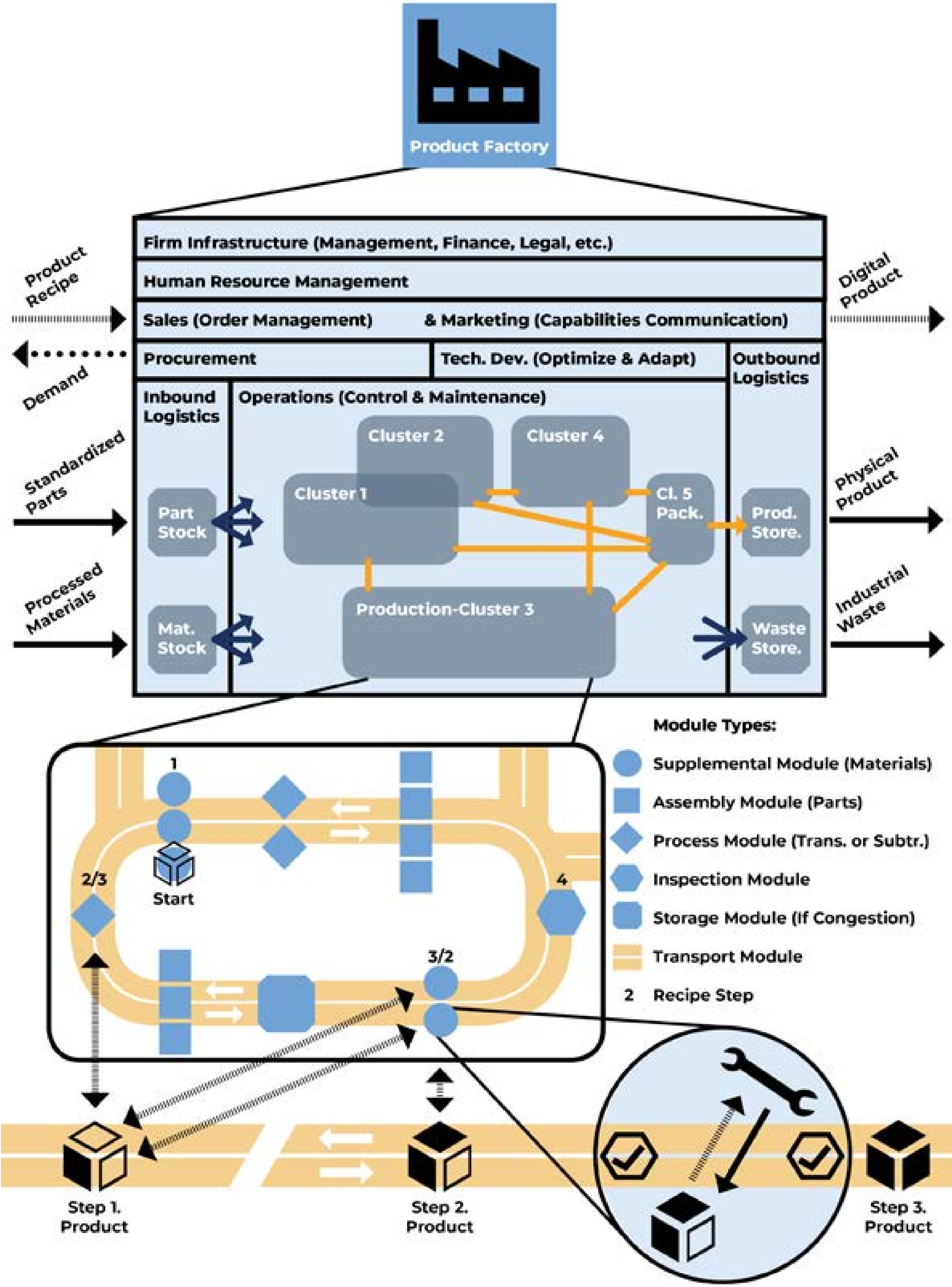
2.2.1.13 A digital Order Management System will be required to track flow of parts and products during different design and production stages of the value chain.

2.2.2. MASS-CUSTOMIZATION PRODUCT FACTORY

Within the mass-customization product-life-cycle the factory has the complex task of transforming unique product-recipe files and stocked goods into finished products at a mass-production pace. This is no easy task and requires Industry 4.0 Cyber-physical System technologies, described in the previous chapter.

The Cyber-physical Factory consists of participants on al hierarchical levels, from process-equipment, to products, to whole departments. They are connected in an industrial network and digitally represented in a real-time digital model following the Digital Twin principle. The Factory is in essence a multi-agent-system and requires a method to track each participant their physical state and synchronize it with the digital model. The system must be transparent and enable standardized communication between participants. They must be able to act autonomously on the gained information.

The factory departments can optimize and reconfigure the internal systems constantly. To do this the system must be modular and flexible. The hierarchical structure of the factory consists of multiple levels and is discussed below (in an arbitrary layout):



THE FACTORY LEVEL:

Since a single product life-cycle view is chosen, the top layer in the vertical structure is the product factory itself. The factory is due to its flexibility not specifically defined by the one or two products it can make. It is defined by the capabilities in terms of production processes and therefore all the product categories it can make.

THE DEPARTMENT LEVEL:

The factory consists of multiple departments that fulfill different value chain activities.

- The Firm Infrastructure department provide support activities to maintain daily operations.
- The Human Resource Management department supports the development of the factory workforce.
- The Sales department provides communication with value chain partners and keeps track of orders going in and out of the factory, with the help of an order management system (OMS).
- The Marketing Department tries to attract brand corporations and communicates factory capabilities and how to implement them.
- The Technical Development department's main task is to optimize the flexible factory layout in terms of capabilities, efficiency, maintenance and performance. They discuss with value chain partners; additional process modules, product-family prototyping, standardize supplier parts, and errors due to computer aided manufacturing software.
- The procurement department orders part and material stock, general office products but also process-modules from companies such as Festo.
- The Inbound Logistics department's purpose is to receive store and distribute parts and materials throughout the factory.
- The Outbound Logistics department warehouses finished products and industrial waste and is responsible for transportation out of the factory.
- The Operations departments' first task is to keep track of the product work orders and deliver finished products by operating the production system. Secondly they perform maintenance, replacing expendable parts and solve errors. They also modify the factory layout under instruction from the Technical Development department. The human worker will have a managing, problem solving or complex/creative assembly/production role in the Operations department; simple production labor is performed by robotic assistance.

THE CLUSTER LEVEL:

Within the operations of the factory, multiple production-clusters can be found, they are defined by the size of the parts or products they make, the materials that are used and the process step capabilities and performance. There can be overlap between production-clusters if two parts of the final product are produced in a very different way (for example a wood and textile chair with an electronic remote in the armrest). The goal of the factory's Technological Development department is to constantly optimize the layout of the production-clusters to match output with demand and add new product-family designs to existing, adapted or new Clusters. They could assign one production-cluster to a product-family if its demand is high enough and also if this is the beneficial outcome after optimization. Better optimization is possible if the total demand for all the product-families in a cluster is high.

THE MODULE LEVEL:

One level below the production-cluster are the process-modules. Together they constitute the layout of a cluster, individually they are production machines that provide a process step. They are defined by the type of process, the production size and performance in terms of precision and speed. Since the system is modular therefore modules can be doubled up when they are slow or demand for that module increases; or removed if demand decreases. The process-modules are the ingredients in the product recipe and each module requires its own CAM code and thus software package to handle their production. To perform properly they need to act autonomously in the factory, they need to connect to the Industrial Internet and communicate with other system participants such as products, modules and departments and discuss states and tasks. Six types of modules are defined, they are described below:

PROCESS-MODULES:

- The supplemental-module transforms stock materials into product parts (additive processes, etc.).
- The assembly-module implements a sub-assembly or separately produced parts into a higher level assembly.
- The transformational-module changes the main assembly either by transformation or subtraction (mechanical, thermal, etc.); this does not require any materials to be incorporated in the product (except general machinery wear or consumables like glue).

OPERATIONS-MODULES:

- The inspection-module performs an additional brand corporation pre-designed final test on the part or product (Of course each module performance general inspection after each process step to check the correct execution).
- The storage-module helps overcome congestion due to suboptimal production flow; it forms a buffer to decrease unnecessary active production traffic.
- Transport-module:
- The horizontal transport-modules move the parts and products through the cluster and connects all process-modules; forming the transportation-system and the production-cluster layout.

SUPPORTING-MODULES:

- This can be every extra needed equipment used by one or more process-module. Equipment such as an air compressor, hydraulic pump, motor controllers, power supplies, material stock, waste storage, etc.

THE PRODUCT LEVEL:

The parts and products are initiated from the product recipe before being added to the transportation network. They need to communicate through the Industrial Internet with other system participants and autonomously keep track of their production status by following the product recipe and looking at their next process step. The parts and products must constantly update their physical status digitally for other participants to observe.

Relevant Insights:

2.2.2.1 The mass-customization factory must be reconfigurable and constantly adapted during production towards the most optimal layout.

2.2.2.2 The mass-customization factory is defined by its production capabilities, not the products it makes.

2.2.2.3 The mass-customization factory must be capable of performing maintenance during constant production.

2.2.2.4 The mass-customization factory must have one or more clusters defined by their build-size, used materials, production capabilities, etc.

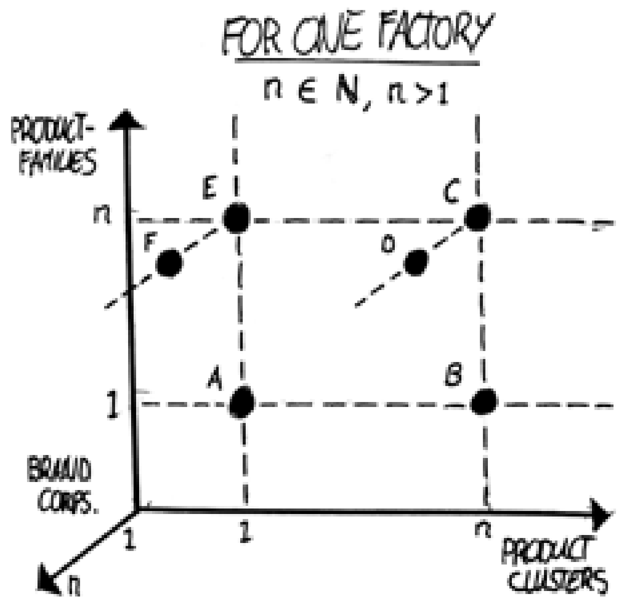
2.2.2.5 The mass-customization factory cluster must be made of modular process-step-performing modules each with their own software driver format to be included as recipe in the product-recipe files (CAM).

2.2.2.6 Parts and products must be treated as smart cyber-physical system participants by being able to communicate, act autonomously, and follow their product-recipe files.

2.2.3.THE MASS-CUSTOMIZATION FACTORY REALIZATIONS

When looking at society, factories exist in all forms and sizes, from specialized factories producing one specific thing, to factories producing a multitude of different products. In this subchapter an abstract overview is given of the possible realizations of the product factory that are possible following the described mass-customization product-life-cycle. A single factory view is used but with three different variables, these are: amount of installed production-clusters (X), amount of producing product-families (Y), and the amount of associated brand corporations (Z).

The production clusters described are able to produce the final product; the clusters required to make sub-assemblies are in this case left out as if being part of the main production cluster.



The particular case where multiple brands are responsible for one product-family is left out in the graph (this is probably not under the roof of one factory). The six factory-realization are described below:

A. **(1 Cluster, 1 Product):** The most basic setup, a brand using a dedicated factory with only one cluster to produce a specific product-family. This setup is somewhat comparable to traditional manufacturing where a company owns his own production line.

B. **(n Clusters, 1 Product):** A brand uses a dedicated factory to produce a slightly complex product-family requiring multiple production-clusters (for example: furniture with integrated electronics).

C. **(n Clusters, n Products):** One brand using a dedicated factory to produce their specific product-families, each requiring its own production-cluster.

D. **(n Clusters, n Products, n Brands):** Within a factory multiple brands are using their dedicated cluster to produce a product-family.

E. **(1 Clusters, n Products):** A brand uses a dedicated factory to produce comparable product-families requiring only one production-cluster. To include all product-families the cluster will be more complex.

F. **(1 Clusters, n Products, n Brands):** Within a factory multiple brands produce their comparable product-family on one shared production-cluster. The required production-cluster is the most complex in this list. Good relation between the brand and factory is required to integrate the different product-families in the cluster.

All the above described factory realizations will be possible following the mass-customization product-life-cycle. One of the reasons for the spread in factory realizations will be because of two different brand mindsets when developing a product-family.

- The first is top-down, a product-family is designed after which the required production-cluster is envisioned and realized.
- The second is bottom-up, a production-cluster exists with certain capabilities, and then a product-family is designed to be produced by this cluster.

Either mindsets, or something in between, will result in completely different factories. Another important aspect influencing the factory realizations is, if the factory is owned by a brand corporation that develops its own product-families or if the factory is independently producing product-families for one or multiple brands. These two cases might steer toward one of the realizations. There will of course be more reasons to choose for one of the realizations, but this is not further discussed.

Relevant Insights:

2.2.3.1 The mass-customization factory must decide on a business-plan with the spectrum of factory-realizations.

2.2.3.2 A multi-product-family cluster must overcome process-generality requirements that are not relevant for a single-product-family cluster.

2.2.3.3 A multi-product-family cluster does not have to be adaptable to overcome market changes such as product-family swapping as opposed to a single-product-family cluster.

2.2.3.4 A multi- and single-product-family cluster must be able to adapt production output to overcome changes in product-family demand.

As described the factories must be flexible to supply constantly changing markets. The described factory realizations have different reasons to be flexible and employ a modular cluster setup. The two largest differences on flexibility are described below:

1. 1In the case that a factory produces only one product-family per cluster (A, B, C and D), the setup must be flexible to overcome changes in demand or switch fast to a new product-family due to market changes; in other words, the business needs to be agile. This is called: **Agile Manufacturing.**
2. In the case that the factory produces multiple product-families per cluster (E and F) the reasons are different. The cluster must still change size to overcome changes in total demand, but the cluster stays generally the same when product-families are added or removed due to changing markets. New process-modules can of course still be added, but only to bring new capabilities to the cluster. Because the cluster already has a wide range of capabilities and products the business setup is in that sense not agile; a fast changing market has no influence of the production-cluster layout. In this report this will be called: **Transcended Manufacturing** (Product-independent Manufacturing). Transcend: ‘To pass beyond the limits of a category or conception.’ Transcended Manufacturing is a subset of Mass-customization.

2.2.4. CONCLUSION

A company has weighed the benefits and drawbacks and decided that their planned business-case lends itself perfectly for applying mass-customization. They find the right partners to develop their product-family and orchestrate the required value-chain.

How they do this depends on the company. Is it a big conglomerate with existing production facilities, or a start-up with a small budget? And it also depends on the product-family, is it producible in existing factories or does it require a new factory built from scratch? These factors will determine the used factory realization. In broader terms, will Agile Manufacturing be applied, or Transcended Manufacturing. The decision to explore Transcended Manufacturing in this project, and why is discussed below.

MORE PRONOUNCED MASS-CUSTOMIZATION BENEFITS

The benefits coupled with mass-customization are even more pronounced in Transcended Manufacturing. Because the production system already exists the investment cost will be minimal, reducing the consequences from product market failure and therefore company risk.

Another more pronounced benefit is that of reactivity. No supply lines need to be adapted for a new product-family, resulting in a shorter time-to-market, and helping the company to quickly change course in volatile markets.

Because the production facilities are product-independent, using general-process techniques, they can be spread out geographically in multiple smaller facilities, reducing transport costs and increasing societal benefits as described in the previous chapter.

CURRENT RESEARCH AND DEVELOPMENT BENEFITS

Because the project is developed in a research and development context it is not initially required to make profit and this makes it possible to work directly to the most elaborate or ‘futuristic’ version of the envisioned product-life-cycle, namely Transcended Manufacturing, and try to encounter all the eventual hurdles as early as possible and learn from it.

The project must empower further research and development. The initial research and demonstration business-case must therefore require a strong but simple initial cluster setup, upon which can be added in a later stage, both for new product-families as improving the cluster itself.

This combination of a Transcended Manufacturing production-cluster and a product-family will be the core of this research; the other value-chain activities are not further developed, but the envisioned circular product-life-cycle does form the basis of this research.

2.3. FUTURE FACTORY CONCEPT

WHAT WILL BE REQUIRED?

In the previous chapter it is decided to further develop the Transcended Manufacturing approach of the mass-customization factory. In this chapter the factory is further examined in terms of the factory's hierarchical levels and their core principles are described.

In the second part of this chapter the general classification behind industry factories is explored; with the goal to classify the Transcend Manufacturing production-cluster. As stated the production-cluster is not determined by the product it makes but by its capabilities. It is therefore important that, not only the factory, but the other value-chain partners know what type of cluster it is, and what is possible in terms of product-family design.

2.3.1. PRINCIPLES OF THE TRANSCENDED FACTORY

A framework in the form of core principles of the cyber-physical Transcended Manufacturing factory need to be derived. The paragraphs below follow the hierarchical structure as described in the previous chapter, starting with the factory and zooming in to production part. For each level core principles will be derived in the form of insights.

FACTORY CORE PRINCIPLES

The factory principles described will be related to product manufacturing and its logistics, because the department related tasks are already discussed in the previous chapter.

The core operational tasks of a factory is to perform acquisition to attract brand corporations to develop product-families requiring the factory's capabilities. They will then receive product-recipe files attached to purchase-orders, initiating production. When finished they must then send a sales-order and initiate transport to the user. The additional related tasks are to order necessary materials, components and standard part from pre-suppliers that are needed for the available process steps and distribute them inside the facility.

GEOGRAPHIC PRINCIPLES

An important factory definition will be its geographic location due to local demand for products, and the transport distances to customers. The factory must adapt its production output to local demand for its respective industry type, while minimizing transport time. To smooth out over-capacity, orders can be taken over from other factories at the cost of longer transport distances. Another method, is reducing the production output by transporting process-modules to the other facilities.

LOCAL PRINCIPLES

Other important parameters which define the factory are the floor space, roof height, and the periphery shape of its operations facility; which define its maximum production expandability.

Another important facility dependent parameter is the floor load rating, this defines the expandability in height and the mass it can support, and therefore the type of products. Moreover, the facilities must also have suitable excess to electric power and internet. There must be space for the needed departments, operations, logistics, servers etc..

Relevant Insights:

2.3.1.1 The factory must be able to turn product-recipe files into physical products.

2.3.1.2 The factory must be able to automatically generate and send component and material requests to suppliers.

2.3.1.3 The factory must be adaptable to varying product demand.

2.3.1.4 Process equipment must be exchangeable between facilities.

2.3.1.5 The production-equipment must be designed with different possible floor shapes and roof heights in mind.

2.3.1.6 The factory floor load rating must be taken into account in the design of the production setup and the choice of equipment and products that need to be made.

CLUSTER CORE PRINCIPLES

The cluster is a physically and digitally connected part of the factory that produces products that require comparable process capabilities, the products will be of the same general size and from the same industry type. Its main task is to keep turning product recipe files into finished products and keep production going. To do this it must send requests when necessary to the main factory; requests for parts, materials, waste removal, maintenance, etc.

THE PHYSICAL CLUSTER PRINCIPLES

A production cluster must be designed following an industry standard. It must be able to produce different products, of comparable size, requirements, materials, and industry type (capabilities).

It must be possible to change the cluster layout in between production, to optimize production and minimize module downtime. It must therefore be possible to increase or decrease process-module quantity vertically and it must be possible to extend the transport network horizontally. Used factory space and floor area that is occupied by factory equipment must be minimized while remaining functional.

It must also be able to add new capabilities to the system by adding new process-modules during operation without ever stopping the system.

There must be distribution of process-consumables, standard-components, and materials. Waste must be collected and removed within the cluster.

The system must react to production errors by bypassing transport and communicating for a corrective maintenance request (immediate or deferred) while production continues.

Product and sub-assembly completion must be inspected and checked before continuation or packaging.

THE DIGITAL CLUSTER PRINCIPLES

To keep production continuously running, cluster participants must act autonomously towards reaching their goal, they must understand their goal, gather data, and synthesize information.

Some parts and products have no means or space of carrying computational intelligence with them physically, this must therefore be implemented in the network or cloud. And some of these parts and products also have no means of sensing or tracking their physical state and will be dependent on the system to gain this knowledge.

Every participant is represented in the digital world either with intelligence computed at its physical location or digitally on a server, this intelligence is the digital twin. To connect both worlds some form of industrial production network must be implemented.

This digital world requires an object class framework in which the participants are described in hierarchy, type, and rights. Their state, goals and capabilities are represented and updated, and their decision-making algorithm is defined.

REAL-TIME DIGITAL MODEL PRINCIPLES

For each digital twin to observe and understand the current reality in which they need to act and interact, a real time digital model that represents the whole manufacturing process need to be implemented. This digital representations need to be synced with the real world, to be observed by the system participants as reality. To do this methods must be defined to connect and anchor the systems real states into the digital world. This digital representation is not smart itself it is just a continuously updated mirror image, that the participants can use to make decisions from. It requires that participants can be initialized, recognized, located and the states to be updated. Constant synchronization and checking of states need to take place from sensor data to the model.

COMMUNICATION AND AUCTION PLATFORM PRINCIPLES

All participants want to reach their personal goals. They must interact with each other to communicate their questions, wants and needs and respond to other participants. This requires the development of a digital communication and auction platform as a stage for this interaction. This requires a framework in which communication types and language are defined. All the participants' needs and requests are updated within this platform, respective solutions are offered, the best match is negotiated or auctioned and resulting tasks are initiated.

ORDER MANAGEMENT SYSTEM PRINCIPLES

The system must have an intelligent order management system to receive 'purchase orders', optimally sequence them and putting them in the queue. It must time the initiation of build orders dependent on process-module busyness. When initiated a new product digital participant is created which has the completion of the product-recipe file as goal. When the product is finished and packaged, sales orders are generated and sent to the customer.

This sequencing by the order management system can vary from simple to complex. Using a first-in first-out principle or predictive path planning algorithm based on observations of the real-time digital model where it takes an order expiring and clusters total output efficiency into account.

Relevant Insights:

2.3.1.7 The cluster must be able to send part, material, waste removal, and maintenance requests to the main factory.

2.3.1.8 The cluster must be designed following an accepted industry standard.

2.3.1.9 The cluster must be able to change its layout during production.

2.3.1.10 Used factory space and floor area that is occupied by factory equipment must be minimized.

2.3.1.11 It must be possible to add new process-modules during production.

2.3.1.12 The cluster must contain a distribution and collection system for process-consumables, standard-components, and materials and waste.

2.3.1.13 The cluster must be capable of dealing with production errors while continuing production.

2.3.1.14 The cluster must be able to inspect product completion.

2.3.1.15 The cluster participants must autonomously try to reach their goal.

2.3.1.16 Cluster participant must digitally be represented, following a hierarchy or class system.

2.3.1.17 The cluster must have an industrial internet connecting all participants.

2.3.1.18 The cluster requires a continuously updated digital representation of its physical self.

2.3.1.19 It must be possible for new participants to be initialized, recognized, located and their states to be updated.

2.3.1.20 The cluster must have a communication framework for the participants to interact.

2.3.1.21 The cluster requires a framework to track orders and sequence product-recipe files.

MODULE CORE PRINCIPLES

Modules are participants in the manufacturing system that are digitally represented in the real-time digital model. There are different kinds of modules namely, transport, process, supporting, operations as described in the vertical integration chapter. The core value for each module participants are:

- Process-generality: to provide a product-independent process step.
- Self-contained: include all necessities to achieve a task.
- Capable: being able to interact with the system, complete its task and judge its quality and success.

PHYSICAL AND DIGITAL INTERFACE PRINCIPLES

The modules together form the cluster, they must therefore fit within the grid and specifications of the cluster. This requires a structural frame and a physical connection method between modules to build up the system. It must therefore be possible to stack them vertically and/or horizontally, building out the cluster layout. Initiation of a module in the system must be as easy as putting it down, so called plug-and-produce capability. The module must automatically initialize itself in the real-time digital model and become a participant offering its capabilities. It must digitally define its location within the grid, and its direct neighbors in all directions; this requires a method of tracking or understanding these factors.

This plug-and-produce capability is also important for maintenance, a defect module can directly be replaced by a new one. Also for increased product demand modules can be added in a quickly manner. When the modules experience failure they must not hinder the rest of the system and initiate a corrective maintenance request. All modules must therefore be removable while the rest of the system continues production. If the cluster's transport system fails, it must be quarantined and maintenance must immediately be initiated because production cannot continue in that part of the cluster. It is therefore important that the transport system is in the first place extremely robust and resilient.

PROCESS PRINCIPLES

To provide the process-step, each model must hold all necessary equipment to check its progression; this requires necessary sensors and observation equipment. Each module must therefore connect and transfer electrical power and internet. Internet might also be received wirelessly. Some process steps might require additional conduits such as pneumatics, hydraulics, lubricants or material supplements. AI modules that produce waste or by-products must also have a system to get rid of these materials.

OPERATIONAL PRINCIPLES

To be usable by product-family models and implemented in product-recipe files, all modules have their respective computer aided manufacturing (CAM) code standards that must be known and communicated with the co-creation corporation. The CAM file is then used to operate the module; this requires drivers and digital to analog conversion for its actuators.

To operate within the cluster modules must be designed as one cohesive smart system analyzing clustering sensor data before sharing it to the real-time digital model, this reduces network congestion and reduces server processing requirements and overloading the industrial network.

Relevant Insights:

2.3.1.22 The modules must fit within the grid and specifications of the cluster.

2.3.1.23 The modules must have a structural frame and a physical connection method between each other.

2.3.1.24 The modules must be vertically and/or horizontally stackable, from all arbitrary starting configurations.

2.3.1.25 Module initialization in the system must be as easy as putting it down.

2.3.1.26 All modules must be removable while the rest of the system continues production.

2.3.1.27 The transport and movement system must be designed to be extremely robust and resilient.

2.3.1.28 Each module must hold all necessary equipment to check and analyze its progression.

2.3.1.29 Each module must have an interface to connect and transfer electrical power, internet and other necessary conduits.

2.3.1.30 AI modules must have a system to get rid of their by-products.

2.3.1.31 AI modules must be made with their respective CAM software for in the product-recipe file.

2.3.1.32 The modules must cluster sensor data before sharing it to the real-time digital model.

PRODUCT CORE PRINCIPLES

Within the cluster after initiation by the order management system a product must act autonomously towards reaching its goal of becoming a finished product. It must adapt when necessary due to unforeseen disturbances, and must actively find its route following the product-recipe. The products intelligence will be fully hosted on the server and it is therefore dependent on the sensing capabilities of the system that transports it to be recognized and localized.

Principles related to the product-use-phase of its life-cycle will be discussed in the 2.4. Future Product Concept part of the report

PRODUCT-RECIPE FILE PRINCIPLES

The product-recipe file consists, firstly, of a list (or multiple) with the production step-order. It consists secondly of a series of CAM files for each required process-step; from something as simple as inserting a standard-component, to something as complex as a machining operation. Instead of a CAM file there can also be a whole part-recipe file to produce a sub-assembly, which follows the same structure as a product recipe-file. Each CAM part of the file is accompanied with an equipment setting list and intermediate visual or sensory references to inspect the completed process steps; to compare actual results with the expected current state of the product.

Relevant Insights:

2.3.1.1.33 The products must act autonomously towards reaching its goal of becoming completed.

2.3.1.2.34 The products must be able to adapt to unforeseen disturbances, and find new routes.

2.3.1.3.35 The products must be trackable at all times throughout the production system.

2.3.1.4.36 The product-recipe file must contain all the information needed to complete the product production.

2.3.1.5.37 The product-recipe must contain process inspection references for comparison.

PART CORE PRINCIPLES

Parts are produced or inserted following the product-recipe file, they can be either monolithic (made of one piece of material), sub-assemblies produced earlier in the cluster or standardized supplier-components.

MOVEMENT PRINCIPLES

Parts and core products travel through the cluster towards each other to be assembled into each other. Parts are either smaller than the core product in terms of size-standard, or are around the same size. It could also be possible that the part is bigger than the core product, but this depends on perspective, the product viewed as sub-assembly will in this case be assembled in the bigger ‘part’; in terms of size-standard.

Movement from a smaller to bigger size transport track or system requires an assembly-module to pick-and-place the part into the core product (or another joining technique). Within the same-size transport system an assembly-module is also required; to assemble parts that have the same size as their products (the smaller-track assembly-module could also fulfill this purpose).

TRACKING PRINCIPLES

Because countless unique parts, sub-assemblies and products move throughout the different transport-tracks it is really important to track where they are at all times, firstly for each product to know where they are in the production process. Secondly to keep the real-time digital model up to date; keeping the system observable for all participants. And thirdly to notice transport failures and signal lost parts. The same challenges arise in warehousing and logistics, therefore multiple warehouse inventory tracking methods are explored, these can be found in the Appendix: 7.1.2. Production Tracking.

TRACKING DECISION PARAMETERS

The design of the manufacturing tracking architecture will depend strongly on the industry and material types but also on the parts themselves. The following parameters will be really important in the choice of part tracking:

- Part form: If the parts are really small or thin there will be no room for certain trackers.
- Financial viability: If the parts are really inexpensive and the needed quantity high, it will not be financially viable to use for example RFID sensors.
- Material type: If the material is non-solid or the surface texture is not appropriate certain trackers will not work.
- Use case: If the part’s exterior must be aesthetically pleasing it might not be appropriate to use an engraved barcode to track that part.
- Uniqueness: If a part is standard and easily replaced it is not always needed to track it before inserting it in the product.
- Loss risk: If part has a complex production transport path to follow that takes a lot of time it will be important not to lose it, this requires a more reliable tracking technology.

Relevant Insights:

2.3.1.6.38 Parts require an assembly-module to move from a small to a bigger size transport track/system.

2.3.1.7.39 Parts with the same size as their product require an assembly-module.

2.3.1.8.40 Parts must be trackable at al times within the transport system.

2.3.1.9.41 For each part a tracking method must be chosen depending on the cluster, product and the described decision parameters.

2.3.2. FACTORY TYPES

The factory to be researched follows the Transcended Manufacturing method. It handles multiple product-families that require the same production capabilities resulting in one-of-a-kind personalized products. This also means that the factory exists before the products are known.

The production-cluster is not determined by the products it makes but by its capabilities. It is therefore important that not only the factory, but the other value-chain partners know what type of cluster it is, and what is possible in terms of product-family design; what size, which materials, which output capacity, performance, etc. To synchronize the value-chain and create transparency and communication. To work toward the same product centric goals industry standards must be set, for product factories, brand corporations and manufacturing-equipment suppliers (such as Festo) to communicate with each other, and have a framework to build onto.

And although some manufacturing suppliers might want to deploy their own standards and hold the market captive, it is in the best interest of society to make these standards general and enable an open market platform with a high product diversification for consumers.

To determine what overarching: principles, requirements, and definitions can be standardized and what determines a specific Transcended Manufacturing production-cluster, current classification behind industry factories is explored. In the following paragraphs different axes of factory realization are analyzed; these axis types are: Industry types, Material types, Performance types, Size types

INDUSTRY TYPES

When looking at the world's existing products they obviously can be categorized by different industry types, due to the market segments they cater, but mainly because of the overlapping process steps they require. From either continuous process production such as soda, or oil to discrete manufacturing such as chairs or laptops. But also from big, such as cars, to small such as bicycle lights.

The following list is a clustering of the secondary industry types as defined by the North American Industry Classification System to get an insight into the types of manufacturing (in the Appendix: 7.1.3. Industry and Material Types the list with the respective NAICS codes can be found).

- Food, Beverage and Tobacco
- Textile, Apparel, and Leather
- Wood, Paper, and Printing
- Petroleum, and Coal
- Chemical
- Plastics, and Rubber
- Nonmetallic Minerals
- Primary Metal, Fabricated Metal, and Machinery
- Computer, Electronic, Electrical Equipment, Appliance, and Components
- Transportation Equipment
- Furniture
- Miscellaneous Manufacturing

The products related to the industry types in this list require different process capabilities from their production setup and are dependent on the type of product to be developed. Products comparable in required process-steps can be produced by the same cluster. When these requirements differs too much, different production setups will be required. A product that requires two different production clusters must also be able to switch between clusters, requiring overarching transport and size standards for both clusters (this is discussed later).

An important fact to keep in mind is that most products and most industry types will not require a Transcended Manufacturing business-case and a more traditional production manufacturing chain will be sufficient.

The division of industry types is probably the most important when designing the cluster for certain product-families, but the resulting design considerations are extremely dependent on this type, therefore no overarching principles are derived towards a general industry standard.

From this point on in the report, industry type will refer to a product-category of shared process-capabilities and requirements (e.g. small consumer electronics, or government approved kitchen utensils, etc.).

Relevant Insights:

2.3.2.1 For every industry type cluster the required capabilities must independently be analyzed.

MATERIAL TYPES

The manufacturing capabilities required for the described industry types are in direct relation with the material used to build the products. These materials bring their own requirements to the production cluster, not only practical, but also, legal and ethical. After general design- and engineering-dependent requirements such as elasticity, strength, viscosity, resistivity, opacity, etc., the most important material type categorizations to consider are described in the two example lists below:

Hazardous materials as defined by the US government in document 49 CFR 172.101 (In the Appendix: 7.1.3. Industry and Material Types the list with classifications can be found):

- Explosives
- Gases
- Flammable liquids
- Flammable solids
- Oxidizers/organic peroxides
- Toxic and infectious substances
- Radioactive material
- Corrosives
- Miscellaneous hazardous materials

Process contamination as defined by the American Society for Testing and Materials:

- Pigmented drawing compounds
- Unpigmented oil and grease
- Chips and cutting fluids
- Polishing and buffing compounds
- Rust and scale
- Others

The above categorized material types, require different process considerations and capabilities from their production-setup and are dependent on the type of product to be developed. Product-families requiring the same considerations can be produced by the same cluster. Design aspects resulting from these considerations are: dust free, closed off, air conditioned, flame retardant, non-corrosive, disinfected, and submersible, etc.

The division of material types is extremely important when designing the cluster, but the resulting design considerations are dependent specifically on the product-family type, therefore no overarching principles are derived towards a general industry standard.

Relevant Insights:

2.3.2.2 For every material type cluster the production requirements must independently be analyzed.

PERFORMANCE TYPES

When looking at the production within each industry, it is found that the parameters that describe the performance of a production-step, are the same throughout completely different industry sectors. These performance categories are described in the paragraphs below.

LOAD CAPACITY

Different products will have a different weight for their size; their average density. This will have influence on the cluster design. Firstly because the safe working limit (SWL) of the transport system must be high enough to support the weight of the product. And secondly, low weight products provide a low normal load on the transport system, resulting in low horizontal contact friction, requiring slow movement clamping or locking of the product to prevent sliding.

This performance type must be included and defined in the overarching industry standard.

MAX INERTIA FORCE

Another influence of the product's density is the resulting inertia force due to the change in velocity. High weight products will requiring stronger actuators to accelerate and stronger clamping forces for stability. In addition, for low weight products the influence of air resistance will be more impactful on product stability. And also actuated product manipulation provides a challenge, because the low-mass products are easily disturbed by the actuators.

The inertia forces at the center of mass will also generate a moment around the holding or clamping position that must be counteracted. The height of the product and therefore the height of the center of mass has a (positive) linear influence on this moment and must be kept minimal.

The performance parameter is directly related to the load standard and will not require its own definition.

BUILD VOLUME (SCALING LAW)

A really important consideration is the length-mass relation following the physical scaling law; meaning: a product with a cross-section twice as long has an eight times bigger volume and therefore eight times as much mass; assuming the same density. Also a product halve the size, has one eighth of the mass.

To derive an overarching industry standard it could for example be decided that for a certain build volume the transport system must be able to hold and transport that build-volume completely filled with lead (or another high-density material). Thereby opening up the transport system for every possible product in terms of weight. This is certainly an excellent idea for tiny to small product sizes, putting no significant requirements on the transport system; for example cubic centimeters of lead. But from medium to big products this standard becomes unrealistically excessive and also expensive; for example a cubic meter of lead. To illustrate: a bicycle does not need a transport system capable of moving a car engine block. This scaling law can clearly be seen when calculating the cuboid shaped minimum build-volume for different sized products and calculating their density; the density is inversely related to the length of the product. Some products and material densities are described below.

- *Mechanical Watch = 3.292 Kg/m^3*
- *Charger = 520 Kg/m^3*
- *PC mouse = 530 Kg/m^3Kg)*
- *Senseo = 144 Kg/m^3*
- *Car engine = 483 Kg/m^3*
- *Washer dryer = 314 Kg/m^3*
- *Car = 129 Kg/m^3*

- *Styrofoam = 75 Kg/m^3*
- *Cork = 240 Kg/m^3*
- *Oak = 710 Kg/m^3*
- *Water = 1.000 Kg/m^3   (by definition)*
- *ABS = 1.070 Kg/m^3*
- *Aluminum = 2.700 Kg/m^3*
- *Steel = 8.000 Kg/m^3*
- *Lead = 11.000 Kg/m^3*
- *Gold = 19.320 Kg/m3*

Another important fact: when the build-volume and transport-system is small enough, the requirements for building a mechanically working structure are the determining factor, not the product mass it transports; in other words, the system will automatically be strong enough to hold the product mass.

This performance type is extremely important in designing the production system as well as the products to be produced, and it will require its definition within the industry standard.

FLOOR LOAD RATING

The transport system must not only hold a certain load, but also the factory floor, which will hold the production equipment. Factory floors are normally rated for a certain amount of kilograms per square meter and give an overarching parameter in defining the industry standard.

Just as the product load capacity described above defines how heavy the product can be, the floor load rating defines how heavy the production equipment can be. This will need to be included and defined in the overarching industry standard.

MAXIMUM TRANSPORT ACCELERATION AND SPEED

The maximum change in speed of a product is directly related to its mass-density. A heavier mass will have a higher inertia and will require stronger actuators to accelerate the product with the same rate as a low-mass product. Also, for a set actuation strength, the mass physically defines the maximum acceleration. This set actuation strength must therefore be tweaked to match the so called rhythm of the transport system, which is dependent on the intermediate process-steps; thereby reducing investment cost and energy consumption. The rhythm of the transport system, which is the timing between movement steps, in combination with the minimum product acceleration will determine the transport speed of the system (this rhythm is not necessarily discrete or consistent).

This performance type does not require its own standard, because this can directly be derived from the load standard in terms of power. The defined power division of velocity-torque can possibly be added to the standard, but is not further elaborated in this report.

ACCURACY AND REPEATABILITY

The required capabilities in producing different industry type products will differ depending on the product and its application, requiring different levels of accuracy and repeatability. This in turn depends on the precision of the process equipment, with how much tolerance it is built and the hysteresis and backlash in its moving parts.

Another important factor is the size of the product, the relative influence of absolute deviation is inversely related to the size of the part or product. Meaning, for smaller parts geometrical deviations are proportionally more impactful.

Due to this size dependent relation, an accuracy and repeatability industry standard could be devised that relates to the build-volume size, which could be used when choosing the production setup for certain product-families. But accuracy and repeatability design considerations are very dependent on the specific process, it is therefore not beneficial to add principles relating to this performance type to the Industry Standard, and let these capabilities be defined for the process-module itself.

Relevant Insights:

2.3.2.3 The load capacity must be defined in the industry standard.

2.3.2.4 The height of the build-volume must be kept minimal in the industry standard.

2.3.2.5 The scaling law for product density must be taken into account in the load standard.

2.3.2.6 The build volume must be defined in the industry standard.

2.3.2.7 The floor load rating must be included in the industry standard.

2.3.2.8 Accuracy and repeatability capabilities must independently be defined per process-module.

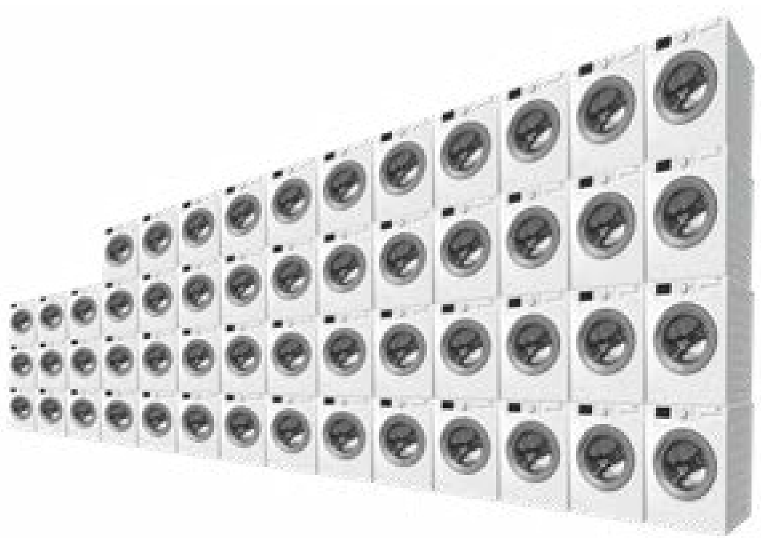
SIZE TYPES

This factory realization axis is extremely important in designing the production system as well as the product-families to be produced, and it is probably the most important overarching definition within the industry standard. Below this size type and its influence is further elaborated.

Small to medium products are more numerous than bigger products, because they fit our human surroundings for which they are designed, especially hand-size products. This puts an increased demand on production of these smaller build-dimensions. This demand is even bigger when considering that products consist of smaller parts, which in turn must be manufactured in their respective smaller build-dimension production system. And some of these parts consist of even smaller parts and so on, from big to tiny product sizes. In short, the demand on production is inversely related to size.

To cope with this demand, production must either be fast or numerous. For slow process-steps the output can be doubled by either doubling the speed or doubling the process equipment. For a lot of manufacturing methods it is not possible to increase its output speed much, it is therefore necessary to incorporate a system to multiply the process steps without losing functionality and minimizing loss of resources. Resources such as production speed itself, factory-floor real estate, factory usable height, equipment investment and setup costs, operations and maintenance cost and energy expenditure.

When looking at factory real estate, it is really important for parts and products to be produced by equipment made for their respective size. If the production of a 10 centimeter long product requires for example 500 process-modules to meet demand, but the product is made with modules capable of making products 20 centimeters long, the build-volume and therefore the process modules will be eight times as big. If the process module is assumed to be a cube that requires an additional 50% in each direction for the actual equipment, the extra factory occupying volume is the difference between 1.7 m^3 and 13,5 m^3. That is of equal volume to the difference between 7 and 53 washer-dryer units. It is important to remember that this case the increased factory volume has exactly the same production output. To reduce equipment, energy, maintenance and real estate costs, it is paramount that products are made in the smallest possible build-volumes and process-modules. The size of modules is especially important if the process-step is required a lot, or in other words, slow. For fast, and therefore rare, process-steps this is not as necessary.



Relevant Insights:

2.3.2.9 The size type must be defined in the industry standard.

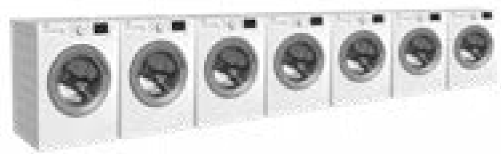
2.3.2.10 To cope with demand, process-modules must either be fast or numerous.

2.3.2.11 The industry standard must enable process-module stackability minimizing loss of resources (floor area, ceiling height, etc.).

2.3.2.12 It is paramount that products are made in the smallest possible build-volumes and that the space for the process-modules must be reduced in all directions.

2.3.2.13 The industry standard must enable gradual increase between progression steps.

It was already stated in the introduction of this chapter that it will be important to have a framework of industry standards, especially in dimensioning and volume. This way industry-type crossover products are able to switch between clusters, and also smaller produced parts, can be transferred into bigger products. If a new product-family is developed, it must either fit with the current production setup, or not. In that case, it must be allocated to a bigger size-standard cluster. For the module defining size-standard, it becomes clear that space in all directions must be reduced. Firstly the floor space, requiring modules that fit together leaving no gaps; also modules of different sizes. Secondly the ceiling height, requiring modules to vertically fit together to optimally use the factories available volume; also for modules of different sizes.



2.3.3.CONCLUSION

DISCUSSION

By definition the Transcend Manufacturing production-cluster is not determined by the product it makes, but by its capabilities. The factory exists before the products are known and it handles multiple product-families that require the same production capabilities. As a result, it is capable of producing one-of-a-kind personalized products.

But to manufacture these products at mass-production output capacity, process-modules must either be: fast, or numerous. And in the last case, it is paramount that they are as small as possible. This is one of the main reasons that an overarching Industry Standard must be derived, classifying process-modules for certain build-volumes.

Following the core principles and insights described in this chapter, a future Transcended Manufacturing factory can be envisioned which is described below:

This future factory supplies one or more Industry-type products to a small province or city. Within this factory, production takes place in a reasonably large hall, with long rows of stacked process-modules connected by different standard-size transport-systems. Here production continuous constantly, while maintenance is applied, modules get removed for inspection, the newest type of process modules are added, unused modules are shipped to other facilities, and the quantity of congested modules is increased. Every part, everywhere in the system is accessible, removable and transportable, not only the process-modules, but also the transport tracks and elevators systems. This factory is, as metaphor, comparable to the human body, it holds its identity but grows, adapts and changes with its surrounding. The living body remains, but as time progresses, no one cell remains the same and the system is eventually fully replaced.

The factory layout of clusters and modules can eventually be optimized and controlled by machine-learning, taking all costs and speeds into account, placing some modules dispersed throughout the system while grouping others, planning maintenance and end-of-life for the modules. Eventually the transport tracks might even disappear, instead using omnidirectional transport-robots, where parts and modules are being transported crisscross throughout the factory. The process-modules themselves will be produced in such a future factory, in the respective build-volumes of bigger process-modules. And finally factories are equipped with their own recycle capabilities, not only for process-waste, but to retrieve all consumer products locally, no longer needing fresh materials to sustain the ever rotating population of products.

CONCLUSION

The above described story is of course a rather hopeful vision of the future, but something to work towards nonetheless. The described system is also beneficial in an initial research context because it can start small. Only a couple modules are needed, an initial cluster and one exemplary mass-customization product, after this first proof of concept is realized it can be extended with new capabilities and product-families. To start this off, an industry- and size type will need to be decided for the first production-cluster. This in turn requires and industry standard to be proposed, so the product and modules can immediately comply with this system.

2.4. FUTURE PRODUCT CONCEPT

WHAT DOES IT BRING?

In the 2.2. Future Life-cycle Concept chapter it was stated that a company deciding for a mass-customization business-case, has to weigh the benefits versus the drawbacks and determine if their planned business-case lends itself for this manufacturing approach.

One of these benefits is that mass-customization can provide an increased profit margin. This benefit is fully dependent on what is probably the main reason the company wants to implement mass-customization, and that is personalization. By producing customer specific products they might be able to provide benefits that were otherwise impractical or impossible. These benefits could provide new customer value and therefore more company revenue.

The company must determine the extent of the applied personalization, what is strictly necessary to provide extra customer value they want to give, and how does this relate to configuration and therefore value-chain complexity. Is mass-customization even needed, might traditional multiple batch-production be acceptable. This will be discussed in the next part of the chapter.

In the second part of this chapter a framework of core principles for the cyber-physical Transcended Manufacturing product are described in the form of insights. This is in line with the product core principles described in the 2.2.2. Mass-customization Product Factory chapter but taking the whole product-life-cycle into account; omitting the beginning-of-life production phase of the product.

2.4.1. PRODUCT PERSONALIZATION

Probably the most important reason for companies to choose mass-customization as manufacturing method is the valuable products they are able to make. They will be able to bring consumers one of a kind products that perfectly solve their problems and fit their wishes. Indeed these one-off products are the result of mass-customization but this is not a straightforward task. This requires an intermediary service to transfer consumer needs and wishes into a final design. This service could be a salesperson, an interaction at an outlet, or an online or offline software tool. This service assumes some form of product-family model and uses this to converge user wishes into a final product design. Once the final design is defined by the user it is converted into a product-recipe; this is the term used in this text meaning: information or file standard that can be used by the factory to produce the finished product.

SERVICE CO-CREATION LEVELS

The methodology of including the consumer in the product design process is called co-design or co-creation. Sanders and Stappers (2008) recognize the importance of expertise, passion and creativity in fulfilling the role of co-designing a product. They describe four levels of creativity, the purpose of each level is described below:

1. “Getting something done”
2. “Make things my own”
3. “Make with my own hands”
4. “Express my creativity”

Co-design can be implemented in the very early stages of the product design process named the fuzzy-front-end. This text covers the required product configuration service needed in mass-customization; further called configuration service. A company could of course still implement co-design as a design method, but this text focuses on co-design in the configuration of a product-family. Therefore the full relevance of co-design falls out of the scope of this service. It is important to note that the co-design process in itself can bring the consumer more value than the product itself (Merle, et al., 2010).

Sanders and Stappers (2008) say that each of the four level of creativity require a different method of facilitating the co-design process for the consumer; from level one to four, these are: Lead, guide, provide scaffolds, provides a clean slate. Following this line of thought six service co-creation levels are defined, constituting creative involvement, starting point in the design process and personalization freedom.

All levels are abstractly defined with mass-customization in mind while keeping the product type and specific service undefined (consultant, software, etc.).

1. Choose from repertoire: The consumer is able to satisfy his or her needs by choosing the right product from a product repertoire. This requires a service that showcases the available products and their features. (MacBook) Customer order decoupling point (CODP): build-to-stock.
2. Combination of sub-designs: The consumer is able to combine parts of a design to increase personal satisfaction in terms of functionality and experience. This requires a service that presents the available options and makes it possible to select between these sub-designs and gives a transparent real-time representation of the resulting product. (Dell laptops, Ikea) CODP: build-to-stock, build-to-order, configure-to-order.
3. Criteria dependent design: The consumer is able to implement his or her needs by choosing product functions through the service and adapting these to fit. This requires a service that gives a clear overview of the available functions and their properties. The user is then able to select and adapt these criteria-dependent-functions and the service generates a design dependent on the selection. The service then gives a representation of the resulting product, producibility, required cost, and time. (Cars) CODP: build-to-order, configure-to-order.
4. Parameter dependent design: The consumer is able to optimize his or her product by tweaking predefined parameters of the design. The user iteratively works towards a design that fits his or her needs and wishes as best as possible; within the time and effort he or she is willing to spend. This requires a service that gives a clear overview of the available configurable parameters and

their impact on the overall design. It gives an intuitive method of adapting the value of each parameter and gives a transparent real-time representation of the resulting product, required cost, and time. (printed t-shirts, tailor-made suits, glasses, kitchen) CODP: configure-to-order and engineer-to-order.

5. Consumer generated designs: The consumer is able to design the product him or herself by using a service that allows to select and adapt available features and components. To reach a satisfactory design the consumer needs to have a clear understanding of his or her wishes and requirements when developing through the service. This requires a service that gives a clear overview of the design options and components available in the production setup, including the method of using and implementing these. It gives design freedom to the user while keeping the possibilities grounded in the reality of production. The service gives a transparent real-time representation of the resulting product and gives feedback on the producibility, required cost, and time. (wedding rings, photo album) CODP: configure-to-order and engineer-to-order
6. Professionally generated designs: The professional customer is knowledgeable about the available production capabilities, is able to develop a design that fits with his or her requirements. The customer is then able to shares this design through the service. This requires a service that is able to accept the design in its specific format and communicates feedback about the producibility, required cost, and time. (ordering a job-shop part) CODP: engineer-to-order.

PRODUCT PERSONALIZATION LEVELS

A company can use different co-creation levels within the service for different aspects of the product-family model. The above described co-creation levels describe the user's creative involvement in the service and therefore the personalization freedom they have. This in turn determines the general range of configuration complexity that is implemented for a product-family aspect. But Fischer (2002) described the human involvement in the design process as a continuum from passive consumer up to meta-designer, and as such within each co-creation level there is a whole resolution range following this involvement, that can be implemented to customize the product-family aspects as much as needed. This resolution can be the inputs in a software tool, the questions of a sales-person, or the outcome of measuring. These different resolution ranges are the following:

- One selected option (fixed product-family aspect)
- Choose between two options (Boolean)
- Choose between multiple options (Natural numbers)
- Choose within a defined range (Rational numbers)
- Choose a value (Real numbers)
- Use an extracted value (measurement)
- Use combined extracted values (scan)

This chosen resolution determines the total resulting realizations of that product-family aspect and thus the complexity of the applied personalization, this complexity is defined as the personalization level.

The last factor that determines the complexity of the personalization service and product-family model, is the amount of personalisable aspects that are implemented (that are not a fixed aspect). The combined personalization levels of all aspects determines the amount of theoretically possible product realizations (TPPR). From a certain ratio between TPPR and product-family market demand, traditional build-to-stock mass-production with defined batch sizes becomes impractical, and configure-to-order mass-customized production will be required.

THE CUSTOMIZATION-CATEGORIES

The different aspects of a personalisable product-family can be clustered into three customization-categories that are defined below. These three product aspect groups differ greatly in how they impact product experience and user value. By including personalisable aspects belonging to all three customization-categories the TPPR of the product-family model will increase very fast. Theses Customization-Categories are:

- Customization in **Identity** (perception): form, texture, color, print, smell, taste, sound, feel, etc.

- Customization in **Fit** (presence): shape, size, mass, area, amount, quantity, color palette, etc. (Fit in relation to consumer self and interaction environment; including other owned products).

- Customization in **Capabilities** (features): performance, ingredients, components (electrical, mechanical, fluidic, and thermal), etc.

PERSONALIZATION VALUE INCREASE

In summary, a company wants to use mass-customization to develop their personalisable product, they need to develop a product-family model and an accompanying configuration service. They understand there will be a personalization level applied to the product-family aspects, which will result in a mount of theoretically-possible-product-realization. But what does this mean for the user? As Piller and Müller (2004) say:

In the end, it is very important to remember the words of Pine (1998: 14): 'Customers don't want choice. They want exactly, what they want.' Customers are not buying individuality; they are purchasing a product or service that fits exactly to their needs and desires. Only few customers honor long configuration processes. Most users want to find their fitting solution as smooth and simple as possible.

Therefore customer investment in a product-family or specific aspects of it are a driving factor. When investment increases, so does expertise about the product-family. Expertise increases while thinking, researching and learning about the possible product options; it means having very specific requirements and wishes about these aspects. Meeting these wishes perfectly ultimately result in a higher product value for the user. The expertise level a user has on a product-family consist of their own expertise, but can also be extended by additional expert help when personalizing that aspect; this can be taken into account in the configuration service.

The customer's investment in a product-family aspect, starts in one of the three customization-categories: Identity, Fit or Capabilities; they lie on a different experience-axes. Therefore initial expertise will be focused on product aspects belonging to one of these categories. The customer's investment and expertise might eventually leak out to the other customization-categories when researching and thinking about the product-family. This investment relates to potential extra user value when meeting the newly acquired wishes. It is therefore beneficial to have a very clear variety of personalisable product-family aspects that the customer can invest in. This diversity can be created by implementing personalisable product-family aspects belonging to each of the three customization-categories. These aspects will have different user expertise levels and thus different requirements on personalization. The expertise level must determine the applicable personalization level implemented in the configuration service.

It is important to note, that a high overall personalization level can have an influence on the brand associations and thus the final product value. This needs to be kept in mind by a brand, when determining the personalization level of a product aspect within the customization-categories. The influences on brand-identity are defined below related to each customization-category.

- Identity: High Brand identity versus high personal identity.
- Fit: Replaceable general standards versus best personal fit.
- Capabilities: Brands quality choice versus best personal preference.

Another possible disadvantage to keep in mind is that for products personalized to fit a specific consumer perfectly, the chance for a second life by a different user, after selling or giving it away, becomes smaller.

To summarize, a customer invested in a product-family aspect will have a higher expertise level, and therefore will appreciate additional personalization freedom. When properly implemented this will result in a higher final product value. But when the personalization level is set to high, and not matching with the customer's expertise level, it will result in configuration-option overload, with way too much options, possibilities, and decisions for the customer to make. It is therefore imperative to fit the configuration service on the customer by matching expertise in a product aspect, with the right personalization level.

FINDING A GOOD PERSONALISABLE PRODUCT

To find a product that shows off and requires mass-customization as production method, an exemplary-product need to be found with a high value increase due to personalization, that is not producible with traditional mass-production or job-shop manufacturing. Methods for companies to find product-families that fit this specific goal are described below:

- Look for existing products that people have bought, where people after researching and comparing, find a product that has one or two aspects that are not aligned with their wishes, but they do choose to buy it, although it is not perfect because it was the best option they had. This product-family might benefit from mass-production (or a broader and more detailed selection). This can be done by performing interviews etc. Example: Someone wanted to buy a headphone, and after research needed to choose between two, one had more bass-sound and less weight which are seen as big benefits, but the other had better aesthetics, thus that one was finally chosen. With personalization of these aspects higher product value could be achieved.
- Find a market group with high existing personal investment in one customization aspect of a product-family and medium to high investment in the other two Customization-Categories (Higher expertise result in a high personalization requirement). By brainstorming etc. Example: parents buying children bicycle helmets, safety is really important for them (high personal investment) thus the fit and capabilities category must be 'perfect', color might also be of medium importance. Expertise from parents and outlet owner could result in a 'perfect fit' or highly personalized product choice.
- Find experts or professional, people that use a type of product extensively on a daily basis, high expertise result in a high possible personalization level and thus a bigger step up in final product value. By research in etc. For example: athletics, workers, artists and hobbyists.

Relevant Insights:

2.4.1.1 The personalizable product must be designed with a configuration service and adaptable product-family model in mind.

2.4.1.2 The personal realization of a product-family model must have the form of a product-recipe file.

2.4.1.3 The product-family must have a set of different customizable aspects with an applied resolution range.

2.4.1.4 Mass-customization requires a product-family with a high amount of theoretically-possible-product-realizations (TPPR) to be relevant, otherwise traditional batch-production will be practical.

2.4.1.5 For the configuration of a product-family to have an impact on different experience-axes, aspects within the three customization-categories must customizable (Identity, Fit, Capabilities).

2.4.1.6 The product-family must have customization aspects with a high expertise or investment consumer group.

2.4.2. PRINCIPLES OF THE TRANSCENDED PRODUCT

Personalization is not the only way to generate more value, by applying a mass-customization business-plan. As discussed in the 2.1.4. Why Mass Customization chapter, the required Cyber-physical technologies make it possible to generate an increased profit margin. To explore this, a framework of core principles for the mass-customization product-life-cycle are described in the form of insights. Including the middle-of-life (MOL), end-of-life (EOL), and product inception phases. This is in line with the product core principles described in the 2.2.2. Mass-customization Product Factory chapter but taking the whole product-life-cycle into account; omitting the beginning-of-life (BOL) production phase of the product.

CYBER-PHYSICAL PRODUCT CORE PRINCIPLES

In this mass-customization life-cycle designers stop working towards a target group and instead become product-family designers, taking into account a whole range of individuals. The product-family is an objective representation of a product, defined by its universals; commonalities in properties, relations, and functions. The product-family has clear parallels with Plato's theory of forms, he held that the world of forms and ideas is transcendent to our own world, and these forms are the only objects of study that can provide knowledge. As a result no one perfect product, such as chair, exists. They are all imperfect representations of the non-physical perfect chair. In more practical terms no one chair is perfect for every individual. It is the role of the designer to capture the universal of a chair, into a product-family-model. Thereby giving the consumer the opportunity to get something close to the perfect chair.

The customer is convinced through personal investment, peer influence and advertising to obtain a personalized product. He conveys his or wishes through a co-creation service and the product gets made. The production of this one-of-a-kind personalized product requires, as described in the 2.2.2. Mass-customization Product Factory chapter, tracking of every part and product within the factory transport-system. The product is eventually finished, packaged and stored at the outbound logistics department. It is sent to the customer together with the sales order. These processes require a tracking-system, linking and updating the product with their digital counterpart; the Digital Twin. This system can therefore also be implemented during the use-phase of the product-life-cycle. And after shipping the customer receives ownership over the product both physically and digitally.

DIGITAL OWNERSHIP CORE PRINCIPLES

As described in the 2.4.1. Product Personalization chapter, it is really important for the mass-customization business-case, that the personalized realization of the product-family-model, generates increased customer value. But ultimately the user 'determines' the value extracted from the product and what it will be worth during the course of the product life-time. This Cyber-physical product can increase this, thereby improving user-experience.

How tracking is implemented and what benefits it can bring depends strongly on the industry type and the type of product. Some products require for example maintenance (e.g. power-equipment), here component diagnostics and replacement can be beneficial. Some products on the other hand are made to be depleted, the materials cannot be replaced when damaged, they are fashion dependent, or the user requires to have state-of-the-art technology. Other user benefits that are enabled by cyber-physical anchoring are the following:

- Diagnose problems and initiate maintenance.
- Ownership identification, to receiving physical services, network connecting, and software updates.
- Using the Digital Twin as a part of a digital service.
- Using the Digital Twin to save product settings and preferences, and reviewing personalization design settings for future products.
- To keep warranty, receive insurance and locate the product.
- To sell and transfer proof of ownership of the product to a different user or to a

recycle company.

USE TRACKING CORE PRINCIPLES

It is not only beneficial for the user, but also for the brand-corporation to keep track of the product and record its use; to get feedback, improve future product-family design, discover new trends, and adapt their business-plan. For a brand to apply these middle-of-life cyber-physical anchoring aspects, a framework must be designed by the R&D department and implemented during manufacturing of the product. The type of tracking implemented in the products depends on the needed updating moment to synchronize the Digital Twin with its physical counterpart in terms of state and gathered data. Not all products can be tracked in real-time, firstly, because not all products are always online and secondly, it is in most cases not beneficial to constantly transfer data. The type of update moment, to synchronize the stored product-use data, depends on the product and industry type. Below the product data update-types are listed:

- End-of-life readable product: Product with no internet connection, the gathered data is readable at the end-of-life.
- Synchronizable product: The product stores, clusters, and transfers the data at a designated syncing moment. The user, for example, needs to actively ‘reactivate’ a product-aspect generating a syncing opportunity to transfer gathered data.
- Intermediary online product: The product has an internet connection by means of an intermediary product. The products connects, for example via Bluetooth or USB, to a device with an internet connection, being able to upload the gathered data.
- Internet capable product: The product has its own network IP and is able to transfer gathered data when needed.

The actual knowledge the company will gather to support their market research fall in the following categories (these categories are also found in the PESTEL analysis method):

- Technical: Does the product operate well?
- Economical: Does the product provide value well?
- Environmental: Does the product minimize consumption, pollution?
- Social: Does the product provide comfort, security, safety well?

The brand R&D must decide what the data will look like and this is already a complex task: is it static or dynamic, is it constantly recorded, is it event/trigger based, is it time dependent, is the data expressible in on or multiple numbers, is it a selection of predefined options, or is it a yet unknown string of letters.

Some more general big challenges that arise for the R&D department when designing the use-data tracking framework are: when to synchronize or extract knowledge following the describe update-types. When does the product need to be online or offline and how to minimize network congestion. How to gather relevant data and keep it compact. Which data translates into usable insights or knowledge? How to respect and ensure the user’s privacy. And how to keep product experience and therefore user-value from deteriorating. These challenges must all be tackled while developing the product-family.

PRODUCT RECYCLE CORE PRINCIPLES

The brand R&D department designs the product with an integrated recycle plan. The bill-of-materials, a digital representation of the design, and the implemented disassembly sequence are added to the Digital Twin of the product. At the product end-of-life, the user can transfer physical and digital ownership to the recycle corporation.

The recycle corporation collects the remaining end-of-life data and sends it to the brand corporation. The products recycle plan is applied to retrieve the last material and component value and the Digital Twin is destroyed. The material and components are transported to their respective part factory, process plant and product factory to be reused in new products.

The remaining end-of-life data must be collected and sent to the brand corporation before destroying the product digitally and physically. The types of end-of-life data that can be gathered are described below:

- Product life duration.
- Amount of product owners.
- Failure mode of product or parts.
- The retained value, what can be reused.
- Physical and visual state of the product.
- Integrated user questionnaire information.

Relevant Insights:

2.4.2.1 The product-family-model must capture the universals of the product form without defining them.

2.4.2.2 The personal product must have a tracking method for both warehousing and shipment, as well as its use-phase.

2.4.2.3 The product-family use-case must be analyzed on the benefits Cyber-physical tracking enables for the user, and those must be implemented.

2.4.2.4 The product-family must be designed with a Cyber-physical tracking framework, including update-type, data system, and the knowledge they want to gain.

2.4.2.5 The product-family must be designed with an integrated recycle plan.

2.4.3. CONCLUSION

By producing customer specific products, a company might be able to provide benefits that were otherwise impractical or impossible. These benefits could provide new customer value and therefore more company revenue. Depending on the demand and complexity of the product, the company must implement mass-customization as production method.

But for research and demonstration of this manufacturing method, this question must be turned around, in this case mass-customization requires a product-family with a lot of complexity (a high TPPR) to be relevant; otherwise traditional batch-production would be more practical.

Although this project is set up in a research context, it is still very important for demonstration purposes that the product-family has an understandably relevant business-plan. The configurable product-family must therefore have an impact on different experience-axes, relevant for different kind of users. This is achieved by implementing personalisable aspects within all three customization-categories: identity, fit, and capabilities. A product-family must be found with invested or ‘expert’ user groups attached to these aspects.

Because these users must theoretically be able to personalize the product in a co-creation service the product-family must be designed with this in mind. But because the products are not initially developed for commercial use, the design and implementation of this service falls in this project out of scope.

The other big way of generating value and therefore revenue for the company is by applying a cyber-physical tracking framework: for warehousing and delivery, cloud-based user benefits, use-data based company benefits, and recycle-based value extraction.

The product-family must demonstrate a framework to include these tracking based benefits, and present the cyber-physical technologies to be implemented.

2.5. DESIGN BRIEF

HOW TO GO FURTHER

In this part of the report a new manufacturing method is explored and a future vision described. The core findings in relation to Transcended Manufacturing are described below:

UNIVERSAL AND CUSTOMIZABLE

The product-family-model captures the essence of the product through its universals. It is customizable on different experience axes, resulting in unique personal product realizations.

CLOSED-LOOP AND CYBER-PHYSICAL

Transcended products are traceable through beginning-, middle-, and end-of-life. They generate and retain as much value as possible.

SELF-CONTAINED & GENERAL

The Transcended production system aspects are self-contained and capable.

It uses process-generality to make unique products within a standardized framework.

SCALABLE & REPLACEABLE

The Transcended production processes are either fast or small. All aspects are scalable, accessible, and replaceable.

It is important to remember that the project is research based, a possible framework for Transcended Manufacturing must be developed. An initial research step is taken and the aspects with most importance are answered first. The developed final system will not be commercially viable, the goals are demonstration and enabling further research. This requires an exemplary-product, and a framework to produce this product.

In the next chapter the 5W1H method is used to describe the design brief for this project. In the two following chapters the directing requirements for both the product-family and the Transcended Factory are collected from the insights and clustered.

2.5.1. 5W1H

To get a grip on the design challenge the 5W1H method is used to develop design brief for the rest of the project. The questions are answered in a research and a final development goal context.

WHAT WILL THE DESIGN BE?

- A mass-customization exemplary-product business case. For this product a hypothetical product-family model needs to be developed, integrating a range of customizable aspects. A selection of product realizations need to be modelled and the product production files need to be made.
- A production-cluster consisting of modules that provide the required process steps to make the chosen exemplary-product. An initial factory framework must be developed that is capable of producing this product-family. The most important aspects and principles of this framework need to be chosen and validated.

FOR WHO WILL THE DESIGN BE RELEVANT?

- For cyber-physical systems and mass-customization research organizations such as Festo and the Agile Manufacturing Center (IDE, TU Delft).
- For companies and factories that want to manufacture mass-customized products.
- For product users that are invested in a product and have expertise in a part of the product, ether in identity, fit, or capabilities (one of the customization-categories).

WHERE WILL THE DESIGN BE RELEVANT?

- Initially at the TU Delft faculty of Industrial Design Engineering and at Festo's local operational company in Delft.
- Eventually in local Transcended factories throughout the world.
- Eventually at individual product-family users throughout the world.

WHEN WILL THE DESIGN BE RELEVANT?

- During the project for validation.
- After this project to build onto the results.
- Eventually in the envisioned Transcend Manufacturing product-life-cycle.

HOW WILL THE DESIGN BE RELEVANT?

- By providing an initial Transcended Manufacturing production framework for further research.
- By providing an initial relevant business case that is synonymous with Transcended Manufacturing.

WHY WILL THIS DESIGN BE RELEVANT?

- To solve the most important challenges within the developed framework.
- To provide the first step in research and demonstration.
- To showcase the possible benefits Transcended Manufacturing could bring.

2.5.2. PRODUCT-FAMILY REQUIREMENTS

The envisioned insights are clustered in groups of comparable directing requirements for the design of the exemplary product. The first three clusters form the core functional requirements and they are used to decide and validate the exemplary-product-family.

EXEMPLARY-PRODUCT CORE FUNCTIONAL REQUIREMENTS:

1 THE EXEMPLARY-PRODUCT MUST PROVIDE A REALISTIC BUSINESS-CASE.

2.1.1.7 The personalized product must have an increased emotional value and customer satisfaction.
2.1.3.5 The exemplary-product must be recognizable as a clear personal consumer product.
2.1.3.9 The exemplary-product must be designed in both a commercial business-case, as well as a research and demonstration context.
2.1.4.1 The mass-customization factory products must generate high customer value through personalization.
2.1.4.9 The mass-customization business-case must make up for a higher per-product production-cost; compared to traditional mass-production methods.
2.2.1.8 The mass-customization business-case must make up for the loss in efficiency (as compared to traditional manufacturing), by generating more user-value and minimizing, supplier, transport, and warehousing costs.
2.4.1.6 The product-family must have customization aspects with a high expertise or investment consumer group.

2 THE EXEMPLARY-PRODUCT MUST EXEMPLIFY MASS-CUSTOMIZATION.

2.4.1.5 For the configuration of a product-family to have an impact on different experience-axes, aspects within the three customization-categories must customizable (Identity, Fit, Capabilities).
2.4.1.4 Mass-customization requires a product-family with a high amount of theoretically-possible-product-realizations (TPPR) to be relevant, otherwise traditional batch-production will be practical.

3 THE EXEMPLARY-PRODUCT MUST ENABLE RESEARCH AND DEMONSTRATION.

2.1.3.1 The cyber-physical factory and exemplary-product must promote and enable further research, integrating aspects of: Industry 4.0, Cyber-physical Systems and Mass-customization.
2.1.3.6 The exemplary-product production process must be clean, in terms of dust, chips, waste, lubricants, post-processing, spoiling ingredients, etc.
2.1.3.7 The exemplary-product must be disassemblable to reuse the materials for new test or demonstration runs of the production system.
2.1.3.8 The exemplary-product must demonstrate unique cyber-physical product aspects through form and functionality.

THE REMAINING REQUIREMENT CLUSTER

The remaining insights must be tackled in the development of the exemplary-product.

DESIGN FOR LIFE-CYCLE:

2.2.1.5 Product-family models must be designed with the potential users, factory production capabilities, co-creation-system capabilities, and recycle capabilities in mind.
2.4.1.1 The personalizable product must be designed with a configuration service and adaptable product-family model in mind.
2.4.1.3 The product-family must have a set of different customizable aspects with an applied resolution range.
2.4.2.1 The product-family-model must capture the universals of the product form without defining them.

MIDDLE-OF-LIFE VALUE:

2.1.4.5 To improve future mass-customization products they must be designed with a method to keep track of their use.
2.4.2.2 The personal product must have a tracking method for both warehousing and shipment, as well as its use-phase.
2.4.2.3 The product-family use-case must be analyzed on the benefits Cyber-physical tracking enables for the user, and those must be implemented.
2.4.2.4 The product-family must be designed with a Cyber-physical tracking framework, including update-type, data system, and the knowledge they want to gain.

END-OF-LIVE VALUE:

2.2.1.3 The mass-customization product must be designed to retrieve remaining end-of-life value through recycling.
2.4.2.5 The product-family must be designed with an integrated recycle plan.
Product-recipe file:
2.3.1.4.36 The product-recipe file must contain all the information needed to complete the product production.
2.3.1.5.37 The product-recipe must contain process inspection references for comparison.
2.4.1.2 The personal realization of a product-family model must have the form of a product-recipe file.

BEGINNING-OF-LIFE (PRODUCTION, TRACKING):

2.2.1.6 The supplier parts must be standardized to be used in different products by multiple factories.
2.2.2.6 Parts and products must be treated as smart cyber-physical system participants by being able to communicate, act autonomously, and follow their product-recipe files.
2.3.1.3.35 The products must be trackable at all times throughout the production system.
2.3.1.8.40 Parts must be trackable at al times within the transport system.
2.3.1.9.41 For each part a tracking method must be chosen depending on the cluster, product and the described decision parameters.

2.5.3. TRANSCENDED FACTORY REQUIREMENTS

The envisioned insights are clustered in groups of comparable directing requirements for the design of the Transcended Factory. Not all requirements will be relevant in the development of the initial prototype production setup.

MODULES

MODULES CAPABILITIES

2.1.1.3 The CTO/ETO mass-customization factory must use direct-digital-manufacturing techniques to integrate process-generality and make engineer-to-order products.
2.1.3.4 The cyber-physical factory must integrate mass-customization in its modular production setup, to make individually different parts and products.
2.1.4.2 The mass-customization factory's production systems and processes must be 'general' to produce varying build-to-order products.
2.2.2.5 The mass-customization factory cluster must be made of modular process-step-performing modules each with their own software driver format to be included as recipe in the product-recipe files (CAM).
2.3.1.5 The production-equipment must be designed with different possible floor shapes and roof heights in mind.
2.3.1.6 The factory floor load rating must be taken into account in the design of the production setup and the choice of equipment and products that need to be made.
2.3.1.28 Each module must hold all necessary equipment to check and analyze its progression.
2.3.1.30 Al modules must have a system to get rid of their by-products.
2.3.2.10 To cope with demand, process-modules must either be fast or numerous.

MODULE PHYSICAL CONNECTION:

2.1.2.6 The factory process-modules need to have a digital but also physical interface (USB) to log into the system and connect to each other.
2.3.1.3 The factory must be adaptable to varying product demand.
2.3.1.4 Process equipment must be exchangeable between facilities.
2.3.1.11 It must be possible to add new process-modules during production.
2.3.1.22 The modules must fit within the grid and specifications of the cluster.
2.3.1.23 The modules must have a structural frame and a physical connection method between each other.
2.3.1.24 The modules must be vertically and/or horizontally stackable, from all arbitrary starting configurations.
2.3.1.25 Module initialization in the system must be as easy as putting it down.
2.3.1.26 All modules must be removable while the rest of the system continues production.
2.3.1.29 Each module must have an interface to connect and transfer electrical power, internet and other necessary conduits.

CLUSTER

CLUSTER CAPABILITIES:

2.1.2.5 The human worker must have a managing or creative problem solving role in the factory.
2.2.1.2 The product factory must be able to convert stocked materials directly into personalized product without waiting on suppliers.
2.1.4.7 The mass-customization factory must be able to quickly add new, and subtract products from production.
2.2.2.4 The mass-customization factory must have one or more clusters defined by their build-size, used materials, production capabilities, etc.
2.1.3.3 The cyber-physical factory framework must be scalable for different product sizes.
2.2.3.2 A multi-product-family cluster must overcome process-generality requirements that are not relevant for a single-product-family cluster.
2.2.3.3 A multi-product-family cluster does not have to be adaptable to overcome market changes such as product-family swapping as opposed to a single-product-family cluster.
2.3.1.7 The cluster must be able to send part, material, waste removal, and maintenance requests to the main factory.
2.3.1.12 The cluster must contain a distribution and collection system for process-consumables, standard-components, and materials and waste.
2.3.1.13 The cluster must be capable of dealing with production errors while continuing production.
2.3.1.14 The cluster must be able to inspect product completion.

CLUSTER CHANGING LAYOUT:

2.1.3.2 The cyber-physical factory must consist of a modular setup to be able to change the production-setup quickly.
2.1.3.3 The cyber-physical factory framework must be scalable for different product sizes.
2.1.4.6 The mass-customization factory must be able to increase and decrease production capacity continuously.
2.2.2.1 The mass-customization factory must be reconfigurable and constantly adapted during production towards the most optimal layout.
2.2.2.3 The mass-customization factory must be capable of performing maintenance during constant production.
2.2.3.4 A multi- and single-product-family cluster must be able to adapt production output to overcome changes in product-family demand.
2.3.1.9 The cluster must be able to change its layout during production.
2.3.1.10 Used factory space and floor area that is occupied by factory equipment must be minimized.
2.3.1.8 The cluster must be designed following an accepted industry standard.
2.3.1.27 The transport and movement system must be designed to be extremely robust and resilient.
2.3.1.6.38 Parts require an assembly-module to move from a small to a bigger size transport track/ system.
2.3.1.7.39 Parts with the same size as their product require an assembly-module.

INDUSTRY STANDARD

INDUSTRY STANDARD PROPOSITION:

2.1.2.1 Communication standards will be required for inter and intra factory communication between digital and physical participants.
2.2.1.12 Industry standards will be required to synchronize value chain partners streamline their interaction.
2.3.2.1 For every industry type cluster the required capabilities must independently be analyzed.
2.3.2.2 For every material type cluster the production requirements must independently be analyzed.
2.3.2.3 The load capacity must be defined in the industry standard.
2.3.2.4 The height of the build-volume must be kept minimal in the industry standard.
2.3.2.5 The scaling law for product density must be taken into account in the load standard.
2.3.2.6 The build volume must be defined in the industry standard.
2.3.2.7 The floor load rating must be included in the industry standard.
2.3.2.8 Accuracy and repeatability capabilities must independently be defined per process-module.
2.3.2.9 The size type must be defined in the industry standard.
2.3.2.11 The industry standard must enable process-module stackability minimizing loss of resources (floor area, ceiling height, etc.).
2.3.2.12 It is paramount that products are made in the smallest possible build-volumes and that the space for the process-modules must be reduced in all directions.
2.3.2.13 The industry standard must enable gradual increase between progression steps.

DIGITAL

DIGITAL OPERATIONS:

2.1.2.2 The Digital Twin principle must be implemented for every part/participant in the manufacturing system.
2.1.2.3 A real time digital model will be required to make the complex process observable, transparent and understandable for every system-participant.
2.1.2.4 Every factory system-participant (product, module, employee, etc.) must be able to act autonomously on the available operations data.
2.1.4.4 The mass-customization factory must keep track of each part and product during manufacturing.
2.2.2.6 Parts and products must be treated as smart cyber-physical system participants by being able to communicate, act autonomously, and follow their product-recipe files.
2.3.1.15 The cluster participants must autonomously try to reach their goal.
2.3.1.16 Cluster participant must digitally be represented, following a hierarchy or class system.
2.3.1.18 The cluster requires a continuously updated digital representation of its physical self.
2.3.1.20 The cluster must have a communication framework for the participants to interact.
2.3.1.32 The modules must cluster sensor data before sharing it to the real-time digital model.
2.3.1.1.33 The products must act autonomously towards reaching its goal of becoming completed.
2.3.1.2.34 The products must be able to adapt to unforeseen disturbances, and find new routes.
Digital Logistics and Procurement:
2.3.1.1 The factory must be able to turn product-recipe files into physical products.
2.3.1.2 The factory must be able to automatically

generate and send component and material requests to suppliers.

2.3.1.17 The cluster must have an industrial internet connecting all participants.

2.3.1.19 It must be possible for new participants to be initialized, recognized, located and their states to be updated.

2.3.1.21 The cluster requires a framework to track orders and sequence product-recipe files.

2.3.1.31 AI modules must be made with their respective CAM software for in the product-recipe file.

BUSINESS

BUSINESS CAPABILITIES:

2.1.1.4 The CTO/ETO mass-customization factory must overcome the direct-digital-manufacturing disadvantages of being relatively expensive, requiring more energy, and being relatively slow.

2.1.1.5 The CTO/ETO mass-customization factory must be able to produce one-off products.

2.1.1.6 The CTO/ETO mass-customization factory must be capable of a high output-capacity.

2.1.4.3 The mass-customization factory requires low dependencies and overhead costs.

2.2.2.2 The mass-customization factory is defined by its production capabilities, not the products it makes.

2.2.3.1 The mass-customization factory must decide on a business-plan with the spectrum of factory-realizations.

BUSINESS MANUFACTURING-CHAIN:

2.1.4.8 There must be a lot of (relatively small) mass-customization factories to provide local production and reduce transport and warehousing.

2.2.1.7 The physical location of the mass-customization value chain links must be optimized to reduce transport costs.

2.2.1.1 The mass-customization factory must reduce supplier dependencies and incorporate as much manufacturing steps as possible (this is called vertical integration).

2.2.1.9 Minimal supplier dependencies will be important for the product factory in order to change production quickly in volatile markets.

BUSINESS ORDER MANAGEMENT:

2.1.1.1 The CTO/ETO mass-customization factory must postpone manufacturing of materials and part into a product until product is configured and ordered.

2.1.1.2 The CTO/ETO mass-customization factory must accommodate a short customer-order-cycle.

2.2.1.4 The mass-customization factory requires an influx of customer orders in the form of product-recipe files to operate and therefore brands that keep designing and promoting the product-families.

2.2.1.10 The mass-customization factory must automatically recognize when stock runs low and put out purchase orders to suppliers.

2.2.1.11 The mass-customization factory must automatically initiates packaging and transport to the customer when products are finished.

2.2.1.13 A digital Order Management System will be required to track flow of parts and products during different design and production stages of the value chain.

3. ACTUALIZATION

Following the design brief defined in the Envision phase, the conceptualization of both product and production need to go hand in hand. A realizable future production system must be accompanied by a product that showcases this manufacturing method and the other way around: the personalizable product-family requires a production system that is capable of producing these one-off-products at a high production-capacity. Both design tasks were performed in parallel, but they will be described in sequence in this part of the report. First the exemplary-product will be discussed: the choice, the conceptualization, and the embodiment. Then the Transcended production system will be discussed: the required standardization, the proposed production cluster, conceptualization of the production framework and embodiment of the initial prototype. This prototype can then be used for validation of the propped framework in the phase after the Actualization phase.

3.1. THE EXEMPLARY PRODUCT

CHOICE, CONCEPTUALIZATION, AND EMBODIMENT

In this part of the report, the Transcended Manufacturing exemplary-product is: firstly decided; which product-family is the best candidate as demonstrator of the manufacturing method. It is then conceptualized; what will the product-family look like. And finally embodied; how is the product made.

3.1.1. PRODUCT-FAMILY CHOICE

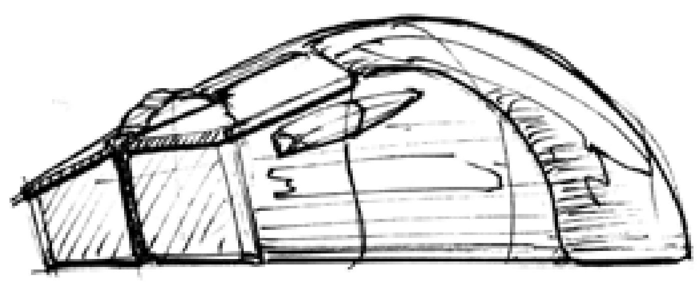
The parallel development of both product and production was part of the generation of a list of possible exemplary-products. This parallel development was implemented using two creative strategies, bottom-up and top-down. In the bottom-up approach all manufacturing processes are inspected and evaluated in the context of a modular mass-customization production system (process-generality, direct-digital-manufacturing, etc.). In the top-down approach all industry sectors are evaluated on the need for high volume personalized products and possible product-family directions are generated.

Next to these strategies small interviews on personalization where performed to support idea generation (the questions can be found in the Appendix: 7.1.4. Personalization Interview Questions).

Ultimately one exemplary-product-family direction is chosen, the ergonomic computer mouse, with personal features, look, and feel (a list of possible product directions and the decision process can be found in the Appendix: 7.1.6. Exemplary product Choice). The product vision for the computer mouse is analogous to a perfectly fitting orthopedic sport shoe that can be bought fitting a casual, professional, or recreational use-case in terms of features, and in a personal style.

Current computer mousses can be found in all forms and colors: from RSI office mousses, to slim Starbucks-setting MacBook mousses, to adaptable pro-gaming mousses. The core solution stays the same, but user preference varies as much as there are people.

In the next paragraphs this choice for a computer-mouse is elaborated following the decision clusters in the 2.5. Design Brief chapter.



THE PERSONALIZABLE COMPUTER MOUSE PROVIDES A REALISTIC BUSINESS-CASE.

Directing Requirements: **2.1.1.7, 2.1.3.5, 2.1.3.9, 2.1.4.1, 2.1.4.9, 2.2.1.8, 2.4.1.6**

To enable a realistic business-case, the computer-mouse must generate high user value. This is done through personalization of product aspects that have highly invested users. This is the case for the computer mouse, the most important reasons why are discussed below.

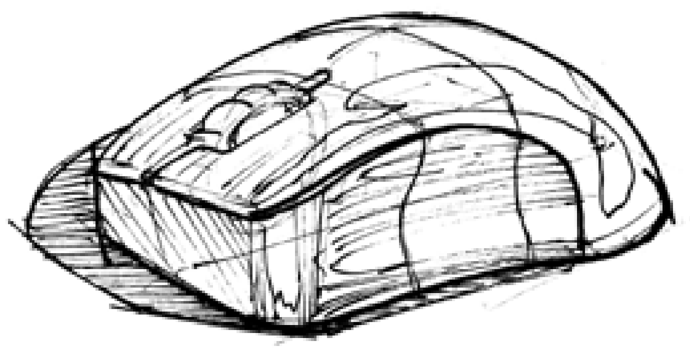
Repetitive Strain Injury (RSI) or Complaints Arms Neck Shoulder (CAMS) is a big societal issue that only increases with the digitalization of the work environment. Especially the handling of the mouse is an important contributor to RSI. To solve this, multiple computer mousses have appeared on the market that are either adaptable in shape or follow an 'optimal' average strategy in their ergonomic design. A perfect fitting personal computer mouse is part of the solution.

An important trend is the increase of the gaming industry both as a recreational activity as well as professional, with almost 2 billion gamers worldwide. There are two forms of professional gaming: one, content creation for entertainment purposes, this is seen in the rise of both gaming related YouTube channels and twitch streamers, most notably the streamer Pewdiepie with currently 102 million subscribers the largest channel on YouTube. And two, professional gaming in terms of e-sports, which keeps growing with an expected 427 million people watching e-sports worldwide in 2019 and the announcement of a 100 million in prize money for the game Fortnite in 2019. PC gaming has the biggest share of participants and they all use a computer mouse. Gamers and especially professionals have high standards and expectations for their gaming hardware; on features, form, and style.

The most immediate threat to the existence of the computer mouse is the technological development of new input device that connects the human with the computer. With the rise of augmented reality and Virtual reality new ways to control these systems will be developed eventually making the computer mouse obsolete. This could be the case, but only in its current form, the production and knowledge implemented in the development of an ergonomically sound personal computer mouse can be used directly in the development of these new input devices, making these the direct follow up strategy of the computer mouse business-plan.

In addition to this, the hands are the most important part of the human body to interact with the world around us. These have evolved through millennia of evolution, gaining opposable thumbs and the highest amount of nerve terminations of all body parts in the primary motor cortex and primary sensory cortex. It can be concluded that hand depended input devices, such as the computer mouse, remain for humans the most fast and precise way to interact with the digital world.

THE PERSONALIZED COMPUTER



MOUSE EXEMPLIFIES MASS-CUSTOMI-ZATION.

Directing Requirements: **2.4.1.5, 2.4.1.4,**

The different users described in the paragraph above, have a high investment and therefore high expertise in the product use case. This results in very specific requirements and wishes of certain product-aspects.
This high expertise on the aspects must be matched by a fitting personalization level.
The computer mouse has widely different user-groups, invested in product-aspects on all experience-axes, from aesthetics to performance.

It is therefore personalizable on all three customization-categorie, providing the needed personalization level for each user (defined in the 2.4.1 Product Personalization chapter).

The possible personalizable aspects of the computer-mouse within each customization-category are:

FIT:

- Ergonomics (body shape, left/right handedness)
- Comfort (grip, movement)
- Other owned products (bag, laptop, keyboard, desk)

CAPABILITIES:

- Buttons (amount, location, characteristics)
- Sensors (sensitivity, height)
- Physical (weight, movement resistance, heat dissipation)
- Cord or Bluetooth, battery and charging (yes, no, type)
- Extra features (RSI padding, left right handed)

IDENTITY:

- Colors and print
- Material and texture
- Lighting (amount, location, characteristics)
- Size and form (decorative shape)
- Sound (clicking, moving)

The personalizable computer mouse requires a high personalization level on all the described customization-categories; identity, fit and capabilities. This results in a high number of theoretically-possible-product-realizations (TPPR) that cannot be realized with small-batch-size traditional production methods, thereby exemplifying the need for a mass-customization factory.

The computer mouse is a high volume mass-produced product that almost everyone uses. The profit margins companies make per product are small. Therefore traditional artisan and job shop production methods, that are for example used to produce personal inlay soles or custom furniture, are not possible. High efficiency and performance are required of the cyber-physical factory. Thereby also exemplifying the need for a mass-customization factory.

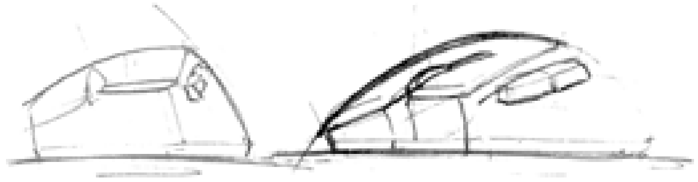
Multiple process-modules of different types will be required to produce the personalizable computer mouse, thereby showing the need for a real Cyber-physical Factory cluster setup. This in comparison with more monolithic products that only require for example one additive or subtractive module (3D printer, CNC mill).

THE PERSONALIZED COMPUTER MOUSE ENABLES RESEARCH AND DEMONSTRATION.

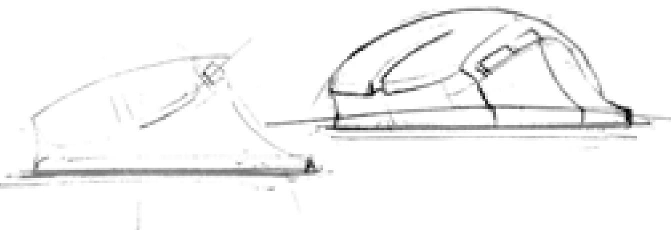
Directing Requirements: **2.1.3.1, 2.1.3.6, 2.1.3.7, 2.1.3.8**

The initial computer mouse production-cluster can be setup for demonstration and research purposes, at the operational companies of Festo, at trade fairs, but also at universities. These cyber-physical factories show off the capabilities in terms of personalization, production and infrastructure. It also gives a starting point, namely a hardware system and framework for further research and development in cyber-physical system technologies, the mass-customization design approach, and all aspects surrounding the product-life-cycle of the computer mouse; co-creation service, product-use tracking, etc.

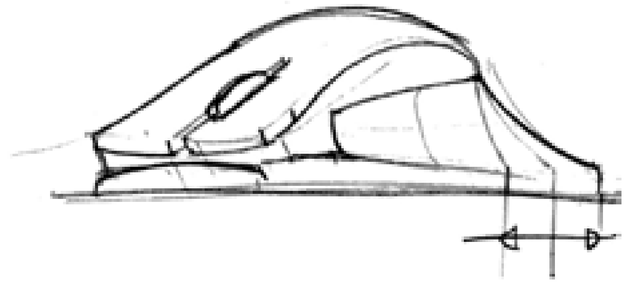
An important aspect of the cyber-physical factory to demonstrate is that of the Digital Twin. The visible differences between realizations of the personalizable computer mouse clearly show this important principle and also why it is needed in this specific supply-chain. This visibility also helps in developing the required framework for communication between al system participant, such as modules, products, parts, and people.



The manufacturing process of the computer mouse is also clean, meaning no waste is produced during production that cannot be recycled. The required materials for the computer mouse are non-spoilable. And the process-modules within this consumer electronics production-cluster requires almost no cleaning as compared to other Industry types. This is important to keep demonstration and research going without the need for additional labor.



In the early research stages there will be minimal to no product demand, therefore the designed product-family realizations need to be recycled to keep the system going. The consumer-electronic computer mouse can be engineered to be dismantlable, recyclable, and its components reusable. The demonstration production cycle can then be reiterated with the same parts and materials. This will also be important for prototyping purposes, for the design of both the product-family as well as the cyber-physical factory.



3.1.2. PRODUCT-FAMILY CONCEPTUALIZATION

In the previous chapter the computer mouse is chosen as exemplary-product for demonstration of the Transcended Manufacturing method, because it provides a realistic business-case, it exemplifies mass-customization, and it enables research and demonstration. To further design this product-family, existing mousses are analyzed. Below an overview is given of the insides of a computer mouse (In the Appendix: 7.1.5. Existing Computer mouse photos are found, that were disassembled for analysis).

It must first be decided how the exemplary-product will be customizable. Which aspects can be adapted to personalize the product, and what will the product-family realizations look like. It must also be decided how the Transcended computer mouse will go through its product-life-cycle and what cyber-physical advantages can be gained.

Directing Requirements: **2.4.1.5, 2.4.2.1**

As described in the 3.1.1. Product-family Choice chapter, the mouse has a lot of invested user groups with a wide range of use-cases. It is used by computer gamers in different ways for different types of games, from action to strategy types. Mousses are used for general office work from excel to InDesign. It is used in engineering for computer aided design (CAD). And it is used for casual browsing on the couch or at a table.

Requirements are different for people with different hand gripping types: palm-, claw-, or tip grip. And for different physiological and medical conditions, hand shape or afflictions such as RSI or CAMS.

Because the possible realization of this product type very so much it is decided that the exemplary-product will not be designed around specific targeted use cases. Adaptable product aspects are applied to a universal mouse, with the goal to generate a solution space wide enough to cater all invested user groups.

To do this, it is important to have an impact on different experience axes. This is achieved by applying customizable aspects in all customization categories described in the 2.4.1. Product Personalization chapter. In the 3.1.1. Product-family Choice chapter it is found that the computer mouse is customizable within all categories on multiple identified aspects.

Decisions:

A customization category design perspective will be applied in the personalization of the computer mouse, as opposed to a target-user-group perspective.

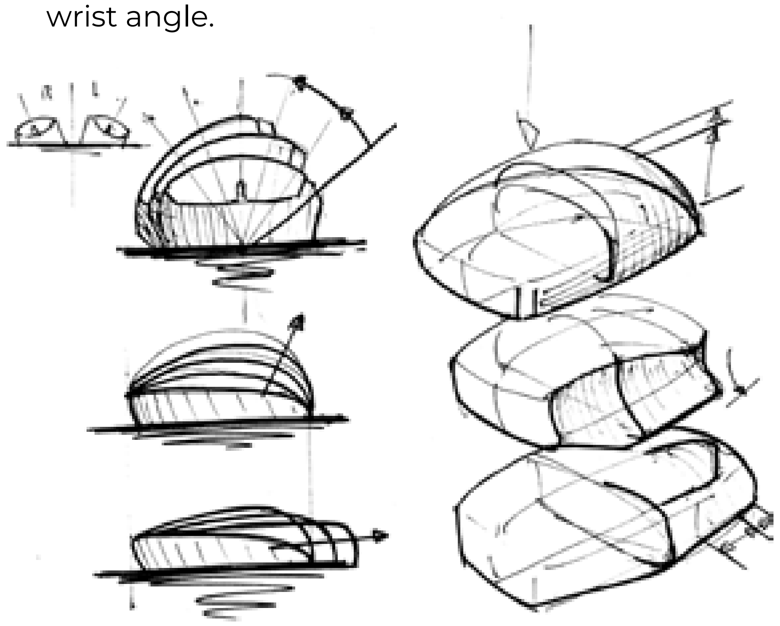
EXTERIOR DESIGN

Directing Requirements: **2.4.1.3, 2.1.3.8**

For the design of the product-family, personalizable aspects need to be decided within each of the customization categories. As a research project it is important to clearly demonstrate the spectrum of possible realizations while keeping the options concise and the initial design proposal feasible. The leading requirements are: the personalization must be visible on the outside (demonstration), and that they are archetypical for the computer mouse within their respective customization category. Below the three chosen personalization aspects are described.

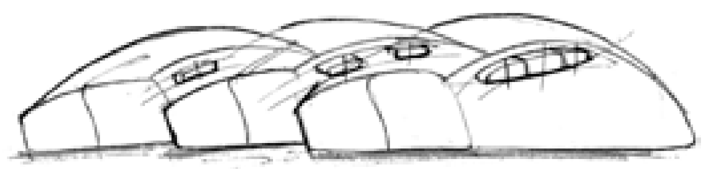
FIT:

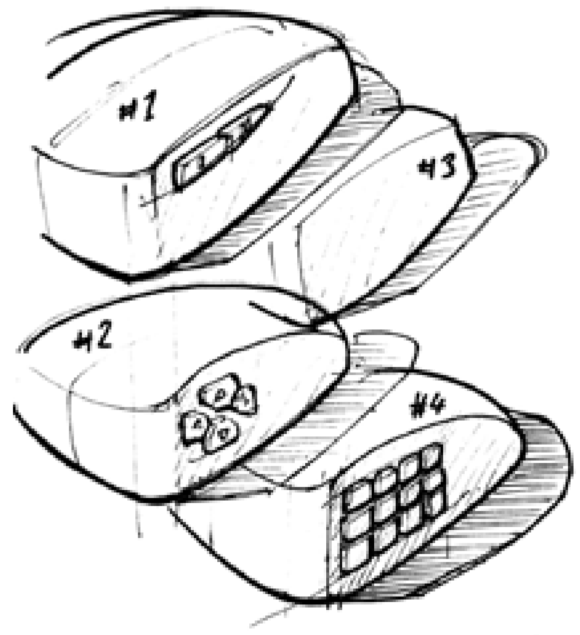
Ergonomic form of the mouse. Three arbitrary different shapes (mock 3D-scan based). Varied on, height, width, length, and wrist angle.



CAPABILITIES:

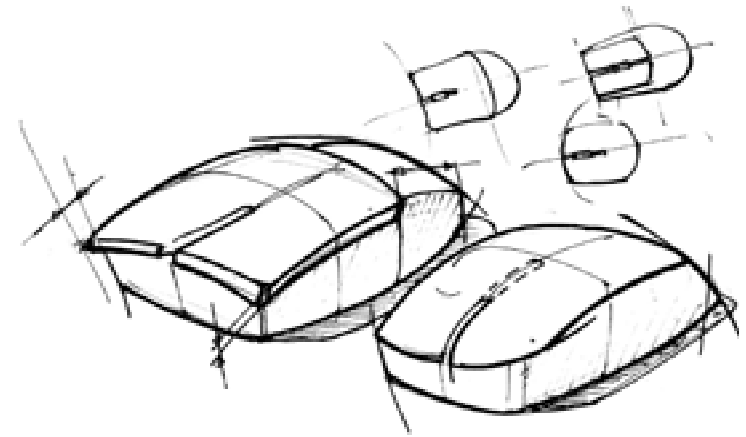
Thumb buttons on the side. Choice between: no buttons, two buttons or button matrix.





IDENTITY:

Shape of the main button top shell. Three aesthetically different shapes. Varied on round - sharp, symmetric - asymmetric, overhang, and big - small.



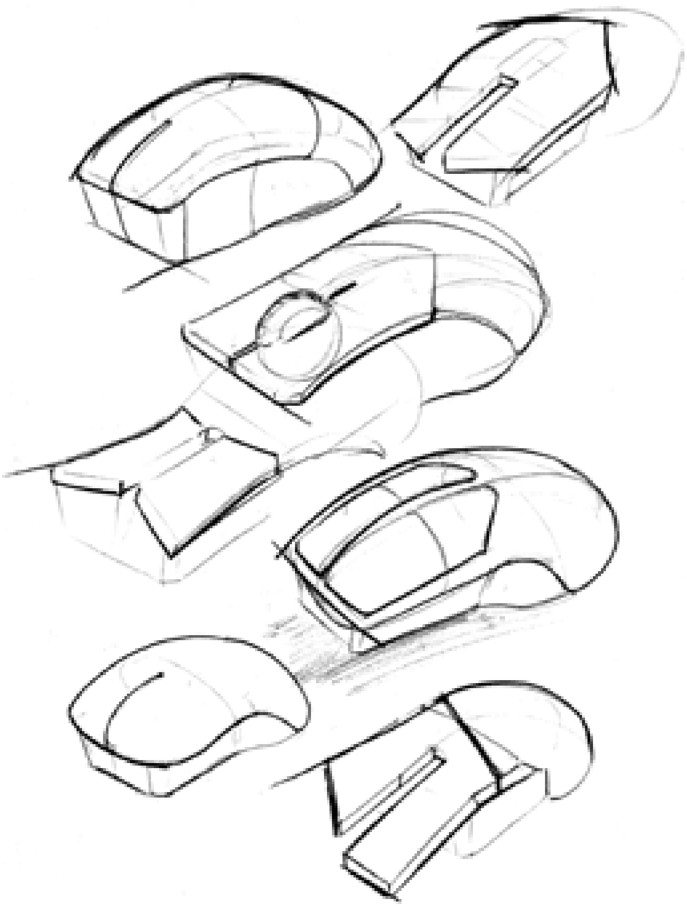
Directing Requirements: **2.4.1.1, 2.4.1.2, 2.4.1.4**

Each aspect will have three variations to create a symmetric spectrum of possible realizations; this results in 27 unique computer mousses. To overcome the labor of designing 27 independent mousses, a parametric model will be required. Such a model is therefore developed in Solidworks, integrating the three personalizable aspects. 3D-files of all the possible mousses are generated and should be producible in the production setup, thereby demonstrating the need for Transcended Manufacturing. This adaptable parametric model also demonstrates, in a still simple and CAD-program depended version, what will be required of the co-creation system.

Decisions:

The top shell shape, the ergonomic form, and the side-button type will be the personalizable aspects of the mouse.

In-depth research of RSI by use of the computer mouse and the effect personal anatomical differences will be left out.



THE CYBER-PHYSICAL PRODUCT

Directing Requirements: **2.1.4.9, 2.2.1.8**

As described in the 2.4.1. Product Personalization chapter, it is really important for the mass-customization business-case, that the Transcended product, generates increased value. Firstly, through personalization: being a better fit to the user's wishes. And secondly, through the integration of cyber-physical tracking for both the middle-of-life and end-of-life phases of the product-life-cycle.

The value that is generated through cyber-physical tracking is twofold, first through benefits for the user, and second through company benefits. These benefits are discussed below.

USER BENEFITS

Directing Requirements: **2.4.2.2, 2.4.2.3, 2.2.1.3**

The possible user benefits of cyber-physical tracking for the computer mouse are as follows.

Through anchoring of the computer mouse with its digital counterpart it is possible to identify the product. This is important to keep track of ownership in the case of theft or to transfer it to a recycle company, to receive services, and to receive warranty or receive insurance.

Using the Digital Twin it is possible to receive cloud services. This makes it possible to save digital settings and preferences such as sensor sensitivity, lighting colors, movement speed, button-macro's, and task depended shortcut keys. The original personalization design settings can be reviewed or adapted for ordering a new computer mouse.

COMPANY BENEFITS

Directing Requirements: **2.1.4.5, 2.4.2.4, 2.4.2.5**

It is beneficial for the company to keep track of the product and record its use. It is then able to get feedback, improve future product-family design, discover new trends, and adapt their business-plan. This is possible by tracking product-use data at certain moments. The type of update moment, as described in the 2.4.2. Principles of the Transcended Product chapter, to synchronize the stored product-use data of the computer mouse is: 'Intermediary online product'. Because the computer mouse can have an internet connection by means of an intermediary product. It can connect via Bluetooth or USB, to a computer that has an internet connection. This enable the computer mouse to upload the gathered use data.

The types of data that are relevant for the computer mouse are the following. First the initial design data such as the personalization at customer order and owner description. Secondly tracking data, such as, use of the button components, amount of clicks, use per day, sensor travel distance, saved preferences, failure mode, and possibly complaints or end-of-life questionnaire.

THE RFID-BUTTON:

To track the computer mouse it must be equipped with a data storage device that is capable of synchronizing through the USB or Bluetooth interface. It must also be able to connect to a recycle company, when the computer mouse electronics and power source stopped working. This is done through the implementation of RFID technology on a resilient 'button' that is separate but connected to the main circuit. The recycle company is than able to retrieve the recycle plan for the specific computer mouse; it functions like black-box on an airplane.

The data storage device has only limited space, it must therefore be deigned to cluster and compress the acquired data, and send it to the Digital Twin at intervals; when connected through a computer.

The button and electronic interface must be standardized to work for a wide range of different products. The RFID capability also provides a system to track the product through warehousing and transport in the beginning-of-life phase.

3.1.3. PRODUCT-FAMILY EMBODIMENT

The product-family design is now proposed as a possible commercial business-case and as a demonstrator for mass-customization and cyber-physical consumer products. The focus was on the middle-of-life and end-of-life phases. In this part the beginning-of-life is discussed; how will the computer mouse be made, what will it look like on the inside, and what will be required of the production system.

THE MOUSE PRODUCTION DESIGN

Directing Requirements: **2.1.1.3, 2.1.1.5, 2.1.3.4, 2.1.3.6, 2.1.3.9, 2.1.4.2, 2.2.1.2, 2.3.2.10**

FDM-PRINTING

In the 2.2.2. Mass-customization Product Factory chapter it was stated that product-independent process steps are required for the production system to produce individual build-to-order products at a mass-production output capacity; in other words direct digital manufacturing. The 3D-printing method fused deposition modeling (FDM) provides the solution. Through this process-general production method digital designs can directly be translated into physical products, without the need for in-between setup tasks, such as change in work-holding, change in tooling, change in molds, or switching between machines.

This also reduces the complexity of product-family-models, making the translation from a co-creation service to a production file as simple as possible (only a slicer is needed for CAM).

On the other hand, part shapes can be very complex with minimal design requirement's on the dimensioning (thicknesses, ribbing, draft, tool paths, overhang, etc.). This enables integration of enhanced functions, complaint members or flexible hinges, small holes and thin sheets and strength or stiffness were needed. These functions can be used to reduce the total component number, and reduce the number of assembly steps for the same product. It is decided that these benefits of FDM-printing must also be showcased in the design of the exemplary personalizable computer mouse.

The big disadvantage of 3D-printing is the production speed, with a time of three to nine hours per part (when looking at the size of a computer mouse). But as stated in the 2.3.2. Factory Types chapter process-modules must either be fast or numerous. And although further advancements will reduce printing times (variable layer thickness, optimized slicer paths, etc.) the FDM-printing module must be as small as possible and by doing this the disadvantage can be answered.

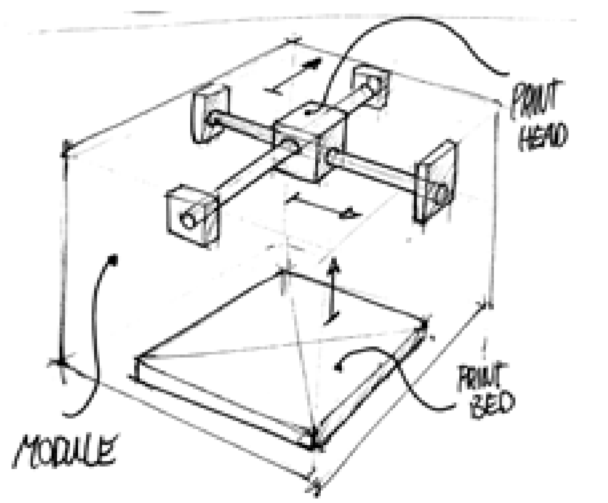
Within direct digital manufacturing there are other methods, such as SLA-printing SLS-printing, CNC-milling. Some of these methods bring better surface quality, and material options. The reason FDM-is chosen is firstly, due to additional complexities and therefore labor of the other methods. And secondly, those methods require more cleaning (chips, lubricants) or the removal of the remaining substrate (resin, powder), this makes the total process step more time consuming and expansive; this is unwanted in a research and demonstration context.

The other important reason to choose FDM is that it is the only 3D-print method that provides the possibility of intermediate pauses and the ability to create hollow cavities within the parts. This enables the placement of sub-components within the 'print', this will be further elaborated later in this chapter.

Decisions:

FDM-printing is chosen as the main direct digital manufacturing method.

The exemplary computer mouse must showcase the enhanced function benefits of FDM-printing.



THE TRANSCENDED MOUSE PROCESS STEPS

To produce commercial quality personalized consumer-electronics products (such as computer mouse) within a Transcended Factory a set of processes are required, below these process are described.

- Transport system: Multi part-size transportation between process steps (and intermediate storage).
- FDM system: FDM additive manufacturing for core product building.
- RFID insertion: Insertion of standardized tracking sensor for digital anchoring of the product.
- Pick-and-place system: Part and component pick-and-placement for assembly.
- Electronic circuit insertion: Electronic circuit/trace placement and electronic component connecting.
- Workpiece handling: Physical handling of parts such as rotation, translation, pressing, pulling, and twisting.
- CNC milling: CNC controlled material subtraction for solid part production such as metal or wood.
- Part finishing: Creating final quality surface finish such as coating, painting, or abrasive finishing.
- Final inspection: Pre-designed end-inspection and testing of product functionality.
- Product packaging: Product packaging and readying for transport.
- Waste recycling: Recycling and reuse of process waste and faulty parts.

This list is extensive and only process steps for a minimal working system tare chosen for initial research and development. Product handling, CNC milling, packaging, final inspection, waste recycling are not needed to make the initial system able to produce a personalizable computer mouse.

SURFACE QUALITY

Another big disadvantage of FDM-printing in its current form is that of the surface quality. If the layer height is not small enough (reducing print time) visible lines will be visible going straight through the product. This will be below expectations for most consumers, as compared to injection molded products. This is something that will require further development of this technology. Making the printers faster might enable smaller layer heights and therefore aesthetic quality. Or small outer layers and thicker inner layers to fill the part, either the same material or foam-like. Another method might be to use the nozzle for burnishing or so called 'ironing', shaping the contour of the layer, a routing operation could also be used to mill away half the filament line. Then there are methods that can be implemented after printing the part, such as abrasion finishing, local melting with heat or chemicals, applying gap filling spray paint, or dip-coating the part.

The last set of methods improve surface quality by solving the problem in the digital design of the part. The layer-lines might follow the aesthetic contour of the design, especially with variable layer thickness. Or they can be celebrated by novel slicing techniques, exaggerating the layers and giving texture to the part.

For the initial production setup, the standard FDM surface finish will be accepted, and need to be solved at a later stage in development, following one of the above described methods. Further improvement will be left out of scope for now.

Decisions:

Product handling, CNC milling, packaging, final inspection, waste recycling are left out of scope.

Decisions:

Product handling, CNC milling, packaging, final inspection, waste recycling are left out of scope.

INTERIOR DESIGN

All the process steps required to make a consumer-electronics product within the scope of initial development are decided. In the following text the internal design of the mouse is described and the individual embodied sub-components are in turn discussed.

Directing Requirements: **2.1.3.7, 2.1.3.7, 2.2.1.3, 2.4.2.5**

CORE-PRINT

The main body of the computer mouse will be 3D-printed from bottom to top; with three ergonomic shapes. The mouse requires a set of components such as the battery, movement-sensor, and micro-switches that must be placed at different locations inside the mouse.

To do this a specific process sequence is chosen. Cavities are printed to fit the components, then the printer stops when the last layer is printed at the top of the cavity, the printed part moves out of the printer to a robotic pick-and-place system that puts the sub-components in the print. The print goes back to the printer and the next layer will be printed on top of the components (or with, so called, bridging to create a vaulted cavity ceiling) and the core-print is finished. This process-sequence is in this report defined as the pick-and-place on-printing technique (on-printing for short).

The benefits of this process is that there are no separate print-parts, no joining techniques or assembly step is required, possibly no visible split line and a watertight seal. An the sub-components can be designed everywhere within the print (the only requirement is that the component does not stick-out above the last print layer, otherwise a nozzle collision would occur).

The components must be standardized and with a digital CAD file including the volume they occupy within a part up to an on-print layer. Also the standardized mechanical and electrical nodes or connection points must be described.

A really important aspect that must be implemented for the on-print process is that of recycling, this can be done through utilizing the on-print pause-line. When the products is split at this point, the top of the cavity falls open and the component can be excessed without damage, and possibly reused or dismantled (with their own recycle method), this is also important in a research and demonstration production setup. The 3D print itself can then be shredded and converted into new filament.

It is already pointed out that the sub-components must have standardized electric interfaces. The components are located throughout the computer mouse, and are connected through these interface nodes by means of conductive traces. Since the design will be personalizable, button and main-PCB location must be as independent of product-family design as possible. For process-generality it is required that different consumer-electronic products could also be produced with the same production setup. The required traces must therefore be placeable everywhere in the computer mouse. The method decided to charge the computer mouse is induction, making use of spiraling electric traces within the bottom of the computer mouse to create an inductor, this way no cable, charging port, or battery compartment will be needed. These electric traces can be achieved by technologies still in development, such as conductive filament FDM printing, deposition of conductive traces on a print layer (with vertical layer crossing bridges), or the filling of printed hollow tunnels with conductive material. It is for this initial production setup assumed that this will be solvable, but not further elaborated in this project. This also means that the designed exemplary-product will not be usable as computer mouse, but only as demonstrator of the Transcended Manufacturing method.

Decisions:

The pick-place and on-print principle is chosen as main production method for the computer mouse.

A break-line for separation and recycling of components must be implemented in the computer mouse.

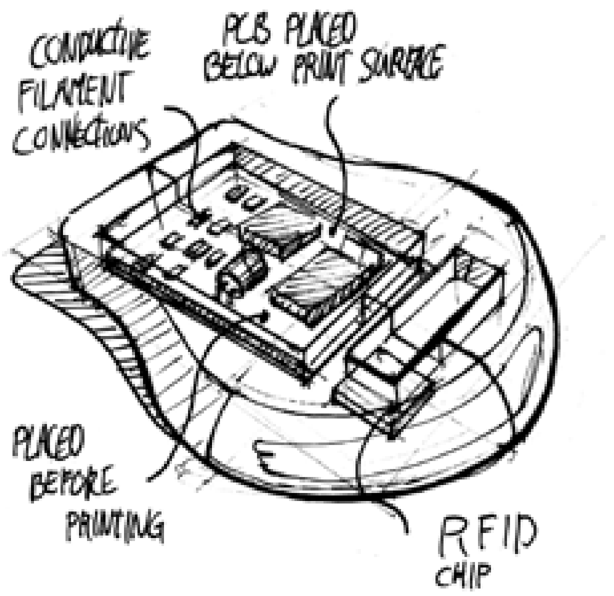
In print conductive trace technology is assumed and used to connect the electronic components within the mouse.

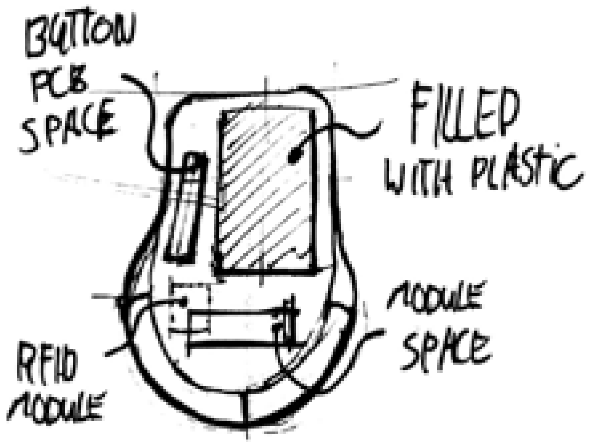
The first version exemplary computer mouse will have no electric traces and does not need to work.

MAIN PCB ASSEMBLY

The main-PCB assembly will be the core integrated component containing as much of the electronic components as possible: optical sensor, lithium polymer battery, power electronics, and Bluetooth receiver. This confines the electrical working to one part which can be left out of scope, leaving room for the personalizable shape and exterior components such as buttons. In the design electric traces are only used to connect standardized components; the required PCB is therefore also part of the main-PCB assembly (it could later also be possible that whole PCB layouts or even elementary components such as resistors, capacitors, or inductors are part of the 3D-print).

The main-PCB assembly will represent a standardized sub-component and will be the same for all the personalized variations of the computer mouse. It will be placed in a cavity below the on-print line. The battery will have the same flat dimensions as the PCB placed above it. On-printing will continue on or just above the battery surface.

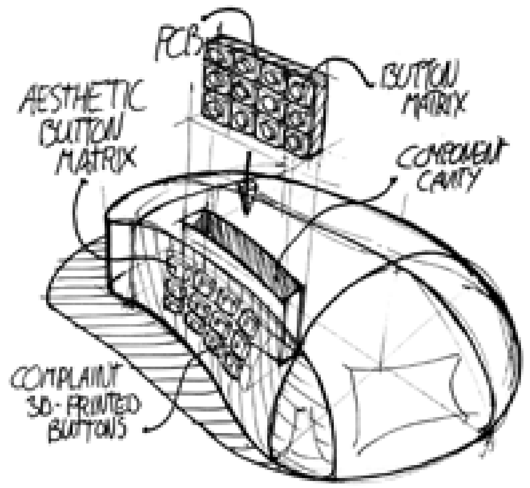




SIDE-BUTTON PCB

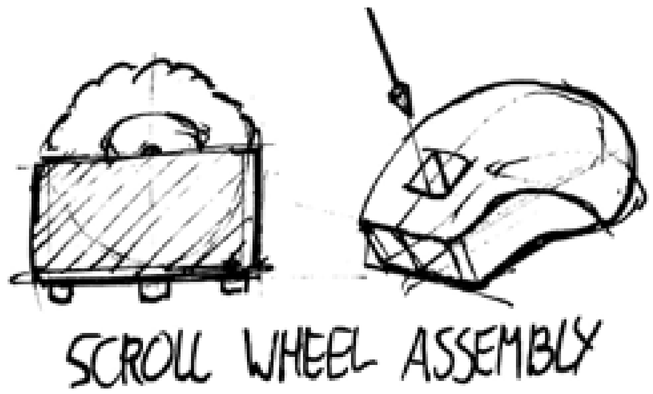
The side-button PCB will have surface-mount (SMD) buttons soldered in a matrix (1x2 or 3x4), these have a lower profile than through-hole buttons. This sub-assembly are also a standardized component that are placed from above into the print (as opposed to from the side). The small gaps at the top can be bridged to close it off with on-printing. The actual buttons that are visible and usable on the outside use 3D-printed compliant members to translate the motion to the PCB. Thereby showing-off earlier described enhanced functions of 3D-printing. This makes it also possible to integrate an aesthetic button design on the outside of the mouse body.

Side buttons-PCBs are a standardized supplier part (initially, later own cluster).



BUTTON-SCROLL-WHEEL ASSEMBLY

The button-scroll-wheel assembly contains the main mouse micro-switches and the scroll wheel and rotary encoder. It is placed and oriented below the main top-shell-buttons. Because it sticks out on the top side of the print it cannot be implemented with the on-print process (due to nozzle collision). It is therefore inserted after the core-print is finished and finally hided from view by the button-top-shell.



BUTTON-TOP-SHELL

The button-top-shell is a separately printed monolithic part that is placed onto the computer mouse, after the other components are assembled. It locks into the mouse and has pins to firstly push the two main micro-switches and secondly to guide the scroll wheel in its ration and translation onto a scroll wheel button.

Decisions:

The main-PCB assembly will be a standardized integrated component for all the computer mousses (for now a 'supplier' part).

The side-button PCB uses on-printing and compliant members to generate aesthetic freedom for the design of the mouse side-buttons, thereby hiding the PCB.

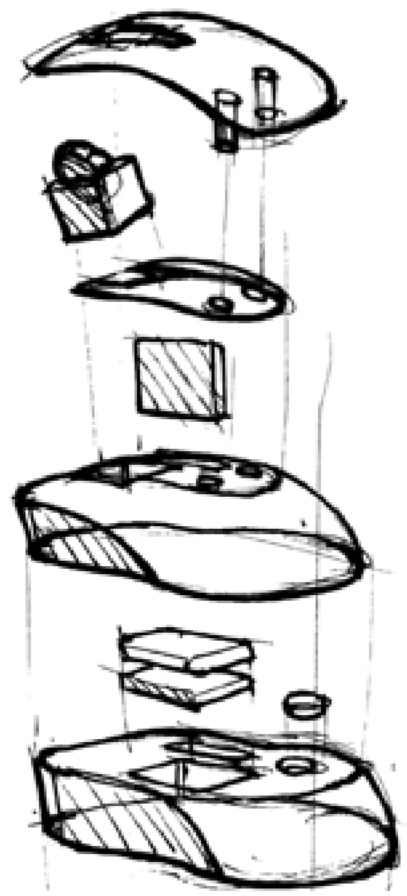
The button-scroll-wheel assembly is pick-and-placed into the top of the finished core-print.

The button-top-shell is a separately printed part that translates the clicking movement to the button-scroll-wheel assembly.

THE MOUSE PRODUCTION SEQUENCE:

All the components in the exemplary computer mouse are embodied. The required production sequence is as follows:

1. The initial core-print is printed.
2. The RFID product life-cycle tracker is inserted.
3. The main PCB assembly is inserted.
4. The second part of the core-print is printed with a break-line for recycling.
5. The side-button PCB is inserted.
6. The core-print is finished with a break-line for recycling.
7. The button-scroll-wheel assembly is inserted
8. In parallel the button-top-shell is printed.
9. The button-top-shell is assembled onto the core-print.
10. The computer mouse is completed.



TRACKING FRAMEWORK

In the beginning-of-life phase of the computer mouse sub-components and the product itself will travel through the cluster towards each other to be assembled into each other. Because of personalization every part will be unique. As described in the 2.3.1. Principles of the Transcended Factory chapter, when they move throughout the transport-system it is really important to track where they are at all times. Firstly, to keep track on progress by finding where each product is in their production process. Secondly, to keep the real-time digital model up to date; keeping the system observable for all participants. And thirdly to notice transport failures, signal that a part is lost (or found), to not mix up comparable parts, and to avoid collisions. Some parts and products have no means of sensing or tracking their physical state and will be dependent on the system to gain this knowledge.

For each sub-assembly used in a product a tracking method must be decided this is done following the tracking decision parameters described in the 2.3.1. Principles of the Transcended Factory chapter. The parameters include: part size, financial viability, material type, use case, uniqueness and loss risk. Below a general tracking system is described as well as the specific tracking method for each sub-assembly.

MOUSE BEGINNING-OF-LIFE TRACKING

Directing Requirements: **2.2.2.6, 2.3.1.13, 2.3.1.14, 2.3.1.3.35, 2.3.1.4.36, 2.3.1.5.37, 2.3.1.8.40, 2.3.1.9.41, 2.3.1.27, 2.3.1.28**

As described in the previous chapter, the finished computer-mouse will be equipped with an RFID-button to track the product in the middle-of-life and end-of-life phases. But this can also be used to track it during packaging, warehousing and transport.

But for the mouse to completed other methods need to be applied. For general tracking two main methods are chosen. First the carrier tracking system described in the Appendix: 7.1.2. Production Tracking this is already used in Festo's CP factory, including an RFID chip and a barcode to recognize the specific carrier. This extensive system is possible because the carrier is being reused within the factory until depleted. This also means that the carrier could be enhanced with other, more expansive measuring technology (this is not further explored in this report).

The other main tracking method is based around camera/sensor in the process-modules. During production parts must first be checked, before the process step, to accept the part and possibly optimize digital and physical settings. And also after the process step to validate completion and send the part on its way. This can be done through technologies such as point-cloud, height-map, or model based image recognition, using a CAD type intermediate 'screenshots' from the product-recipe file. This helps to keep production failure localized in the module, while other transport and production can continue. When this happens the module must be able to immediately throw maintenance request.

As stated above the core-print will have the RFID-button inserted before on-printing, at the same time as the main-PCB assembly. The core-print relies on the general tracking methods, with the RFID-button as backup. If this part fails during the printing operation it can immediately be removed and recycled while a new product can gets restarted in another printer.

This is also true for the button-top-shell if it fails during printing. It depends strongly on the general tracking system because it cannot carry extra tracking systems; the part is firstly thin and secondly visible by the user. It is on the other hand relatively unique in terms of shape, which is beneficial for image recognition, and easily restarted in a new printer if necessary.

The main PCB assembly, the button-scroll-wheel assembly, and the side-button-PCB, are standardized not-unique components that end up hidden within the mouse. They have as backup tracking system a barcode printed on the outside by the supplier. This is important if the internal components get reused after print failure.

Decisions:

Festo's CP Factory carrier system implemented in the transport system.

Camera/sensor system implemented in every process-module.

The core-print has a RFID-button tracker as backup method.

The button-top-shell has no backup tracking method.

Standard components have a barcode tracking system.

3.2. THE PRODUCTION SYSTEM

CONCEPTUALIZATION AND EMBODIMENT

In this part of the report an initial design and framework will be describe to form the first step within Transcended Manufacturing research. The required framework will be explored and the challenges prioritized, resulting in concept and integrated first design that encompasses a production system able to produce the personalizable computer mouse and provide solutions to the most important challenges. But before this specific production system can be developed an industry standard must be proposed as was determined in the Envision part of the report. This can be found in the following chapter.

3.2.1. TRANSCENDED CLUSTER STANDARD

As described in the Envision part of the report, by definition the Transcend manufacturing production-cluster is not determined by the product it makes, but by its capabilities. It theoretically exists before it is known that a personalizable computer mouse will be produced and its should be able to handle multiple different product-families with comparable process-requirements. Because of this, it is important that it is clear for all stakeholder what the capabilities and specifications are of the cluster. Therefore industry standards must be set, for product factories, brand corporations, and manufacturing-equipment suppliers (such as Festo) to communicate with each other, and have a framework to build into and onto. In this chapter a possible industry standard is proposed to form part of this framework. Also the personalizable computer mouse and necessary process-modules can immediately comply with this standard and framework.

If an overarching standard would not be implemented, physical process-equipment connections would not match, products would be designed for one factory, but not for others. Or for one process-equipment brand. Products would be made too big or too small for certain build volumes, etc. An Industry Standard must be decided upon, even if the proposed standard is not chosen.

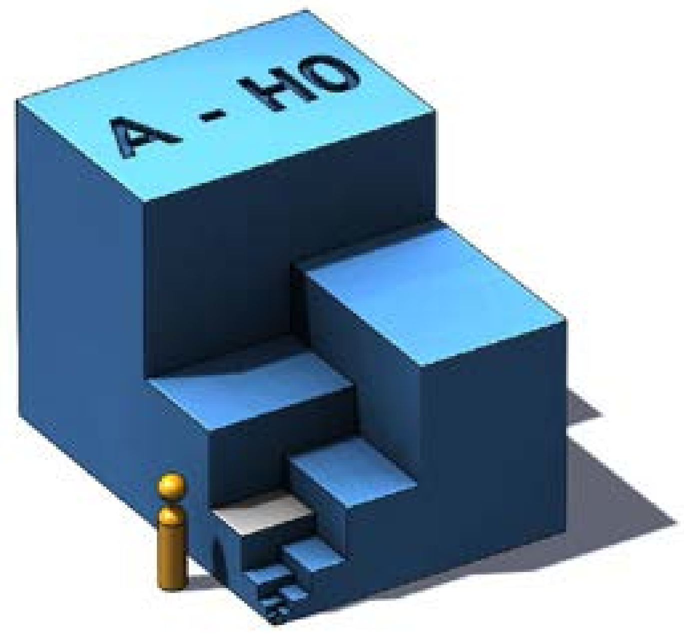
To manufacture the product-families at a mass-production output capacity, it was found in the 2.3.2.Factory Types chapter, that process-modules must either be: fast, or numerous. And if they are numerous it is (due to the scaling-law) paramount that they are as small as possible (two times the length, is eight times the volume). Therefore size forms the basis for the proposed standard. The other found industry overarching performance classification is that of load, which is also included in the standard.

As a result if a new product-family is developed, it must either fit with the current production setup, or not. In this case, it must be allocated to a bigger size-standard cluster. The same holds for its mass and the load it applies to the production system. Therefore the steps between progressions of the standard must be as small as possible. Below the standard is defined and after that the implications for the cluster layout.

Directing Requirements: **2.1.2.1, 2.2.1.12, 2.3.2.1, 2.3.2.2, 2.3.2.3, 2.3.2.4, 2.3.2.5, 2.3.2.6, 2.3.2.7, 2.3.2.8, 2.3.2.9, 2.3.2.11, 2.3.2.12, 2.3.2.13**

The above Directing Requirements are translated in the following workable requirements, they will be leading in the design of the proposed standard:

- The standard includes a definition for size and load in the standard.
- The standard height definition must be in the same order of the other dimensions.
- The standard utilizes the factory floor surface area, no gaps.
- The standard enables utilization of the factory roof ceiling height.
- The standard enables production output scalability by means of horizontal and vertical scaling.
- The standard must use a gradual size increase between progressions.
- The standard holds a defined statement in the range from minus infinity to infinity.
- The standard enables incorporation of space for process equipment.
- The standard must have a clear and relatable standard definitions that can be derived from SI units.
- The standard uses understandable naming conventions.



AREA SCALING

The ratio, one-to-the-square-root-of-two, is used for the scaling between size standards, just as the A paper standard. This is done because no gaps will occur by means of two dimensional tiling of the differently sized rectangles. Also the area is exactly halved with each progression, which will be beneficial when defining the SI definition for volume and load, which are discussed below. Also the classic definition of product size is length, and because it is paramount for the build-volume to match the product size as best as possible, the size must decrease slowly per progression within the standard; by using the square root of two relation, the length decreases slowly, namely in multiples of ~0.71 (2^-½).

Height and volume scaling

Different options could be chosen for the height standard (and automatically the volume scaling).

- First the square root of two could be chosen as the height scaling factor just as the paper standard, the benefit would be that the shape of the cuboid would be the same for all progressions within the size standard. But different-size modules will not be stackable to the same height. This is because the ratio between progressions does not consist of rational numbers. Also using rational numbers makes the SI relation between progressions more clear for all parameters.
- Another height scaling ratio that could be chosen is one to two (1:2), this would mean that for every size, two smaller sizes would fit vertically, enabling perfect stackability. The disadvantage would be that, if the width would scale with the square root of two (1:~1.41), the small progressions would become really flat and the big progressions really tall. It is therefore important to be close to the square root of two for the choice of the vertical scaling parameter.
- The candidates following this principle are 1:3/2, 1:4/3, and 1:7/5.

It is decided to use the ratio two to three (1:1.5) because it's close to the square root of two, reducing the described 'flattening' and 'tallening' problem. And because the industry standard must accommodate different height definitions for the same horizontal area, the small remaining problem falls within this definition.

It also has the most simple stacking configuration of the candidates, namely two stacked as high as three smaller sizes.

Another important benefit is the volume scaling. Namely, between each progression the area reduces by two and the height by two thirds, resulting in a volume scaling of one third. This volume progression is extremely easy to relate through all progressions within the standard.

MASS AND LOAD CAPACITY

The base load standard is chosen as the above described base volume (A0 x 1 m) filled with water. Which is one thousand kilograms (per definition of the kilogram, defined with water at 4°C). The standard can therefore directly be related to SI units.

The load standard scaling between progressions is chosen as one-to-two (instead of one-to-three which is the volume scaling). In other words, it is scaling with the horizontal area; meaning that one progression smaller (A1) will have a load standard of five hundred kilograms. This is beneficial for multiple reasons, first the factory floor load rating, which is in kilograms per square meter, stays the same for smaller and bigger sizes of the progression. Secondly the scaling law is counteracted (as opposed to using a volume scaling, with constant density), this is checked with the list of differently sized products and their density in the 2.3.2.Factory Types chapter (it is found that smaller products are more dense). Thirdly the amount of mass each progression can hold decreases with one half for every step, which is easy to relate exactly.

NAMING CONVENTION

The core industry standard is defined but the naming convention must still be described. But before that, the last addition to the standard must be defined. For both the height and the load, different standards must exist, not just the normal A-standard progression. For the height this means flatter or taller product build-volumes for the whole progression. And for the load very heavy or very light product types across the whole progression. These variations are visualized below. For developing the naming code the following requirements were used:

- Code does not change with lowercase or capital letters.
- No special characters used, only letters and numbers.
- The minus sign is reserved for separating parts of the code.

The area convention is the first part of the code, this follows the same naming as the A paper standard because this is easily understood. It gives an absolute naming of the horizontal size of the product. Starting with A0, A1, A2 etc. For going bigger the 'N' annotation for negative is used from AN2, AN1, A0 etc. (The M for minus was considered, but the acronym AM is already used for amplitude modulation in radio transmission).

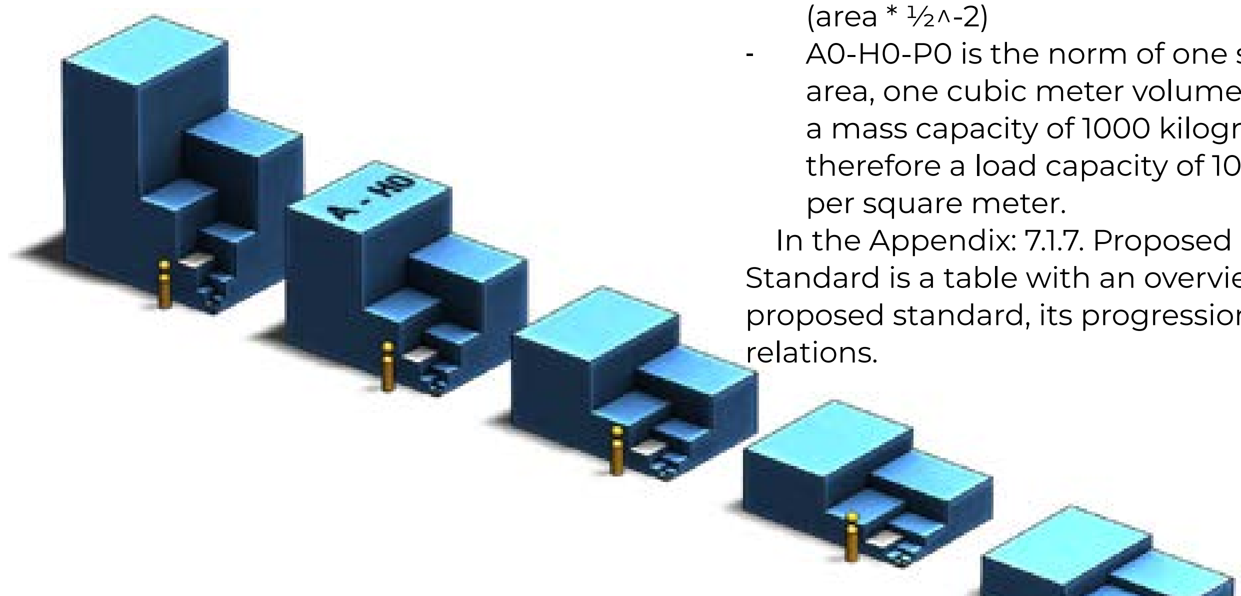
The second defining parameter is height, which is relatively described, whereas A was absolute. This means that for H0 the whole A progression holds. One production setup for example, will be designed in H0 with multiple build volumes defined by Ax. The progression of HN1, H0, H1, H2, etc. define complete more tall or flat standards different from the base H0 standard.

The third defining parameter is load, which is also relatively described, and also defines complete standards different from the base standard. The progression is PN1, P0, P1, P2, etc.

An example of the resulting code structure in the main H0-P0 standard is given below:

- A1-H0-P0 has halve the area of A0 (area * ½^1)
- AN2-H0-P0 has four times the area of A0 (area * ½^-2)
- A0-H0-P0 is the norm of one square meter area, one cubic meter volume and has a mass capacity of 1000 kilograms and therefore a load capacity of 1000 kilograms per square meter.

In the Appendix: 7.1.7. Proposed Industry Standard is a table with an overview of the proposed standard, its progressions, and relations.



From left to right: Ax-HN1, Ax-H0, Ax-H1, Ax-H2, Ax-H3.

ON MODULE OUTSIDE DIMENSIONS AND BUILD VOLUME DIFFERENCE

There is a difference between the actual build volume and required equipment. They share the same industry size standard as definition, only for example two steps bigger in the progression.

ON STRANGE SHAPE PRODUCTS

Strange shape products that are long thin flat etcetera do exist, for personalized production they need to make-do with the existing 'normal size' production clusters. But if the demand for such products is high enough specialized protection clusters could be installed.

For such clusters the height and length must be different from the norm.

To specialize the cluster for extremely tall or flat products (such as standing lamps or televisions) a different height standard (HN1, H1, etc.) could simply be chosen.

For long products that need to be lying down, multiple units of one size standard can be added together to form long build/transport sizes. Another solution will be splitting the 'long' product design in multiple subassemblies that get put together at the very end of production, or by the user itself.

THE FACTORY CLUSTER GRID

The size standard as described above refers to the size of products and the process build-volume they require. This is the primary function of that standard, but the secondary function is in defining the process modules themselves. The described industry standard can be used to generate a grid or tile system to stack the modules in all directions.

Normally a factory-floor follows an arbitrary square layout, which could still be the case implementing only the build-volume standard for manufacturing. But the proposed standard can also be used to define the floor-grid itself, defining a tiling layout for the equipment.

An important result from this is the 'quarter turn phenomenon' meaning the required ninety degree rotation to fit two A papers together with their bigger counterpart. This phenomenon results in a floor grid of all negative A numbers in the x-direction (A1, A3, AN1, etc.) and all positive A numbers in the y-direction (A0, A2, AN4, etc.). Thereby predefining the grid and module orientation in the room. This is not necessarily a problem but might reduce layout flexibility; angled or square adapter-modules can be a solution to change this orientation.

The transport and process modules must be at least two size-standard levels bigger than the product build-volume, because space for the supporting frame and process-equipment is required. And this way the build-volume can be rotated around its vertical axis without extending out of the module boundaries.

The following picture is an abstraction, showing the size difference of the build-volume part as well as the equipment part of the modules.

TOWARDS ZERO-DOWNTIME

The above described structure gives a framework for an almost continuously scalable factory, to overcome errors, add processes in the form of new module types, and increase or decrease productivity by extending the transport system horizontally or stack process modules vertically.

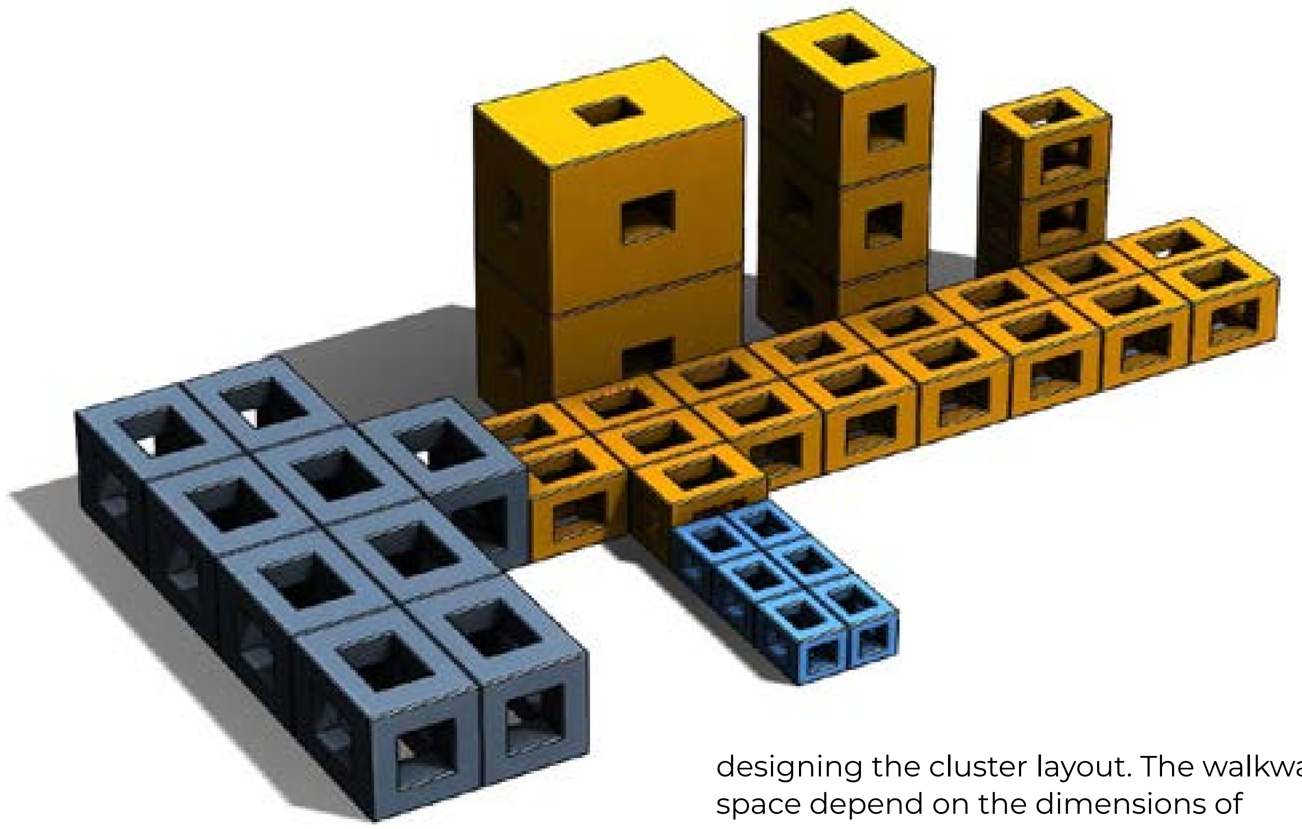
The layout of this factory, either designed by human operators or a machine learning algorithm, must minimize module downtime while coping with changes in product demand and product types. The layout must change and adapt continuously through time to cope with these market changes in a state of constant productivity.

Below the parameters defining this changing cluster layout are described.

VERTICAL SCALING PARAMETERS:

For vertical scaling, in other words the amount of stacked process-modules, the following parameters apply:

- Transport-module downtime: If the process-steps requires more time and the transport system is not working at full capacity, the stack height can be increased.
- Human or robot height: The process modules must be accessible to add or remove modules for scaling or maintenance. Therefore the stacking height is limited to this parameter.
- Ceiling height: The stacking height is also limited to the actual ceiling height of the factory.
- Module vertical strength: The stacking height is also limited to the structural strength of the lowest process module, which determines the maximum weight it can handle and in turn the amount of stacked modules.



- Floor load rating: The specified factory floor load rating defines the maximum pressure it can handle, which determines the stacked weight and the maximum number of stacked modules.
- Operation-module capacity: If the stack of process-modules require extra equipment in an operations-module to perform a process-step, for example an air compressor, the stacked amount is limited to the specifications of the operations-module; how much process-modules it can handle.

HORIZONTAL SCALING PARAMETERS:

For horizontal scaling, in other words the linking of transport modules to expand the transport system, the following parameters apply:

- Process-module downtime: If the transport system is working at over-capacity and process modules are waiting to in- and output parts, the process-modules must be spread out over a bigger transport system, thereby providing a minimum on the amount of transport-modules.
- Accessibility: The process modules in the cluster layout must be removable while in operation, this requires walkways to each stack of modules and free floor space on at least one side of it. This forms a limiting factor in filling the factory floor space and designing the cluster layout. The walkway space depend on the dimensions of the applied modules and the minimum human or robot walking space.
- Factory floor size and shape: The width and length of the factory floor gives a maximum on the extension of the transport system. If the factory room is not rectangular, the shape can form a limiting factor on the horizontal scaling of the transport system.

When looking at the two extremes of process- or transport speed, the conclusions are as follows:

- If the process-steps are slow, the stacks per transport-module must be high.
- If the process-steps are fast, the stacks must be low and the transport system extensive. The whole transport system itself might be stacked on top of each other in different 'floors', if the factory floor space is not sufficient.

ON COMBINING MODULES

Also, in the described scenario there is one process-step per module, but it is not unthinkable that following the standardized grid, for example 3 by 3 process-modules are combined into one design that can accommodate sixteen process-steps at once due to equipment-space overlap. Or three transport-modules are combined to reduce expensive components such as stepper motors etc.

3.2.2.TRANSCENDED CLUSTER PROPOSITION

The computer mouse is developed to show off the Transcended Manufacturing principles and capabilities. From this point in the report an initial framework will be designed that forms the first step in the research and development process towards Transcended Manufacturing.

When evaluating the engineered computer mouse described in the 3.1.3. Product-family Embodiment chapter on its production sequence the required corresponding process-modules can be determined. Firstly the horizontal transport modules are required to transport products and parts throughout the cluster, secondly a pick-and-place module will be required to assemble smaller parts and components into the products. And lastly an FDM 3D print module will be required to make the personal ergonomic mouse shape, implementing the on-print principle to form a frame for the individual components. The design and decisions relating to the required production cluster are discussed below:

Directing Requirements: **2.1.1.3, 2.1.3.4, 2.1.4.2, 2.2.1.2, 2.2.2.2, 2.2.3.2, 2.3.1.6.38, 2.3.1.7.39, 2.3.1.8**

The production of the computer mouse happens in one build-volume size of the proposed standard, with smaller size parts as inputs and the larger size product as outputs. The minimum build-volume to fit a normal computer mouse is the A6-H0-P3 standard; matching the dimensions of a computer mouse as close as possible. This follows the rule of using the smallest possible build-volume to produce a product. The load standard is defined as P3 which corresponds to 2 Kg, Festo's transport carrier is for example rated for max 3 Kg (P2 would corresponds to 4 Kg).

Separate parts such as the main PCB assembly and the side-button-PCB are inputted from a smaller production transport-line, or these parts are inputted as a supplier part directly in the main assembly. The development of the main production transport line is initially more important, therefore the transport and actual production of these smaller sub-assemblies have lower priority in the initial research and developments stages.

At the end of the main production sequence, the mouse would be transported to a larger transport size for packaging, this will be left out of scope for the same reason.

Decisions:

Transport and production of parts and sub-assemblies has lower priority and is left out of scope (initially 'supplier components').

The output of the computer mouse to a bigger transport-track for packaging has lower priority and is left out of scope.

The A6-H0-P3 build-volume size standard must form the framework for further development of the production system (size: 105 × 149 x 88 mm, max mass: 2 Kg).

As decided in the tracking framework, the transport system is based on a carrier transport system, giving tracking capabilities to 'unconnected' parts. Another reason is that, without a carrier, transportation of strange shape products might get caught or damaged during transport. On the other hand, the carrier's placement-surface, does not change throughout the transportation. The product can therefore be designed with this universal transport surface in mind, bringing process-generality to the transport system which is a must for Transcended Manufacturing.

The carriers must accommodate rectangular surface dimensions of the decided size standard A6 and are capable of transporting the predefined height and load standard (H0-P3).

Decisions:

The transport must be based on an universal carrier system.

The carrier transport system could eventually use omnidirectional robots to move the carriers around, or it can be based on a conveyor transport module system just as Festo's current system. The transportation could take place below a false floor, at the ceiling or somewhere in the middle. One of these options might prove to be most optimal, but for fast adaptation and demonstration of the Transcended Manufacturing Factory, it is beneficial to implement the design in an existing system. Therefore Festo's CP Factory and transportation setup (which is actually production-cluster), is used in further design of the cluster. Festo's CP Factory is already made to produce consumer-electronics products, integrating the same material- and performance type requirements. The already developed horizontal transport system can fall initially out of scope in the development of the Transcended Factory.

The cluster modules will be designed following the industry standard, but adapted to fit the existing Festo system, this is not complicated because the A6-H0-P3 build-volume almost exactly fit the carrier shape of Festo's transport system; Festo's carrier build-area is 100 x 160 mm and the A6 build-area is 105 x 148 mm. This decision is accompanied with recommendation to eventually fit the Festo system to the proposed industry standard (Slightly changing the shape of the carrier/pallet and the basic-transport-module).

Decisions:

Festo's patented 'Material flow' carrier conveyor belt principle in combination with their transport-module is used and assumed.

Another important decision is the assembly location of the products within the cluster. For example in the computer mouse FDM printing is the most time-intensive process step. It would therefore make sense to have everything ready at that location for fast assembly; reducing the total product manufacturing time.

The disadvantage is, that this would require a complex pick-and-place 'robot', in every FDM-module, able to directly put very different parts into 3D-prints of all shapes and sizes. Due to the slow speed of the process a lot of FDM-modules are required and each one would require extra space for the pick-and-place equipment. And following this principle, all the other process-modules require this equipment as well (such as CNC-milling etc.).

Stepping back from this idea, the other option is to transport the main FDM print to an assembly-module for part insertion. The benefit of this system is that it requires only a few such assembly-modules, because of the short time required for this simple process, as compared to the FDM printing step. This keeps the complexity and the cost of the FDM-module to a minimum. This framework enables complex sequencing of the manufacturing-steps and puts special process requirements outside the general FDM-print modules.

Decisions:

Assembly steps take place at a dedicated module, at a different location than the FDM-module.

The pick-and-place module puts parts from one carrier into a main-assembly, these parts are either from the same size transport line or from a smaller transport line, in the last case the pick-and-place module forms a bridge between two different size-standard transport lines.

To fit within Festo's CP Factory the existing pick-and-place robotic arm module is used in the manufacturing of the computer mouse. The development of the pick-and-place system has therefore low priority and falls out of scope in the initial development of the Transcended Factory.

Decisions:

Festo's robot arm pick-and-place module is used and assumed in the assembly of the mouse.

As described above, a couple of systems can directly be used from Festo's existing CP Factory, this is beneficial for further development and demonstration of the envisioned mass-customization CP Factory.

Another benefit is the demonstration of the main Transcended Manufacturing princpiple, because the mouse exemplary-product can be produced in parallel with the existing phone-like exemplary-product.

Apart from Festo's existing modules, the most important system for the production of a highly personalizable computer mouse must still be developed, namely the FDM-module. It must follow all findings, principles and standards described in this report, but also fit with Festo's existing CP-Factory. The embodiment of this module is described in the next chapter. To make the system scalable the FDM-modules must fit the proposed industry standard as well; this will be A4-H0-P3 (With build volume A6-H0-P3).

Decisions:

The FDM module is the focus point for further embodiment of the computer mouse production setup.

The industry standard defining the outside dimensions and load standard for the FDM-module is A4-H0-P3 (size: 210 × 297 x 198 mm, max mass: 8 Kg; including build-volume load).

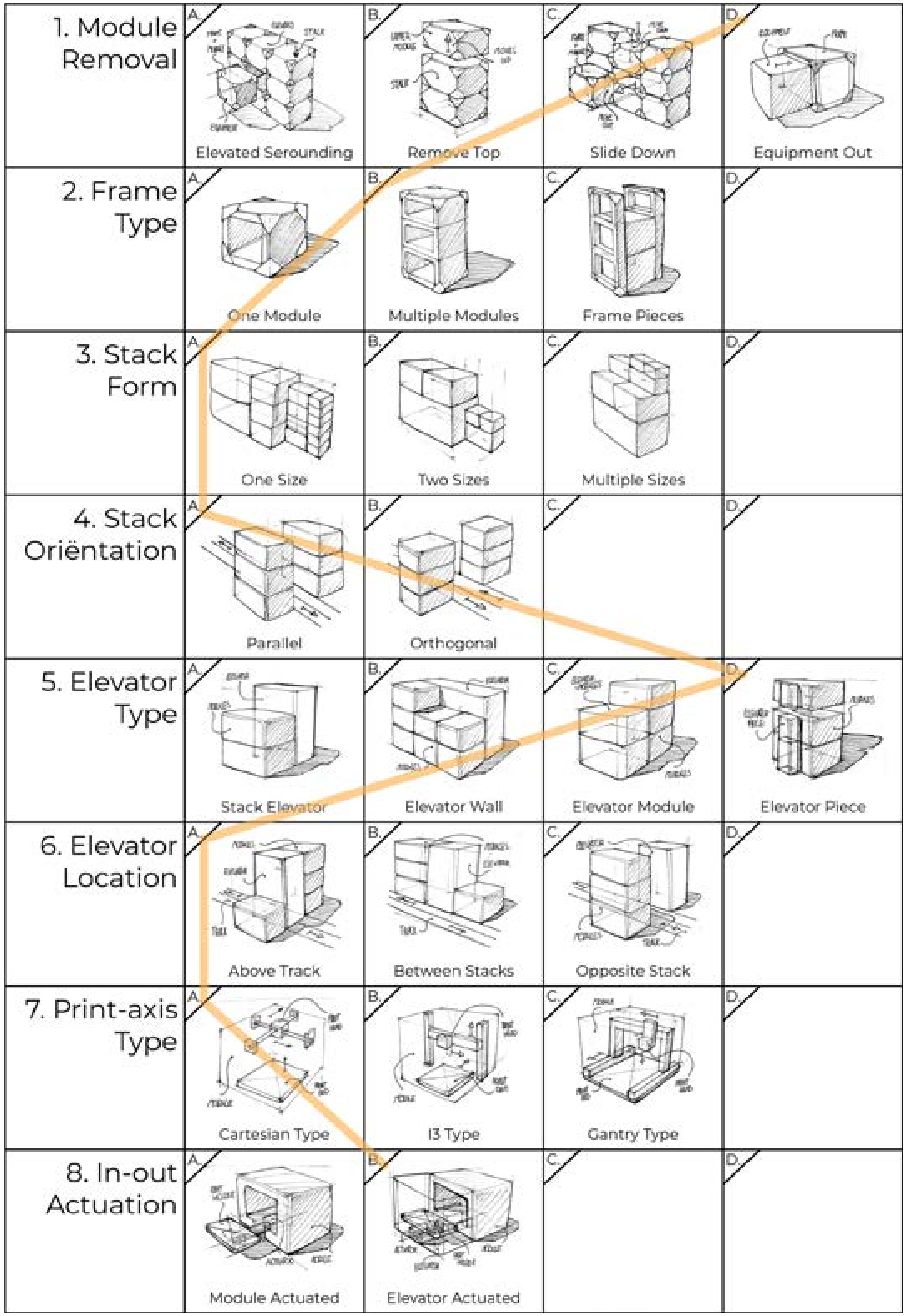
3.2.3. FDM MODULE CONCEPTUALIZATION

As described in 3.2.2. Transcended Cluster Proposition chapter, the only missing module of Festo's CP Factory to produce the personalizable computer mouse is the FDM-module. This is also the most important part to integrate mass-customization into the system. In this chapter a concept is generated that integrates the Transcended Manufacturing requirements described in the Envision part of the report.

In the next chapter an overview is given with the most important design challenges for the embodiment of the FDM module concept. While researching these challenges it became clear that there was a dependency between some of them. This resulted in forced concessions between possible solutions, these challenges where therefore as first step solved in parallel, following a morphological exploration. This resulted in the mentioned concept described at the end of this chapter.

For the morphological exploration all the individual answers to these challenges are used once (the options in the morphological overview, elaborated in the Appendix: 7.1.8. Forced Morphological Concept Method). This is done, not to directly get the best concept, but to generate an as wide as possible solution space and find a clear overview on the core wishes involved and their respective relevance (This method is comparable, but different from the normal morphological-chart method). From this solution space an optimal final concept can be generated, that incorporates the best elements and has the smallest concessions.

On the next page the morphological overview is given. In this chapter only the resulting final concept is described, the five other concept to describe the solution-space can be found in the Appendix: 7.1.8. Forced Morphological Concept Method.



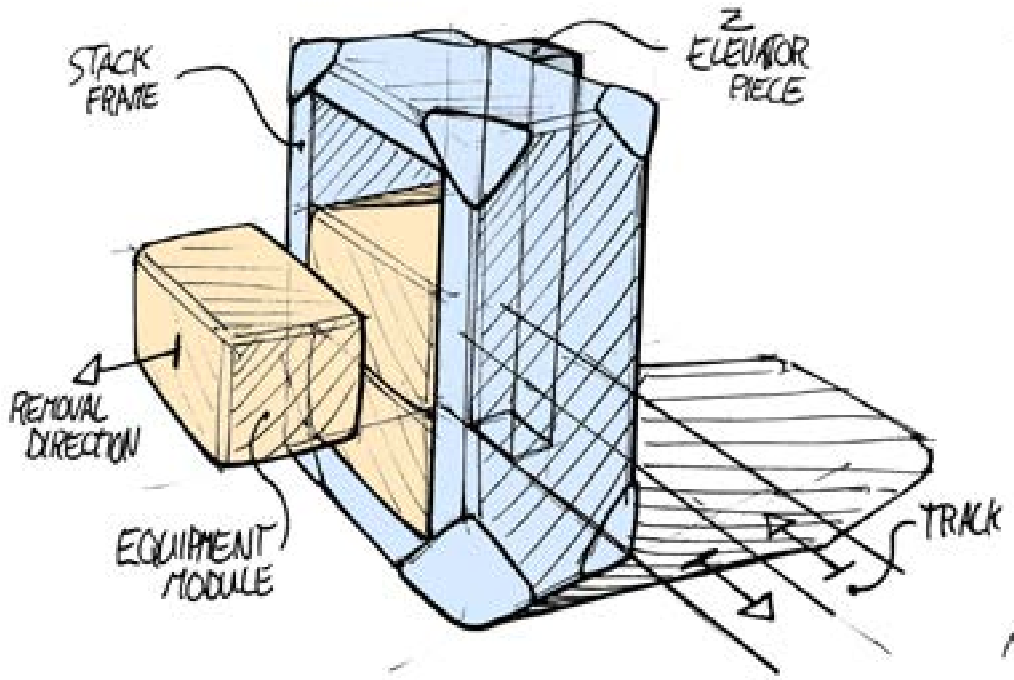
FINAL CONCEPT: THE FDM-CABINET

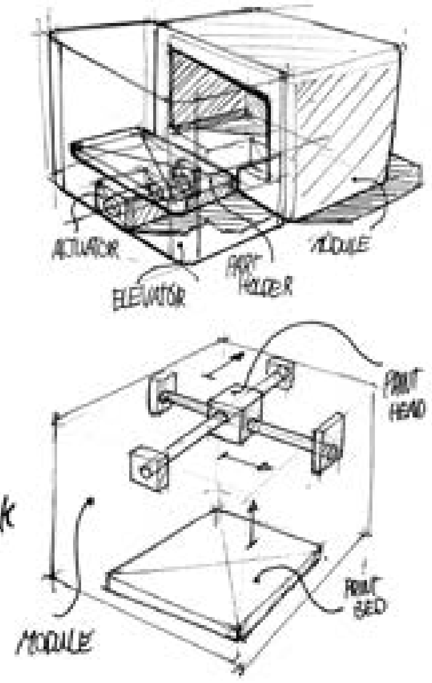
Following the evaluated concepts the leading wishes are derived and an optimal design is generated from these wishes trying to increase the benefits, reducing the disadvantages, or making the best concessions.

- The concept must be as scalable as possible (horizontal, vertical, resolution)
- The concept must be as general as possible (standardized, self-contained)
- The concept must be as accessible as possible (replaceable, repairable)
- The concept must be as non-complex as possible (no extra components, simple design)
- The concept must be as rigid as possible (strong, stiff)

This concept has a stack height defined by the frame and is designed to hold one type of process-module; Darwin style FDM module. An elevator-piece of the same length is attached to the frame, directly above one side of the transport-track and supplies it of parts. The elevator moves the parts up-or-down and has a second actuator to move the parts in-or-out. The elevator grabs the part and lifts it to the right height, the actuator moves it in the printer, places the part down, and extracts again. The vertical print-axis rises and moves the part towards the xy-axes at the roof of the printer and starts on-printing on the part. Afterwards the steps are followed in reverse until the part is again on the transport-track.

The stack in combination with its frame and elevator system is an 'FDM-cabinet', the interface point to the rest of the factory, that must be standardized for all different cabinet-types is therefore between the gripper and the carrier on the track.





Below the benefits of this concept are discussed (positives as compared to the other morphological concepts).

+ Due to the set height of the stack, strength is directly derivable from the proposed industry standard and the cabinet can be designed with a certain roof height and human accessibility predefined (as compared to vertical scaling concepts).

+ Because the whole frame is designated for only one type of process-module, the outside dimensions of the frame can follow the proposed industry size-standard. And the space inside can be designed in the most optimal way, making the frame-equipment system as slim as possible (as compared to multi-process-module, standardized frame concepts).

+ The whole cabinet uses only two actuators reducing the relative cost for each module and the design complexity of the process-module itself (as compared with module integrated actuator concepts).

+ The actuator movement has only two part-hand-over moments, reducing the number of critical movement situation and therefore the complexity of the gripper design (as compared with module-integrated-actuator and separate elevator-actuator concepts).

+ The vertical print axis moves only when a new layer is printed, thus the part stays relatively still during printing, resulting in no vibrations due to inertia and low requirements for the holder-part interface (as compared to i3 or gantry type concepts).

+ The frame and elevator, which are more durable than the process-equipment, stay when the modules get replaced over time. The whole elevator system is attached to the frame which can be accessed for maintenance by removing the whole cabinet (as compared to separate elevator tower/wall concepts).

Below the necessary concessions within this concept are discussed (negatives as compared to the other morphological concepts).

- When the elevator breaks down all the modules in the stack are out of order as well (as compared to integrated-elevator-piece concepts).

- The scalability is maximized by using only one stack per elevator, but the set height reduces the flexibility and continuous scalability of the system slightly (as compared to 'infinity' high stackable module concepts).

3.2.4. FDM MODULE CHALLENGES

In the previous chapter a concept is generated that integrates the Transcended Manufacturing requirements as best as possible. To further develop and embody the FDM-cabinet a list of challenges is generated. These challenges must be solved to create a fully working FDM system fitting the first iteration of the Transcended Manufacturing cluster. This system is then able to produce personalized consumer electronics products, following a production sequence as described in the 3.1.3. Product-family Embodiment chapter.

As described in the previous chapter, while researching the challenges it became clear that there was a dependency between some of them. These challenges are already tackled in the FDM-Cabinet concept.

From the remaining challenges the ones with the most relevance in proving the core-principles will be chosen and further developed in this project. Solutions will be generated and integrated in a first prototype design proposal. The remaining challenges need to be solved at later stage, in future research.

1. Mechanical & Stacking
    a. Frame equipment spatial relation challenge (equipment removal, frame type, stack form and orientation)
    b. Module connection challenge (industry standard grid, vertical placement, horizontal connection, interlocking, module in and out framework, maximum stacking height)
    c. Module structural challenge (static strength, deflection, dynamic strength, vibration)
    d. Festo CP Factory physical integration challenge (relation, location, orientation)

2. Transport & Movement
    a. Movement framework challenge (elevator location and type, in-and-out actuator location)
    b. **Vertical movement challenge (carrier relation, actuation, guiding)**
    c. **In-out movement challenge (carrier relation, actuation, guiding, placement)**
    d. **Holding framework challenge (print-bed, pallet, part, printer relation, print-release)**

3. Equipment & Printing
    a. Printer configuration challenge (axis type, printer structure, frame and printer relation)
    b. Module interface challenge (power internet connection, module neighborhood recognition, digital initialization)
    c. **On-print challenge (framework, tolerances, continuation, g-code)**
    d. **Print challenge (plastic heating/ shrinking, bed and nozzle cleaning, material type)**

4. Maintenance & Operation
    a. Sensor/camera inspection challenge (tracking, start, progress and completion inspection, Failure recognition, print-surface recognition)
    b. Filament spool challenge (spool switching, spool replacement framework)
    c. Printer removal challenge (in-and-out movement, accessibility, unlocking, handling, maintenance)

5. Software & Tracking
    a. Tracking challenge (part/carrier recognition, localization)
    b. FDM firmware challenge (product recipe file g-code translation, feedback recognition and implementation)
    c. Digital model interface challenge (fit Festo's system, digital twin representation, precompute and cluster sensor data)
    d. Autonomous digital communication challenge (fit Festo's system, materials/ maintenance requests, order confirmation, downloading gcode files)

The light-gray challenges are already solved in the previous chapter. And the blue challenges will be solved in the following chapter. These are the minimal set of challenges to be solved, when developing a system that is able to print the computer mouse product-family demonstrating the on-print method. This requires a framework to be proposed for the full on-printing process. And a working prototype to be designed. The goals for this prototype are, firstly to demonstrate an initial framework that is able to produce a personalized consumer electronics product from start to finish, at a mass-production output capacity (theoretically). And secondly to validate the pick-and-place on-printing process as a feasible method to produce multi-component parts.

FDM-CABINET CORE FUNCTIONAL REQUIREMENTS:

The chosen embodiment challenges goals are translated into functional requirements, for the design in the next chapter. The FDM-Cabinet Core Functional Requirements are as follows:

1. The system must fit the production process using Festo's CP Factory system processes, and fit in an overarching production framework.
2. The system must be able to autonomously insert and remove parts and products from the printer to Festo's transport system and perform the whole process without failure (collisions, placement errors, etc.) and general operations labor (cleaning, waste removal, etc.)?
3. The system must be able to print variations of the designed personalized computer mouse, and other products shapes of the same size-standard (base-prints and monolithic parts such as the button-top-shell).
4. The system must be able to initiate the production steps of a unique computer mouse, and the next product in the queue, following production sequencing that minimizes printer downtime (requiring the mouse to switch from printer).
5. The system must be able to apply the on-print principle without failure (layer adhesion, nozzle collisions, etc.), by creating component cavities and continue printing on both, the last print layer, as well as the placed components.
6. The resulting on-printed product must be of comparable quality, in terms of strength, to the same directly printed shape (without pauses).
7. The resulting on-printed product must be of comparable quality, in terms of aesthetics, to the same directly printed shape (without pauses).

3.2.5. FDM MODULE EMBODIMENT

In this chapter the embodiment of the first Transcended Manufacturing prototype is described following the goals set in the previous chapter. The prototype will integrate the first core functional requirement: 'The system must fit the production process using Festo's CP Factory system processes, and fit in an overarching production framework.'

This chapter is divided in the (grouped) embodiment challenges from the previous chapter. These are discussed in turn, but first the challenge of building the structural prototype is discussed.

Directing Requirements: **2.1.1.3, 2.1.3.4, 2.1.4.2, 2.1.4.2, 2.1.2.5, 2.2.1.2, 2.2.2.4, 2.2.3.2, 2.3.1.27, 2.3.2.10**

PROTOTYPE CHALLENGE

To tackle the core functional requirements and demonstrate the on-print process, it is not needed to fit Festo's CP Factory transport and pick-and-place system. These systems are substituted by a test operator placing and removing a carrier on a 'mock' transport track included in the prototype and performing the sub-component pick-and-place operation.

This automatically demonstrates the on-printing framework as an autonomous process.

A prototype setup must be build that includes at least two FDM-printers in a vertical cabinet type structure or frame. This is necessary because on-printing at mass-production speed of a single product will almost always take place in multiple different printers. When the product moves out of the printer for component placement, the respective printer must immediately continue printing another product; to reduce machine down-time and make the cluster more efficient.

Each printer will be a little different due to a different production life-time, different backlash and hysteresis due to wear. This prototype must demonstrate that on-printing is possible, even with these differences.

The two required Darwin-style FDM-printers that will be used are Ultimaker 2+ printers. These are available at the faculty of IDE. It will therefore be required that the printers are not modified in terms of software and hardware to fit the prototype. The part gripping/holding framework must therefore accommodate the existing print bed.

The prototype requires a method to hold the two Ultimaker printers. The printers must in the future be replaced with versions fitting the proposed industry standard. The frames only function is to support the rest of the prototype. It does not need attention in terms of strength and stiffness in the current iteration, it must simply perform its task.

The system will use a welded steel frame. The printers can be placed above each other in this frame. It must also support a vertical actuator that can be mounted on the front above the mock-transport track.

This decision is made instead of other options such as aluminum t-track profile, because the material is easily strong and stiff, it is locally and immediately available without transport, the frame is really fast to produce by means of welding, and the materials are cheap.

Decisions:

The only interaction of the test is by putting the carrier on and from the track and placing components in the printed part.

Two printers will be used to demonstrate part switching between on-printing.

The setup uses the Ultimaker 2+ Darwin-style FDM-printers.

The prototype will use an arbitrary welded steel frame.

MOVEMENT CHALLENGE

The task of the movement system is to move the part from the transport track to the printer and back. This requires vertical and horizontal linear movements. The time required to print a production-step of the computer mouse takes between one and seven hours, the movement system will therefore not be a bottleneck in this process (even for nine-modules-high-FDM-Cabinets a minimum of one 1 move per 7 minutes), a faster movement system does mean shorter overall production time per mouse.

For this prototype the movement system must simply work to demonstrate the autonomous on-print process. In a later version, a better or cheaper option of this system might be beneficial. A requirement of the movement system is: that the end-positions must be precise enough to 'hand-over' the part to the next holding point (printer or and carrier), this requires calibration and will be solved by means of set- and stop-screws in every hand-over point for all horizontal rotations and translations, accept for the movement system itself which will be directly connected to the frame (this will be the ground). Within the movement sequence there are only two hand-over moments, from the carrier to the gripper and from the gripper to the printer (and in reverse).

The system uses only two movements (axes) to place the (vertical and horizontal in-and-out of printer). No extra movements to scoop up the parts or make a gripping motion. The part holding framework must accommodate the fact that only two actuators are used, which will be a decisive factor in the holder design. On the other hand, using only two actuators reduces the cost and design complexity of the prototype. Because the system must support only a small weight (A6-H0-P3 standard) timing belt actuation will be the best option for both axes. And because the system must be repeatable, four-track circulating ball carriage linear guides will be used for this prototype, in a next stage cheaper options might be beneficial (In the Appendix: 7.1.9. Linear Movement different linear guides and actuators are evaluated). An important requirement will be that the part acceleration must be low enough that the gripper holding forces are not surpassed and the part will fall out of the gripping system, a software set maximum acceleration coeficient will be implemented that will be kept below this point by means of trial-and-error.

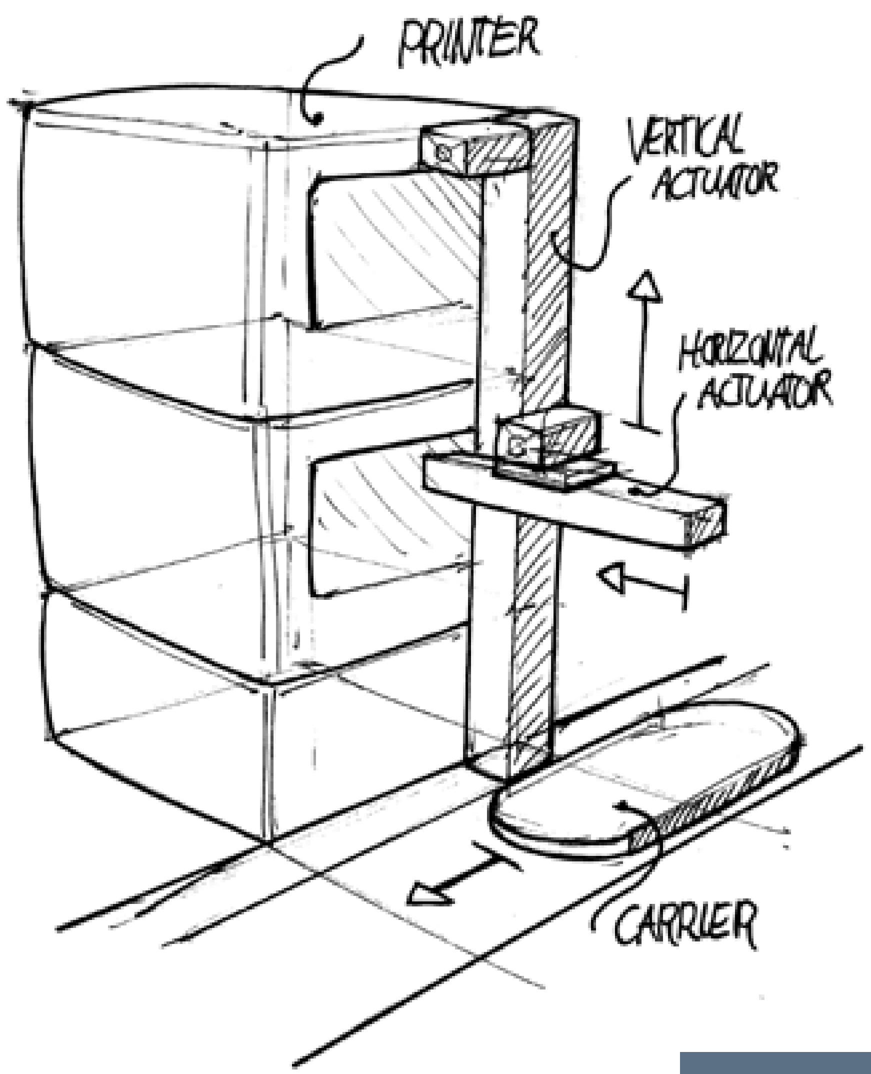
The two integrated linear movement systems that will be used are Festo's electric timing belt linear actuators; normal-type for the vertical axis (EGC-TB) and cantilever type for the horizontal axis (ELCC-TB), this is important because the mass of the motor will be held stationary while the whole actuator moves. It was fortunate that exactly the types needed could be sourced from Festo as project partner. These actuators are electric and therefore not pneumatic, this is chosen because the system could then be controlled without air-pressure equipment; only motors drivers, micro-controller, and power-supply are needed.

To drive the linear actuators two 4Nm Nema 24 stepper motors and digital stepper drivers are used. These are in turn controlled by means of a frequency-modified 50% duty-cycle PWM signal from an Arduino-UNO.

As stated before, the movement must be smooth enough that the holding forces are not surpassed. To make a linear move, the software calculates the number of steps to move a certain distance. It then calculates the duty-cycle delay for each step. This delay follows the graph of an inverse half-period sine, resulting in a half-period cosine ramp-up-ramp-down movement (time integral). The amplitude is calculated from the set maximum acceleration coefficient (time derivative, which is optimized by trial-and-error).

All the location coordinates and the trajectories between those coordinates are coded into movement programs in the software (printer A in and out, printer B in and out). To find the physical zero location for both axes a homing sequence with two micro-switches is implemented. Micro-switches are also used to register a finished print by means of a print-head movement (implemented in g-code), and to register if a carrier is ready for part placement or removal. The full Arduino code can be found in the Appendix: 7.1.20. Motor Control Arduino Code.

Because the system must work without modifying the FDM-printer the movement system is also responsible for starting the print sequence by means of the original rotary-encoder and button on the front of the printer. A compliant swipe and push finger is placed next to gripper to perform this operation.



Decisions:

All physical holding locations must be calibrated by means of set- and stop-screws.

The prototype uses only two actuators for the movement system.

Festo's electric timing belt linear actuators are used, normal and cantilever type

The actuation system will be controlled by an Arduino-UNO, stepper motors and stepper drivers.

A ramp-up-ramp-down movement is implemented for the trajectories.

Due to the micro-switches and a compliant-finger the full production sequence will be initiated and finished by placing the carrier on the transport track.

HOLDING FRAMEWORK CHALLENGE

The task of the holding framework is to lock the part into place, be it the carrier, the printer, or the movement system end-effector (called gripper). The gripper holding-forces must be high enough to withstand forces do to the inertia of the part. And the holders and gripper must be able to support the vertical downward force of 2 Kg (A6-H0-P3 standard).

Both aspects are not fully relevant in this prototype because only the computer mouse will be produced, which is much lighter. In a next iteration of the prototype the holding system must be matched to the movement system in terms of performance such as holding forces structural strength, stiffness and fatigue. For now it must only work for the tests and demonstrations of the proposed production framework.

Another important aspect of the holding framework is that the system must be standardized, not just for FDM-printing. The part hand-over between the carrier/printer and the gripper must also work for different process-type cabinets.

To perform the task a gripping-holding framework is designed that uses an inner-outer single kinematic coupling hand-over system, assisted by gravity (see picture). Kinematic coupling means that two objects are mathematically defined in space by six points of contact. The orthogonal relation between the resultant force vectors lock all translations and rotations. The hand-over system makes use of a pallet as print-bed to print parts upon. This pallet is what will be moved from the carrier into the printer; the gripper and holder interfaces with this pallet. The gripper and holder uses three precision-ground metal balls which fall in v-grooves at the underside of the pallet, positioned radially around the center; thereby defining the pallet's location in local-space (of the holder or gripper). The metal balls of the gripper are more close together, this way the pallet hand-over is possible; this is comparable to the handing-over of a tray between two waiters. The center of mass of the pallet and product must fall above the equilateral triangle that the metal balls form, otherwise the pallet cants over. The carrier and the Ultimaker print-bed will get a 3D-printed holding frame to mount the metal balls on. The holder in the printer can directly be printed on the original print-bed, resulting in a calibration free system, because the horizontal location will match for both printers (relative to their zero locations).

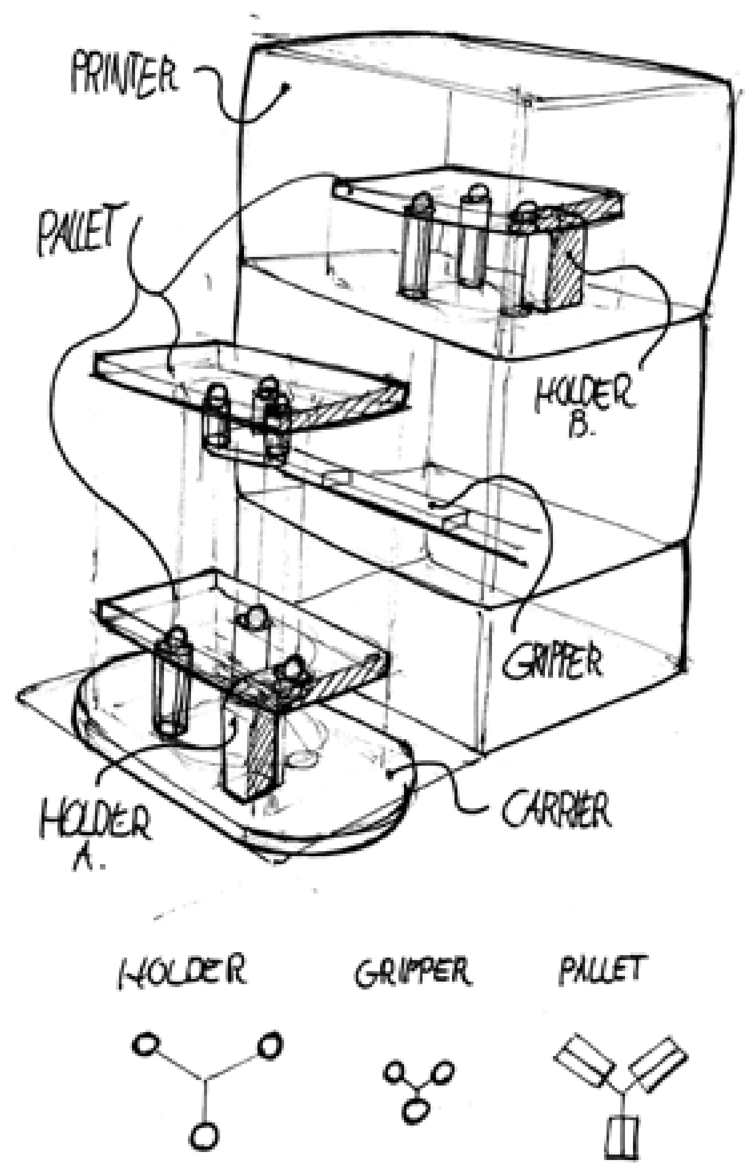
Decisive design requirements were: that the framework accommodates the Ultimaker print-bed, and that the framework accommodates a movement system with only two linear actuators.

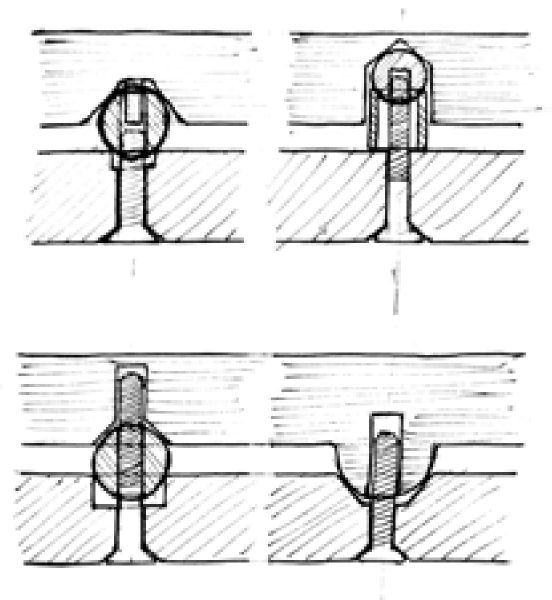
Due to the radial symmetry of the v-groves the pallet will be thermally stable, meaning that the pallet can shrink and expand due to temperature, but the center will remain at the same location, preserving centricity. To improve this even more the design will be made symmetric by creating three extra mirrored v-grooves that will not be used.

As described, the system must be general, which is the case with this framework, this could be used for every process-type cabinet. The setup uses a general system to handover pallets, no extra or specific gripping location is required for the FDM-Cabinet. This universal holding/gripping system can be improved with a mechanically or electrically actuated locking system at the center of the pallet (such a systems might be beneficial for production-processes requiring workpiece-holding such as turning, spray-painting, etc.). This is not implemented in the current prototype, but can be further explored in later research. The pallet will also have horizontal dimensions of for the A-paper standard thereby fitting the proposed Industry Standard.

The pallet will be made out of the same material as the printing filament, because the mouse production already uses the on-print principle for production, this can also be implemented to print the initial product and support-structure onto the pallet. This standardized component can eventually be made by injection molding, or be milled from a flat sheet to minimize the costs per unit. Using a one-time print bed removes the need for a rather complex cleaning operation, that requires labor and washing chemicals. Because the material used will be the same as the product and support material itself, it can directly be recycled into new pallets and print-filament.

The pallet surface can also be used to pré-extrude nozzle material, for a clean print. This material does not end up in the printer and gets recycled with the rest of the pallet and support material reducing cleaning of the equipment.





It is really important to remember that the pallet will be small compared to the product. If the pallet generates significantly more waste, the pallet is probably one standard progression to big. And the product will already produce waste due to support-material.

It must not be possible for the part to fall/tip-over from the gripper by sudden movements. It is beneficial that the vertical axis moves very slowly in a Darwin-type printer.

Sudden horizontal changes in velocity, can cause the pallet and product to cant over on two of the metal balls. This can be solved by locking the pallet to the gripper, with a mechanical or magnetic actuator, integrating passive anti-canting structures, or minimizing acceleration. The last two are applied in this prototype (some anti-canting structures can be found in the picture below).

Decisions:

The gripping/holding framework uses a pallet-based inner-outer single kinematic coupling hand-over system.

The pallet will be made out of the same material as the printing filament.

To prevent canting low acceleration and anti-canting pins are implemented. Not an actuated locking system.

PRINTING CHALLENGE

The task of the printing system is to print parts with the Fused Deposition Modeling (FDM) production method on a plastic pallet. Within the process the printer stops when the part is printed up to a height where a necessary component can be placed in the print. The pallet and print go out of the printer for the pick-and-place operation and back again. The component cavity gets sealed by the bridging-method of the first on-printing layer and the print continues until finished.

An important decision within the framework is that every product will be made with printed frame-structure (comparable to support-material); as opposed to directly on the pallet. And although the bottom of the computer mouse is flat this decision is made to preserve process-generality. The system must be capable to print all kinds of shapes, convex and concave; the button-top-shell for example. This support material will be optimized for the part-pallet separation step, the support is strongly bonded to the pallet which is held rigid while the part is pulled free. This will require specially modeled frame-structure with a smooth layer between itself and the part, or some sort of release agent (these options are not further explored in this project). For now the printed frame structure is a combination of Cura slicer settings; namely ‘raft’ (with 1 top layer) and ‘support’ (concentric 8% infill). As stated in the previous chapter, the printed frame-structure can directly be recycled with the pallet without a complex separation and cleaning operation. The current frame-structure is not yet optimized and will require for now separation labor from a test operator. Pictures of the current frame-structure can be found in the Appendix: 7.1.10. Raft Frame Structure.

The systems prints without heating the build-plate of the original printer. This also means that the air around the print will be of a lower temperature. Normally heated build plates provide, due to convection a cheaper version of a heated chamber (Dr. ir. E.L. Doubrovski, personal communication, 11-12-2019). When the chamber is overall temperature is higher, bonding will be better and warping will be less, often resulting in better print quality. In a factory setting this would be disadvantageous, because of the high amount of power required to keep the chambers heated and the rest of the factory cool. It would be extremely beneficial if the material is thermally stable and the prints are of good quality at room temperature; especially if parts move in and out of printers for other process operations.

The material PETG is chosen as printing filament for the printed parts, frame-structure, and pallet support-structure. The material is relatively durable and strong which is important for general product use (impact resistant). The material is non-brittle, which is important for the flexible buttons etc. (ductile, it does not shatter). The material is thermally stable as compared to other materials; it almost does not warp due to heat, which is important for printer switching after pick-and-place on-printing. Reduced warping is especially important when printing without a heated chamber. The material is also fully recyclable, it produces no fumes or smell during printing, it is food grade approved and it is a reasonably good gas and moisture barrier. A disadvantage is that the material is hygroscopic, it absorbs moisture from the air making it print worse and slightly more brittle; but the material is already ductile and the product is to be used inside. PETG has a printing temperature of 240 degrees Celsius, this is higher than PLA (190) and almost equal to ABS.

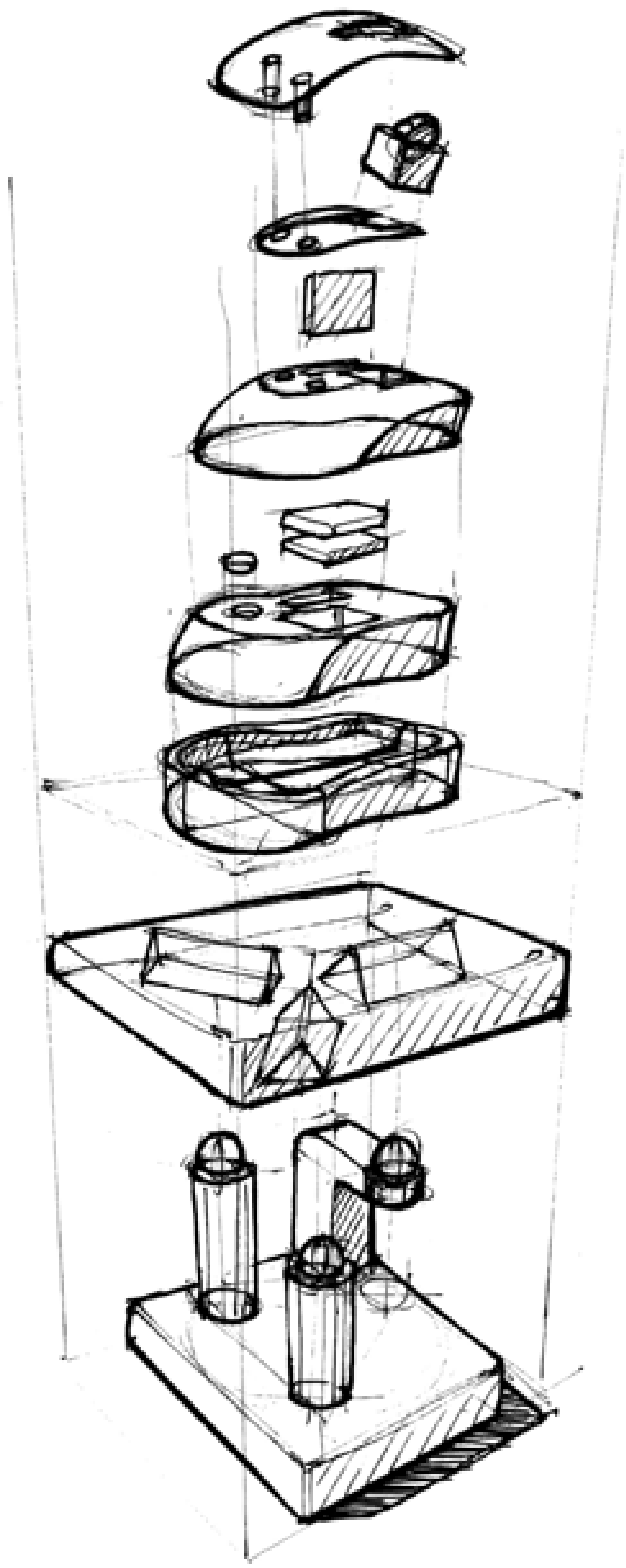
PETG filament is at this moment only slightly more expensive than PLA and ABS; the reason is probably that PETG filament is still more novel; because the raw material price per kilogram is lower. The average price of PET-G is 0.43 euros/Kg, that is as cheap as PE and cheaper than PC (0,90), PP (0,55), ABS (0,62), making it one of the cheapest plastics on the market.

Price: 0.00043 euro/g
Density: 1.38 g/cm^3
Injection molded A6 pallet:
- *67 cm^3,*
- *91 g*
- *0.04 euro*

Milled/formed sheet A6 pallet:
- *115 cm^3*
- *159 g*
- *0.07 euro*

Injection molding cost 10.000 st: 2.60 euro
Injection molding cost 100.000 st: 0.90 euro

Pallet cost indication: 0.94 - 2.67 euro



Decisions:

The product will be made with a printed frame-structure as opposed to directly on the pallet.

The print support separation assumed to be solvable with future research.

For printing the material PETG is chosen for both making the build-platform, frame-structure, and product.

4. VALIDATION

In the Actualization phase a framework is proposed for the full, so called, pick-and-place on-printing process. This framework should be able to produce the designed computer mouse discussed in the 3.1. The Exemplary product chapter. And a prototype is developed solving the most important FDM-Cabinet embodiment challenges, resulting in a working system.

The goals for this prototype are, firstly to demonstrate an initial framework that is able to produce a personalized consumer electronics product from start to finish at a mass-production output capacity (theoretically). And secondly to validate the pick-and-place on-printing process as a feasible method to produce multi-component parts.

The Core Functional Requirements for this prototype are discussed and validated in each of following sub-chapters. The last subchapter validates the Core Functional Requirements for the exemplary-product itself described in the 2.5.2. Product-family Requirements chapter (at the end of the Envision phase). The research findings will then be used for evaluation in the phase after the Validation phase.

4.1. CABINET DEMONSTRA-TION

SHOWING THE FRAMEWORK

The primary goal of the developed FDM-Cabinet prototypes is to demonstrate an initial framework that is able to produce a personalized consumer electronics product from start to finish. The prototype and framework must be validated on the respective Core Functional Requirements described in the 3.2.4. FDM Module Challenges.

FDM-CABINET CORE FUNCTIONAL REQUIREMENTS:

2. The system must be able to autonomously insert and remove parts and products from the printer to Festo's transport system and perform the whole process without failure (collisions, placement errors, etc.) and general operations labor (cleaning, waste removal, etc.).
3. 3The system must be able to print variations of the designed personalized computer mouse, and other products shapes of the same size-standard (base-prints and monolithic parts such as the button-top-shell).
4. 4The system must be able to initiate the production steps of a unique computer mouse, and the next product in the queue, following production sequencing that minimizes printer downtime (requiring the mouse to switch from printer).
5. The system must be able to apply the on-print principle without failure (layer adhesion, nozzle collisions, etc.), by creating component cavities and continue printing on the last print layer and placed components.

4.1.1. METHOD

The core functional requirements for the first FDM-Cabinet prototype are translated in the following research questions:

RESEARCH QUESTIONS:

1. Is the system able to autonomously insert and remove parts and products from the printer to Festo's transport system and perform the whole process without failure (collisions, placement errors, etc.) and general operations labor (cleaning, waste removal, etc.)?
2. Is the system able to print variations of the designed personalized computer mouse, and other products shapes of the same size-standard (base-prints and monolithic parts such as the button-top-shell)?
3. Is the system able to initiate the production steps of a unique computer mouse, and the next product in the queue, following production sequencing that minimizes printer downtime (requiring the mouse to switch from printer)?
4. Is the system able to apply the on-print principle without failure (layer adhesion, nozzle collisions, etc.), by creating component cavities and continue printing on the last print layer and placed components?

These question are answered by going through the production of two different computer mouse core-prints (with and without side-buttons) and one button-top-shell with the developed FDM-Cabinet prototype; resulting 6 print operations for two printers (the print sequencing and model renders can be found in the Appendix: 7.1.11. Cabinet Demonstration Test). The goal is to let the setup work autonomously without intervention of the operator, the only interaction of the human operator during the test, will be the removal and placement of the carrier on the mock transport track for component placement (mock pick-and-place robot). Below the operation of the prototype is discussed:

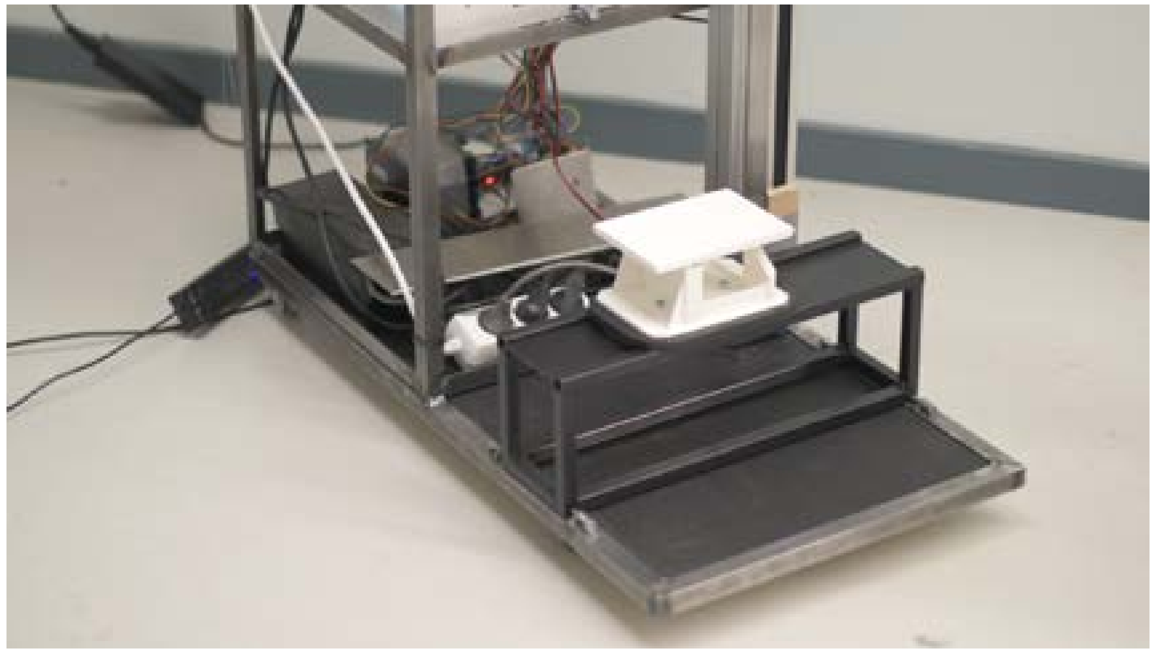
1. The system is prepared by loading the two gcode files on the sd-cards of each printer and start running both files. Within these files a pause-and-wait command is coded. When both printers reach this stage they will wait until the round button is pushed.
2. Then the test operation will be initiated by physically moving the carrier with the pré-produced pallet to the position on the track in front of the printer cabinet. A sensor will see the carrier and starts the first pallet lifting sequence. The pallet gets placed in the printer and the end-effector will push against the main print button to start the print.
3. After the first part of the mouse is printed, the printer-bed moves down, and the print head moves against a switch that initiates the next actuation sequence. The pallet is moved from the printer back to the carrier, if the carrier is waiting on the track.
4. Then the test operator removes the carrier, places the first components in the print. And step 2 and 3 are repeated on another printer, until the mouse is finished. Parallel to this the button-top-shell and the next computer mouse in the que will be initiated. The total production of all the parts follows a 'minimal downtime' print sequence; switching between printers.

The demonstration of the solution of each embodiment challenge, can be found in the results as well as the completion of the final demonstration test. The research questions are validated in the discussion.

4.1.2. RESULTS

PROTOTYPE SYSTEM:

The prototype aspects such as the operator carrier interaction, housing two Ultimaker 2+ printers, and the metal frame to support it all worked flawlessly.



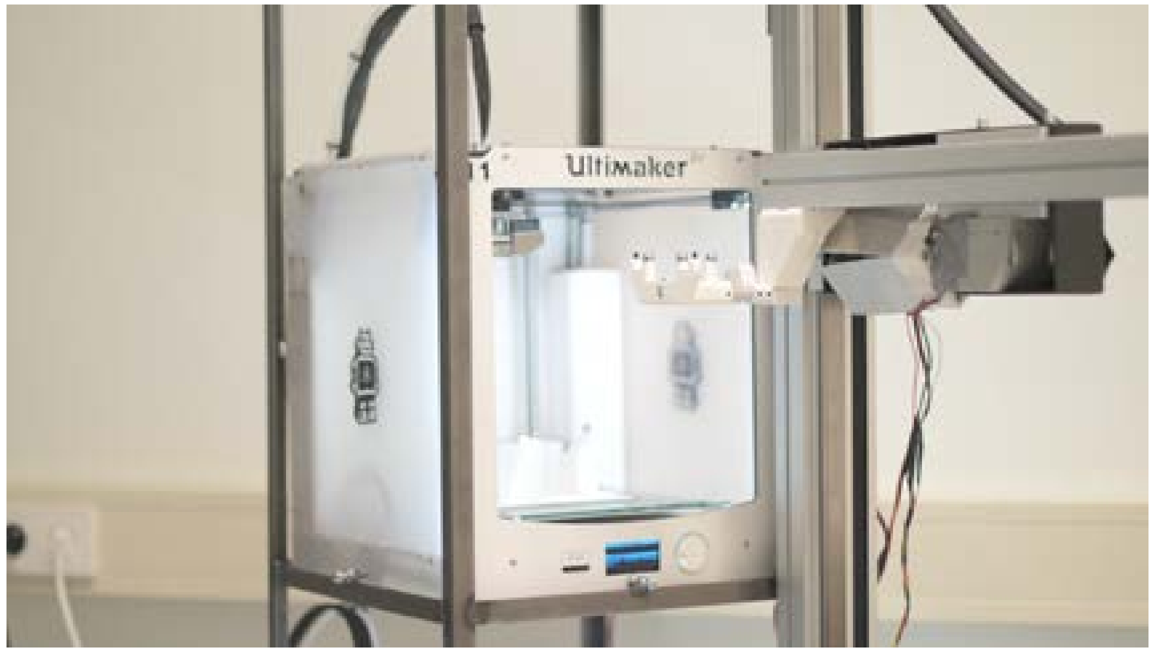
MOVEMENT SYSTEM:

The two printers and the transport-track were calibrated on the yz-plane of the movement end-effector. This worked perfectly, due to the stiffness of the frame and the precision of the calibration stop-screws. The two types of actuators from Festo worked perfectly, they had almost no play. The stepper motors were strong enough to carry the weight of the movement system, without the need for counter balancing (they did get to hot mounted on plastic, therefore aluminum cooling-fins were made).

The control software implementation worked flawlessly. But the limit-micro-switches had problems with false positive due to long wires and electromagnetic interference (this was solved by using step-down resistors instead of step-up, and by separating and shielding the signal wires from the power wires). The limit-mico-switches themselves were hand-modified, and sometimes kept there state instead of witching back, this sometimes resulted registering false positives.

The compliant-finger worked flawlessly, swiping the menu selector to the right and clicking the continue-print option. It only failed when the round indent in the rotary knob was angled to the compliant finger.

The full production sequence could be performed with only requiring operator-interaction with the carrier.



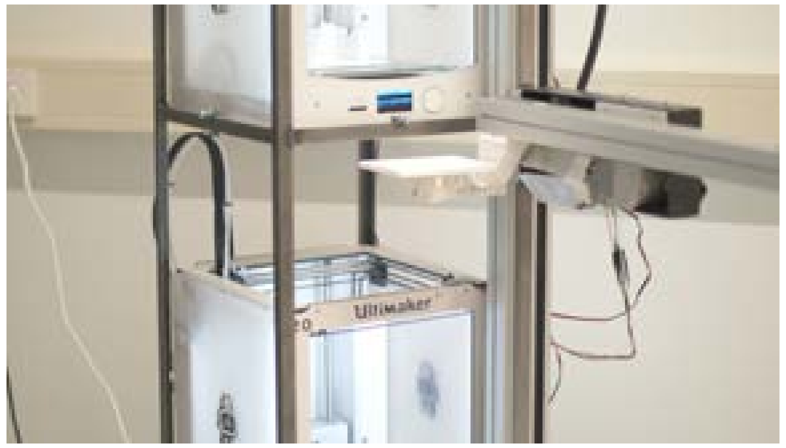
HOLDING SYSTEM:

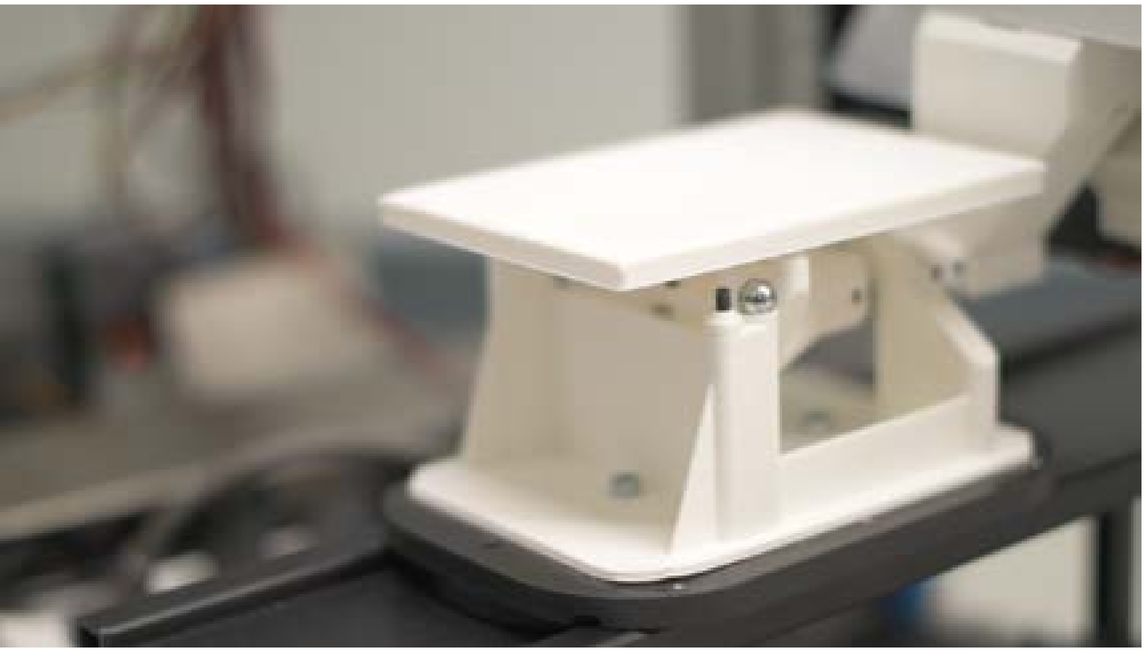
The pallet-based inner-outer single kinematic coupling hand-over system, worked perfectly, the gripper was able to set-down and lift-up the pallet every single time, in the right location on the precision ground metal balls. But it was important that the carrier was moved into the track to the location within one millimeter.

The pallet was made from the same material, and the bonding between printed frame-structure and the pallet was as strong as the print itself; even without a heated build plate.

The anti-canting system was sub-optimal, it sometimes got stuck on the screw-thread tipping the pallet from the gripper. The required extra precision to meet the hole with the screw-pin resulted in tipping over, when there were small calibration errors. The anti-canting pins worked for sudden changes in velocity, but due to the half-cosine ramp-up-ramp down this was not needed in normal operation.

During printing the nozzle applies pressure on the pallet to produce the first layer, this pressure resulted sometimes in small canting movement around two of the three metal balls. In most cases this was not a problem for the final result, but sometimes the print failed (the Cura 'raft' function reduced this problem almost completely).



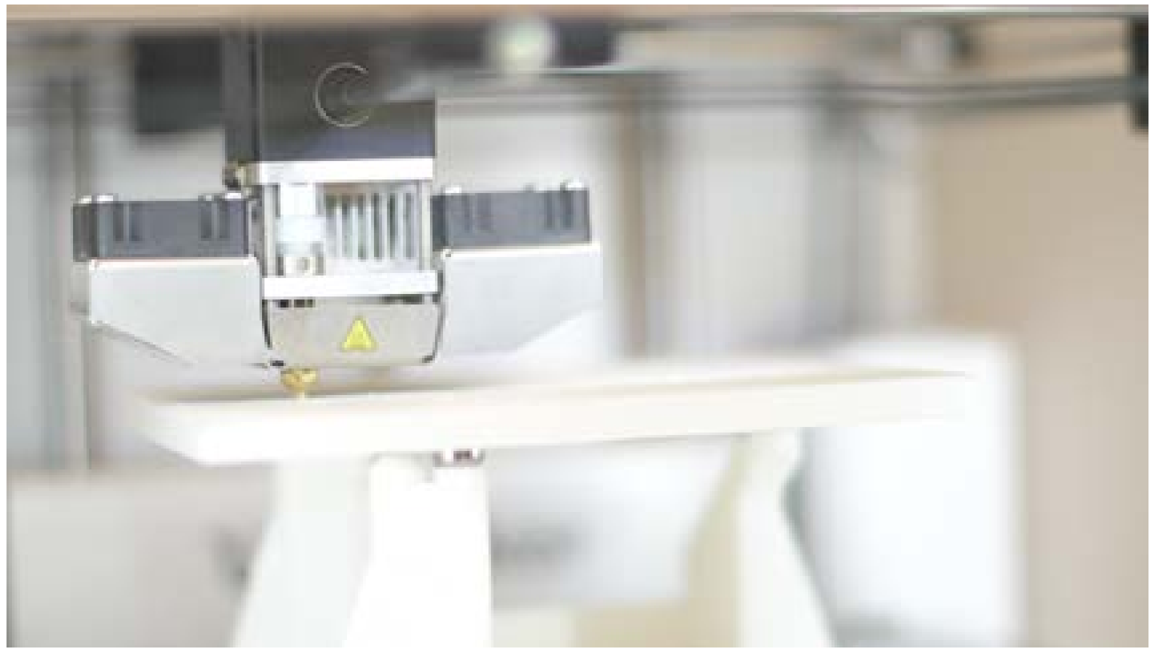


PRINTING SYSTEM:

The frame-structure consisting of a 'raft' and 'support' slicer function, worked for both the mouse and the top-shell, but still required a laborious print-separation step.

The material PETG was used in the pallet, frame-structure, and product. It should be a good material for this purpose because it shrinks less due to heat, the problem is that it is also less stiff (2.2 GPa) than for example PLA (3.5 GPa). The pallet warps therefore more easily into a slightly concave shape, because of to heat from the nozzle during printing. Because this is gradual, the print does not fail, and after switching between printers the top layer is still aligned with the xy-plane of the printer (of the three metal balls are calibrated in the same way). This does mean that the pallet cannot be reused after separation and cleaning (which was necessary due to the print-time of pallets, for testing and prototyping, and more stiff pallet was designed to reduce this effect).

The outside quality of the mouse was very clean and shiny. This was the case because this was closed and convex form, but when there were multiple shapes in one print, a lot of plastic hairs between each object were visible at each layer; this was also found between the print-infill of the product. There were a couple of other disadvantages as well, which are discussed in the 4.3. On-printing Aesthetics analysis chapter.



DEMONSTRATION TEST:

The final demonstration test was successfully completed resulting in the three planned parts with, mock internal-components, following the sequence discussed in the Method sub-chapter (a picture of the three pallets with their respective mouse-part can be found in the Appendix: 7.1.11. Cabinet Demonstration Test). To perform this test in a reasonable amount of time the print speed and layer thickness were doubled (resulting in lower than 'normal' print quality).

There were only small interventions by the test operator: the anti-canting pin tipped the pallet over at one time; requiring it to be put back (*). The bed-height need to be lowered slightly for the last print sequence (**). And the transport-track limit-micro-switch registered a false-positive resulting in an activation of a movement sequence, fast placement of the carrier by the operator was sufficient to solve this problem.

4.1.3. DISCUSSION

One of the big findings is that the printer can directly on-print on the plastic pallets with perfect adhesion without some sort of heating or coating. The heat of the nozzle does generate shrinkage in the top side of the pallet, making it warp. The warping was not symmetric and localized around the v-groves. This was reduced with the second pallet design, which had the full thickness of the pallet in material and extra bridges for stiffness. This design was not injection-moldable, but could be milled out of sheet-stock. A future design could also be made with thicker overall. Both pallet designs could be 3D printed on a normal FDM-printer, but the heated-bed made them warp. To solve this they were printed 2 mm above the print bed with the slicer's support function enabled.

When reusing the warped pallets, the printing chance of success dropped a lot (although the raft frame-structure helped). If the pallet production supply-line is not setup, it will be beneficial to temporarily use glass or stainless steel versions, for prototyping 3D-prints.

When the nozzle printed on the outside of the pallet it sometimes tipped a couple of degrees. And to get a good bonding between the print and the pallet, some pressure is needed. This can be solved by an actuated locking system, pulling the pallet onto the three metal balls. It can also be solved by optimizing the printed raft-like frame-structure, by increasing the filament flow for the first layer. The raft also helps with a course surface roughness and reduced flatness of the pallet.

During the test there was an operator intervention, lowering the print bed, because the nozzle collided with the last print layer after switching to a new printer. This shows that the calibration between the metal balls is extremely important.

The prototype demonstrates a general framework to carry a standardized pallet from a carrier into a process-module. But the system could be more general if the gripper and holder where the same thing, able to hand-over the pallet (this is explores during the project but required more than two actuated degrees of freedom).

The necessity of a passive anti-canting system must also be researched. And if needed a better version need to be designed. The acceleration limited movement was sufficient in this prototype.

If a new version was to be developed, interaction with the printer firmware must be enabled. And the carrier must be recognized as individual entities, initiating the specific g-code. Although the limit-switches and compliant finger automated the system well enough, this was just a prove-of-concept, and not reliable enough for more rigorous tests.

Another important aspect that must be implemented is the integration of the proposed industry standard into the outside dimensions of the prototype, requiring custom FDM-printer modules. This firstly makes the system 'numerous' and therefore fast in terms of production-output and it will enable the prototype to evolve, due to the set modularity size, system aspects are replicable over time.

CONCLUSION:

1. The system was (almost*) able to autonomously insert and remove parts and products from the printer to Festo's 'mock' transport system and perform the whole process without failure.
2. The system was able to print variations of the designed personalized computer mouse, and other products shapes of the same size-standard (top-shell).
3. The system was able to initiate the production steps of a unique computer mouse, and the next product in the queue, following production sequencing that minimizes printer downtime (including switching between printers).
4. Is the system was (almost**) able to apply the on-print principle without failure by creating component cavities and continuing to print on the last layer and placed components.

4.2. ON-PRINTING STRENGTH ANALYSIS

TESTING THE JOINING PROCESS

The secondary goal of the developed FDM-Cabinet prototypes is to validate the on-printing process and framework as a feasible method to produce multi-component parts. The products that are made must not fail in normal use (impact due to falling, pressure from human or surrounding).

FDM printing is, due to the partition lines between printing layers, less strong than injection molding. But due to increased design freedom it is assumed that FDM printed parts can be as strong as injection molded parts, by changing the shape and dimensions of shell and rib structures. Also FDM printed parts are already used in commercial products.

Within the proposed framework for on-printing the part goes out of a printer and into another printer after component-placement. No two printers are exactly the same, they have slight differences due to wear, resulting in varying backlash and hysteresis. Nozzles change due to abrasion on the inside, but also on the outside, making them shorter. And the calibration between the virtual and physical axes can be different in translation and rotation. These printer differences in combination with part placement, shrinking, and warping result in an accumulation of error and possibly a weaker bond of the on-print-layer.

To find out if this is the case, the material strength including this on-print line is validated on the Core Functional Requirement described in the 3.2.4. FDM Module Challenges chapter.

FDM-CABINET CORE FUNCTIONAL REQUIREMENTS:

6. The resulting on-printed product must be of comparable quality, in terms of strength, to the same directly printed shape (without pauses).

4.2.1. METHOD

The core functional requirements for the first FDM-Cabinet prototype are translated in the following research question and sub-questions:

RESEARCH QUESTIONS:

Is the resulting on-printed product of comparable quality, in terms of strength, to the same directly printed shape (without pauses)?

1. What is the influence of the on-printing process with perfectly calibrated printers on material strength?
   a. Will the print able to successfully finish the sample (gap, finished second halve)?
   b. Will the average ultimate tensile strength be significantly different from a normal print?
   c. What will be the relative strength in comparison with a normal print?
2. What is the influence of the on-printing process of printers without calibration on material strength?
   a. Will the print be able to finish successfully?
   b. Will the average ultimate tensile strength be significantly different from a normal print?
   c. What will be the relative strength in comparison with a normal print?

To test material strength, a dog-bone Tensile test is applied to a series of samples. The samples are printed on pallets placed in the printers (A and B). There are three types of samples.

1. First the control group samples, these samples are printed in one go.
2. The second group is printed with a break of 10 minutes in the middle of the sample (arbitrary time for transport and component placement). This group emulates the on-printing process on different printer with perfect calibration.
3. The third group is printed with a break of 10 minutes in the middle while they are swapped to the other printer for on-print continuation.

Every sample is at least printed five times, on each of the two printers (A and B). And for the third group with both swap situations (A → B and B → A). Resulting in six groups (A, B, AA, BB, AB, and BA).

The tensile test is based on the ASTM D638 test standard (ASTM International. 2016), specimen type I, at a strain rate of 5 ± 25% mm/min. This is a standard test for the tensile properties of plastics.

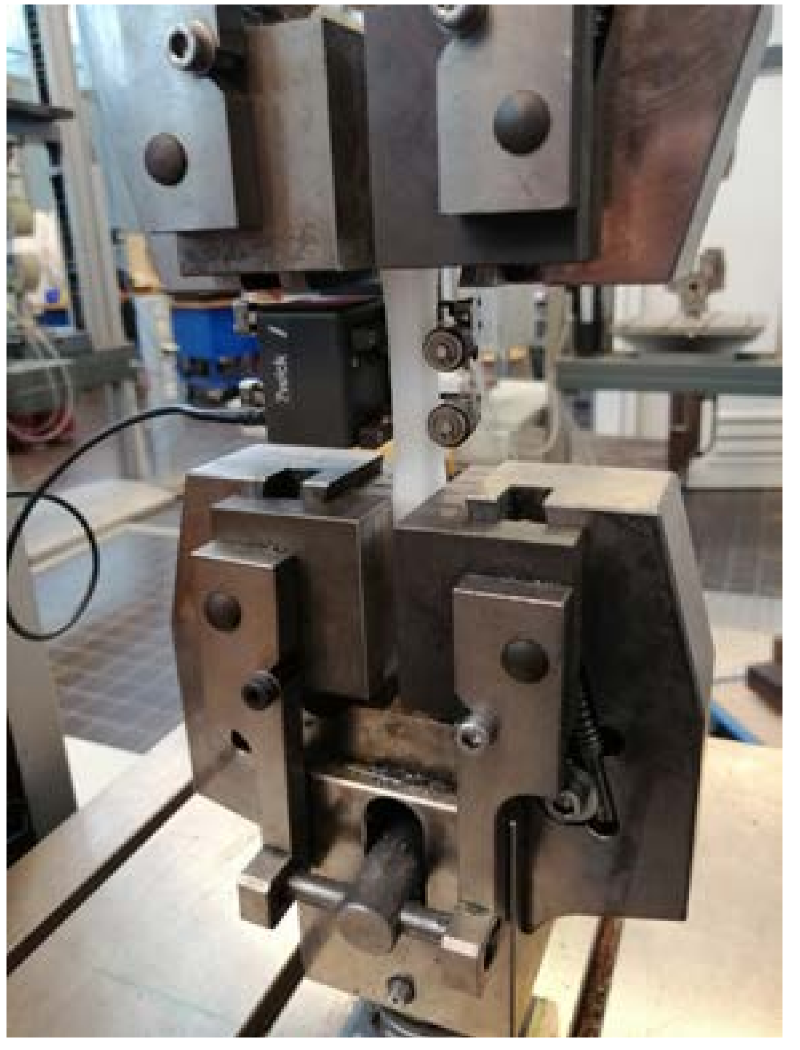
There are almost no officially documented tests for 3D printed materials (Ing. M.A. Leeflang, Laboratory Manager TU Delft 3mE BME dep., personal communication, 12-12-2019), because the FDM-printing is anisotropic, data cannot be compared with existing material test results, but because a control-group test is performed comparison can be drawn between groups.

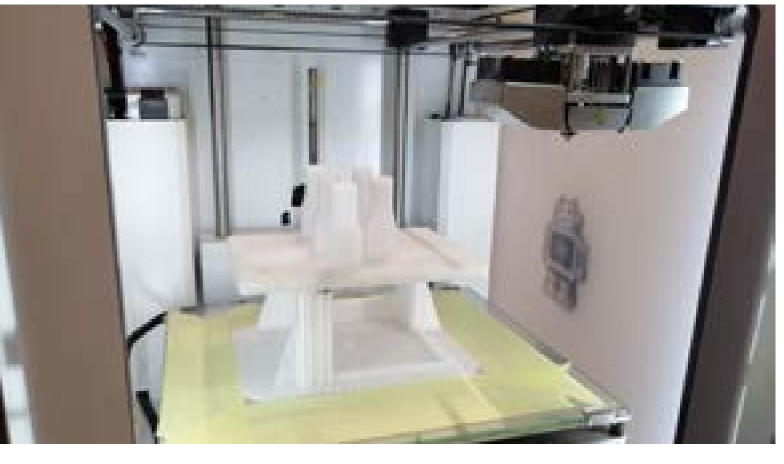
Another important change in the test is the design of the specimen. It is changed due to the instability of printing structures that are long, thin, and vertical. The goal of this change was to shorten the specimen without changing the overall shape; the radius and straight segment lengths are reduced to 50%. The cross-sectional area is maximized by increasing the thickness to 9 mm; fitting the jaws of test equipment. This is done to reduce the relative effect of small deviations or inclusions in the material (an overview of the dimensions can be found in the Appendix: 7.1.13. Tensile Strength Test). These samples are tested on axial load on the on-print line.

Other samples were redesigned and made following the ASTM D3164 test standard for 'strength properties of adhesively bonded plastic lap-shear sandwich joints in shear by tension loading'. The samples were redesigned for the print setup, but broke in an axial mode instead of shear thereby failing the experiment (the design of these samples can be found in the Appendix: 7.1.14. Shear Strength Test).

The dog-bone samples where printed at different times over the course of two weeks (the printer and slicer setting can be found in the Appendix: 7.1.12. Printer & Slicer Settings). Each group was printed only once each on one pallet, failure to print is taken as part of the research, and the failure mode is described in the results.

The sample dimensions are measured and also described in the results. The stress is calculated from the measured cross-sectional area. The number of samples used in the analysis will be that of the group with the lowest number of successful samples; except for 0. As a measure for 3D-printing strength, the breaking point of the samples is used (assuming brittle fracture); the ultimate tensile strength (UTS).





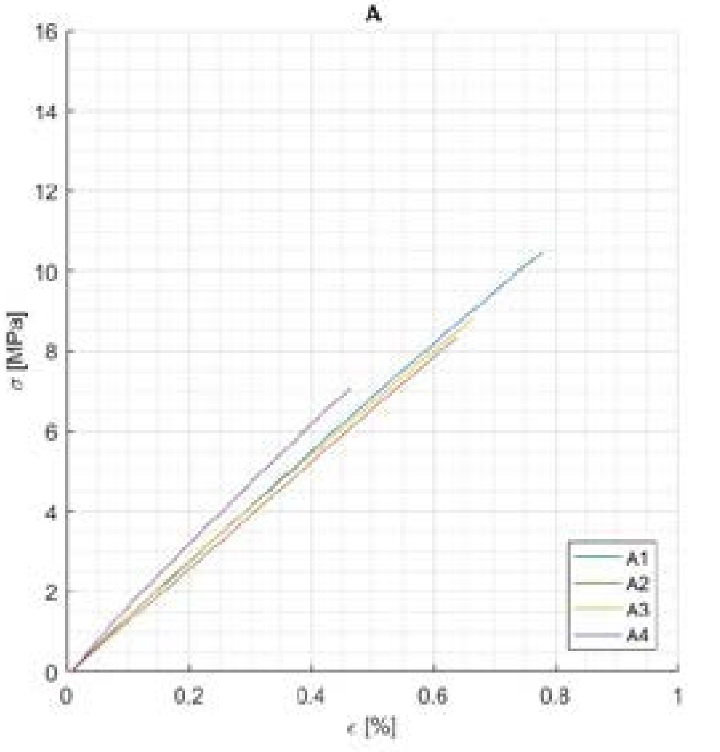
4.2.2. RESULTS

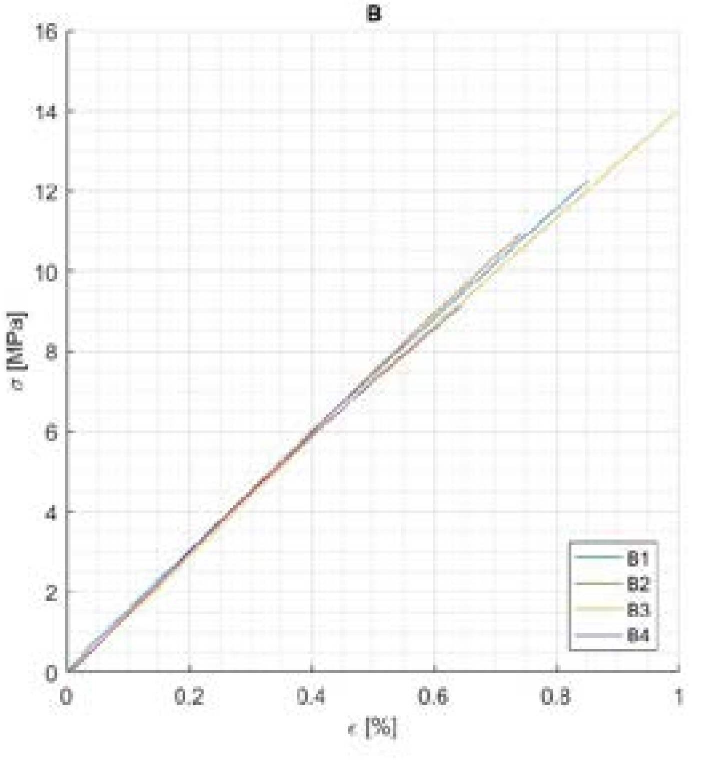
GROUP A:
Baseline: Printed in printer A.

SAMPLE MEASUREMENTS:
- Successful samples: 5
- Area length: 13.1 ± 0.1 mm (13)
- Area With: 9.1 ± 0.1 mm (9)
- Offset: 0 mm

ULTIMATE TENSILE STRENGTH:
- Mean: 8.6845 MPa
- STD: 1.4112 MPa

EXTRA INFORMATION:
- Sample A1 and A5 break line at the rounded corner.
- Sample A2 and A3 break line in the rounded corner.
- Sample A4 break line in the middle.





GROUP B:
Baseline: Printed in printer B.

SAMPLE MEASUREMENTS:
- Successful samples: 5
- Area length: 13.1 ± 0.1 mm (13)
- Area With: 9.1 ± 0.1 mm (9)
- Offset: 0 mm

ULTIMATE TENSILE STRENGTH:
- Mean: 11.5655 MPa
- STD: 2.0443 MPa

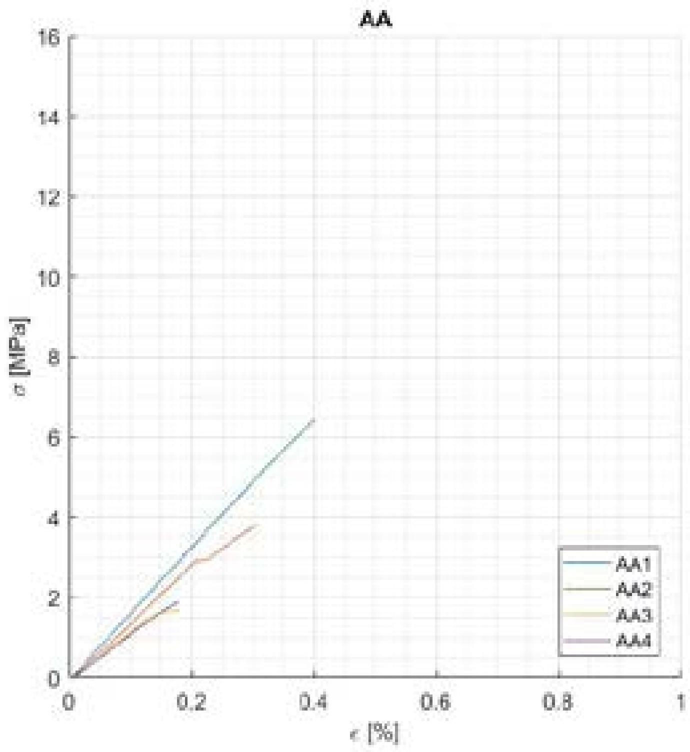
EXTRA INFORMATION:
- Break line for all samples at the rounded corner.

GROUP AA:
From printer A to A (10 min. pause).

SAMPLE MEASUREMENTS:
- Successful samples: 4
- Area length: 13.1 ± 0.1 mm (13)
- Area With: 9.15 ± 0.1 mm (9)
- Offset: 0 ± 0.1 mm

ULTIMATE TENSILE STRENGTH:
- Mean: 3.4563 MPa
- STD: 2.2157 MPa

EXTRA INFORMATION:
- Sample AA5 failed when releasing it from the pallet.
- Break line for all samples at the on-print line.
- Sample AA4 small clod inclusion at the on-print line.



GROUP BB:
From printer B to B (10 min. pause).

SAMPLE MEASUREMENTS:
- Successful samples: 0

EXTRA INFORMATION:
- Not successful during print session, due to blob of filament sticking to the nozzle.

GROUP AB:
From printer A to B (10 min. pause).

SAMPLE MEASUREMENTS:
- Successful samples: 0

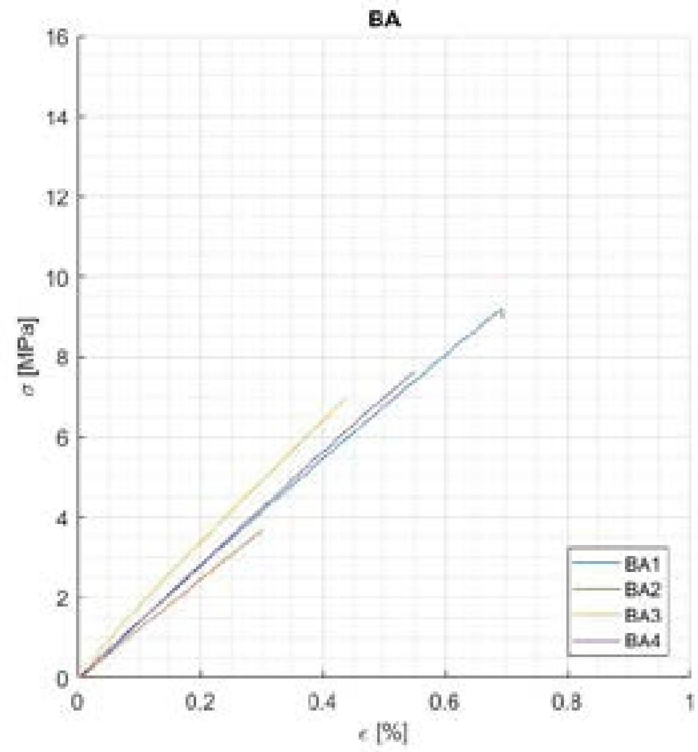
EXTRA INFORMATION:
- Not successful during print session, due to failed bonding; the nozzle printed to high.

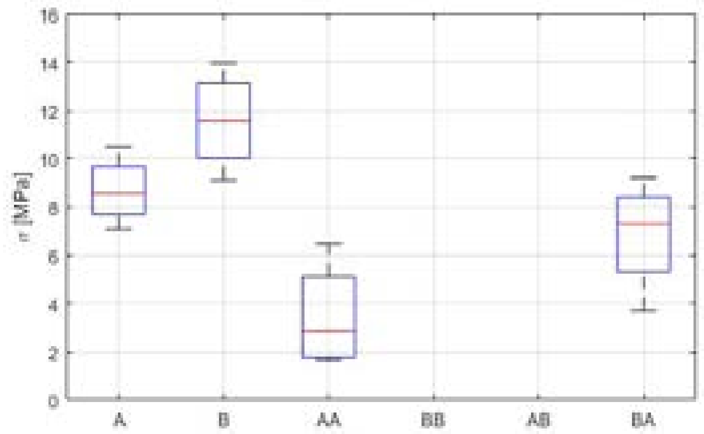
GROUP BA:
From printer B to A (10 min. pause).

SAMPLE MEASUREMENTS:
- Successful samples: 5
- Area length: 13.1 ± 0.1 mm (13)
- Area With: 9.1 ± 0.1 mm (9)
- Offset: 0.4 ± 0.1 mm

ULTIMATE TENSILE STRENGTH:
- Mean: 6.8829 MPa
- STD: 2.3246 MPa

EXTRA INFORMATION:
- Successful because of low nozzle
- Sample BA1, BA2, and BA3 broke just below the on-print line (5mm).
- Sample BA3 and BA5 had a filament thread inclusion around part of the contour, BA3 broke at this location.
- Sample BA4 broke at the rounded corner.
- Sample BA5 was the only sample that broke at the on-print line.





A – B: h = 0, p = 0.060, t = -2.3, df = 6

A – AA: h = 1, p = 0.007, t = 4.0, df = 6, μ = 40%

B – AA: h = 1, p = 0.002, t = 5.4, df = 6, μ = 30%

A – BA: h = 0, p = 0.233, t = 1.3, df = 6

B – BA: h = 1, p = 0.023, t = 3.0, df = 6, μ = 60%

AA – BA: h = 0, p = 0.077, t = -2.1, df = 6

DIFFERENCE BETWEEN MEANS:
To compare the difference of ultimate tensile stress (UTS) means between the sample groups a two sample t-test is performed.

The null hypothesis is that the data in the UTS vectors of two groups comes from independent random samples, from normal distributions with equal means and equal but unknown variances.

At alpha = 0.05 level of significance, assuming normality and equal variance, for a p < alpha, the null hypothesis can be rejected.

Below the results of the independent sample t-tests can be found, for the difference of means between the two control-groups, the difference between each of the two (remaining) groups and the two control-group samples, and the difference between the two groups under examination.

4.2.3. DISCUSSION

GROUP A & B:

All baseline samples (accept for A4) broke at the outside of the middle section, which is expected since there is nothing weakening the print in the middle (no offset), the difference in geometry can create a stress-concentration that can propagate and break the sample.

There is no significant difference between the two printers; this is probably due to the small sample size. There is strong statistical indication (p = 0.060), but also logical reasoning that the two printers are different. This might influence the results of the other sample groups.

GROUP BB:

Sample group BB failed due to a burned filament clod on the nozzle of the printer, the clod grew when it should have printed the on-print layer, failing the sample batch. This indicates the importance of a framework to deal with this oozing problem of the PETG material. Although the pause slicer command was already optimized to reduce the effects, it could be further improved by implementing the right filament retraction speeds. Other methods include rapidly cooling and heating the nozzle, using a wiping location on the pallet, within the printed object, or within the printer itself. A different nozzle design could also be developed using different shapes and materials (Teflon, long and thin form, anti-curling shape).

GROUP AB:

Sample group AB failed because the nozzle was too high when placing the on-print layer, the filament did not bond and was immediately dragged around the part, failing the sample batch. This indicated the importance of height calibration between the metal balls and the nozzle plane, to swap pallets between printers.

A solution could also be to fill the space by reprinting the last layer (with a Cura slicer setting), or by increasing the material flow for the on-print layer. A disadvantage might be that the layer is visible and aesthetically displeasing. Another solution might be to make a digital height map of the pallet and print, by means of a point-distance sensor mounted on the print-head. And to use this information to adapt the vertical movement accounting for deviations between the print-layer and the nozzle plane.

GROUP BA:

The BA sample group was successfully printed on two different printers. This was not the case for the AB group because the nozzle was too high. Due to opposite calibration error the nozzle was too low for the BA group. This did not prove to be devastating for the print, the on-print layer was just more pressed together. As a result all the samples, but one, broke at a different locations than the on-print line indicating increased strength. The nozzle pushed the filament line flat against the top-layer creating better adhesion, thereby also increasing the heat-transfer and as a result material bonding. An important finding is that a decreased nozzle height but also an increased material flow strengthens the bond between layers for PETG.

There is no significant difference between the mean ultimate tensile strength of this group and the baseline group A. There is a small statistical indication (p = 0.233) of a difference between means, but this would require a much bigger samples size.

There is a significant difference between the mean ultimate tensile strength of this group and the baseline group B. Group BA break at around 60% of the stress that can be applied to group B.

The above described impact could also come from the effect of printer A, since there is strong indication that this printer makes weaker prints, making it the weakest link under load. This is in line with the proximity of means between group A and BA (in future research the ends of the sample must be marked with their printer code to determine break location).

The slightly lower mean of group BA relative to A did not come from the reduced cross-sectional area from the translation between print halves creating an offset in both axes (0.4 ± 0.1 mm), because the samples did not break at the on-print line.

GROUP AA:

The AA sample group was successfully printed with a pause of 10 minutes. Sample AA5 broke really fast at the on-print line when releasing it from the pallet, indicating a weak spot. The rest of the sample al failed at the on-print line.

There is a significant difference between the mean ultimate tensile strength of this group and the baseline group A (also B). Group AA break at around 40% of the stress that can be applied to group A. This indicates that the pause of 10 minutes weakens the printed part by more than a half. This is probably due to cooling of the top-layer during the pause, reducing adhesion of the on-print layer. It is also possible that this comes from warping, creating increased nozzle height and therefor decreased adhesion. In the previous paragraphs methods to improve this are discussed. But in some measure the on-print line must be weaker to enable separation for recycle purposes.

FURTHER RESEARCH:

The sample batches were printed at different times during two week, this might influence the results and should be taken into account in future research. The test could also be repeated with more samples and better printer calibration to successfully print the six sample groups.

During printing the samples bended following the nozzle movement. This slight instability demonstrates the need for the shortened dog-bone sample type. The developed shear-sample on the other hand was not functional, and further research must be done to develop standard test methods for 3D-printed materials.

CONCLUSION:

To answer the research question: it is not clear if the resulting on-printed product is of comparable quality, in terms of strength, to the same directly printed shape. Although there is an indication that it is slightly weaker without optimizing the on-print layer printing settings. And it is shown, that on-printed parts can be made with some measure of strength

4.3. ON-PRINTING AESTHETICS ANALYSIS

TESTING THE JOINING PROCESS

The secondary goal of the developed FDM-Cabinet prototypes is to validate the on-printing process and framework as a feasible method to produce multi-component parts. The products that are made must be of comparable aesthetic quality as existing products.

But quality is subjective and depends on a lot of factors. Normal plastic consumer electronic products can be smooth, shiny or textured, it is almost always part of the design, showing designer's intent.

Some natural materials such as wood but also carbon-fiber go against this principle, especially if the 'grain' does not follow the design, but these materials have other qualities such as craftsmanship or authenticity (they are 'hard to work with' materials). But these qualities are part of FDM-printing. In its current state, the layer lines are visible to the eye and to the touch. These lines go straight through the design.

As decided in the 3.1.3. Product-family Embodiment chapter FDM quality surface finish is accepted for now and it is assumed to be solvable. But this normal printing quality might be worse due to the on-printing process, creating a line straight through the product, without any clear designer's intent. This could be in the same ballpark as the normal layer lines, it could also be so extreme that on-printing must be abandoned as possible product assembly method.

To be commercially viable the on-print line must not be felt by touch or visible by eye in the finished product. "On assembled products, visually perceived deviations from the nominal shapes, locations and orientations of parts can have negative impacts on the Visual Quality Appearance." (Forslund, K., et.al. 2006).

To find out if this is the case, the aesthetics of the on-print line need to be validated on the Core Functional Requirement described in the 3.2.4. FDM Module Challenges chapter.

FDM-CABINET CORE FUNCTIONAL REQUIREMENTS:

7. The resulting on-printed product must be of comparable quality, in terms of aesthetics, to the same directly printed shape (without pauses).

4.3.1. METHOD

The core functional requirements for the first FDM-Cabinet prototype are translated in the following research question and sub-questions:

Research Question: Is the resulting on-printed product of comparable quality, in terms of aesthetics, to the same directly printed shape (without pauses)?

1. What is the influence of the on-printing process with perfectly calibrated printers on product aesthetics?
   a. How much is the on-print line visible to the touch?
   b. How much is the on-print line visible to the eye?
2. What is the influence of the on-printing process of printers without calibration on product aesthetics?
   a. How much is the on-print line visible to the touch?
   b. How much is the on-print line visible to the eye?

To test the aesthetics of the on-print line, three printed samples are made. Just as in the on-print strength tests, a control-group sample is made that is printed without a pause (printer C), one with a pause of 10 minutes (mock perfect calibration, printer C) and one with both a printer swap and a pause of 10 minutes (from printer B to A, successful in strength-analysis). The sample represents a consumer product. This is chosen to visibly relate the severity of the on-print line in a real scenario. The chosen product for this experiments is designed computer mouse. The same print file is used for every sample, and the button-top-shell is also made and assembled to complete the consumer products.

Each of the samples is described on their aesthetic quality in terms of surface finish (only what is different from normal FDM printing).

4.3.2. RESULTS

SAMPLE C:

Baseline: Printed in printer C

At the back of the mouse a black sport of burned PETG clod is noticeable just below the surface.

The upper and lower half should be the same, but there is an offset just noticeable by touch on the right side, where the on-print line would be. It also has a slightly darker in tone at this location.

SAMPLE CC:

From printer C to C (10 min. pause).

There is a slightly dark inclusion at the on-print layer where the nozzle entered the print after the pause.

The on-print line is unnoticeable to the touch and to the eye on the left side of the print.

On the other right side a small overhanging ridge is recognizable. It is slightly darker at this location as well. Both aspects are slightly more noticeable than in the baseline print.

Measured offset from strength-analysis samples AA offset: 0 ± 0.1 mm (measurable because of rectangular shape).

SAMPLE BA:

From printer B to A (10 min. pause).

The on-print line is noticeable by eye and to the touch. Some part of the ridge are overhangs some parts are plateaus. The mouse is printed in the center of the pallet and the ridges indicate a slight rotation between the two halves, a just noticeable scaling (bigger second halve), and no translation.

Offset from strength-analysis samples BA offset: 0.4 ± 0.1 mm (measurable because of rectangular shape).

4.3.3. DISCUSSION

SAMPLE C:

Within the baseline sample a clod, characteristic for PETG printing with the used test setup and settings, is found. The nozzle picks up residue over time and this plastic residue burns into a brown or black color. When the clod of residue becomes too big, it pushes on the print layer and binds to the part; then the process starts all over. These clods can also be found on the inside of the part where they are not visible. PETG is also a really stringy material, creating plastic hairs between printed objects; this can also be found on the inside of printed parts. Since the computer mouse is one big convex shape, this stringy-ness is not a problem, resulting in a very clean, smooth, and shiny part, demonstrating the possibilities of PETG. But not all products are convex, the stringy-ness in addition to the residue-problem, must therefore be solved to successfully implement PETG as commercial product FDM-print material.

Another finding of the baseline sample was that the component cavity has influence on the surface quality, even without an on-print pause. This must be taken into account in both the design of the part as well as the slicing program.

SAMPLE CC:

The CC sample has the same plastic clod that had a negative effect on the strength-samples. It also has a negative influence on the product aesthetics. In the discussion of the strength-analysis methods are described to solve this problem. An additional solution that can only be used in parts with semi-hollow infill is inside priming, extruding some filament to purge the clod within the part and wiping it off on the top layer, from the inside-out. A lot of the problems of printing with PETG can be solved with slicing software, this will require more research and development, but the metaphorical roof of this material is really high.

SAMPLE BA:

In the strength analysis it was found that the BA on-print samples had an offset due to a translation due to calibration difference of the printer. In this sample it is found that the offset is actually a rotation. This also relates to the strength-samples, since they are scattered around the center of the pallet during printing, the rotation will be unnoticeable. The mismatched calibration can come from printing errors in producing the pallet holders, or by a shift of the original glass-print bed. This can be minimized by better fastening holder and making it more stiff. This can be done by using for example, a metal material. A big benefit of the original printed system is that it does not required within-the-printer calibration, a solution can be to only print the parts just below the metal-balls, or even the balls itself; reducing calibration labor.

Another solution might be the previously discussed sensor based digital height-map

FURTHER RESEARCH:

In this mini research project the samples C and CC were printed in a separate Ulimaker 2+ printer on the glass bed. In future research it would be better to print them in the A and B printers on a pallet. Only the BA sample was printed in this setup because it was successful in the strength-analysis. By further optimizing the setup, all six sample types could be printed. Another important direction within this topic is to perform a survey research, to not only get discrete researcher observation and Boolean results, but comparable statistical results; to analysis the relative difference between sample groups.

CONCLUSION:

To answer the research question: the resulting on-printed product is not of comparable quality, in terms of aesthetics, to the same directly printed shape. That is, without optimizing the calibration between printers. For the perfect calibration sample (AA), there is almost no noticeable difference.

Other solutions to create better surface finish are discussed in the 3.1.3. Product-family Embodiment chapter. One additional take away from this analysis, is to give the product aesthetics intent, by giving texture or split-lines following the shape of the part.

4.4. MOUSE DEMONSTRATION

SHOWING THE FRAMEWORK

The primary goal of the exemplary-product is to propose a probable business-case that needs and demonstrates the Transcended Manufacturing. To find out if this is the case, the developed computer mouse product-family, need to be validated on the Core Functional Requirement described in the 2.5.2. Product-family Requirements chapter.

EXEMPLARY-PRODUCT CORE FUNCTIONAL REQUIREMENTS:

1. The exemplary-product must provide a realistic business-case.
2. The exemplary-product must exemplify mass-customization.
3. The exemplary-product must enable research and demonstration.

4.4.1. METHOD

The core functional requirements for the first FDM-Cabinet prototype are translated in the following research question and sub-questions:

RESEARCH QUESTIONS:

1. Does the exemplary-product exemplify mass-customization, by demonstrating three variations of a personalizable aspect within each of the customization categories?
   a. Can the three ergonomic variations be created from the parametric model?
   b. Can the three side-button variations be created from the parametric model?
   c. Can the three aesthetic button-top-shell variations be created from the parametric model?
2. Does the exemplary-product demonstrate a realistic business-case, by showing a possible- and physically working product-family?
   a. Can all the required computer mouse sub-assemblies fit within the smallest realization of the product-family-model?
   b. Will the scroll wheel and main buttons physically work in terms of look and feel?
   c. Will the side-buttons physically work in terms of look and feel?
3. Does the exemplary-product enable research and demonstration?
   a. Does the exemplary-product show enhanced functions of FDM-printing?
   b. Which possible research and development directions are created, towards Transcended Manufacturing?
   c. What Transcended Manufacturing aspects does the exemplary-product demonstrate?

To validate the above described research topics, a parametric module of the computer-mouse needed to be developed and perfected. To do this a lot of prototypes where printed, iteratively optimizing the design. The resulting final computer-mouse is demonstrated in the next part of this chapter.

4.4.2. RESULTS

ERGONOMIC FORMS:

Within the parametric Solidworks model three arbitrary variations of the mouse form were generated. The parameters that where adapted where the base length, the base width, the top-shell height, the-top shell width, and the top-shell axial rotation. A picture of the parametric model can be found in the Appendx: 7.1.16. Parametric Model.

BODY-FROM 1:

Goal: As small as possible, fitting all sub-components
Base length: 100 mm
Base width: 70 mm
Top height: 40 mm
Top width: 65 mm
Top rotation: 10°

BODY-FROM 2:

Goal: A mouse for bigger hand-size
Base length: 120 mm
Base width: 85 mm
Top height: 50 mm
Top width: 65 mm
Top rotation: 10°

BODY-FROM 3:

Goal: An ‘ergonomically’ angled mouse
Base length: 110 mm
Base width: 70 mm
Top height: 50 mm
Top width: 70 mm
Top rotation: 25°

DESCRIPTION:

All the ergonomic mousses felt and looked distinctly different. When asking other people they all preferred different ergonomic forms.

SIDE-BUTTONS:

Within the parametric Solidworks model three selectable discrete variations of the mouse side-buttons were created. Al the design iterations of the side-buttons can be found in the Appendix: 7.1.17. Button Iterations. By implementing a compliant button structure and bringing functionality to the exemplary-product, it demonstrates the enhanced functions FDM-printing can bring.

BUTTON-TYPE 0 GOAL:

- Filling the button location with the original design.

BUTTON-TYPE 1 GOALS:

- A 3-by-4 matrix of compliant buttons.
- Able to translate the motion to the PCB-buttons.
- Following the form of the mouse.
- Being producible by an FDM-printer.
- Providing a cavity for the button-PCB.

BUTTON-TYPE 2 GOALS:

Goals:

- A 1-by-2 matrix of compliant buttons.
- Able to translate the motion to the PCB-buttons.
- Following the form of the mouse.
- Being producible by an FDM-printer.
- Providing a cavity for the button-PCB.

DESCRIPTION:

In the last design iteration every button is clickable accept for the lower right button of the 3-by-4 matrix. The clicking sensation can be felt clearly through the plastic. The slits to create flexibility of the material, almost do not show the inner PCB, due to their small size and the internal pillars created for this reason. And the shape of the buttons follow the shape of the rest of the mouse.

The quality of the button material differs per printer, in some instances they have tiny holes (see aesthetics picture).

AESTHETIC SHAPES:

Within the parametric Solidworks model three selectable discrete arbitrary variations of the mouse shape were generated. They each consist of two profile sketches capturing the aesthetic goals; one for the front halve and one for the back. Renders of the three individual top-shell parts can be found in the Appendix: 7.1.18. Button Top Shell Designs.

TOP-SHELL 1:

Goal: An 'angular', 'concave', 'symmetric' shape, covering the front halve the mouse.

TOP-SHELL 2:

Goal: A 'rounded', 'concave', 'asymmetric' shape, diagonally covering the front halve the mouse.

TOP-SHELL 3:

Goal: A 'rounded', 'convex', 'symmetric' shape, fully covering the mouse.

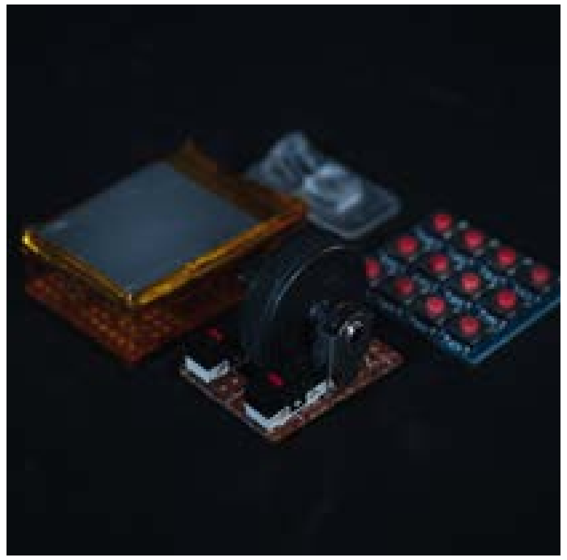
DESCRIPTION:

The main and scroll wheel button clicking sensation can be felt clearly through the plastic. And the scroll-wheel can turn freely without rubbing or sticking; due to guiding pillars created for this reason. The components are hidden from view by the top-shell.

SUB-ASSEMBLIES:

Al the components of an existing computer mouse (micro-switches, button, rotary encoder, Bluetooth module, resistor, capacitor, LED) were de-soldered and placed, with the addition of a lithium-ion cell, onto two perfboard PCB's to form the required sub-assemblies. A picture of the original computer mouse is found in the Appendix: 7.1.5. Existing Computer mouse.

The sub-assembly dimensions where measured and the parametric model was optimized to fit all the needed components within the on-print cavities.



DEMONSTRATION:

For trade fair exhibition and making research visible.

What Transcended Manufacturing aspects does the exemplary-product demonstrate?

The first demonstration aspects are integrated in the first two core functional requirements for the exemplary-product and are therefore core aspects of the computer mouse.

- The exemplary-product demonstrates a realistic business-case.
- The exemplary-product exemplifies mass-customization.

Other demonstration aspects of the computer mouse are:

- It physically demonstrates Digital Twin differences.
- It demonstrates a full life-cycle tracking framework.
- It demonstrates a zero-waste circular life-cycle product-business-case.
- It demonstrates the need for 'numerous' production (being a mass-production product). And therefore the need for scalability and accepted industry standards.
- It demonstrates product independent production (Transcended Manufacturing).
- It demonstrates the need for direct-digital (additive) manufacturing.
- It demonstrates the pick-and-place on-printing principle.
- It demonstrates enhanced 3D-printing functions.

RESEARCH & DEVELOPMENT:

For further development towards Transcended Manufacturing:

Which possible research and development directions are created from the exemplary product?

During the design of the exemplary computer mouse, out-of-scope research and developments topics are found. These are:

COMPUTER MOUSE:

- Research into products subscription platform (more incentive to return end-of-life product).
- In-depth research of RSI by use of the computer mouse and the effect of personal anatomical differences.
- The translation of physiological information into an ergonomic product realization from a computer mouse parametric-model.
- Development of a co-design service to customize the product-family model to fit customer wishes, matching the expertise and creativity level.
- Development of a fully functional exemplary computer mouse.
- Development of a computer mouse personalization program integrating an adaptable parametric-model (Grasshopper).
- Development of a better mouse with more and better personalization options.
- Development of a separate Transcended manufacturing cluster for computer-mouse sub-assemblies.
- Development of more highly personalizable exemplary products that can be produced parallel to the mouse.

GENERAL CLUSTER:

- Development of: product handling, CNC milling, packaging, final inspection, waste recycling within the production cluster.
- Development of a digital standard-component framework (hit-box, mechanical and electrical connectivity, pick-and-place guidelines).
- Development of a camera/sensor framework to be implemented in every process-module.
- Development of the standardized RFID-button life-cycle tracker.
- Development of a separate Transcended Manufacturing cluster for product output and packaging.
- Integration of the A6-H0-P3 build-volume size standard for the whole computer-mouse cluster both the transports system, the build-volumes as well as the module outside dimensions.
- Research into factory human labor integration.
- Research into a sensing smart carrier transport system.
- Development of a kinematic coupling calibration system.
- Development of a general design, making the holder and carrier the same.
- Research into pallet anti-canting framework.

FDM-PRINTING:

- Research into increasing FDM quality surface finish to commercial standards.
- Research into FDM on-print break-line for recycling of components and materials.
- Research into FDM-print conductive trace technology to connect the electronic components.
- Research into the printed frame-structure product release framework.
- Research into cold FDM printing; without chamber heating.
- Researching circular commercial quality PETG (or other material) printing framework (nozzle design and slicing).
- Research into standard test methods for 3D-printed materials.
- More elaborate research into on-printing strength.
- More elaborate research into on-printing aesthetics.
- Development of the remaining FDM-Cabinet embodiment challenges.
- Development of FDM-printer firmware interaction framework.

4.4.3. DISCUSSION

The ergonomic mouse forms clearly demonstrate the capabilities of a physiological parametric-model. But further in-depth research into personal physiological differences and ailments such as RSI, related to computer mouse form, will be required. Also further development into measuring these differences and translating this information into the parametric-model.

buttons were printed with PLA, instead of PETG. PETG should be a better material since it is less brittle, but the current material stringy-ness might cause problems in these small compliant structures. A solution can be to mill the small flexibility-slits after the mouse is finished, resulting in a more structurally-sound and therefore cleaner print.

The buttons should be further optimized to make the last matrix button work. Other aesthetic designs and matrix layouts could be designed as well. The current button-PCB are placed horizontally in the print, further research will be required to have an internally rotated PCB.

The aesthetic shapes show a clear range of aesthetic possibilities. New shapes can be designed and added in the parametric-model, or parameter dependent shapes could be developed.

The current button and scroll-wheel framework demonstrated a physically working mouse and can be used in a future iteration.

The same is true for the pick-and-place on-print production sequence of the computer mouse.

One aspect that is not validated is on-printing on the battery without destroying it with nozzle heat. This can still be researched or one of the following solutions can be applied; using a vaulted ceiling in the battery cavity, using the bridging method to print just above the battery, or to have a heat resistant layer on the battery sub-assembly.

The button life-cycle-tracker is not developed. The cavity within the mouse fits the RFID-tracker used in Festo's transport carrier, but the actual button must still be developed.

It is clear that the computer mouse demonstrates important Transcended Manufacturing aspects. In future iterations of the computer mouse all the demonstration aspects need to be kept in mind, and if possible extended.

It is also clear that the computer mouse enables a lot of possible research directions that can be explored, to further develop the Transcended Manufacturing method.

CONCLUSION:

1. The exemplary-product exemplifies mass-customization by demonstrating three variations of a personalizable aspect within each of the customization categories.
2. The exemplary-product demonstrates a realistic business-case by showing a possible- and physically working product-family.
3. The exemplary-product enables research and demonstration.

5. EVALUATION

In the Validation phase the developed framework is analyzed on different axes, and the resulting findings discussed and validated. In this final chapters the achievements of the project: the developed future context, the exemplary-product and the production-framework are evaluated in terms of the original problem definition. Recommendations for the next step in research and development are described in terms of the original design brief. And finally a personal reflection is given.

5.1. CONCLUSION

THE FIRST AND FOLOWING STEP

Within the Validation phase the developed exemplary-product and production system are concluded and the specific findings discussed. In this chapter a reflection is given on the original problem definition and the next step that should be taken.

The underlying societal problems that require a paradigm-shift within manufacturing were the core driving factors within this project. This paradigm-shift is still under-explored in terms of research and development, this project tried to solve this by taking a first step. Thereby trying to solve the stated threefold problem.

UNSATISFIED CONSUMERS

The world's population has more time and money to fulfill their personal needs and express themselves; with high expectations on consumer products that cannot be met with traditional mass-production methods.

A product-family business-case is generated and translated in a customizable parametric-model. This model integrated three personalizable aspects resulting in a 27 theoretically possible product realizations. These aspects fell in completely different categories, namely ergonomics, button-features, and aesthetics. With this product-family the consumer can fulfill its personal needs and express themselves.

PRESSURED SUPPLY-CHAINS

Short product-life-spans and volatile markets make it hard for companies to adapt their existing efficient supply-chains and keep delivering novel products.

A mass-customization future context is envisioned. One mass-customization factory realization subset, uses product-independent process steps to make individual and unique products. This subset is proposed as separate manufacturing method called Transcended Manufacturing. And within this method a specific production framework is proposed and developed. By making the factory independent of new product introductions companies can move in parallel to changing volatile markets instead of behind.

GLOBAL IMPLICATIONS

Production and development seem to go faster than our ability to change our mindset and reflect on the implications resulting in an unsustainable global ecosystem.

A full product-life-cycle future context is envisioned. This life-cycle goes from product inception up to recycling back to the inception of the next product. Within this life-cycle all information and material streams are continuous, trying to minimize dissipation of time, knowledge and material value. Within this life-cycle an exemplary-product is proposed and developed. By applying a minimal-loss full life-cycle mindset, a sustainable global ecosystem can be achieved.

5.1.1. THE NEXT STEP

Although a first step is taken into solving the big societal problems described in the conclusion. We are not there yet, society is still in need of a global paradigm-shift and a lot of research and development remains to be done.
But within this project, the first step taken and a solution is proposed in the form of Transcended Manufacturing. A framework and an exemplary-setup is given to demonstrate this manufacturing method, but also to build onto. From the development within this project a lot of research directions are found and described in the 4.4. Mouse Demonstration chapter. This is a long list and some research directions have more priority than others. Below the most important recommendations are discussed in regard to the next step that should be taken.

The next step should be a working research and demonstration cluster that can be extended in terms of production capabilities, performance and new product-families. Providing a Transcended Manufacturing production system for further research in all related topics and demonstration of the manufacturing method and its benefits. This will be beneficial for cyber-physical systems and mass-customization research organizations such as Festo and the Agile Manufacturing Center (Industrial Design Engineering, TU Delft).

This goal is almost completely the same as stated in the original design-brief (the production part). The only difference is that original goal was a framework and now a working system. The described research organizations could help develop the working production-cluster and support it with already developed technologies that can be integrated in the system.

For this working production system it is important to apply the defined core Transcended Manufacturing findings of the Envision phase. These are described below:

SELF-CONTAINED & GENERAL

The Transcended production system aspects are self-contained and capable. It uses process-generality to make unique products within a standardized framework.

SCALABLE & REPLACEABLE

The Transcended production processes are either fast or small. All aspects are scalable, accessible, and replaceable.

The design goal for the exemplary-product as defined in the design brief is reached. A mass-customization exemplary-product business case and a product-family that is synonymous with Transcended Manufacturing were developed. They product-family-model had a range of integrated customizable aspects. These aspects were combined to create a multitude of printable product realizations that can already be used to demonstrate the production system.

But the exemplary-product could eventually be improved as well. Because these developments are also important for companies that want to manufacture mass-customized products, especially computer mousses. And also for users with high investment or expertise level such people with RSI, professional gamer, or CAD designers.

For the next iterations it is then important to apply the defined core Transcended Manufacturing findings of the Envision phase. These are described below:

UNIVERSAL AND CUSTOMIZABLE

The product-family-model captures the essence of the product through its universals. It is customizable on different experience axes, resulting in unique personal product realizations.

CLOSED-LOOP AND CYBER-PHYSICAL

Transcended products are traceable through beginning-, middle-, and end-of-life. They generate and retain as much value as possible.

For the next step some research directions have more priority than others and the aspects with most importance must be answered first. The next iteration of the system will again, not be commercially viable. The goals are still demonstration and enabling further research.

The computer mouse does not need to work yet. But this would be beneficial, especially if the ergonomics are also correct; this would boost attention to the project.

The first goal must be, to produce the mouse from start to finish, including the transport and pick-and-place operations, without normal production labor. The cluster must be build to the dimensions of the proposed Industry standard and the principles of the Transcended Manufacturing vision.

Three really important research directions that were not explored in this project and that must eventually be tackled are the following:

- An analysis of Transcended factory production cost and production flows.
- An analysis of the role of human labor within the Transcended Factory.
- The development of a design methodology for Transcend products.

5.2. PROJECT REFLECTION

A LAST PERSONAL WORD

WHAT WERE MY HARDSHIPS?

To first get the hardships out of the way.

When looking back at the project, starting officially on 4 December 2018 and ending on 13 February 2020, a lot has happened and at the same time not much at all.

Not much at all, because every working day of the week, over the course of fourteen months I sat at the long white table of the faculty of Industrial design engineering. A feeling, of a never ending project, was increased by the fact: that I never knew what was enough, both on a small scale for each day, as well as on a larger scale for the research steps. This led, together with my ability-and-curse of fully focusing on the topic at hand, to some (too) in-depth research and development steps. Thereby increasing the product duration far more than I originally wanted. This also resulted in an enormous amount of research content, much more than I was used to, this led to underestimating certain tasks especially in documentation (the acknowledgements for example took me one and a half hour).

Another big hardship and a constant theme of reluctance and doubt was this documentation. I have dyslexia and writing costs me allot of energy and time. This results in reluctance and I therefore postpone by doing more research and design work; in the process creating more documentation work.

To go into some smaller disappointments for the project: literature research is something I did during my studies, but nothing came close to the scope of this project. I learned allot from this in terms of approach, but a little too late for the project itself. Another small disappointment is simply not doing enough with Matlab. I always liked losing myself in the Mechanical Engineering Matlab assignments. This was the main reason I did the BioRobotics specialization for this master. Luckily there was some Arduino programming within the project.

Al these factors in combination with a multitude of ailments including RSI (ironic), and the passing away of a family member made this project not the best time of my life.

WHAT HAVE I LEARNED?

Even before the project began, I made a list of goas. A directly translated list is found below (picture in the Appendix: 7.1.22 Personal Goals):

- Don't be too perfectionistic.
- Learn to ask for help.
- Learn to write down your thoughts (in this notebook).
- Be faster in contacting people (calling, mailing).
- Learn to not exaggerate ToDo's (in my head).
- Learn to like documentation a little bit more.
- Learn to plan better (per hour).
- Apply (new) IDE methodologies.
- Apply 3mE engineering methodologies.

It was great to suddenly find this list after all these months and also, to come to the conclusion that each of the items is tackled. Some less than others and they will remain a challenge for the future.

Some other skills I did not write down in my notebook, were to learn surface modeling in Solidworks, as one of the last tools within the program I was not familiar with. This I have done through the parametric-model of the computer mouse.

And learning to draw in notebook instead of A4, this in combination with immediately drawing the final sketch; instead of making pre-sketches.

WHAT WAS I HAPPY WITH?

Although it was tough year, I am really happy with the result. I did not think I would ever be happy with the final report, but here we are, I am happy with it. This comes also from the fact that this extremely big, complex, and interconnected project finally fell into place; logically, in my head, as well as in the report (I think).

I am also really proud of the final porotype, how pragmatic I was in making it work, and how my research around it came together. I was starting to worry that there wasn't enough time to go all-out with this part of the project, the part I should like the most, but this was not the case.

WHAT ARE MY HOPES?

I rediscovered that my passion not only lies in product design and engineering, but actually also in the products that make these products. Also, the discipline of mechanical engineering goes more and more into the digital domain, but manufacturing remains physical and that is something that speaks to me.

During this project I became also more and more interested in the research context and the underlying problems. I am not necessarily that 'sustainable' (I over-rationalize certain approaches), but something does need to change. And a global paradigm-shift in manufacturing can have the necessary impact we need.

It is therefore my hope to find further opportunities within this field of work. And also that the ideas behind my developed future context gain some traction within society.

5.2.1. ACKNOWLEDGE-MENTS

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7. APPENDIX

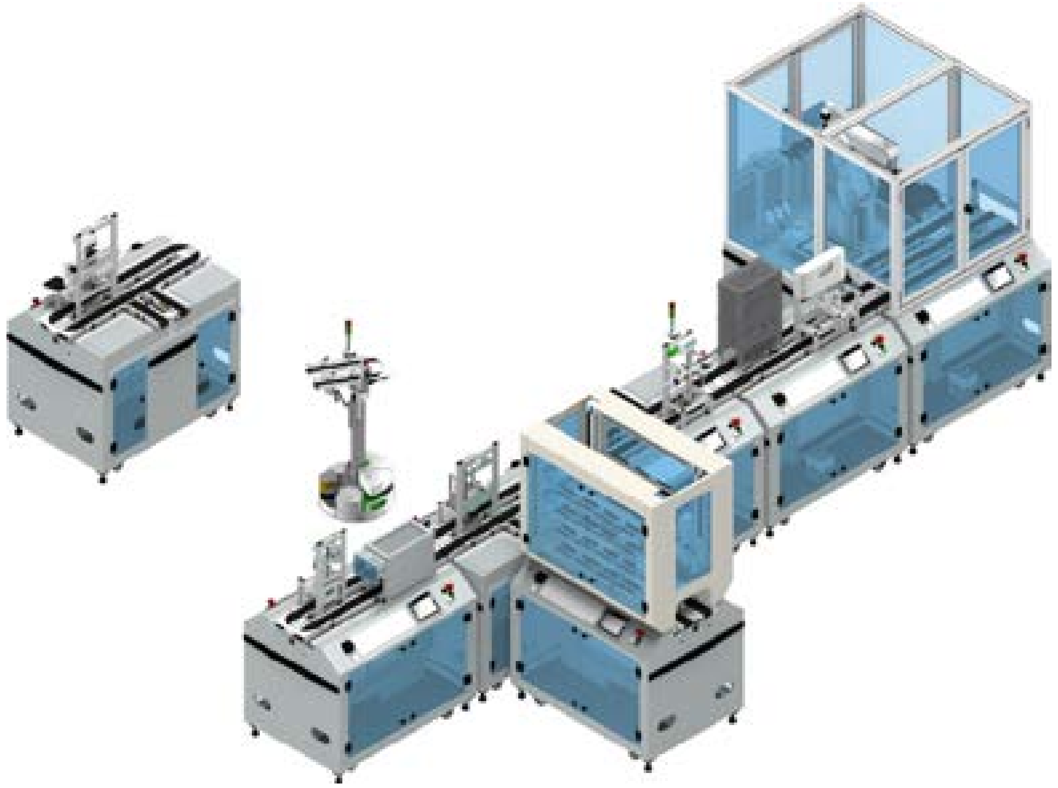
7.1.1. FESTO LEARNING SYSTEMS

Festo Didactic currently has three Industry 4.0 training systems see with rising complexity targeted at different education levels ("Learning Systems for Industry 4.0", n.d.).

MPS training system: Small Modular Production System for trainings purposes, configurable mini factory.

CP Lab: Cyber Physical system for training purposes, with a one way conveyor belt. Application-modules are place above the belt.

CP Factory: Uses the same application modules as the CP Lab but are placed on different basic transport modules that have two conveyor belts moving in opposing directions.



7.1.2. PRODUCTION TRACKING

Multiple warehouse inventory tracking methods are explored in the process of finding Transcended Factory part and products related core principles and described below. Their advantages and disadvantages are discussed in relation to the Transcended Manufacturing cluster transport system:

RFID

Passive radio frequency identification uses magnetic fields to charge a tag which sends a string of code back in a radio frequency bandwidth that can be read by the identification device; thereby recognizing the tag.

Precautions must be taken to protect RFID receivers from magnetic induction charging methods. Active tags have their own power supply enabling them to send data over longer distances at the cost of being much bigger in size.

Interference can be a problem when reading neighboring RFID tags and could in some cases not be used close together. Anti-collision techniques such as smaller range, and time-slot transmission can be applied to use multiple tags in close proximity. Active RFID is due to the long transmission ranges in most cases not beneficial in a manufacturing environment.

RFID can be used to let nfc-protocol-enabled-devices establish a secure connection between the simple tracker and the internet. This can be used to track identity, ownership, and make transactions.

RFID sensors come in different forms and sizes such as stickers, buttons, cards, etc. Reading is really fast, the trackers are reasonably cheap, reasonably small, and can store enough data for product tracking.

VISUAL CODE SCANNING

Visual scanning of two dimensional patterns such as 1D barcodes, 2D barcodes and QR codes works by scanning or mapping the brightness levels on a two dimensional surface and translating this information into a string of code. These pictures can be placed on pieces of label that can be placed or glued on a surface; there exist labels that are easily removable or soluble by water or wet cloth. The picture can also be printed directly on the surface, by use of inkjet, etching, laser-engraving or other methods (material dependent harmful emission must be taken into account); there also exist printable labels that use invisible fluorescent-ink that can be scanned in certain wavelengths. The codes can also be integrated in parts by means of a three dimensional relief, making use of generated shadow, or texture and scanning the resulting contrast difference.

The codes are extremely cheap and quickly placed. They need a relatively flat surface area with a line of sight to read. They are relatively slow to read (as compared to RFID). And it might be undesirable to be placed on a visible part of the product.

Robot vision

Because the parts and products are known in terms of CAD design, sensors (optical, ultrasone, laser) and image recognition techniques can be used to recognize and track the parts throughout their transport. This is a valid solution because sensors will already be needed to check and evaluate process step progression, reducing the need for additional equipment.

It is beneficial to have no tracker, physically or visually on the parts, reducing time and cost. The camera or distance sensors do need a line of sight to track a part. Additionally the image recognition program requires capable processing power from the system, for every camera. Errors might occur if parts used for different products look visually the same, this must be taken into account.

CARRIER TRACKING

This form of tracking can be used is the cluster allows parts and products to be transported by means of a carrier system. The carriers themselves can be recognized by means of one of the above described tracking technologies. This eliminates the need for tracking the product itself. This does require the two to be inseparable, otherwise the part might get lost when an error occurs. Because the carriers can be reused for new production runs the system will be very cheap. A benefit of this tracking system is that it imposes no additional requirements on the part and product design.

7.1.3. INDUSTRY AND MATERIAL TYPES

The following list is a clustering of the secondary industry types as defined by the North American Industry Classification System (NAICS 31-33) to get an insight into the types of manufacturing.

- Food, Beverage and Tobacco (NAICS 311, NAICS 312)
- Textile, Apparel, and Leather (NAICS 313, NAICS 314, NAICS 315, NAICS 316)
- Wood, Paper, and Printing (NAICS 321, NAICS 322, NAICS 323)
- Petroleum, and Coal (NAICS 324)
- Chemical (NAICS 325)
- Plastics, and Rubber (NAICS 326)
- Nonmetallic Minerals (NAICS 327)
- Primary Metal, Fabricated Metal, and Machinery (NAICS 331, NAICS 332, NAICS 333)
- Computer, Electronic, Electrical Equipment, Appliance, and Components (NAICS 334, NAICS 335)
- Transportation Equipment (NAICS 336)
- Furniture (NAICS 337)
- Miscellaneous Manufacturing (NAICS 339)

Hazardous materials as defined by the US government in document 49 CFR 172.101:

- Class 1: Explosives
- Class 2: Gases
- Class 3: Flammable liquids
- Class 4: Flammable solids
- Class 5: Oxidizers/organic peroxides
- Class 6: Toxic and infectious substances
- Class 7: Radioactive material
- Class 8: Corrosives
- Class 9: Miscellaneous hazardous materials

7.1.4. PERSONALIZATION INTERVIEW QUESTIONS

Interviews where performed on the topic of personalization and customizable products. The interviews had an open character and each question was elaborately discussed in a natural style conversation. The interview questions are in Dutch described below:

- Er zijn steeds meer producten die je aan kan passen aan je wensen. Als je kijkt naar je eigen producten, wat voor producten zou je willen 'customizen'?
- Zijn er producten die je ruimtelijk zou willen personalizeren?
- Zijn er producten die je in uiterlijkheid zou willen personalizeren?
- Zijn er producten die je in 'features' zou willen personalizeren?
- Vraag verder over: lifestyle producten, home appliences, customer electronics, medical and healthcare, sports.

7.1.5. EXISTING COMPUTER MOUSE

One of the analyzed computer moussed. The electronic components of this mouse, are de-soldered and used in the computer mouse prototype sub-assemblies.

7.1.6. EXEMPLARY PRODUCT CHOICE

From a long list of products for different industry sectors, a smaller list of possible exemplary-product directions is derived following the pre-requirements.

The main wishes for the exemplary product are clustered and the most promising options scored on these clusters (This is an old process description, and the wish clusters are updated in the 3.1.1. Product-family Choice chapter describing the choice of the computer mouse).

PRE-REQUIREMENTS

- Physical Products (Not pure services)
- Mass-Customization Products (Mass-production and personalization)
- Business to Person Products (A one person target is needed for personalization)
- Non-consumable Products (Must be disassembled, discrete production required)

Found products with high personalized value:

- Mini speaker [features, size, performance, form, color, materials]
- Headphones [capabilities, features, ergonomics, style]
- Camera (professional, hobby) [size, weight, features, performance, style]
- Computer mouse, keyboard (business, gaming) [style, features, ergonomics, size]

- Cabinet, cupboard (tools, tv, books, clothing, storage) [fit with, fit in, style, features]
- Table, bureau, chairs [size, comfort, style, features]
- Backpack, bag, case, belt (travel, work, business, hobbies) [ergonomics, features, colors, materials]
- Shoes (sports, work) [ergonomics, features, style]
- Jacket, pants (life, travel, work) [style, ergonomics, features, performance]
- Wallet [size, features, style]
- Sports equipment (tennis racket, snowboard/ski and shoes) [size, weight, features, print]
- Sports protection [type, capabilities, ergonomics, color]
- Helmets (kids, bicycle, work, sports) [ergonomics, performance, color, features]
- Bike [type, ergonomics, form, color, accessories]

- Glasses [lens fit, ergonomics, form, color]
- Wheelchair, rollator [ergonomics, features, style]
- Prosthetic, brace (arms, legs, body) [ergonomics, features, style]

THE MAIN WISH CLUSTERS:

0 PROJECT REALIZATION

- Project timeframe
- Use Festo capabilities
- Minimal amount of Modules in Cluster
- Small Module size
- Low in depth-understanding required of chosen product familie (not to complex)
- Low to medium complexity materials required

1 BUILDS ON FACTORY VISION

- Shows off Industry 4.0 CPF principles (connected, ...)
- Multiple Modules needed (multiple types, non-monolithic product)
- Mass-Production (efficiency, performance)
- High personalization (low supplier dependencies, computer numerical control)

2 RESEARCH BENEFICENT

2.1 Direct benefits

- Clean production (minimal waste, goods do not spoil)
- Dismantlable products
- New resulting research topics
- Societal value

2.2 Scalable production

- Strong but basic initial setup
- Encourages multiple product families in a cluster,
- Expandable cluster complexity,
- Scalable in production capacity (module duplication)

3 PRODUCT VALUE MARGIN

- High value increase due to personalization
- Personalization within three Customization Categories
- Good match of user investment with personalization level
- Low cost per product (production, human labor, supplier, transport)

THE MOST PROMISING PRODUCT OPTIONS:

These are decided keeping in mind the Project realization cluster.

- Perfect fitting Medical Brace, following your preferences, in your color.
- Ergonomic Headphones/Computer Mouse, with the features you want, with favorite, material accents.
- Perfect size Cupboard/workbench, in your style, storing what u own, with your features (For: tools, tv, books, clothing, storage).

SCORING TABLE:

The products get a score from one to five for each wish cluster.

	Medical Brace	Headphone/mouse	Cupboard
1 Builds on Vision	2	5	4
2 Research Benefit	4	4	2
3 Product Value	4	2	3

The chosen exemplary-product is the Computer Mouse, which is more elaborately discussed in the 3.1.1. Product-family Choice chapter.

7.1.7. PROPOSED INDUSTRY STANDARD

The proposed size and load industry standard overview (values, relations),
For: AN4 – A8, H0 - H1, and PN1 – P3.

-H0							-PN1		
h:	0	p.					-1		
	a:	A [m^2]	W [m]	L [m]	H [m]	V [m^3]	P [Kg/m^2]	M [Kg]	D [Kg/m^3]
Formula:		(1/2)^a	2^(-1/4)*2^(-a/2)	2^(1/4)*2^(-a/2)	(2/3)^(a+h)	A*H	1000 (1/2)^p	P*A	M/V
Column relation:		1 : 2	1 : sqr(2)	1 : sqr(2)	2 : 3	1 : 3	1 : 1	1 : 2	3 : 2
AN4	-4	16.000	3.364	4.757	5.063	81.000	2000	32000	395
AN3	-3	8.000	2.378	3.364	3.375	27.000	2000	16000	593
AN2	-2	4.000	1.682	2.378	2.250	9.000	2000	8000	889
AN1	-1	2.000	1.189	1.682	1.500	3.000	2000	4000	1333
A0	0	1.000	0.841	1.189	1.000	1.000	2000	2000	2000
A1	1	0.500	0.595	0.841	0.667	0.333	2000	1000	3000
A2	2	0.250	0.420	0.595	0.444	0.111	2000	500	4500
A3	3	0.125	0.297	0.420	0.296	0.037	2000	250	6750
A4	4	0.063	0.210	0.297	0.198	0.012	2000	125	10125
A5	5	0.031	0.149	0.210	0.132	0.004	2000	63	15188
A6	6	0.016	0.105	0.149	0.088	0.001	1000	16	11391
A7	7	0.008	0.074	0.105	0.059	0.000	2000	16	34172
A8	8	0.004	0.053	0.074	0.039	0.000	2000	8	51258

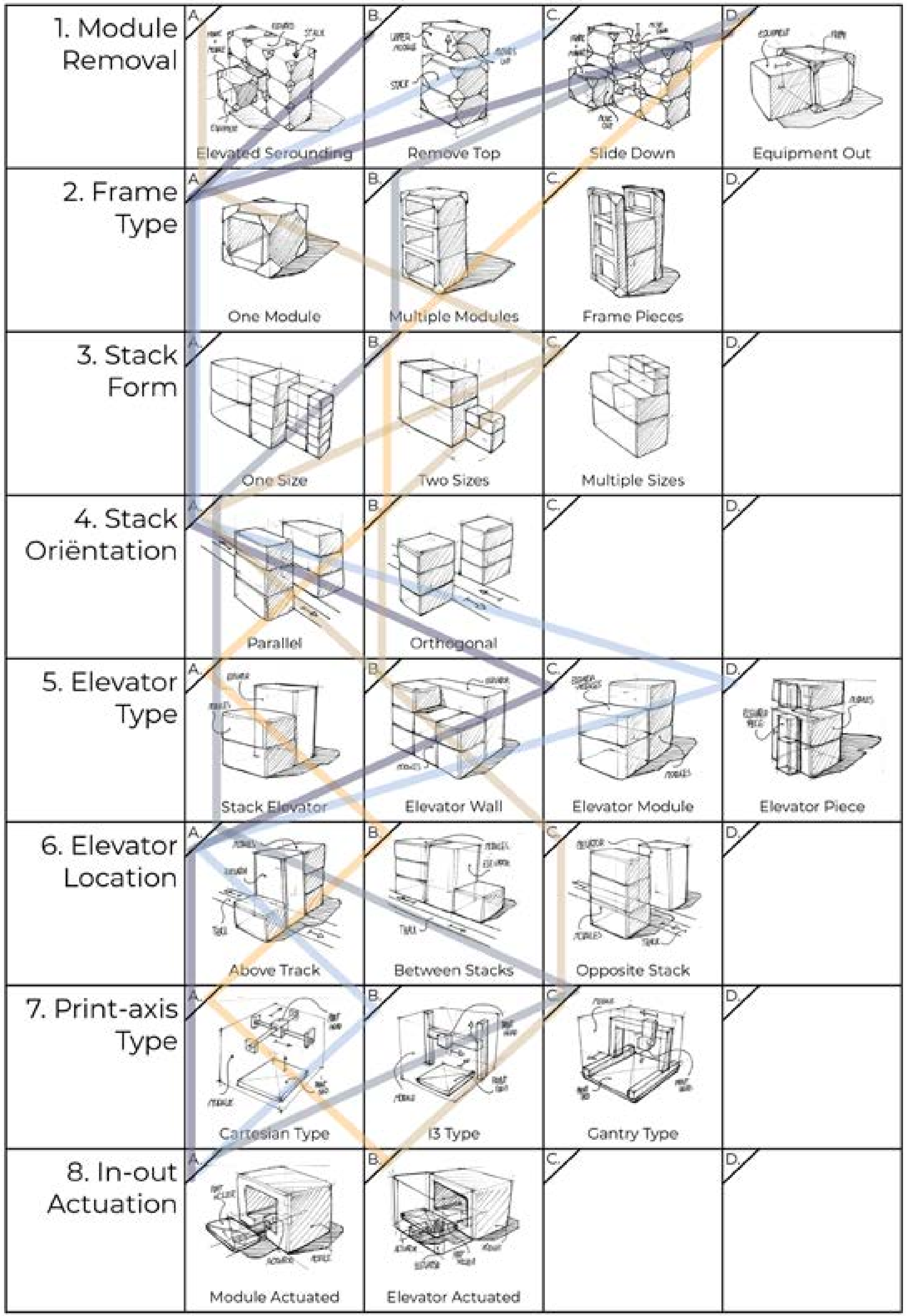
-P0			-P1			-P2			-P3		
0			1			2			3		
P [Kg/m^2]	M [Kg]	D [Kg/m^3]	P [Kg/m^2]	M [Kg]	D [Kg/m^3]	P [Kg/m^2]	M [Kg]	D [Kg/m^3]	P [Kg/m^2]	M [Kg]	D [Kg/m^3]
1000 (1/2)^p	P*A	M/V	1000 (1/2)^p	P*A	M/V	1000 (1/2)^p	P*A	M/V	1000 (1/2)^p	P*A	M/V
1 : 1	1 : 2	3 : 2	1 : 1	1 : 2	3 : 2	1 : 1	1 : 2	3 : 2	1 : 1	1 : 2	3 : 2
1000	16000	198	500	8000	99	250	4000	49	125	2000	25
1000	8000	296	500	4000	148	250	2000	74	125	1000	37
1000	4000	444	500	2000	222	250	1000	111	125	500	56
1000	2000	667	500	1000	333	250	500	167	125	250	83
1000	1000	1000	500	500	500	250	250	250	125	125	125
1000	500	1500	500	250	750	250	125	375	125	63	188
1000	250	2250	500	125	1125	250	63	563	125	31	281
1000	125	3375	500	63	1688	250	31	844	125	16	422
1000	63	5063	500	31	2531	250	16	1266	125	8	633
1000	31	7594	500	16	3797	250	8	1898	125	4	949
1000	16	11391	500	8	5695	250	4	2848	125	2	1424
1000	8	17086	500	4	8543	250	2	4271	125	1	2136
1000	4	25629	500	2	12814	250	1	6407	125	0	3204

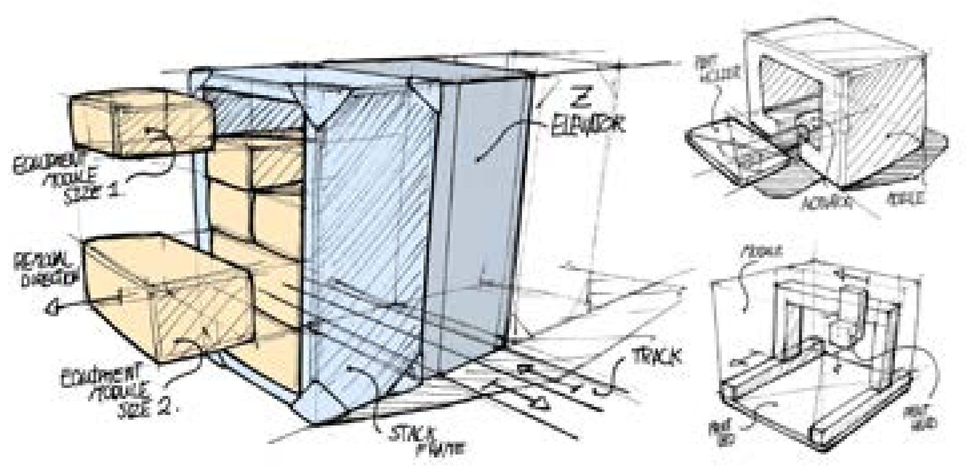
-H1							-PN1		
h:	1	p:					-1		
	a:	A [m^2]	W [m]	L [m]	H [m]	V [m^3]	P [Kg/m^2]	M [Kg]	D [Kg/m^3]
Formula:		(1/2)^a	2^(-1/4)*2^(-a/2)	2^(1/4)*2^(-a/2)	(2/3)^(a+h)	A*H	1000 (1/2)^p	P*A	M/V
Column relation:		1 : 2	1 : sqr(2)	1 : sqr(2)	2 : 3	1 : 3	1 : 1	1 : 2	3 : 2
AN4	-4	16.000	3.364	4.757	3.375	54.000	2000	32000	593
AN3	-3	8.000	2.378	3.364	2.250	18.000	2000	16000	889
AN2	-2	4.000	1.682	2.378	1.500	6.000	2000	8000	1333
AN1	-1	2.000	1.189	1.682	1.000	2.000	2000	4000	2000
A0	0	1.000	0.841	1.189	0.667	0.667	2000	2000	3000
A1	1	0.500	0.595	0.841	0.444	0.222	2000	1000	4500
A2	2	0.250	0.420	0.595	0.296	0.074	2000	500	6750
A3	3	0.125	0.297	0.420	0.198	0.025	2000	250	10125
A4	4	0.063	0.210	0.297	0.132	0.008	2000	125	15188
A5	5	0.031	0.149	0.210	0.088	0.003	2000	63	22781
A6	6	0.016	0.105	0.149	0.088	0.001	1000	16	11391
A7	7	0.008	0.074	0.105	0.059	0.000	2000	16	34172
A8	8	0.004	0.053	0.074	0.026	0.000	2000	8	76887

-P0			-P1			-P2			-P3		
0			1			2			3		
P [Kg/m^2]	M [Kg]	D [Kg/m^3]	P [Kg/m^2]	M [Kg]	D [Kg/m^3]	P [Kg/m^2]	M [Kg]	D [Kg/m^3]	P [Kg/m^2]	M [Kg]	D [Kg/m^3]
1000 (1/2)^p	P*A	M/V	1000 (1/2)^p	P*A	M/V	1000 (1/2)^p	P*A	M/V	1000 (1/2)^p	P*A	M/V
1 : 1	1 : 2	3 : 2	1 : 1	1 : 2	3 : 2	1 : 1	1 : 2	3 : 2	1 : 1	1 : 2	3 : 2
1000	16000	296	500	8000	148	250	4000	74	125	2000	37
1000	8000	444	500	4000	222	250	2000	111	125	1000	56
1000	4000	667	500	2000	333	250	1000	167	125	500	83
1000	2000	1000	500	1000	500	250	500	250	125	250	125
1000	1000	1500	500	500	750	250	250	375	125	125	188
1000	500	2250	500	250	1125	250	125	563	125	63	281
1000	250	3375	500	125	1688	250	63	844	125	31	422
1000	125	5063	500	63	2531	250	31	1266	125	16	633
1000	63	7594	500	31	3797	250	16	1898	125	8	949
1000	31	11391	500	16	5695	250	8	2848	125	4	1424
1000	16	11391	500	8	5695	250	4	2848	125	2	1424
1000	8	17086	500	4	8543	250	2	4271	125	1	2136
1000	4	38443	500	2	19222	250	1	9611	125	0	4806

7.1.8. FORCED MORPHOLOGICAL CONCEPT METHOD

1. Maintenance removal (worker, forklift, crane):
   A. Remove module, rest of the stack sinks down
   B. Remove module the rest stays elevated (by stacks on the side or elevator shaft)
   C. Remove only the uppermost module of the stack
   D. Leave the frame and remove only equipment
2. 2. Module frame:
   A. Single module frame
   B. Whole stack frame (Multi stack frame, side-by-side, opposite of track, both)
   C. Separate frame pieces between the modules (building scaffolding, podiums, modular type cabinets)
3. Stack form:
   A. Stack consist of one module standard size
   B. Stack consists of two module standard sizes
   C. Stack may consists of multiple module standard sizes
4. Stack orientation:
   A. Parallel to track
   B. Orthogonal to track
5. Lift configuration:
   A. Full elevator shaft tower.
   B. XYZ-pick and place wall (as Festo's storage module).
   C. Stackable elevator 'modules'. and transport itself upwards
   D. Separate elevator-piece attached onto the process module.
6. Elevator location:
   A. Above transport track
   B. Between module stacks
   C. Opposite of the stacks
7. Printer axis type:
   A. Darwin type (Cartesian)
   B. I3 type
   C. Gantry type (fixed bed)
   D. (Delta type) (left out: to high and to big circular build-area in a square space module)
8. In-and-out movement:
   A. Process module puts part/pallet inside. (Print axes puts part/pallet inside. Separate actuator)
   B. Elevator puts part/pallet inside



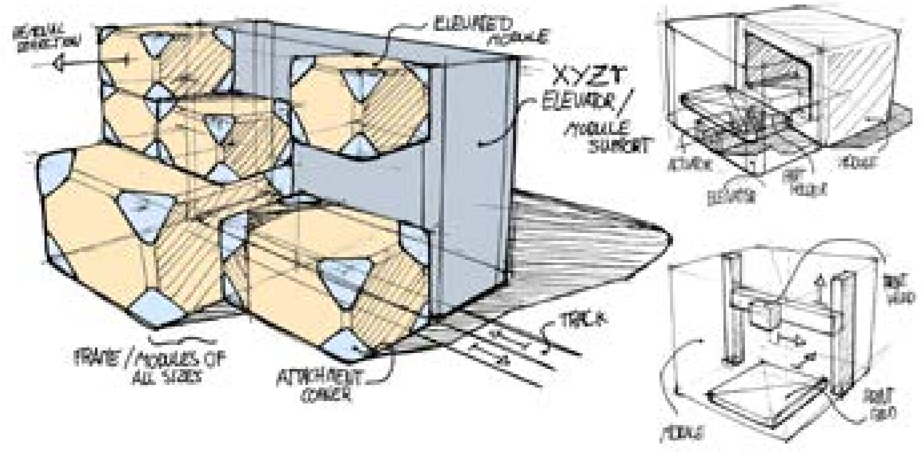


1. THE DOUBLE CABINET

This concept has a defined stack height and is capable of holding two module sizes. An elevator of the same height directly above the transport track supplies two module stacks of parts. The elevator is relatively simple, only capable of lifting the parts up to the right module. The module is then capable of putting the part in and holding it still while the three axis gantry-type printer performs the on-printing process on the part and putting it back in the elevator for further production.

+ Due to the set height strength is directly derivable from the industry standard.
+ All the complex components are located in the 'equipment' part of the module which is easily removable.
+ The part stays still during printing, resulting in no vibrations due to inertia and low requirements for the holder-part interface.

- The set height and the fact that one elevator supplies two stacks reduces the flexibility and continuous scalability of the system.
- The frame and the elevator stay when the modules get replaced over time. When the elevator breaks down all the modules in both stacks are out of order as well.
- Because process-modules of different standard-sizes can be placed in the frame the frame must be one size-standard bigger than the biggest module, which makes it bulky and overkill in terms of strength.
- Because the print bed remains still and the print axes contain all three dimensions of the printer is relatively complex in design. Also play and hysteresis become more prominent.

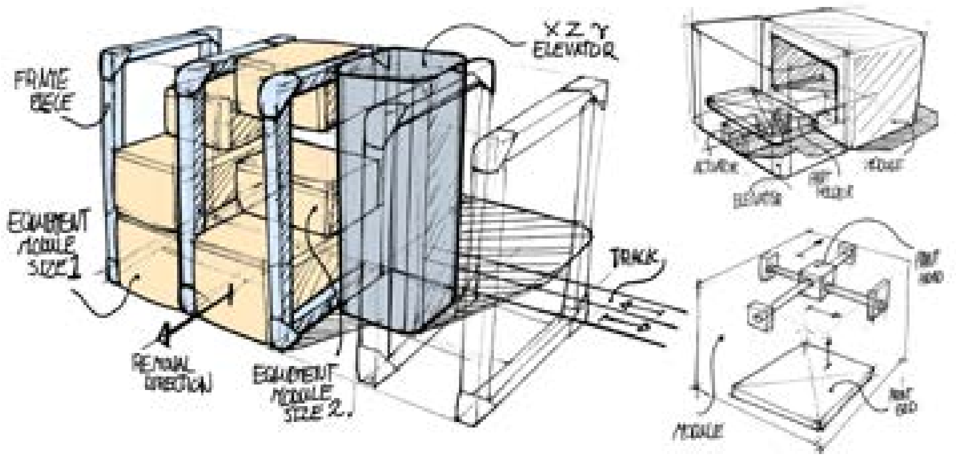


2. THE STICK-ON ELEVATOR WALL.

This concept has a height and width defined by the elevator wall which is placed on one side of the transport track and is capable of holding modules elevated on one side. These can be of multiple different sizes due to the pattern in the industry size-standard. The elevator-wall is capable of gripping a part moving it to the right xy-location rotating it if necessary and moving it inside and placing it down at the right stationary location. The three axis gantry-type printer performs the on-printing process and the part is picked back up by the elevator and put back on the track.

+ Due to the set height strength is directly derivable from the industry standard.
+ The part stays still during printing, resulting in no vibrations due to inertia and low requirements for the holder-part interface.
+ The process of simply placing the part down on an indexing point in the gantry-type printer is rather simple in design.
+ (The elevator-wall already exists in the warehouse module of Festo's CP Factory.)
+ Due to the combination of different modules sizes the factory can be better optimized to group certain modules together and reduce part-transport distances.

- The set height and width reduces the flexibility and continuous scalability.
- The elevator-wall stays where it is when the modules get replaced over time. When the elevator-wall breaks down all its modules are out of order as well.
- The elevator-wall has a four degree of freedom end-effector which makes the design rather complex.
- Only one side of the track contains process-modules, reducing the number of modules per meter of track, resulting in more occupied floor-space.
- Because the print bed remains still and the print axes contain all three dimensions of the printer is relatively complex in design. Also play and hysteresis become more prominent.



3. THE SIDE-BY-SIDE ADD-ON FRAME

This concept has a stack height defined by the frame-pieces, that hold up the modules and is capable of holding two module sizes. An elevator of the same height is placed in between two stacks on one side of the transport-track and it supplies these two stacks of parts. The Elevator picks parts up from the transport-track rotate them if necessary and moves them into the printer. Here the vertical print-axis rises, picks up the part towards the xy-axes and starts on-printing on the part. Afterwards the part is lowered on the elevator arm which puts the part back down on the transport-track.

+ Due to the set height strength is directly derivable from the industry standard.

+ Because the elevator is accessible from the side, the module stack remains intact when the elevator is replaced.

+ The vertical axis moves only when a new layer is printed, thus the part stays relatively still during printing, resulting in no vibrations due to inertia and low requirements for the holder-part interface.

+ The vertical movement of the printer can be used to pick up the part from the elevator arm, reducing the complexity of the design.

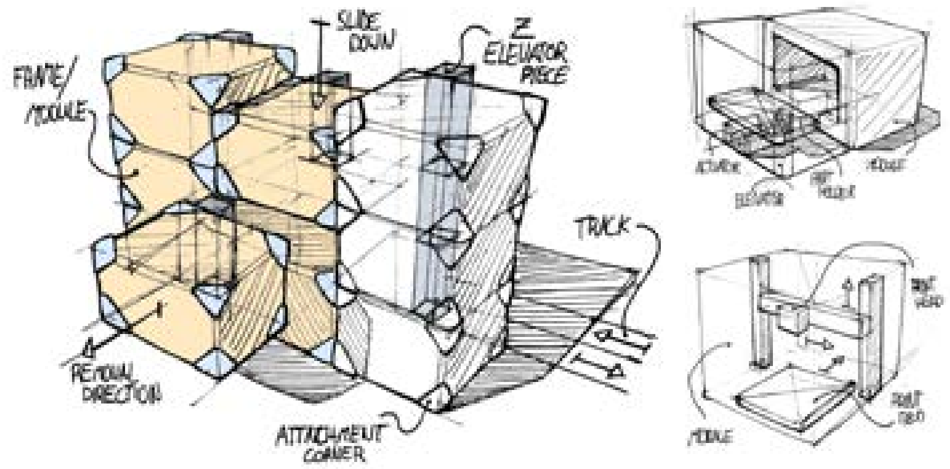
- The set height and the fact that one elevator supplies two stacks reduces the flexibility and continuous scalability of the system.

- The elevator has a three degrees of freedom end-effector which makes the design rather complex.

- The frame-pieces requires extra components to be stored, transported, placed, and mounted.

- Because process-modules of different standard-sizes can be placed in the frame the frame must be one size-standard bigger than the biggest module, which makes it rather bulky and overkill in terms of strength.

- The elevators are placed between the module stacks reducing the number of modules per meter of track, resulting in more occupied floor-space.



4. THE ALL INCLUDED MODULE.

This concept has no defined stack height, and modules can be stacked as high is the structure allows on either side of the transport track. The modules can be removed from everywhere in the stack, where the modules on top will slide down after it is removed; new modules are placed on top. Each module has an elevator-piece attached to it, able to carry the part up to the module on top. When the part is lifted to the right height, the horizontal y-axis of the printer moves out below the part, the elevator moves down until the part is supported by the print axis, and the module can start on-printing. Afterwards the steps are followed in reverse until the part is again on the transport-track.

+ The system of separate individual modules is fully scalable in both the horizontal and vertical directions.

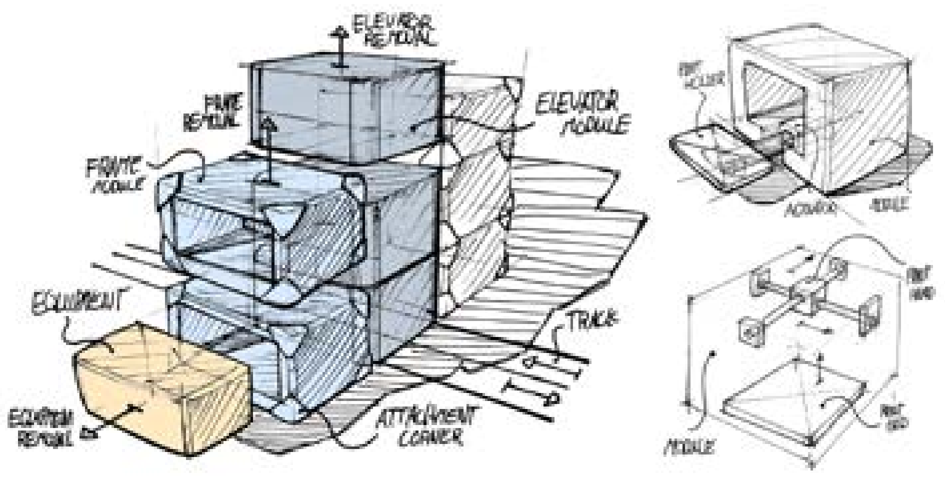
+ Every part of the system gets updated when modules are added and removed through time, even the elevator and the structural frame.

+ The movement of the part into the system requires only two actuators, of which one is also the print axis. Reducing complexity in movement and design.

- The unknown stacking height result in an undefined strength requirement for the module frame.

- The stacking and removing of modules requires sliding and locking system that is complex in design and application.

- The used printer-axis configuration result in fast horizontal movement of the part during printing, resulting in vibrations due to inertia and a high requirements for the holder-part interface.



5. THE ALL MODULE SYSTEM

This concept has no defined stack height, and modules can be stacked as high is the structure allows on either side of the transport track. The module frames can be added and removed from the top, the same as for the elevator-modules. The equipment can be quickly replaced from the frame-modules because these hold the most maintenance heavy components. The elevator-modules are able to carry the part up to the module on top. When the part is lifted to the right height, an actuator moves out below the part, the elevator moves down until the part is supported by the actuator. The actuator moves inside and the vertical print-axis rises, picks up the part towards the xy-axes and starts on-printing on the part. Afterwards the steps are followed in reverse until the part is again on the transport-track.

\+ The system of separate individual modules is fully scalable in both the horizontal and vertical directions.

\+ Every part of the system is in some way accessible to be replaced when necessary.

\+ The vertical axis moves only when a new layer is printed, thus the part stays relatively still during printing, resulting in no vibrations due to inertia and low requirements for the holder-part interface.

\+ The vertical movement of the printer can be used to pick up the part from the elevator arm, reducing the complexity of the design.

\- The unknown stacking height result in an undefined strength requirement for the module frame.

\- To replace the bottom frame- or elevator-module, the whole stack on top needs to be removed. All the modules will be out of order when this happens.

\- To connect and lock all modules a lot of components and a complex design must be required.

7.1.9. LINEAR MOVEMENT

These linear guides and actuators are examined as options for the movement system.

LINEAR GUIDES

- Sliding contact
- Rod/supported rod
- v-groove
- Rolling element
- Rod/supported rod 3 circulating ball tracks linear bearing
- Opposing rods/edge/gouve v/n-groove bearing
- Rail circulating ball carriage 2/4-track
- Drawer slide (normal, telescopic)

LINEAR ACTUATORS

- Belt drive/timing belt
- Lead/ball screw
- Cable spool
- Rack and pinion or friction wheel
- Solenoid
- Hydraulic/pneumatic cylinder (normal or telescopic)
- Magnetic track
- Lifting rotor
- Scissor lift
- Helical band or segmented spindle
- Rigid belt/chain

DETERMINING ASPECTS:

- Speed and acceleration
- Power/torque
- Stroke-length and footprint
- Precision repeatability (backlash, hysteresis)
- Life-time and maintenance
- Price and costs

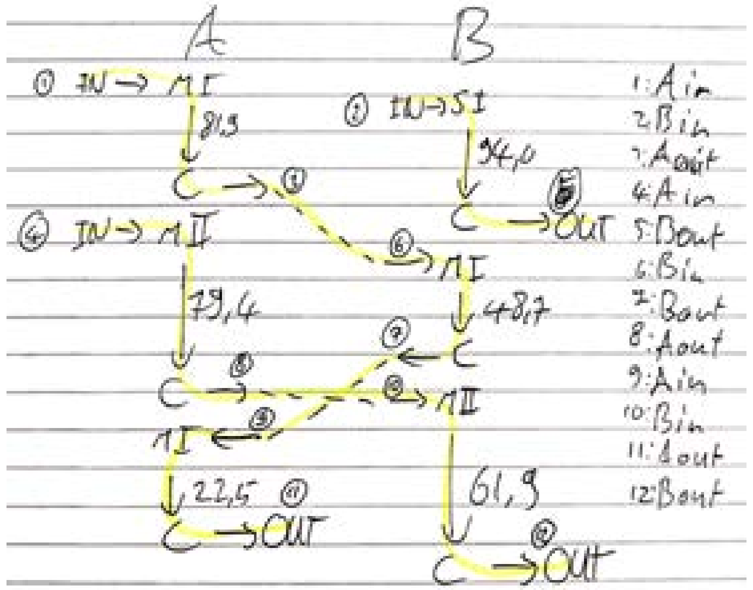
7.1.10. RAFT FRAME STRUCTURE

The used printed frame-structure, consisting of Cura's Raft and Concentric Support Functions.

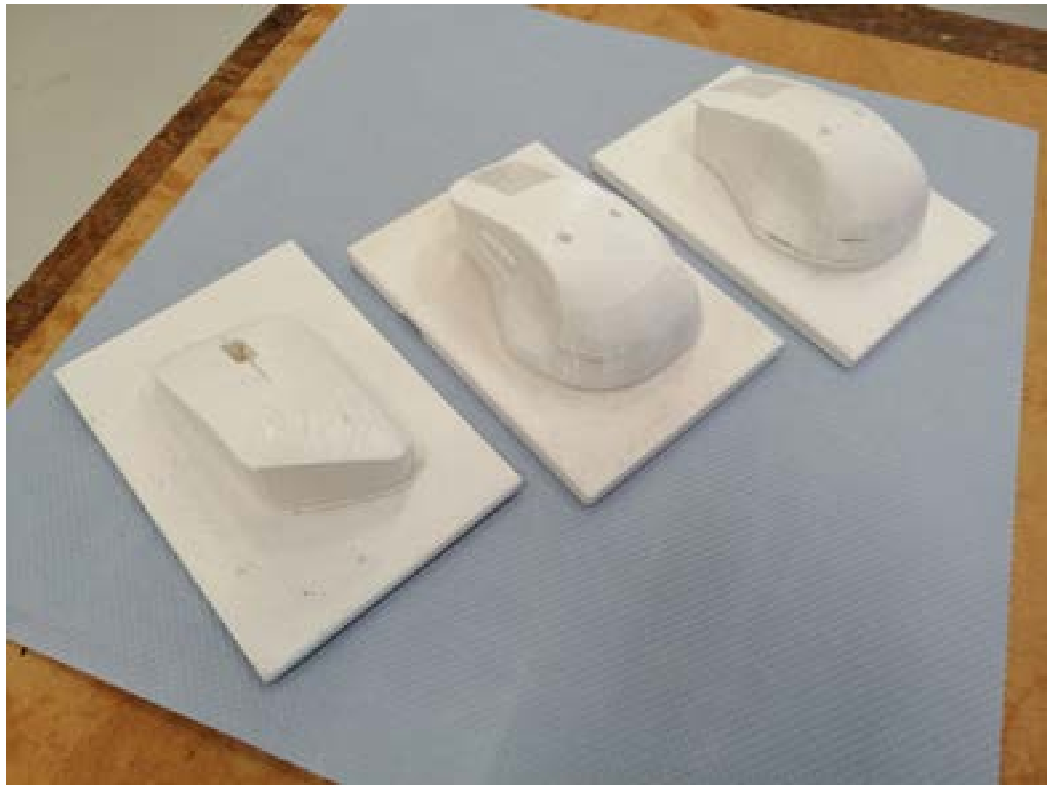
7.1.11. CABINET DEMONSTRATION TEST

The three CAD files used in the test in order of print staring time.

Test time-table, for printer A and B.



Printed with double the layer height and double the speed, therefore a low quality prints.



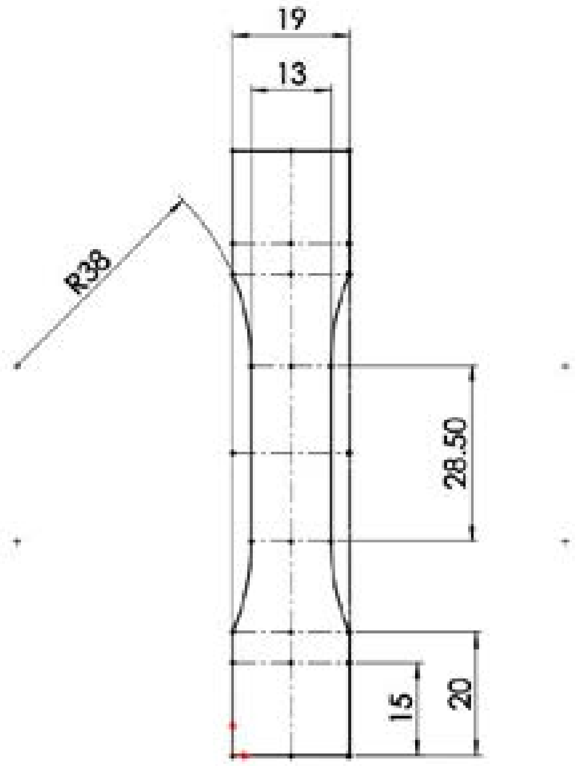
7.1.12. PRINTER & SLICER SETTINGS

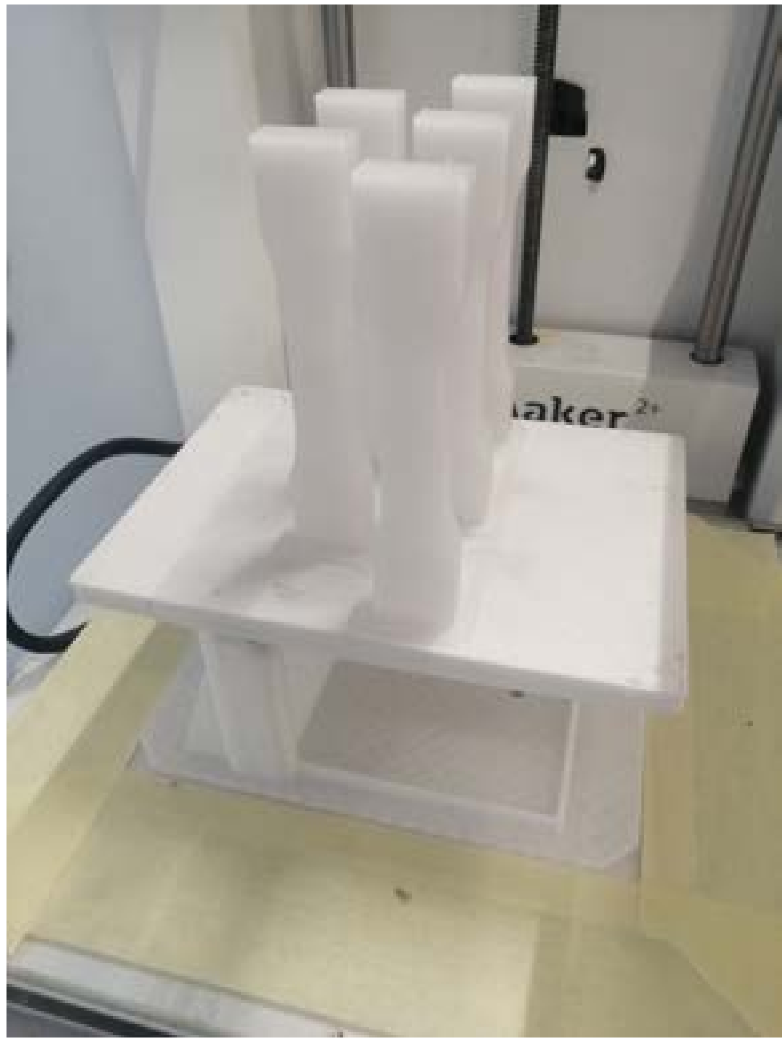
Settings and specifications for the FDM-printer and Cura slicer. These are the setting used during all tests.

- Printer: Ultimaker 2+
- Nozzle: 0,4 mm
- Filament diameter: 2.85 mm
- Layer height: 0.15
- Wall line count: 1
- Bottom and Top layer count: 2
- Infill type: lines 100%
- Print speed: 45 mm/s
- Retraction: Enabled
- Heated bed: 0°C
- Nozzle: 240°C
- Flow 100%

7.1.13. TENSILE STRENGTH TEST

The dimensions of the tensile test sample (Thickness: 9 mm):



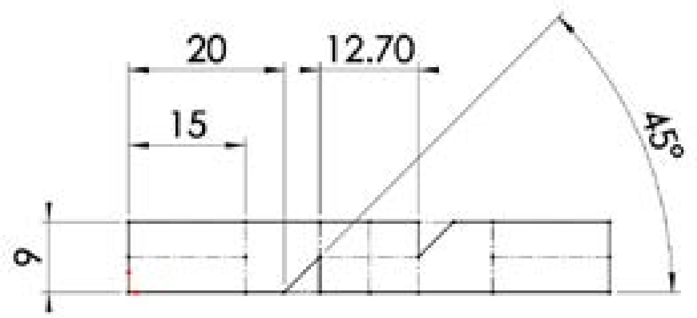


7.1.14. SHEAR STRENGTH TEST

Shear test based on ASTM D3164 (ASTM International. 2003):

Standard Test Method for Strength Properties of Adhesively Bonded Plastic Lap-Shear Sandwich Joints in Shear by Tension Loading. At a strain rate of 1.27 mm/min. 8.3 to 9.7 MPa of shear area per minute.

The samples had the same cross sectional shear area, but printed instead of metal substrate. Designed shorter and thicker than the prescribed sample, to fit the printer setup. The samples where printed lying flat with the break line in the middle layer and two printed notches (Width: 25.40 mm).



7.1.15. PAUSE AT HEIGHT PLUGIN

A gcode modification needed to be applied to reduce filament oozing and nozzle movement path dragging-around of a filament blob and destroying the on-print-layer and therefore the samples. The Cura slicer post-processing options: 'Pause at height' and 'Search and replace' functions where used to automate this process.

PAUSE AT HEIGHT:

Pause Height: 'middle layer of specimen'
Standby Temperature: 240
Other options: 0

SEARCH AND REPLACE:

Search: 'G1 F300 Z'
Replace: ';'

SEARCH AND REPLACE:

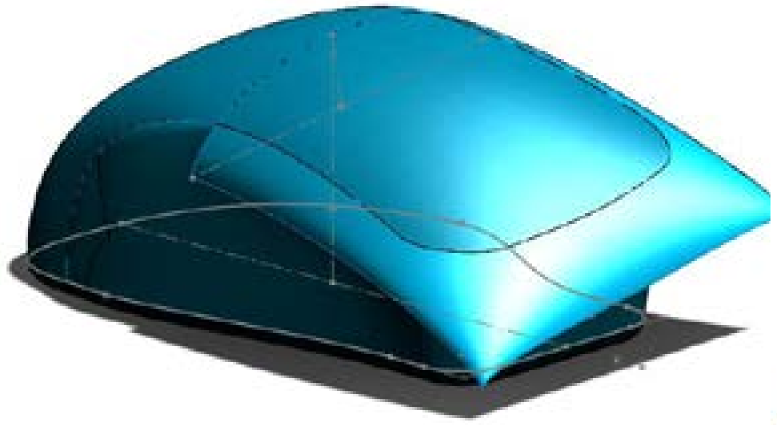
Search: 'M0;Do the actual pause'
Replace: 'G91: G0 Z30: G1 F1800 E-100: M0: G0 F600 Z-30: G1 F1800 E100: G90' (used in AB and BA)

Or,

Replace: 'G91: G0 Z30: G1 F1800 E-100: P60000: G0 F600 Z-30: G1 F1800 E100: G90' (used in AA and BB)

7.1.16. PARAMETRIC MODEL

The underlying parametric ergonomic model and the respective customizable sketches.



7.1.17. BUTTON ITERATIONS

Al the button prototype iterations to develop the final mouse design.

The two outermost buttons of the small button-PCB are not in use in this Computer Mouse Realization.

7.1.18. BUTTON TOP SHELL DESIGNS

Aesthetically different variations of the button-top-shell component.

7.1.19. DIRECTING REQUIREMENTS

This is the full chronological list of directing requirements (Relevant Insights). A clustered version can be found the 2.5. Design Brief chapter.

2.1.1.1 The CTO/ETO mass-customization factory must postpone manufacturing of materials and part into a product until product is configured and ordered.
2.1.1.2 The CTO/ETO mass-customization factory must accommodate a short customer-order-cycle.
2.1.1.3 The CTO/ETO mass-customization factory must use direct-digital-manufacturing techniques to integrate process-generality and make engineer-to-order products.
2.1.1.4 The CTO/ETO mass-customization factory must overcome the direct-digital-manufacturing disadvantages of being relatively expensive, requiring more energy, and being relatively slow.
2.1.1.5 The CTO/ETO mass-customization factory must be able to produce one-off products.
2.1.1.6 The CTO/ETO mass-customization factory must be capable of a high output-capacity.
2.1.1.7 The personalized product must have an increased emotional value and customer satisfaction.

2.1.2.1 Communication standards will be required for inter and intra factory communication between digital and physical participants.
2.1.2.2 The Digital Twin principle must be implemented for every part/participant in the manufacturing system.
2.1.2.3 A real time digital model will be required to make the complex process observable, transparent and understandable for every system-participant.
2.1.2.4 Every factory system-participant (product, module, employee, etc.) must be able to act autonomously on the available operations data.
2.1.2.5 The human worker must have a managing or creative problem solving role in the factory.
2.1.2.6 The factory process-modules need to have a digital but also physical interface (USB) to log into the system and connect to each other.

2.1.3.1 The cyber-physical factory and exemplary-product must promote and enable further research, integrating aspects of: Industry 4.0, Cyber-physical Systems and Mass-customization.
2.1.3.2 The cyber-physical factory must consist of a modular setup to be able to change the production-setup quickly.
2.1.3.3 The cyber-physical factory framework must be scalable for different product sizes.
2.1.3.4 The cyber-physical factory must integrate mass-customization in its modular production setup, to make individually different parts and products.
2.1.3.5 The exemplary-product must be recognizable as a clear personal consumer product.
2.1.3.6 The exemplary-product production process must be clean, in terms of dust, chips, waste, lubricants, post-processing, spoiling ingredients, etc.
2.1.3.7 The exemplary-product must be disassemblable to reuse the materials for new test or demonstration runs of the production system.
2.1.3.8 The exemplary-product must demonstrate unique cyber-physical product aspects through form and functionality.
2.1.3.9 The exemplary-product must be designed in both a commercial business-case, as well as a research and demonstration context.

2.1.4.1 The mass-customization factory products must generate high customer value through personalization.
2.1.4.2 The mass-customization factory's production systems and processes must be 'general' to produce varying build-to-order products.
2.1.4.3 The mass-customization factory requires low dependencies and overhead costs.
2.1.4.4 The mass-customization factory must keep track of each part and product during manufacturing.
2.1.4.5 To improve future mass-customization products they must be designed with a method to keep track of their use.
2.1.4.6 The mass-customization factory must be able to increase and decrease production capacity continuously.
2.1.4.7 The mass-customization factory must be able to quickly add new, and subtract products from production.
2.1.4.8 There must be a lot of (relatively small) mass-customization factories to provide local production and reduce transport and warehousing.
2.1.4.9 The mass-customization business-case must make up for a higher per-product production-cost; compared to traditional mass-production methods.

2.2.1.1 The mass-customization factory must reduce supplier dependencies and incorporate as much manufacturing steps as possible (this is called vertical integration).
2.2.1.2 The product factory must be able to convert stocked materials directly into personalized product without waiting on suppliers.
2.2.1.3 The mass-customization product must be designed to retrieve remaining end-of-life value through recycling.
2.2.1.4 The mass-customization factory requires an influx of customer orders in the form of product-recipe files to operate and therefore brands that keep designing and promoting the product-families.
2.2.1.5 Product-family models must be designed with the potential users, factory production capabilities, co-creation-system capabilities, and recycle capabilities in mind.
2.2.1.6 The supplier parts must be standardized to be used in different products by multiple factories.
2.2.1.7 The physical location of the mass-customization value chain links must be optimized to reduce transport costs.
2.2.1.8 The mass-customization business-case must make up for the loss in efficiency (as compared to traditional manufacturing), by generating more user-value and minimizing, supplier, transport, and warehousing costs.
2.2.1.9 Minimal supplier dependencies will be important for the product factory in order to change production quickly in volatile markets.
2.2.1.10 The mass-customization factory must automatically recognize when stock runs low and put out purchase orders to suppliers.
2.2.1.11 The mass-customization factory must automatically initiates packaging and transport to the customer when products are finished.
2.2.1.12 Industry standards will be required to synchronize value chain partners streamline their interaction.
2.2.1.13 A digital Order Management System will be required to track flow of parts and products during different design and production stages of the value chain.

2.2.2.1 The mass-customization factory must be reconfigurable and constantly adapted during production towards the most optimal layout.
2.2.2.2 The mass-customization factory is defined by its production capabilities, not the products it makes.
2.2.2.3 The mass-customization factory must be capable of performing maintenance during constant production.
2.2.2.4 The mass-customization factory must have one or more clusters defined by their build-size, used materials, production capabilities, etc.
2.2.2.5 The mass-customization factory cluster must be made of modular process-step-performing modules each with their own software driver format to be included as recipe in the product-recipe files (CAM).
2.2.2.6 Parts and products must be treated as smart cyber-physical system participants by being able to communicate, act autonomously, and follow their product-recipe files.

2.2.3.1 The mass-customization factory must decide on a business-plan with the spectrum of factory-realizations.
2.2.3.2 A multi-product-family cluster must overcome process-generality requirements that are not relevant for a single-product-family cluster.
2.2.3.3 A multi-product-family cluster does not have to be adaptable to overcome market changes such as product-family swapping as opposed to a single-product-family cluster.

2.2.3.4 A multi- and single-product-family cluster must be able to adapt production output to overcome changes in product-family demand.

2.3.1.1 The factory must be able to turn product-recipe files into physical products.
2.3.1.2 The factory must be able to automatically generate and send component and material requests to suppliers.
2.3.1.3 The factory must be adaptable to varying product demand.
2.3.1.4 Process equipment must be exchangeable between facilities.
2.3.1.5 The production-equipment must be designed with different possible floor shapes and roof heights in mind.
2.3.1.6 The factory floor load rating must be taken into account in the design of the production setup and the choice of equipment and products that need to be made.

2.3.1.7 The cluster must be able to send part, material, waste removal, and maintenance requests to the main factory.
2.3.1.8 The cluster must be designed following an accepted industry standard.
2.3.1.9 The cluster must be able to change its layout during production.
2.3.1.10 Used factory space and floor area that is occupied by factory equipment must be minimized.
2.3.1.11 It must be possible to add new process-modules during production.
2.3.1.12 The cluster must contain a distribution and collection system for process-consumables, standard-components, and materials and waste.
2.3.1.13 The cluster must be capable of dealing with production errors while continuing production.
2.3.1.14 The cluster must be able to inspect product completion.
2.3.1.15 The cluster participants must autonomously try to reach their goal.
2.3.1.16 Cluster participant must digitally be represented, following a hierarchy or class system.
2.3.1.17 The cluster must have an industrial internet connecting all participants.
2.3.1.18 The cluster requires a continuously updated digital representation of its physical self.
2.3.1.19 It must be possible for new participants to be initialized, recognized, located and their states to be updated.
2.3.1.20 The cluster must have a communication framework for the participants to interact.
2.3.1.21 The cluster requires a framework to track orders and sequence product-recipe files.

2.3.1.22 The modules must fit within the grid and specifications of the cluster.
2.3.1.23 The modules must have a structural frame and a physical connection method between each other.
2.3.1.24 The modules must be vertically and/or horizontally stackable, from all arbitrary starting configurations.
2.3.1.25 Module initialization in the system must be as easy as putting it down.
2.3.1.26 All modules must be removable while the rest of the system continues production.
2.3.1.27 The transport and movement system must be designed to be extremely robust and resilient.
2.3.1.28 Each module must hold all necessary equipment to check and analyze its progression.
2.3.1.29 Each module must have an interface to connect and transfer electrical power, internet and other necessary conduits.
2.3.1.30 AI modules must have a system to get rid of their by-products.
2.3.1.31 AI modules must be made with their respective CAM software for in the product-recipe file.
2.3.1.32 The modules must cluster sensor data before sharing it to the real-time digital model.

2.3.1.1.33 The products must act autonomously towards reaching its goal of becoming completed.
2.3.1.2.34 The products must be able to adapt to unforeseen disturbances, and find new routes.
2.3.1.3.35 The products must be trackable at all times throughout the production system.
2.3.1.4.36 The product-recipe file must contain all the information needed to complete the product production.
2.3.1.5.37 The product-recipe must contain process inspection references for comparison

2.3.1.6.38 Parts require an assembly-module to move from a small to a bigger size transport track/system.
2.3.1.7.39 Parts with the same size as their product require an assembly-module.
2.3.1.8.40 Parts must be trackable at al times within the transport system.
2.3.1.9.41 For each part a tracking method must be chosen depending on the cluster, product and the described decision parameters.

2.3.2.1 For every industry type cluster the required capabilities must independently be analyzed.

2.3.2.2 For every material type cluster the production requirements must independently be analyzed.

2.3.2.3 The load capacity must be defined in the industry standard.
2.3.2.4 The height of the build-volume must be kept minimal in the industry standard.
2.3.2.5 The scaling law for product density must be taken into account in the load standard.
2.3.2.6 The build volume must be defined in the industry standard.
2.3.2.7 The floor load rating must be included in the industry standard.
2.3.2.8 Accuracy and repeatability capabilities must independently be defined per process-module.

2.3.2.9 The size type must be defined in the industry standard.
2.3.2.10 To cope with demand, process-modules must either be fast or numerous.
2.3.2.11 The industry standard must enable process-module stackability minimizing loss of resources (floor area, ceiling height, etc.).
2.3.2.12 It is paramount that products are made in the smallest possible build-volumes and that the space for the process-modules must be reduced in all directions.
2.3.2.13 The industry standard must enable gradual increase between progression steps.

2.4.1.1 The personalizable product must be designed with a configuration service and adaptable product-family model in mind.
2.4.1.2 The personal realization of a product-family model must have the form of a product-recipe file.
2.4.1.3 The product-family must have a set of different customizable aspects with an applied resolution range.
2.4.1.4 Mass-customization requires a product-family with a high amount of theoretically-possible-product-realizations (TPPR) to be relevant, otherwise traditional batch-production will be practical.
2.4.1.5 For the configuration of a product-family to have an impact on different experience-axes, aspects within the three customization-categories must customizable (Identity, Fit, Capabilities).
2.4.1.6 The product-family must have customization aspects with a high expertise or investment consumer group.

- 2.4.2.1 The product-family-model must capture the universals of the product form without defining them.
- 2.4.2.2 The personal product must have a tracking method for both warehousing and shipment, as well as its use-phase.
- 2.4.2.3 The product-family use-case must be analyzed on the benefits Cyber-physical tracking enables for the user, and those must be implemented.
- 2.4.2.4 The product-family must be designed with a Cyber-physical tracking framework, including update-type, data system, and the knowledge they want to gain.
- 2.4.2.5 The product-family must be designed with an integrated recycle plan.

7.1.20. MOTOR CONTROL ARDUINO CODE

```
// Ben Kromhout - Grad. Motor control - 27-12-2019
// Library ////////////////////////////////////////////////////////////
#include <Wire.h>
#include <LiquidCrystal_I2C.h>
LiquidCrystal_I2C lcd(0x3F, 16, 2);
// Pinlabel
#define PIN_PULz 13
#define PIN_DIRz 12
#define PIN_PULy 11
#define PIN_DIRy 10
#define PIN_SEQ1 9
#define PIN_SEQ2 8
#define PIN_CAR 6
#define PIN_PRTA 5
#define PIN_PRTB 4
#define PIN_HOMEz 3
#define PIN_HOMEy 2

// Parameters /////////////////////////////////////////////////////////
int str_z = 1600; // steps/revolution
int str_y = 1600; // steps/revolution
double rd_z = 15/1.28; // revolutions/travel[m]
double rd_y = 15/0.4; // revolutions/travel[m]

double home_forw = 0.005; // [m] Forward step
int pd_home = 350; // homming delay time per step
double a_max = 0.5; //max acceleration

double z_0 = 0.990; // Origin
double y_0 = 0;     // Origin

double z_1 = 0.018; // carrier1
double z_2 = 0.018+0.020; // carrier2

double z_3 = 0.215; // B button1
double z_4 = 0.215 + 0.010; // B button2
double z_5 = 0.265; // B printer1
double z_6 = 0.265 + 0.020; // B printer2

double z_7 = 0.783; // A button1
double z_8 = 0.783 + 0.010; // A button2
double z_9 = 0.835; // A printer1
double z_10 = 0.835 + 0.020;// A printer2

double y_1 = 0.3765; // printer
double y_2 = 0.177; // button
double y_3 = 0.130; // mid
double y_4 = 0.015; // carrier

// Coordinates   //  1   2   3   4    5   6   7   8   9  10   11  12  13  14  15  16   17  18   19  20   21   22
               //  cm1 car1 car2  cm2   b1m1 bu11 bu12 b1m2  p1m1 pr11 prt12 p1m2 b2m1 bu21 bu22 b2m2  p2m1 pr21 prt22 p2m2    Omi   O
double Pos[2][22] = {{z_1, z_1, z_2, z_2,  z_3, z_3, z_4, z_4,  z_5, z_5, z_6, z_6,  z_7, z_7, z_8, z_8,  z_9, z_9, z_10, z_10,  z_0, z_0},  // Z
                     {y_3, y_4, y_4, y_3,  y_3, y_2, y_2, y_3, y_3, y_1, y_1, y_3,  y_3, y_2, y_2, y_3,  y_3, y_1,  y_1, y_3,  y_3, y_0}}; // Y

int Move_Ain[] = {21, 1, 2, 3, 4, 20, 19, 18, 17, 13, 14, 15, 16, 13, 14, 13, 21};
int Move_Aout[] = {21, 17, 18, 19, 20, 4, 3, 2, 1, 21};
int Move_Bin[] = {21, 1, 2, 3, 4, 12, 11, 10, 9, 5, 6, 7, 8, 5, 6, 5, 21};
int Move_Bout[] = {21, 9, 10, 11, 12, 4, 3, 2, 1, 21};

int Order[] = {1, 3, 2, 1, 4, 3, 4, 2, 1, 3, 2, 4};

// Variables /////////////////////////////////////////////////////////
double std_z = str_z*rd_z; //steps/meter
double std_y = str_y*rd_y; //steps/meter
double z = z_0; // vertical axis
double y = y_3; // horizontal axis
double pd = pd_home;
int mtr = 0;  //motor 1 or 2
bool dir = LOW;
bool home_seq = false;
bool run_seq = false;
bool start_seq = true;
int k = 0;  //counter
int i = 0;  //counter
int j = 0;  //counter
bool car_det = false;
bool prta_det = false;
bool prtb_det = false;
volatile bool final_homing = false;
volatile bool z_home_det = false;
volatile bool z_homed = false;
volatile bool y_home_det = false;
volatile bool y_homed = false;
bool homed = false;

// Setup ///////////////////////////////////////////////////////////////
void setup(){
 lcd.begin();
 lcd.clear();
 lcd.print("setup");
 delay(20);

 pinMode(PIN_PULz, OUTPUT);
 pinMode(PIN_DIRz, OUTPUT);
 digitalWrite(PIN_PULz,LOW);
 digitalWrite(PIN_DIRz,LOW);
 pinMode(PIN_PULy, OUTPUT);
 pinMode(PIN_DIRy, OUTPUT);
 digitalWrite(PIN_PULy,LOW);
 digitalWrite(PIN_DIRy,LOW);
 pinMode(PIN_SEQ1,INPUT);
 pinMode(PIN_SEQ2,INPUT);
 pinMode(PIN_CAR,INPUT);
 pinMode(PIN_PRTA,INPUT);
 pinMode(PIN_PRTB,INPUT);
 pinMode(PIN_HOMEz,INPUT);
 pinMode(PIN_HOMEy,INPUT);
 Serial.begin(9600);
 lcd.clear();
}

// Step function ///////////////////////////////////////////////////////
void mStep(int mtr, bool dir, int pd){
 if(mtr==1){
  digitalWrite(PIN_DIRz,dir);
  delayMicroseconds(6);
  digitalWrite(PIN_PULz,HIGH);
  delayMicroseconds(pd);
  digitalWrite(PIN_PULz,LOW);
  delayMicroseconds(pd-6);
 }else if(mtr==2){
  digitalWrite(PIN_DIRy,dir);
  delayMicroseconds(6);
  digitalWrite(PIN_PULy,HIGH);
  delayMicroseconds(pd);
  digitalWrite(PIN_PULy,LOW);
  delayMicroseconds(pd-6);
 }
}

// Motor move function /////////////////////////////////////////////////
void mtrMove(int mtr, bool dir, double d){
 double nst;
 double st;
 double v;
 double std;
 double T;
 double v_peak;

 if(mtr == 1){
  Serial.print(" | mtr:1");
  std = std_z;
  nst = round(d*std);
  d = nst/std;
  z = z - dir*d + !dir*d;
 }else if(mtr == 2){
  Serial.print(" | mtr:2");
  std = std_y;
  nst = round(d*std);
  d = nst/std;
  y = y + dir*d - !dir*d;
 }else if(mtr == 0){
  Serial.print(" | mtr:0");
  std = 0;
  nst = 0;
  d = 0;
 }else{Serial.print(" error mtrMove ");}

 T = sqrt(PI*PI*d/(2*a_max));  // a = PI^2*d /(2*T)
 v_peak = PI*d/(2*T);

 Serial.print("  d:");
 Serial.print(d);
 Serial.print("  nst:");
 Serial.print(nst);
 Serial.print("  T:");
 Serial.print(T);
 Serial.print(" | v_max:");
 Serial.print(v_peak);
 Serial.print("  pd_min:");
 Serial.println(1000000/(2*v_peak*std));

 int b = 1;
 for(int m=0;m<nst;m++){
  st = m;
  v = v_peak*sin((m/nst)*PI);
  pd = 1000000/(2*v*std);
   mStep(mtr,dir,pd);
 }
}
```

```
// To position function ////////////////////////////////////////
void toPos(double z_t, double y_t){
 double d;
 Serial.print("  z:");
 Serial.print(z);
 Serial.print("  y:");
 Serial.print(y);
 Serial.print(" | z_t:");
 Serial.print(z_t);
 Serial.print("  y_t:");
 Serial.print(y_t);

 if(abs(z-z_t) > abs(y-y_t)){
  mtr = 1;
  d = abs(z_t-z);
  if(z_t>z){
   dir = LOW;
  }else if(z_t<z){
   dir = HIGH;
  }else{Serial.print(" error toPos");}
 }else if(abs(y-y_t) > abs(z-z_t)){
  mtr = 2;
  d = abs(y_t-y);
  if(y_t>y){
   dir = HIGH;
  }else if(y_t<y){
   dir = LOW;
  }else{Serial.print(" error toPos");}
 }else{
  mtr = 0;
  d = 0;
  dir = LOW;
 }

 lcd.setCursor(0, 1);
 lcd.print("zt:");
 lcd.print(z_t);
 lcd.print(" yt:");
 lcd.print(y_t);
 mtrMove(mtr,dir,d);
 lcd.clear();
 lcd.setCursor(0, 0);
 lcd.print(" z:");
 lcd.print(z);
 lcd.print("  y:");
 lcd.print(y);
}
```

```
// Run sequence ////////////////////////////////////////////////////
void runSeq(){if(homed){
 int c_t;
 double z_t;
 double y_t;
 if(!digitalRead(PIN_CAR)){
  Serial.println("Carrier detected");
  delay(500);
   if(!digitalRead(PIN_CAR)){
   car_det = true;
   Serial.println("Carrier detected");
  }else{
  Serial.println("FALSE Carrier detect");
  }
 }
 if(!digitalRead(PIN_PRTA)){
  delay(500);
  if(!digitalRead(PIN_PRTA)){
   prta_det = true;
   Serial.println("Printer A detected");
  }else{
  Serial.println("FASLE Printer A detect");
  }
 }
 if(!digitalRead(PIN_PRTB)){
  delay(500);
  if(!digitalRead(PIN_PRTB)){
   prtb_det = true;
   Serial.println("Printer B detected");
  }else{
  Serial.println("FALSE Printer B detect");
  }
 }

 if(j == sizeof(Order)/sizeof(Order[0])){
  Serial.println("Finished Production");
  lcd.print("Finished Production");
  //j = 0;
 }
```

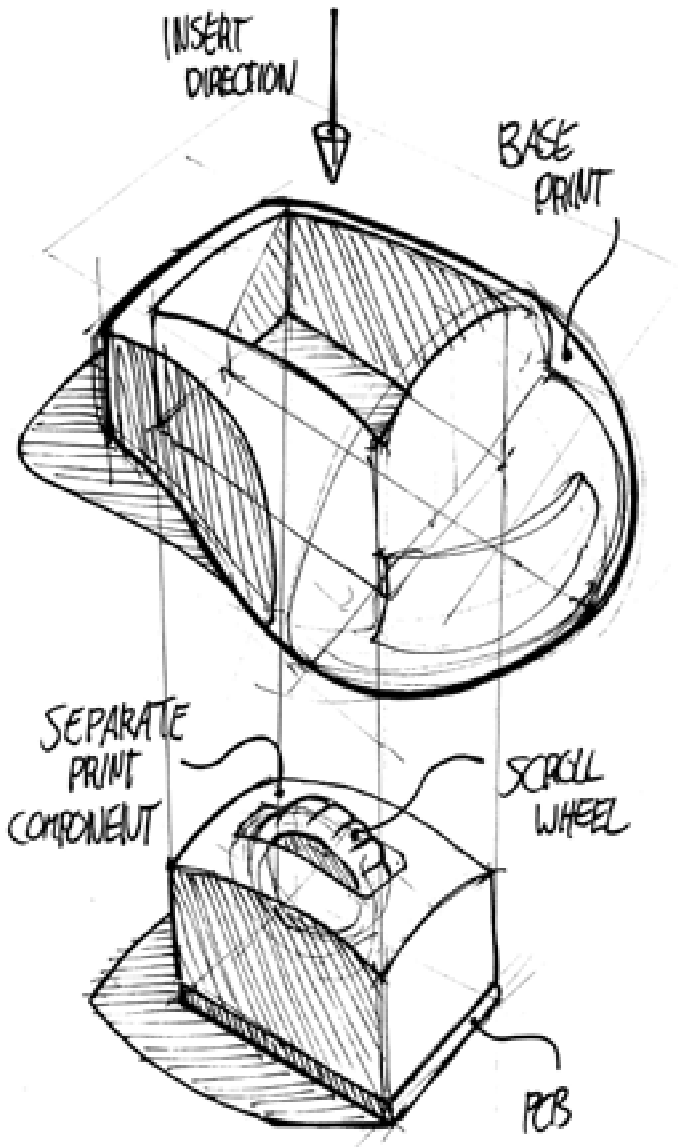
```
 // Move Ain
  if(car_det && Order[j]==1){
   if(i < sizeof(Move_Ain)/sizeof(Move_Ain[0])){
    c_t = Move_Ain[i]-1;
    z_t = Pos[0][c_t];
    y_t = Pos[1][c_t];
    Serial.print("Step:");
    Serial.print(i);
    toPos(z_t, y_t);
    i++;
   }else{
    i = 0;
    j++;
    car_det = false;
    prta_det = false;
    prtb_det = false;
    lcd.clear();
    lcd.print("Move A.in compl.");
    Serial.print("Move A.in compl. Step:");
    Serial.println(j-1);
    delay(1000);
   }
  }

 // Move Aout
  if(prta_det && car_det && Order[j]==2){
   if(i < sizeof(Move_Aout)/sizeof(Move_
Aout[0])){
    c_t = Move_Aout[i]-1;
    z_t = Pos[0][c_t];
    y_t = Pos[1][c_t];
    Serial.print("Step:");
    Serial.print(i);
    toPos(z_t, y_t);
    i++;
   }else{
    i = 0;
    j++;
    prta_det = false;
    prta_det = false;
    prtb_det = false;
    lcd.clear();
    lcd.print("Move A.out compl.");
    Serial.print("Move A.out compl. Step:");
    Serial.println(j-1);
    delay(2000);
   }
  }
```

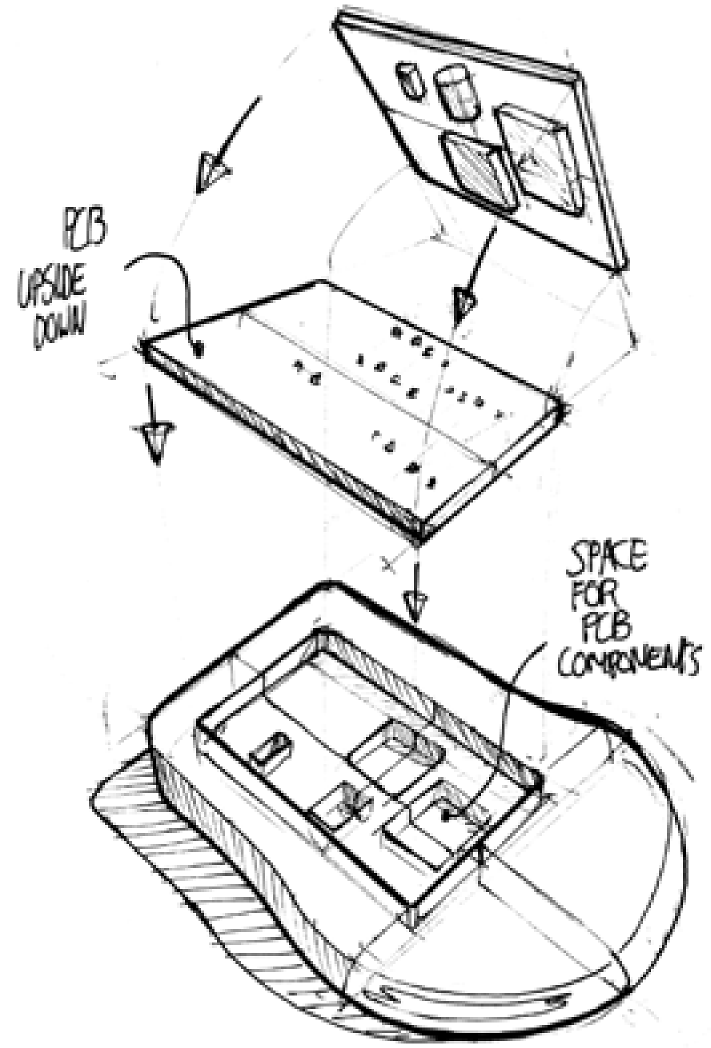
```
 //Move Bin
  if(car_det && Order[j]==3){
   if(i < sizeof(Move_Bin)/sizeof(Move_Bin[0])){
    c_t = Move_Bin[i]-1;
    z_t = Pos[0][c_t];
    y_t = Pos[1][c_t];
    Serial.print("Step:");
    Serial.print(i);
    toPos(z_t, y_t);
    i++;
   }else{
    i = 0;
    j++;
    car_det = false;
    prta_det = false;
    prtb_det = false;
    lcd.clear();
    lcd.print("Move B.in compl.");
    Serial.print("Move B.in compl. Step:");
    Serial.println(j-1);
    delay(2000);
   }
  }

 // Move Bout
  if(prtb_det && car_det && Order[j]==4){
   if(i < sizeof(Move_Bout)/sizeof(Move_
Bout[0])){
    c_t = Move_Bout[i]-1;
    z_t = Pos[0][c_t];
    y_t = Pos[1][c_t];
    Serial.print("Step:");
    Serial.print(i);
    toPos(z_t, y_t);
    i++;
   }else{
    i = 0;
    j++;
    prta_det = false;
    prta_det = false;
    prtb_det = false;
    lcd.clear();
    lcd.print("Move B.out compl.");
    Serial.print("Move B.out compl. Step:");
    Serial.println(j-1);
    delay(2000);
   }
  }

 }else{lcd.clear();lcd.print("NOT
HOMED");delay(20);}
 }
```

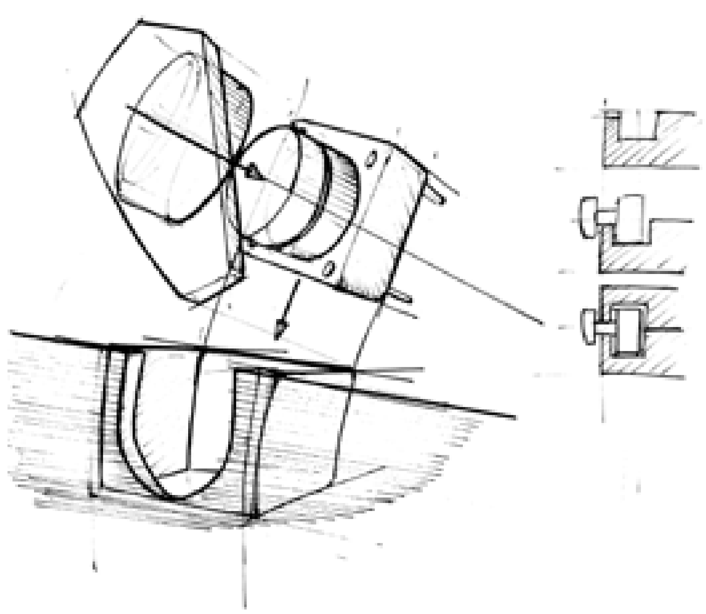
```
// Home Buttons ////////////////////////////////////////////////////////
void zHomeDet(){
  if(!digitalRead(PIN_HOMEz)){

    if(!z_homed && y_homed){
    k = 0;
      if(!final_homing){
        if(!z_home_det){
          Serial.println("z home detected");
          z_home_det = true;
        }
      }else{
        z_homed = true;
        final_homing = false;
        z_home_det = false;

        Serial.println("finished homing z");
      }
    }
  }
}

void yHomeDet(){
  if(!digitalRead(PIN_HOMEy)){
    if(!y_homed){
      k = 0;
      if(!final_homing){
        if(!y_home_det){
          Serial.println("y home detected");
          y_home_det = true;
        }
      }else{
        y_homed = true;
        final_homing = false;
        y_home_det = false;
        Serial.println("finished homing y");
      }
    }
  }
}

// Home sequence ////////////////////////////////////////////////////////
void homeSeq(){
   int nst = 0;
   if(!y_homed && !z_homed){
     mtr = 2;
     nst = home_forw*std_y;
          if(!y_home_det){
            if(k<nst){
              k++;
              dir = HIGH;
              pd = pd_home;
            }else{
              dir = LOW;
              pd = pd_home;
            }
          }else{
            if(k<nst){
              k++;
              dir = HIGH;
              pd = pd_home;
            }else{
              final_homing = true;
              dir = LOW;
              pd = pd_home*4;
            }
          }
    }else if(y_homed && !z_homed){
      mtr = 1;
      nst = home_forw*std_z;
          if(!z_home_det){
            if(k<nst){
              k++;
              dir = HIGH;
              pd = pd_home;
            }else{
              dir = LOW;
              pd = pd_home;
            }
          }else{
            if(k<nst){
              k++;
              dir = HIGH;
              pd = pd_home;
            }else{
              final_homing = true;
              dir = LOW;
              pd = pd_home*4;
            }
          }
    }else if(y_homed && z_homed) {
      mtr = 0;
      if(!homed){
        lcd.clear();
        lcd.print("System homed.");
        delay(500);
        Serial.print("Step:H");
        z = z_0;
        y = y_0;
        toPos(z_0,y_3);
        lcd.clear();
        lcd.print("z: ");
        lcd.print(z);
        lcd.print("   y: ");
        lcd.print(y);
      }
      homed = true;
    }else{Serial.print("error homeSeq");}

    mStep(mtr,dir,pd);
  }

// MAIN loop ////////////////////////////////////////////////////////////
void loop(){
  zHomeDet();
  yHomeDet();
  if(!digitalRead(PIN_CAR)){
    Serial.println("Carrier detected");
  }
  if(!digitalRead(PIN_PRTA)){
    Serial.println("Printer A detected");
  }
  if(!digitalRead(PIN_PRTB)){
    Serial.println("Printer B detected");
  }

// Start home sequence
  if(digitalRead(PIN_SEQ1)){
    if(!start_seq){
      lcd.clear();
      lcd.print("Home Seq.");
    }
    start_seq = true;
    homeSeq();

 // Start run sequence
  }else if(digitalRead(PIN_SEQ2)){
    if(!start_seq){
      lcd.clear();
      lcd.print("Run Seq.");
    }
    start_seq = true;
    runSeq();

// Stay in standby
  }else{
    if(start_seq){
      lcd.clear();
      lcd.print("Standby");
    }
    start_seq = false;
    i = 0;
    k = 0;
  }
}
```

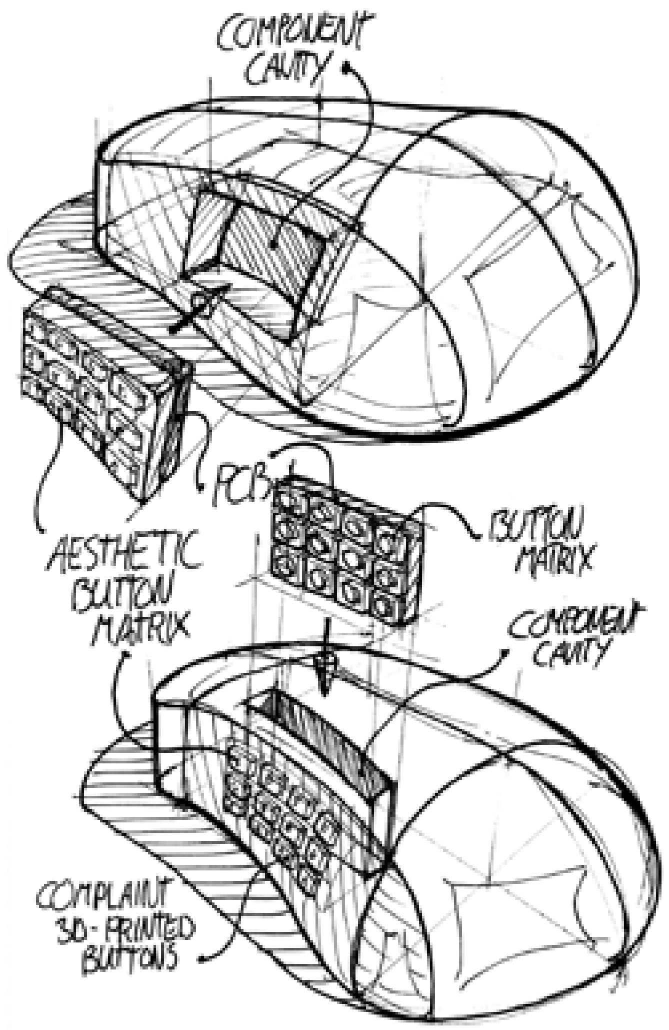
7.1.21. EXTRA IDEATION

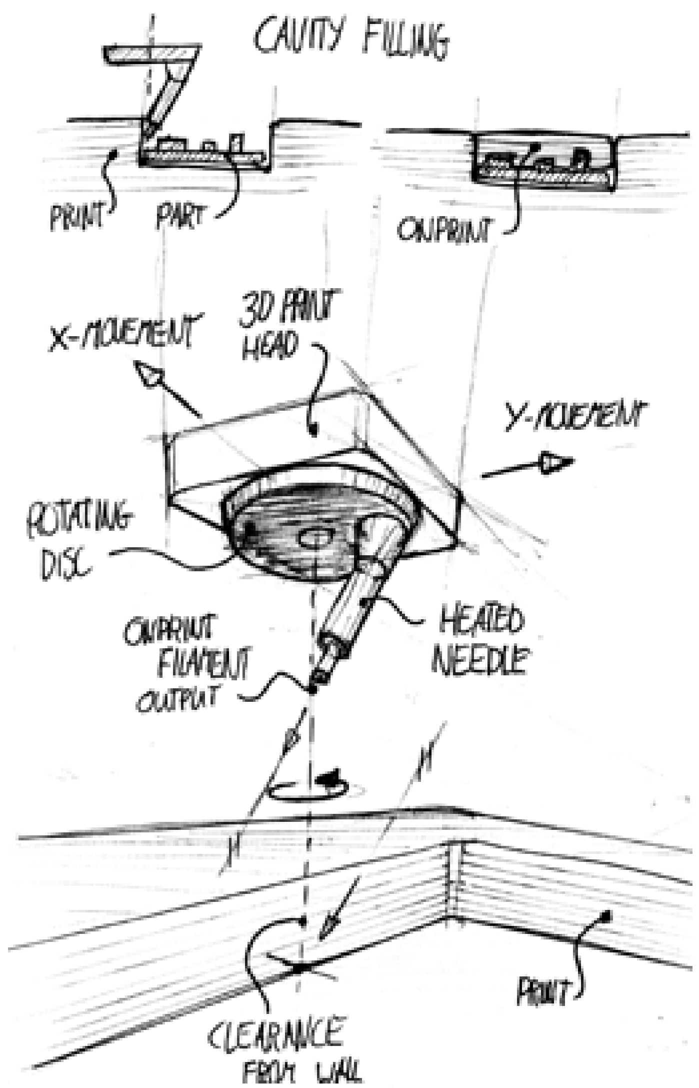
Some extra ideation drawings

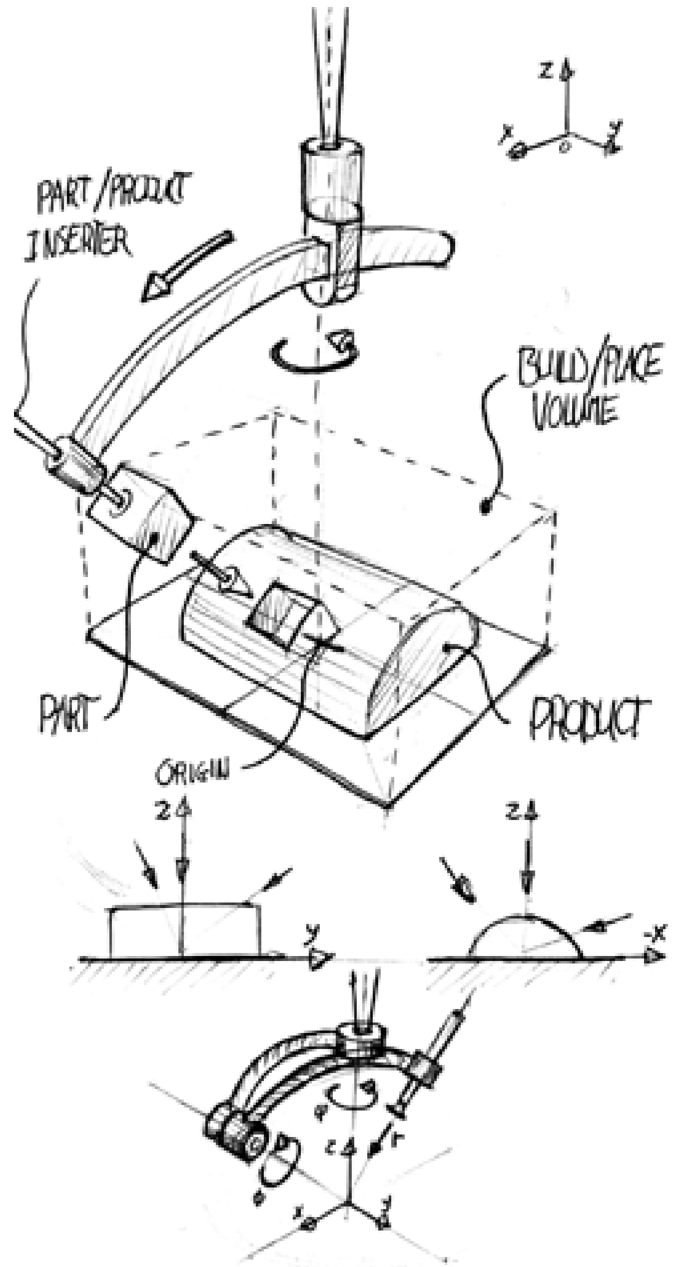


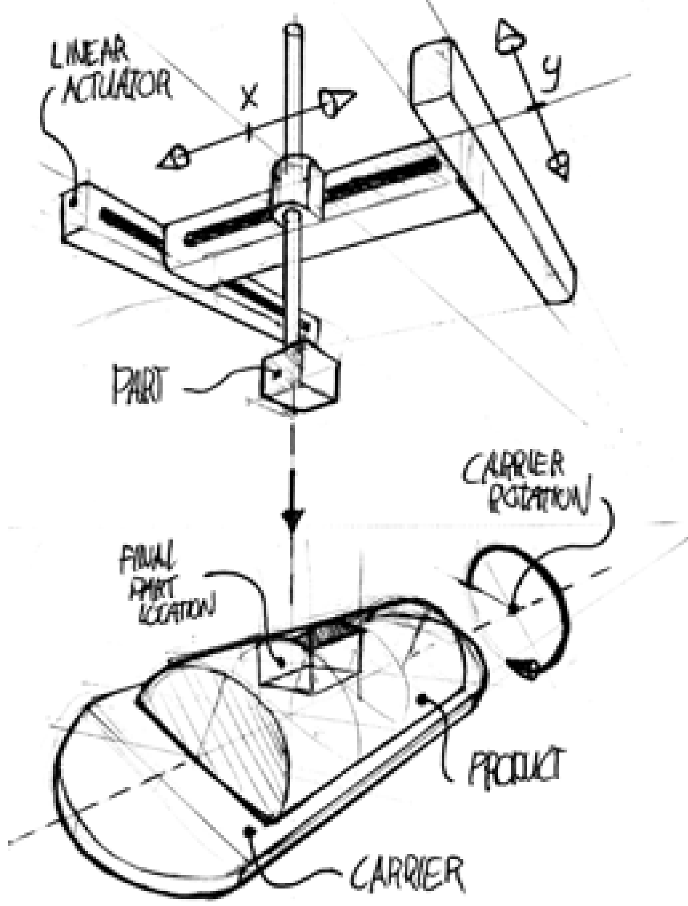


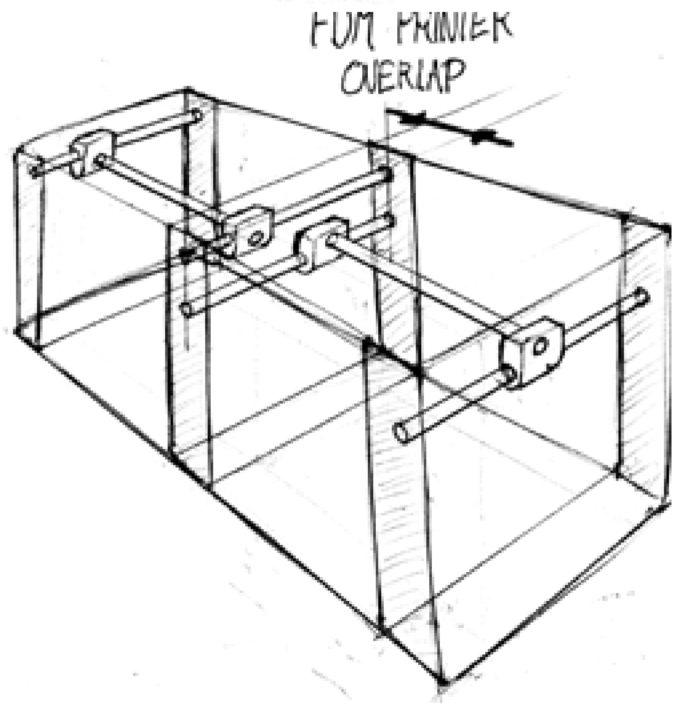


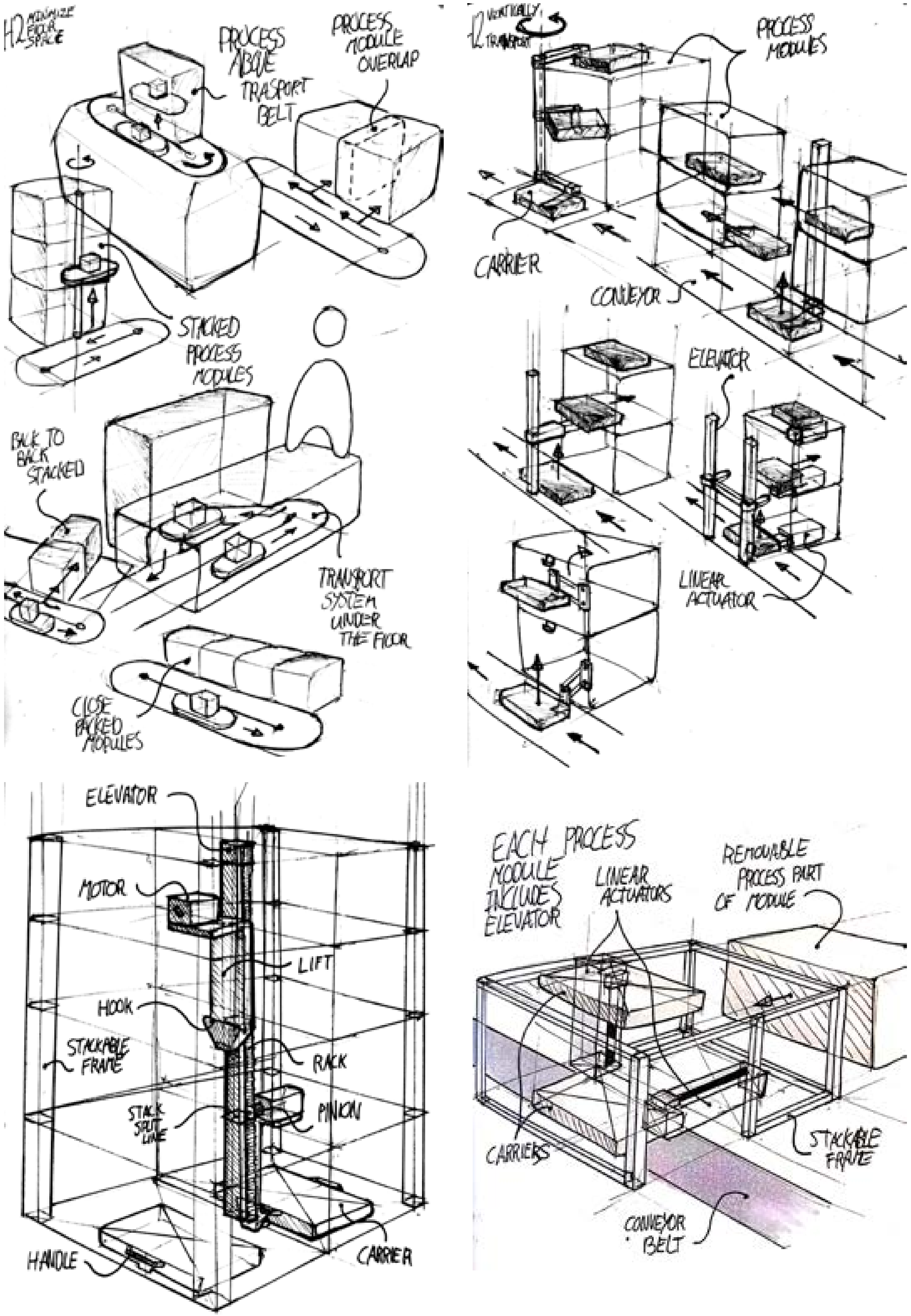






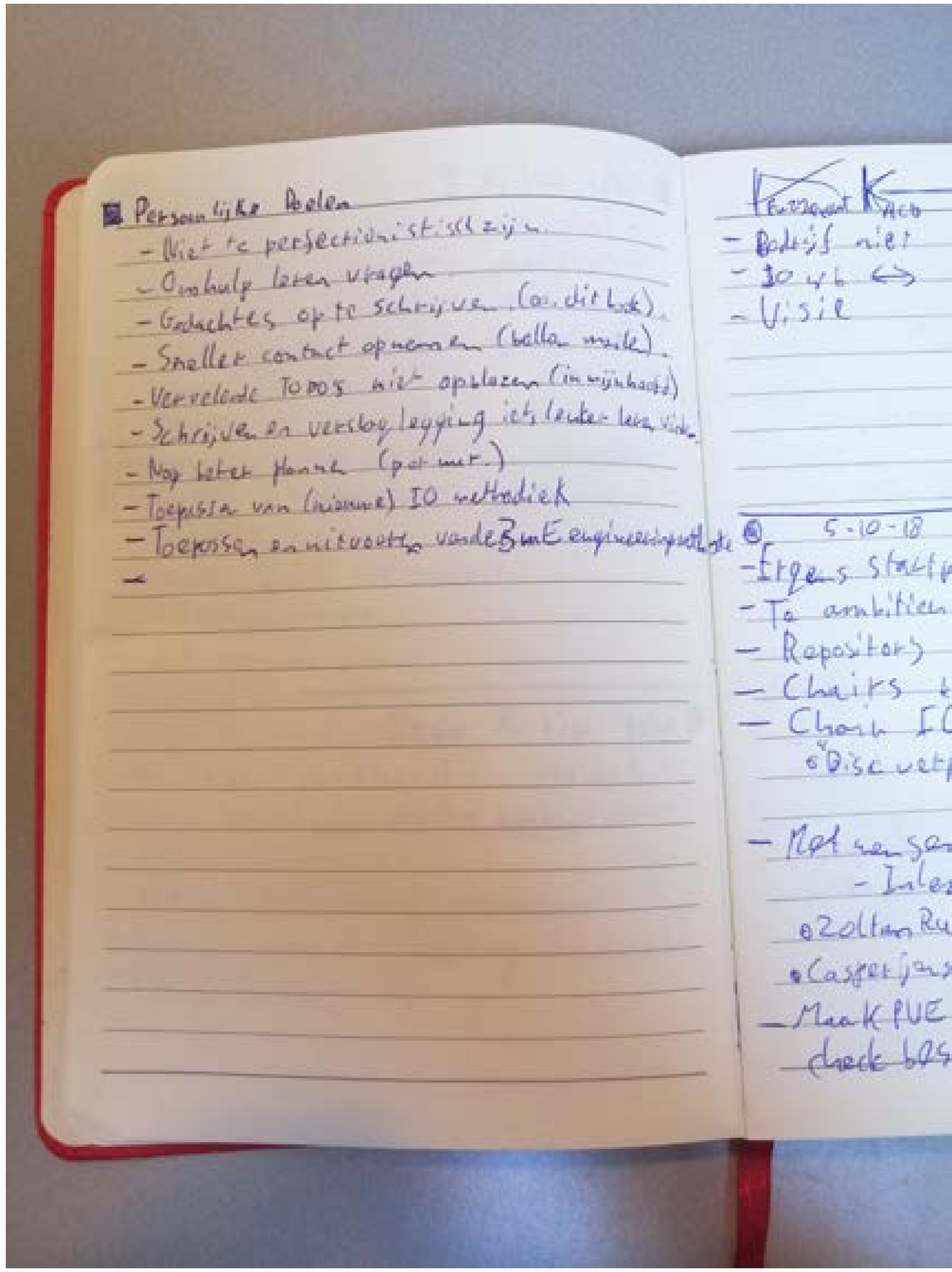






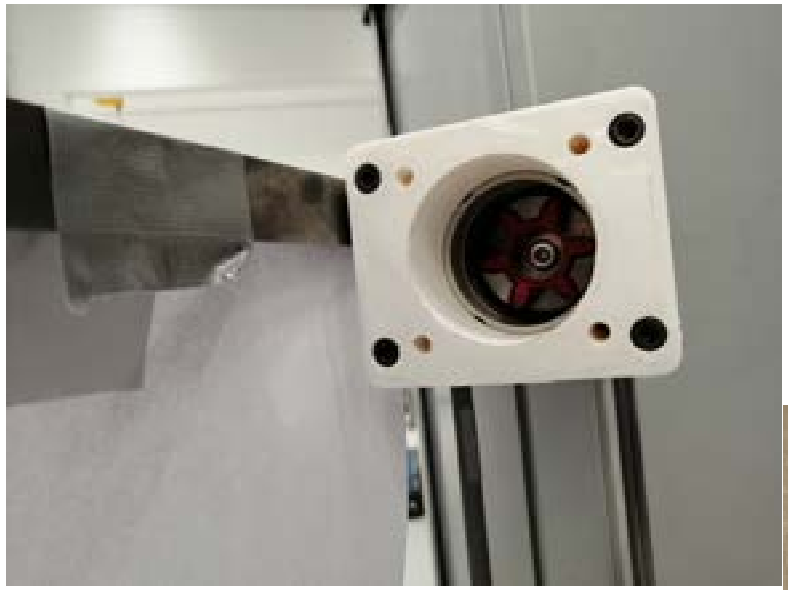
7.1.22. PERSONAL GOALS

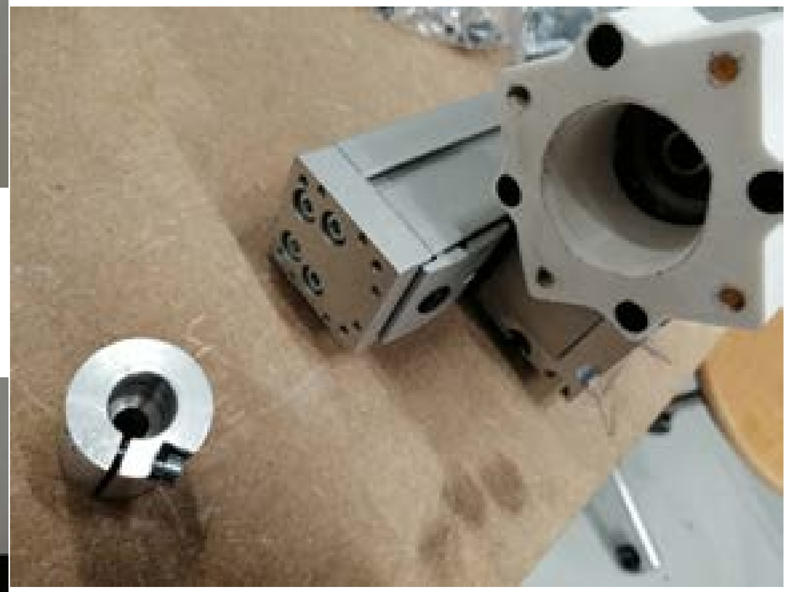
My personal goals for this graduation project.
Written down before 05-10-2018.

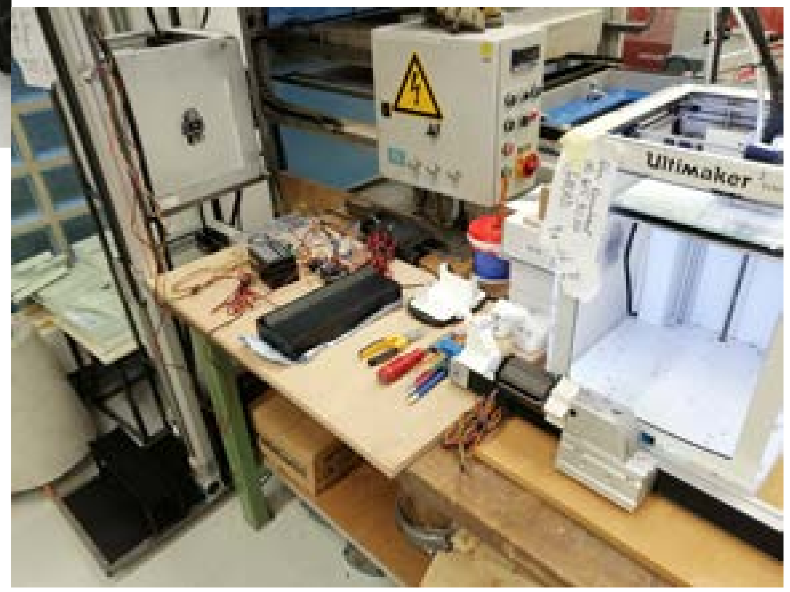


7.1.23. PROTOTYPE COLLAGE

Some extra pictures of the FDM-Cabinet prototype.







7.1.24. ORIGINAL IDE PROJECT BRIEF

IDE Graduation Assignment (version 2017.09.21)
incl. the student's study progress (Appendix 3)

To be completed by the student
Please save your assignment as (format): IDE Graduation Assignment_family name, name_student number_dd-mm-yyyy
Place the proper document name on each page of your assignment in the headline, number the pages

Name student	Ben Kromhout
Student number	4147901
Address	Buitenwatersloot 177
Zip- code, City	2613TE Delft
Telephone	0031631591134
E-mail address	kromhout.ben@gmail.com
Start at IDE 2011 (year)	Start at TU Delft 2011 (year)

Bachelor [1]	**Master** [1]	**Specialisation** [1]
☑ TUD Bachelor IO	☑ IPD	☐ Medisign
☐ TU/e or UT Bachelor ID	☐ DfI	
☐ TU Delft non-IO BSc	☐ SPD	**Annotation** [1]
☐ Other Dutch University Bachelor	☑ BMD. = 2nd non-IDE master	☐ Techn. in Sustainable Design
☐ HBO Bachelor	☐ Individual programme, date of approval [2]	☐ Entrepreneurship
☐ Foreign Bachelor	☐ Master Honours Programme	

Name Chair Prof. dr. ir. Geraedts, J.M.P.

1. Check study progress

To be completed by the Shared Service Centre O&S after approval of the assignment by the chair. The study progress will be checked for a 2nd time just before the green light meeting.

Bachelor degree:	☐ Yes	☐ No	☐ N.A.
Missing 1st year Master courses	1. .... 2. .... 3.	4. .... 5. .... 6.	

Master electives, no. of EC credits accumulated: ....

Name:	Date: ..... / ..... / 20.....	Signature:

2. Formal approval Graduation Assignment by the Board of Examiners

To be completed by the Board of Examiners

Approval of the content of the Grad. Assignment:	☐ Approved	☐ Not Approved
Procedural approval:	☐ Approved	☐ Not Approved

Comments:

Name:	Date: ..... / ..... / 20.....	Signature:

[1] *Tick where appropriate.*
[2] *Date of approval of your individual programme by the Board of Examiners.*

TU Delft / IDE / E&SA Department (update 20160915) Page 1 of 7

IDE Graduation Assignment

GENERAL INFORMATION

Title Graduation Project [3]	Mass Customization in the Cyber-physical Factory		
Chair of Supervisory Team [4]	Prof. dr. ir. Geraedts, J.M.P.		
Department / Section	Design Engineering		
Mentor of Supervisory Team [4]	Ir. Minnoye, A.L.M.		
Department / Section	Design Engineering		
Project commissioned by [5]	☑ Faculty	☐ Company	☐ Other, e.g. entrepreneurial
Project type [5]	☑ Design	☐ Research [6]	☐ Other, e.g. entrepreneurial
Company name, if applicable			
City & Country			
Company Mentor			
Start date	12-11-2018		
End date	05-07-2019		

CONTENT

Ascertain that the text of your Graduation Assignment clearly meets and reflects the general and specific requirements for your specific IDE master. [7]
Write your assignment in a neutral form.
When inserting images or schedules in colour, make sure a print in black and white is still readable.

Introduction

Give a sketch of the context of your assignment. Historical developments, if applicable relevant published scientific research results, new trends, status quo; materials, technologies, usage, etc.

- *In case of a faculty project: describe how your assignment reflects the research portfolio of the IDE Faculty* [6].
- *In case of a company project: provide company information.*
- *If other, e.g. entrepreneurial: describe the future enterprise and how your assignment will be of value to the enterprise.*

Include an illustration or visual which depicts the context of your assignment.
In case one or more extra parties are involved in your project, indicate which role they play.

After the first industrial revolutions starting with the steam engine, to assembly-line production, electricity and finally robot automation the fourth industrial revolution is about to take-off (Kagermann, et al., 2011).

In Industry 4.0, production and manufacturing systems are capable of self-monitoring, are interconnected by the Internet of Things and are connected to the cloud and the Internet of People (Kagermann, et al., 2013). These smart factories make it possible to adapt instantly to demand, maintenance, and the implementation of new designs. This results in an agile manufacturing approach capable of responding quickly to customer needs and enabling personalized products.

These integrated systems consisting of computer networks and physical processes are called Cyber-physical systems (CPS) (Khaitan, & Mccalley, 2014). And this is where the company Festo's Cyber physical Factory comes in. They have built a modular factory with building block style manufacturing machines that can be connected to each other in different arrangements to form a conveyor belt course. This course can include pick-and-place, drill, press and control-stops. The CP factory is promoted as a learning system for training and research purposes, to enable innovation and developments in the fourth industrial revolution ("Learning Systems for Industry 4.0", n.d.).

[3] *Keep the title compact and simple. Do not use abbreviations.*
[4] *Avoid team members from the same section. In case a non-IDE mentor is preferred over an IDE-mentor, the Chair should request so for approval by the Board of Examiners (including a motivation letter and c.v. of the proposed non IDE mentor).*
[5] *Tick where appropriate. See the IDE Graduation Manual, paragraph 2.5. If necessary, explain at Introduction.*
[6] *See webpage http://www.io.tudelft.nl/en/research/*
[7] *For general master specific requirements, consult article 4 of the Master Teaching and Examination Regulations, and the IDE Graduation Manual, especially paragraph 2.4 and 3.1.4.*

TU Delft / IDE / E&SA Department (update 20160915) Page 2 of 7

Festo observes that within the CP Factory the need for mass-customizable production is growing. To enable this they have asked to research and develop an agile manufacturing method to enable mass-customization within a specific module of the Cyber Physical Factory. With this module the factory is then able to produce custom one of a kind products on mass-produced scale (J. Koudijzer from FESTO, personal communication, 25-10-2018).

I am graduating for a Double Degree Integrated Product design (IDE) and Biomechanical Design (3mE) in the biorobotics specialization. Therefore the assignment will be different from both normal graduation projects. Namely longer in time (three quarters of a year) but smaller per separate study, this is possible due to overlap. My graduation team will exist of one mentor and two chairs, one for each faculty and I will deliver two separate thesis reports. Festo will have a supporting role, as opposed to managing role in my project, thus most of my project time will be at the faculties.

Problem definition

Indicate clearly, what should/could be improved compared to the present situation. When executing a research project: indicate the knowledge gap. What opportunities exist, what contradicting demands should be addressed, etc.

The current lean manufacturing mentality of optimizing productivity and reducing cost is not enough (Sharifi & Zhang 2001). Having warehouses in low wage-countries full of the same mass produced goods do not coincide with fast changing markets and the increasing need for mass-customized products; products that permit customized manufacturing on a mass basis (Davis, 1989). The agile manufacturing mentality of the fourth industrial revolution promises the solution.

To be an agile manufacturing company it must be able to respond quickly to unexpected market changes while maintaining a competitive advantage (Sharifi & Zhang 2001). To do this the factory first must be able to switch fast to new production layouts. And secondly have short connections with part- and material suppliers to negotiate new contracts quickly; or instead, is able to integrate most pre production processes into the factory itself.

When analyzing Festo's Cyber physical Factory in its current state it can be seen that the system is able to switch quickly to different production layouts due to its modularity. But the system is still highly dependent on part suppliers for further manufacturing of products. The only pre production module is a robotic arm to pick and place material in a CNC mill for machining. The system consists mostly of assembly type production modules and is not able to produce mass-customized products.

Although Festo's modular assembly line provides an initial throw towards a Cyber physical Factory of the fourth industrial revolution it is only a start, implementing important general ideas but lacking a realistic future vision and exemplary product implementation.

Assignment

Briefly and to the point, describe what you are going to design, create or generate to solve (part of) the problem. In case of a Specialisation and/or Annotation, address specifically how this is/these are included in the assignment.

The graduation project can be divided into three sub-assignments; each requires a different amount of effort from the two master directions:

To create a truly agile Cyber-physical Factory that is able to adapt rapidly to individual customer demands through mass-customization a future manufacturing system must be envisioned and all parts of the value chain evaluated (This will be a major part of the analysis phase).

To form a showcase implementation of this Industry 4.0 Cyber-physical Factory an exemplary product-family must be decided upon. This product-family must then be designed with mass-customized variation in mind (This design process will require mostly industrial design effort to complete).

This mass-customizable product need to be produced, therefore a working implementation of the Cyber-physical Factory must be embodied (This design process will require industrial design but mostly mechanical engineering efforts to complete).

Approach

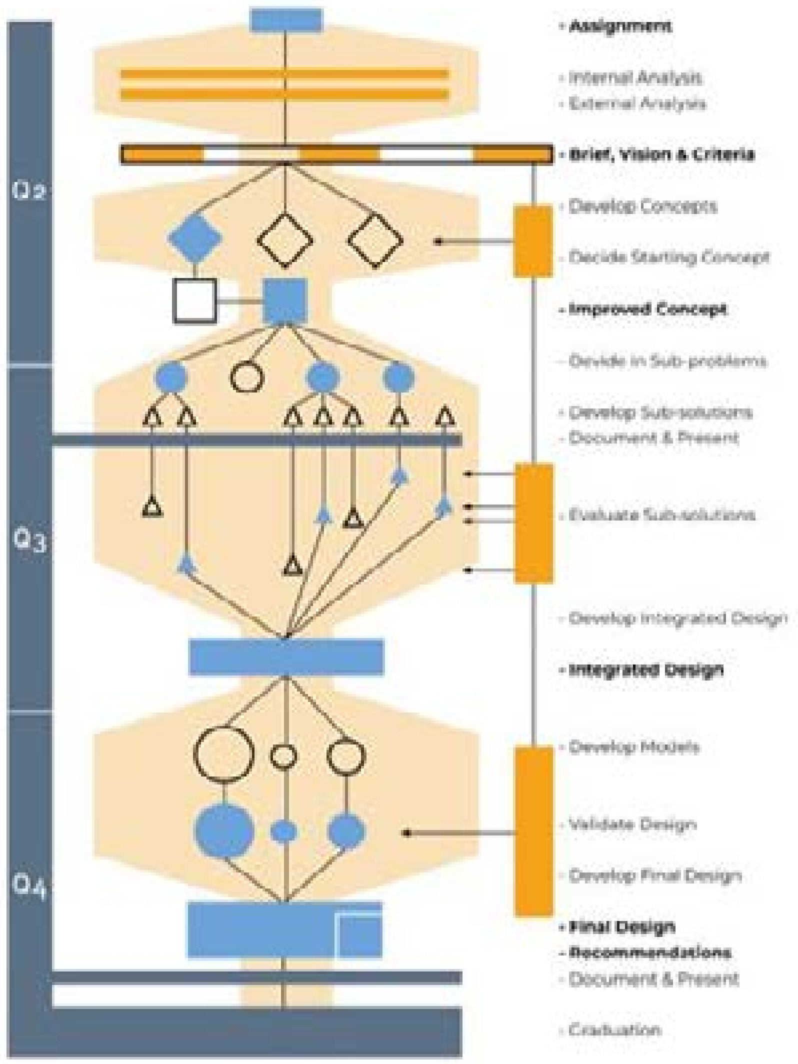
What will be the approach to deal with the complexity of the assignment? What has to be done to meet the challenges? Indicate the main methodologies to be used. Indicate the same project phases as you distinguish in your planning. If one or more extra parties are involved in your project, indicate which role they play.
In case of a Specialisation and/or Annotation, address specifically how this is/these are dealt with.

The process will start with an internal and external analysis and a literature review. The problem gets elaborated, the requirements defined and finally a future vision described.

A conceptualization phase is initiated, concepts are designed for both the exemplary product and the Cyber-physical Factory to fit the results from the analysis. These get developed into starting concepts which get discussed with Festo.

The chosen starting concepts are further improved in the embodiment design phase where the concepts are divided into sub-problems (challenges). Solutions are developed to tackle these problems and are evaluated on their capability and effectiveness by research and simulation

The best combination of solutions is chosen and those become the integrated design. This design will then be validated by simulation of abstract and physical models. Support of Festo will be needed to complete this on the necessary level. The results of the validation will be incorporated in the final design and in recommendations for further development.



Graduation Project results

1. *Describe the expected results or outcome of your Graduation Project. For instance, a product, a product-service combination, a strategy illustrated through product or product-service combination ideas.*
2. *Indicate the expected scientific and/or societal and/or commercial significance of the outcome of your project.*
3. *In case of a Specialisation and/or Annotation, address specifically the relevant results to be expected.*

The graduation project will result in a final design that is validated in its performance and capabilities. This final design will have the form of one or multiple models, either digital (CAD, Matlab etc.) and/or physical (prototype) and will be delivered next to the visual-textual design in the form of an Industrial Design report. There will be a second report in the form of an engineering paper, discussing the research, simulation and evaluation of the sub-solutions and the integrated design.

The resulting final design will form the starting point for research and development of mass-customization in the Cyber-physical Factory. It will add a module to Festo's existing smart factory thereby increasing its capabilities and forming a step in the direction of the fourth industrial revolution.

Deliverables

List the extra graduation deliverables, if any (apart from the mandatory deliverables being the thesis report, annexes if any, the poster and the representative pictures). For instance, a working prototype or a paper.

The mandatory Industrial Design Engineering deliverables being a thesis report, poster and two A4 pictures of the design will be delivered. Also a model will be delivered (digital and/or physical). Next to that a Mechanical Engineering research thesis will be delivered.

Relation and relevance to the domain of Industrial Design Engineering, the chosen master direction and the IDE pillars

Explain the relation of your project with the domain of Industrial Design Engineering and your master direction IPD, DfI or SPD.
1. *Relation of you project to the master IPD, DfI or SPD*

Furthermore describe the interface of your project with each of the IDE pillars:
2. *Business*
3. *Human Interaction*
4. *Technology*

Although the project will require a lot of mechanical engineering development, the design must be tied together in the current Cyber-physical Factory, its users and the current or future market of Industry 4.0. Thus focus need to be found in a concept design phase; resulting in direction that fits on these aspects. Then the design need to be finalized in an embodiment design phase, resulting in a viable product ready for production.

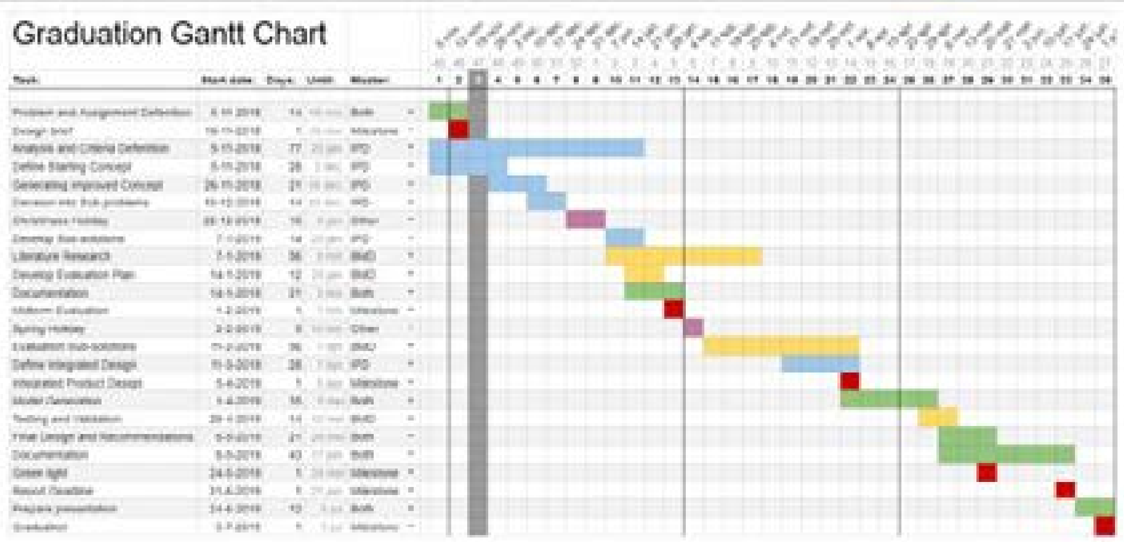
The business aspects of the project will be related to the implementation of mass-production in the Cyber-physical Factory, where concept choice will depend strongly on the chosen market. Furthermore the impact of the final design must be taken into account; what will it mean for Industry 4.0 and the Company.

The Human Interaction aspects of the project will be very interesting, because what role will the human operator take in these Cyber-physical Systems or the fourth industrial revolution as a whole; how will they control the factory, what will maintenance look like and which manufacturing steps are still dedicated to human effort.

The Technology aspects will have the most prominent place within the project. Developing a precision mechanism, fully automated and connected to the Internet of Things making personalized rapid series of one production through digital manufacturing.

Planning

Present your planning in a Gantt Chart, which can easily be made in Excel, see example underneath. Make sure a print in black and white is still readable. Mention the main phases of the project as described at Approach + number of weeks. Indicate only main activities, milestones, meetings. Take notice: 33 EC = 22 full-time weeks! Indicate periods of part-time graduation project activity and/or periods of not spending time on your graduation project, if any, for instance because of holidays[*].



Brief explanatory remarks on the planning, if any.

The planning follows the same structure as described in the approach.

Further comments and information

In case your Assignment needs further comments, please add any information you think is relevant.

References:

Kagermann, H., Lukas, W., & Wahlster, W. (2011). *Industrie 4.0. Mit dem Internet der Dinge auf dem Weg zur 4. Industriellen Revolution.* Retrieved from http://www.wolfgang-wahlster.de/wordpress/wp-content/uploads/Industrie_4_0_Mit_dem_Internet_der_Dinge_auf_dem_Weg_zur_vierten_industriellen_Revolution_2.pdf

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Sharifi, H, & Zhang, Z. (2001). Agile manufacturing in practice - Application of a methodology. *International Journal of Operations & Production Management*, *21*(5/6), 772–794. Retrieved from https://www.emeraldinsight.com/doi/full/10.1108/01443570110390462

Davis, S. M. (1989). From "future perfect": Mass customizing. *Planning Review*, *17*(2), 16–21. https://doi.org/10.1108/eb054249

[*] *Only by approval of the Board of Examiners, a not yet passed course may be combined with the Graduation Project. In such case, show the approval to your Chair and indicate the period of not spending time on your Graduation Project for this reason.*