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Analysis and adaption of manufacturing systems regarding to growing challenges in engineering

MASTER'S THESIS

to achieve the university degree of

Master of Science

Master's degree programme: Production Science and Management

submitted to

Graz University of Technology

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2015

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Acknowledgements

At this point I would like to express my graduate to following persons, who supported and encouraged me throughout my master thesis.

First, I would like to express my deepest graduate to my supervisor Dipl.-Ing. Thomas Stöhr for his useful comments, remarks and engagement. He guided me through the learning process of this master thesis and took always time for giving feedback, which helped me to keep on the right way. Apart from to that, he spent some time for introducing me to the interesting topic of FEM.

Furthermore I would like to thank Ass.Prof. Dipl.-Ing. Dr.techn Christian Landschützer for his continuous support, remarks and his friendly advices, especially at the very beginning of this thesis.

Also, I like to thank all members of the Institute of Logistics Engineering who supported me with their expert knowledge and led me to new ideas and thinking approaches.

Last but not least, I would like to thank my parents, who supported me through my whole study and enabled me to begin my study at the Graz University of Technology.

Abstract

This thesis is dealing with the growing requirements on modern manufacturing systems and their influence on the product development process. Traditional Manufacturing systems often reach their limits due to increasing demand of product variety, decreasing life cycles of products and inconsistent demand of production volume. This leads to a quest for alternative manufacturing systems, which can be adapted in order to cope with that mentioned trends.

Following up on this question, a detailed problem analysis is the base required for a further analysis of different manufacturing systems regarding to their economic efficiency and influence on the product development process and product design. This analysis also considers the emerging Additive Manufacturing. A further measure is a meaningful evaluation to support the decision-making process for suitable systems.

A practical example of a product to be developed and which is linked with almost the identical requirements, as discussed in the theoretical part, points out the influence of a particular manufacturing method on the product development according to VDI 2221.

Zusammenfassung

Diese Arbeit befasst sich mit den immer höher werdenden Anforderungen an Produktionssystemen und deren Einfluss auf den Produktentwicklungsprozess. Der Einsatz von konventionellen Fertigungsverfahren ist durch die steigende Nachfrage von Produktvariationen, immer kürzer werdenden Produktlebenszyklus und fluktuierender Nachfrage von Produkten beschränkt. Daher besteht die Aufgabe dieser Arbeit, ein Produktionssystem zu finden, welches an diesen steigenden Trend adaptiert werden kann.

Ausgehend von dieser Frage dient eine detailierte Problemanalyse als Basis für weitere Analysen verschiedener Produktionssystemen bezüglich ihrer Wirtschaftlichkeit und deren Einfluss auf den Produktentstehungsprozess sowie auf die Produktgestaltung. Analysiert wird zudem auch das aufstrebende Generative Fertigungsverfahren. Als Entscheidungshilfe um schlußendlich ein geeignetes System zu finden, welches den Anforderungen entspricht, dient eine aussagekräftige Nutzwertanalyse.

Um die Erkenntnisse aus der Theorie nochmals zu bekräftigen, umfasst der konstruktive Teil dieser Arbeit die methodische Entwicklung eines Neuprodukts, welches die im theoretischen Teil beschriebenen Anforderungen stellt. Als grundlegende Unterstützung des Produktentwicklungsprozesses dient dabei die Richtlinie VDI 2221.

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Abbreviations

3DP	Three Dimensional Printing (Dreidimensionales Drucksystem)
AM	Additive Manufacturing (Generatives Fertigungsverfahren)
CAD	Computer Aided Design (Computergestütztes Konstruieren)
CNC	Computerized Numerical Control (Computergestützte numerische Steuerung)
DFA	Design For Assembly (Methode und Werkzeug zur montagegerechten Produktentwicklung)
DFM	Design For Manufacture (Methode und Werkzeug zur fertigungsgerechten Produktentwicklung)
DFMC	Design For Mass Customization (Kundenindividuelle Massenproduktion)
DM	Direct Manufacturing (Generative Fertigung von Bauteilen)
DOD	Digitally Optimal Design
DT	Direct Tooling (Generative Fertigung von Werkezeugen)
EBM	Electron Beam Melting (Elektronenstrahlschmelzen)
EP	Evaluation Point (Bewertungspunkt)
FDM	Fused Deposition Modeling (Schmelzschichtungsverfahren)
FEM	Finite Element Method (Finite-Elemente-Methode)
IM	Injection Molding (Spritzgussverfahren)
LOM	Laminated Object Manufacturing
PLC	Product Life Cycle (Produktlebenszyklus)
PJ	Polymer Jetting
PP	Polymer Printing
PT	Prototype Tooling (Generative Fertigung von Negativen aus Prototypenmaterial)
RM	Rapid Manufacturing (Generative Fertigung von Positiven oder Negativen)
RP	Rapid Prototyping (Generative Fertigung von Modellen und Prototypen)

RT	Rapid Tooling (Generative Fertigung von Negativen)
SL	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
TM	Traditional Manufacturing (Subtraktive und formative Fertigungsverfahren)

Note: As this thesis is written in American English, dots are used as a decimal separator (e.g. 0.11) and commas are used as a separator for integer numbers after every third digit from right to left (e.g. 10,000).

1 Introduction

1.1 Initial situation and problem statement

Over time, customer and industry expectations in product quality and reliability have become higher and product variety is increasing. At the same time, the product life cycle (PLC) is decreasing [MUR06, pp. 27-30]. According to Pine and Da Silveira, increasing product variety is caused by the increasing demand of alternative products on the market. Customers are able to choose between different types, colors and sizes of products. The reason for the decreasing PLC is that products are becoming more influenced by fashion trends and rising global competition [PIN93, DAS01]. Increasing competition also leads to the fact that newly developed products must enter the market in time. Otherwise financial loss may be suffered. In order to illustrate these market changes, the development of the Volkswagen Golf series can serve as an example. When the first Golf has been introduced in 1974, two different configurations have been available and the car model itself has been produced until 1984 [FIS01, pp. 188-189]. In comparison to that, the new Golf generation is served with twelve different configurations and the generation before has been produced for three years.

These growing trends lead to new challenges for engineers during the product development phase, but also for manufacturing systems, as they need to be very flexible. It is essential to guarantee the introduction of error-free products and finally to avoid financial disasters. Regarding from the above mentioned content, this thesis is focusing on following problem statements:

- **The want for customization**: Traditional manufacturing (TM) struggles with the increasing demand of customization, since tooling is expensive and often TM is not flexible enough to deal with a high variety of products and small batch sizes (Figure 1-1).
- **Time-to-market and cost efficiency**: Due to the decreasing life cycle of products and the need to adapt to changes rapidly, responsive production gets more essential (Figure 1-1). This requires a fast performing product development.
- **Design for manufacture and assembly (DFM & DFA)**: The increasing geometric complexity of functional parts leads to new challenges for engineers and designers, since traditional manufacturing is often limiting the design freedom.

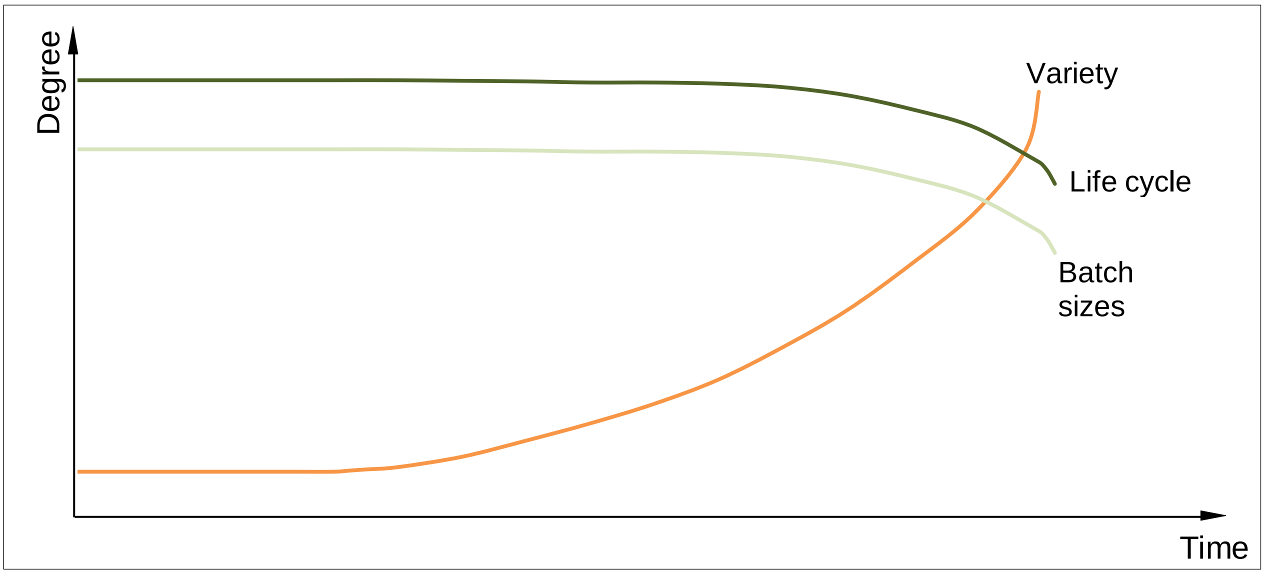


Figure 1-1: Product market trends [MCD01, p. 26]

By the first use of the relatively new Additive Manufacturing (AM), a tool has been established, in order to support and optimize the development of products. It has the potential to compete with traditional manufacturing (TM) methods and finds also application as a stand-alone manufacturing system, especially well-known for the self-fabrication of individual parts.

1.2 State of research

Following list is an excerpt of scientific standard work on the topic of product development and the influence of manufacturing systems that already exist:

- “Product Development” deals mainly with design issues in the product development process. Mital reveals the importance of an optimized product development process from an economical and strategic point of view. The influence of manufacturing systems on the product development process is treated only briefly and the influence of AM is not treated at all [MIT14].

- “Generative Fertigungsverfahren – Rapid Prototyping, Rapid Tooling, Rapid Manufacturing” examines the influence of AM during the whole product creation process. As the title implies, emphasis is put on Rapid Prototyping, Rapid Tooling and Rapid Manufacturing, which are different applications of AM. In addition to that, this literature deals also with strategic approaches in the use of models and prototypes and how they affect the product development. Among fundamentals about AM, Gebhardt reveals on different practical examples. A comparison between AM and other manufacturing systems, regarding the product development process, is not covered [GEB07].

- “Rapid Prototyping Casebook” offers several AM case studies from different industries, which are described by an experienced team of the University of Warwick. Each case describes the advantages and benefits of AM in the particular field of industry, by means of a practical example. The influence of AM or other manufacturing systems, on the product development is not described in detail [MCD01].

1.3 Research objective

As it can be seen above, there have been done hardly any investigations regarding the influence of both, TM and AM systems, on the product development process. The overall objective of this thesis is to develop a methodical approach to find a manufacturing system, which can be adapted to the growing challenges of increasing product variety, increasing product complexity and decreasing PLC. Especially the potential of AM to cope with these trends should be investigated. The findings obtained in this analysis can be put to direct use for faster and more efficient development of products. As a first step, it is necessary to investigate first the problems occurring during the product development process and the challenges for manufacturing systems, caused by the mentioned trends. By means of this gathered information should be investigated at which stages the three main issues influence the product development process in order to derive evaluation criteria. These criteria should enable a meaningful evaluation of various manufacturing systems regarding their specific characteristics.

A product development case study should confirm the findings obtained. In this case study, a solution should be developed to increase the efficiency for a service company, which is focused on table ware renting, by means of introducing a new product.

Finally it should be mentioned that this thesis is exclusively considering the systematical approach to the design of technical systems and products according to VDI 2221 and that the consideration of other approaches of product development can lead to other evaluation criteria and as a result to different findings of the evaluation.

2 Problem analysis and basics

Firstly, this chapter deals with basics and definitions and fundamentals about AM. Secondly, the trends mentioned in chapter 1, are analyzed more accurate in order to get a deeper understanding of these issues.

2.1 Definitions

According to the American Society for Testing and Materials (ASTM) AM is "*a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies*" [ASF12].

TM is defined as "*the act of converting raw materials into finished products by using manual or mechanized transformational techniques*" [DIN03]. This definition includes casting, molding, forming, machining and joining.

2.2 Fundamentals of additive manufacturing

When Gebhardt is talking about AM, he distinguishes between two main application levels, Rapid Prototyping (RP) and Rapid Manufacturing (RM) [GEB11, p. 6]. According to Chua and Leong AM applications are grouped into design, engineering analysis and planning, and manufacturing and tooling [CHU15, p. 6]. In order to get a better overview of the different application levels, this thesis follows the definition of Gebhardt (Figure 2-1).

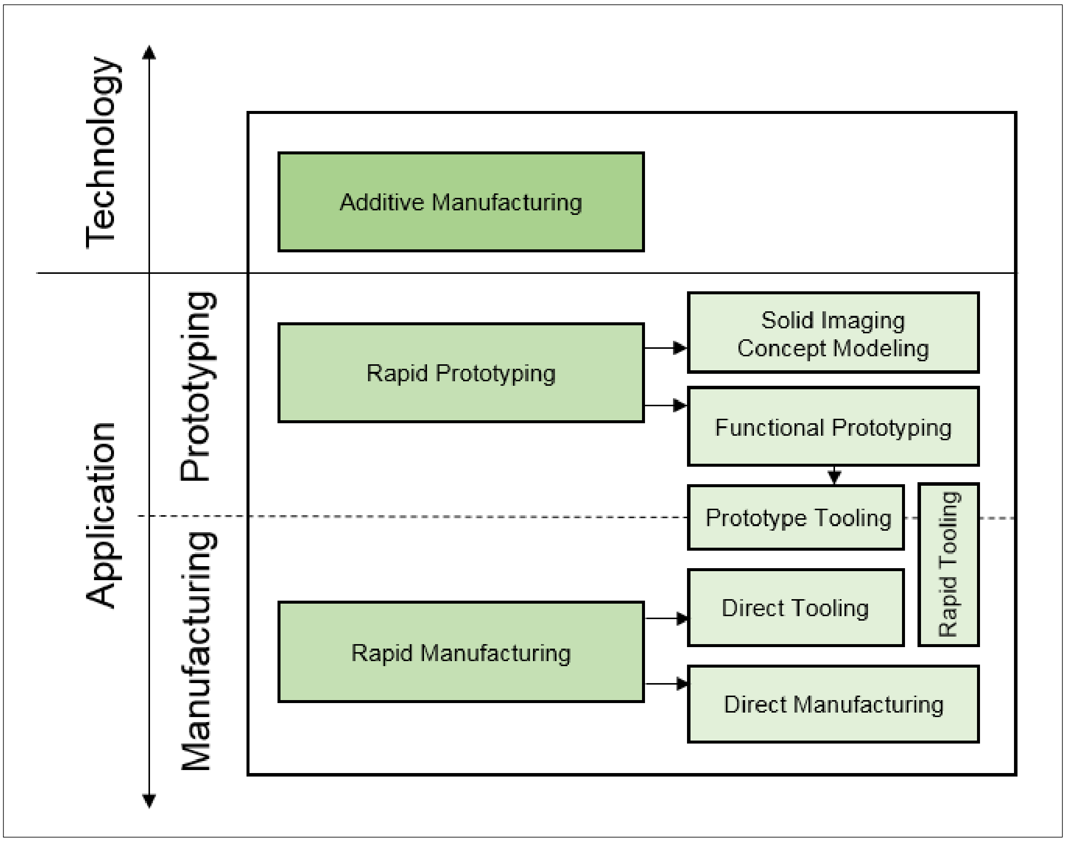


Figure 2-1: AM application levels [GEB11, p. 1]

Rapid Prototyping

In general, RP is divided into Solid Imaging (SI) or Concept Modeling (CM) on the one hand and Functional Prototyping (FP) on the other hand. Solid imaging or Concept modeling is used to meet the needs for three dimensional visualizations, creation of sculptures or concept models. In most cases both applications are not loadable, whereas functional prototypes provide full functions of the coming end product [GEB11, pp. 7-10]. A closer look of the different models and prototypes is taken in section 3.2.

Rapid Manufacturing

Related to Hopkinson and Dickens, RM is defined as the creation of parts that are used directly as finished product or components. A distinction is made between Direct Manufacturing (DM) and Direct Tooling (DT). DM means that the produced part comes directly from the AM process. In contrast to that, DT is a method to create a negative in series quality for further production. Such a negative can be a die, a mold or a gauge [HOP06, pp. 1-2].

Rapid Tooling

Prototype Tooling (PT) is a sufficient way to create a negative out of substitute material with the quality of functional prototypes [OHA11, pp. 15-17]. It is another sub-level and finds its place between Functional Prototyping and Direct Tooling. Rapid Tooling (RT) is not a separate application level, but sums up the sub-levels Prototype Tooling and Direct Tooling, thus, all AM applications that lead to tool inserts, molds and dies.

2.3 Additive manufacturing principles

AM can be divided into three sub-groups, where all AM applications find its place [CHU15]. Figure 2-2 illustrates the most common principles. For more detailed information about different AM principles, the author refers to Gebhardt, 2011 and Chua, 2015.

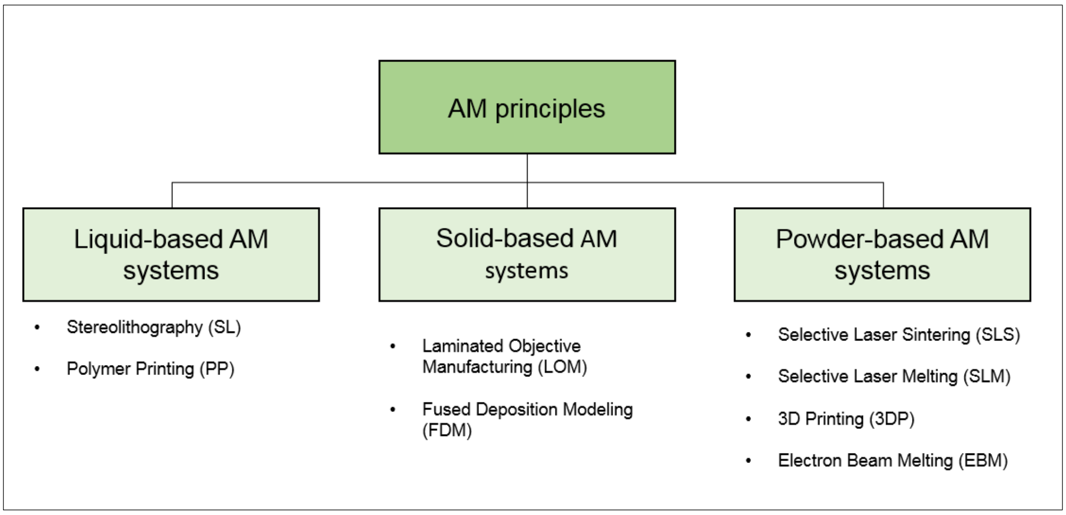


Figure 2-2: Classification of AM systems

Liquid-based additive manufacturing systems

The basic idea of most liquid-based processes is to build parts of photocurable liquid resin that solidifies under the exposure to light. The most photopolymers are curable in the UV-range, but there are many types of liquid photopolymers that are curable by irradiation with light of wavelengths in the gamma rays, X-rays or visible range as well [WIL74, LAW94]. The fundamental approaches are Stereolithography (SL) and Polymer Printing (PP), which is sometimes also called Polymer Jetting (PJ).

- **SL** is the solidification of photocurable liquid out of a vat by photopolymerization caused by irradiation of light in the UV-range [BÀR11, p. 6].
- **PP** is an approach of applying drops via print head of liquid photopolymer to build layers and curing them with UV light [CHU15, p. 31]

Solid-based additive manufacturing systems

In opposite to liquid-based AM systems, solid-based AM systems are processing solid materials in order to fabricate the desired part. The most common solid-based AM systems are the Laminated Object Manufacturing (LOM) and the Fused Deposition Modeling (FDM) process.

- **LOM** is based on stacking adhesive-coated material layer by layer [KAM10, p. 347]. A fundamental advantage of LOM is to build parts with materials whose phase change is not possible or undesired, e.g. paper material [KRU98].
- **FDM** builds layers out of thermoplastic material, which is heated by an extrusion head and applied by nozzles. Once the material is extruded, it solidifies immediately due to the temperature level, which is just above the melting temperature of the filament [YAN95].

Powder-based additive manufacturing systems

Powder-based AM systems are a special group of solid-based AM systems, since they are processing with solid building material, but particles. This sub-group includes the Selective Laser Sintering (SLS), Selective Laser Melting (SLM), the well-known Three Dimensional Printing (3DP) process and the Electron Beam Melting (EBM).

- **SLS** is based on layer-by-layer powder spreading and laser sintering, where particles are fused to each other by raising their temperature above the glass-transition temperature [DON15, p. 16].
- **SLM** is a similar process to SLS, but has the main advantage that full density parts can be produced, due to the powder particles are fully molten [KRU04].
- **3DP** is another way to build parts directly from CAD models in a powder bed. An inkjet print head applies an adhesive binder in order to build layers out of powder material [MIC93].
- **EBM** is a process where metal powder melts through the irradiation of an electron beam in order to fabricate full dense parts without any binding agent, similar to SLM [COR04].

2.4 The want for customization

The increasing demand of customization leads to new challenges for TM systems. In order to ensure the production under the aspects of customization, a wide variety of tools and inventory is necessary. In addition to that, product development must be adapted to the desired degree of customization. In ascending order with respect to the degree of customization, Gebhardt distinguishes following types of customization [GEB11, p. 118]:

- **Small batch production** is the production of a non-modified product on demand.
- **Individualization** is an approach that deals with different variations of a product in order to meet the customers' requirements. The customer has no direct impact on the design.
- **Personalization** is the development and production of a unique product.

Small batch production

Small batch production is the quantitative approach of customization. That means, individual production driven by the quantity of produced goods. A costumer can order one single piece or several pieces over a certain period of time. This production strategy causes the following problems, related to TM [GEB11, pp. 128-129]:

- Either the production runs for uneconomic small batches several times or creates overstock. The units are then kept in stock as long as they are requested.
- Exact process planning is difficult and often linked with a small number of assurance [ARN12, p. 96].

Individualization

Individualization is the qualitative approach of customization. The costumer is able to choose between different variations of the product [GEB11, pp. 129-132]. A concept for individualization is Design for Mass Customization (DFMC), which is a special approach in order to meet demand for customization. DFMC is based on a product family architecture in order to obtain a family-based design, instead of designing a unique product. Along with DFMC, following challenges emerge [TSE96]:

- Enable the reusability of design, production capabilities, tooling, supplier base, process plans and manufacturing logistics.

- Maximizing the repeatability of the unified product family architecture.

Personalization

For personalized production, this approach is not suitable anymore, as the customer requests a unique product. Often only one tool is suitable for a unique product; especially injection molding processes are limited by that fact. Any change in the product design or functionality requires an additional tool, in order to create a part, which meets the desired quality. New additional tools are expensive, especially molds but also tools for machining. Figure 2-3 points out the high costs per part in connection with low volume production. Obviously, these part costs include all fix costs, related to the produced part, like costs for tools and inventory as well [BEA15, p. 110]. Thus, personalization is often limited due to the economic efficiency when producing with TM [GEB11, p.132]

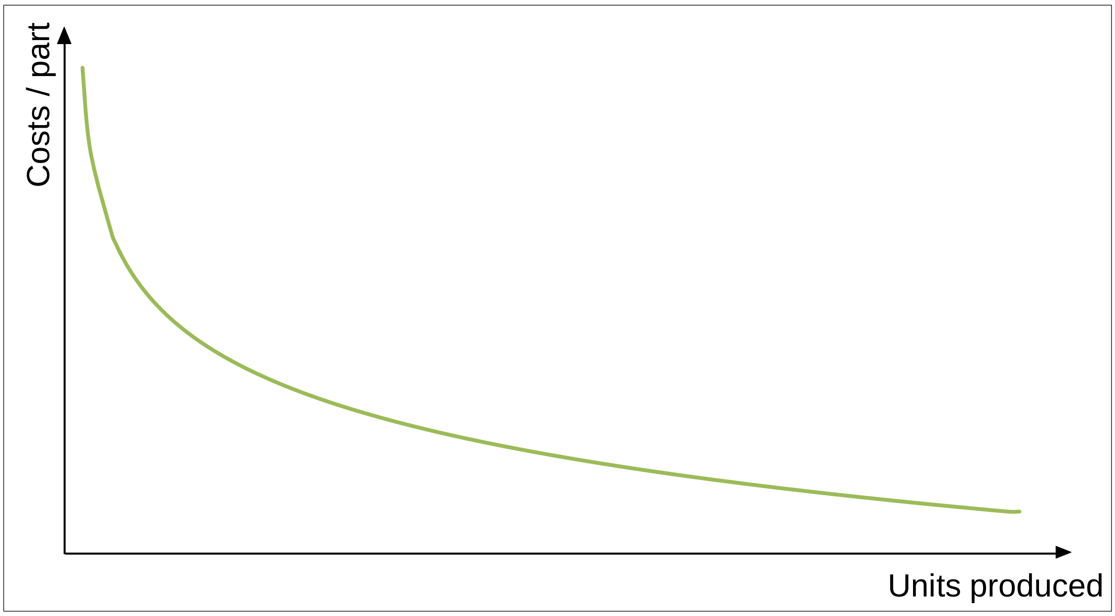


Figure 2-3: Economic of scale [BEA15, p. 110]

2.5 Time-to-market and cost efficiency

Nowadays, many industries are characterized by products with decreasing product life cycles, e.g. automotive industry. Therefore, it is essential, especially for those industries, to have an exact timing for market introduction. Time-to-market is a significant success factor of a product [KOM98, p. 167].

The faster a product can be introduced to the market, the higher is the profit. According to a study by McKinsey, not the development costs but rather the early market introduction is relevant for the company's profit. Introducing a product six months later as planned, leads to 33% of profit loss, whereas doubling development costs, reduces the profit only by 3.5% [KLE00].
In addition to that, during the designing and development phase around 70% of the overall costs are defined but the resulting costs at that stage are only around 7%. This 70% of the overall costs are partly influenceable in that phase (Figure 2-4). That means, any change during that stage can be executed without being too much cost intensive [EHR2013, p. 662].

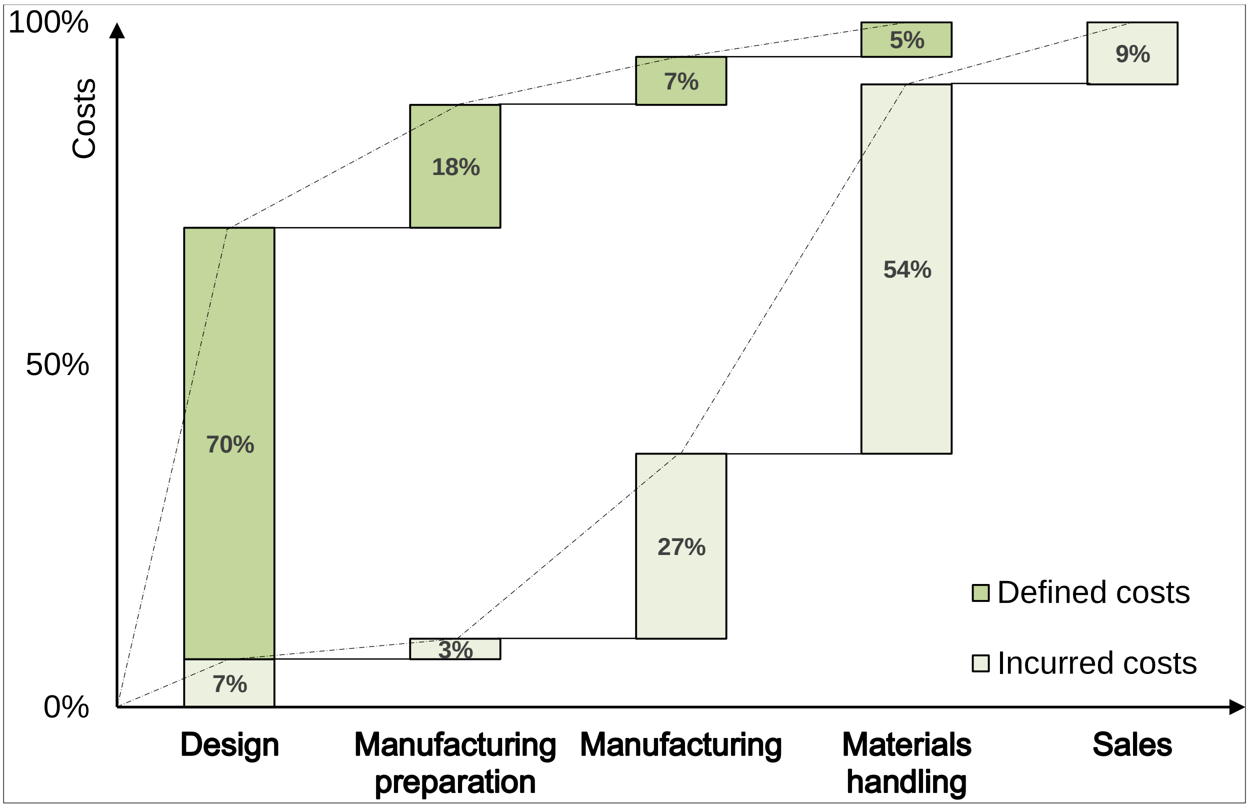


Figure 2-4: Cost incurrence in the different departments [EHR13, p. 662]

This highlights the importance of an efficient product development process. Models and prototypes are suitable to support the product development and to detect errors in the early stages of the product development. Testing the model and improving the design is an iterative process and very useful to prevent avoidable costs and to shorten the time-to-market. Figure 2-5 shows an example of prototyping in the product development with the different types of models and prototypes [KÖN13].

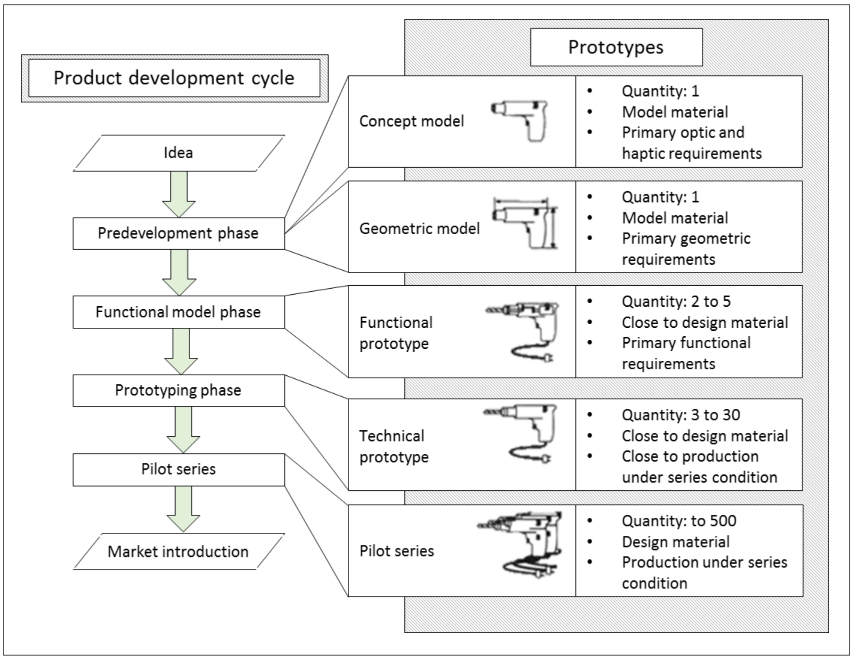


Figure 2-5: Example of prototyping in the product development [KÖN13, p. 232]

A very common systematic approach for product development is the VDI 2221. Figure 2-6 shows the cycles in product creation and the involvement of models and prototypes. This old-fashioned approach highlights following problem according to the iterative design process, mentioned above:

- In order to obtain a first model or prototype for testing, a first concept and a design, followed by manufacturing and assembly is required (Figure 2-6). Latter is often very time-consuming, as the production of functional models or prototypes via TM requires a certain number of machineries and tools.

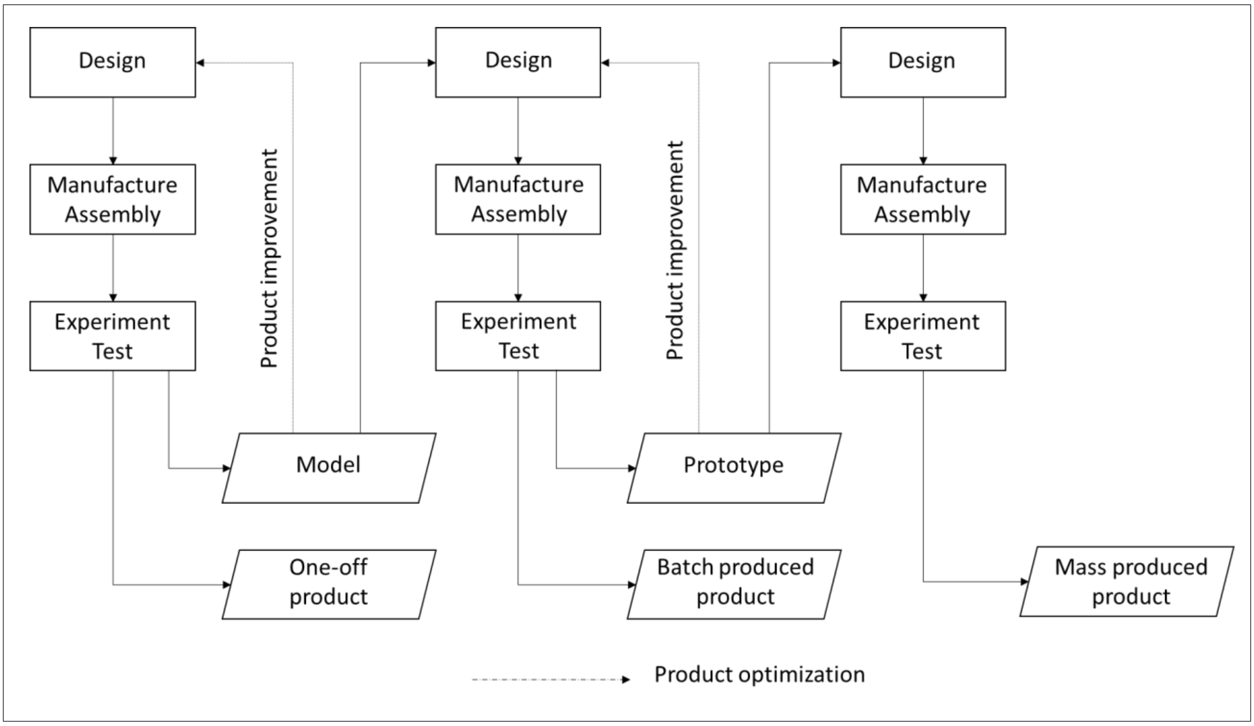


Figure 2-6: Cycles in product creation [VDI93]

2.6 Design for manufacture and assembly

As already mentioned in section 2.5, the design and development department has a huge influence on the following costs. Therefore, it is essential to design a product that can be manufactured easily and economically. In that respect, DFM has been introduced to achieve this goal. DFM is a guideline and stands for the minimization of manufacturing time and costs by the means of design measures. This contains the focus on component structure, choice of material and component design. DFM concentrates on following issues [RIE12, p. 451]:

- Determination of the component structure in order to get an overview of all single pieces and to define a manufacturing method for each one.
- Determination of the component design, where the design is adjusted to the chosen manufacturing method. The design must be aligned to the belonging design guideline, like design for casting, design for forging, design for welding, etc. Table 2-1 gives a brief insight into the design restrictions related to each manufacturing method [MIT14, p. 133-158].

Table 2-1: Design issues related to TM [MIT14, p. 133-158]

Manufacturing method	Design issues
Casting	• Sharp corners and angles should be avoided, due to stress concentration • Thick sections should be avoided, since longer time for cooling and solidification leads to shrinkage • Requires draft angles, in order to release the part from the mold
Metal stamping	• Shapes should be nested close together to reduce the scrap rate • Grain direction should be considered, in respect to the part's strength • Sharp edges should be avoided, as they can cause cracks
Milling	• Tool contour can cause problems when fabricating corner shapes, slots and small radii • Rigid parts are required, in order to withstand cutting forces • The production of undercuts is difficult and should be avoided as far as possible
Injection molding	• Thick sections should be avoided, as they can cause warping, twisting or cracking • Requires draft angles, in order to release the part from the mold • Necessary part line can be complex due to the part geometry

Table 2-1 reveals that a part's design is restricted with every TM method. With increasing geometric complexity, the costs for TM increase exponentially and at a certain degree of complexity, design opportunities are restricted due to TM technology [MER12]. This leads to challenges for engineers and designers, as they must always keep DFM in mind.

The DFA guideline focuses on improvements for easy assembly. Designers are supposed to consider DFA in product development as well. Reduction of parts count, reducing handling time and ease of insertion are, on the whole, rules, which are part of DFA [HOP06, p. 8]:

2.7 Conclusion

The problem analysis points out that customization, short time-to-market and product design have influence on the product development process at different stages and lead to challenges for manufacturing systems.

- Customization has an influence at the very beginning and in the end of the product development process, depending on the degree of customization. As described in section 2.4, small-batch production is the quantitative approach of customization. Therefore, this production strategy has an impact on the realization phase of the end product, whereas personalization has an influence on the product development already in the first stages. Customers often have specific imaginations about functions and features of the requested product. This requires, first, a mutual information flow between customers and designers, and, second, a manufacturing system, which has the capability to fabricate a variety of products.
- As mentioned in section 2.5, models and prototypes are an eminently suitable way to prevent avoidable costs in the development process and additionally shorten the time-to-market. Depending on the related manufacturing method, the time and effort to create a prototype can vary strongly.
- The product design poses challenges during the concept, embodiment and detail design phase for the manufacturing system. Within these design phases, the manufacturing system's characteristics should restrict the requirements, in terms of accuracy, mechanical strength, design freedom and material selection for the product as less as possible.

In terms of these requirements on manufacturing systems within the product development process, a framework has to be developed to evaluate various manufacturing systems. Target of the evaluation should be to get a deeper understanding of the influence of manufacturing systems on the product development process according VDI 2221, as an optimization of the process should be achieved.
A suitable tool for this is the benefit analysis and the technical-economical evaluation according to VDI 2225, ensuring a statement about the significance of the result.

3 Development of a methodical approach

This chapter guides through a development of an approach for the evaluation of manufacturing systems, which in turn serves as an aid to decision-making for an appropriate system.

3.1 Objective target

The research objective is to determine a manufacturing method, which is able to meet the need of customization, short time-to-market and as a result high cost-effectiveness best. Additionally, it is essential that the product design is restricted by the manufacturing system as little as possible. Since there is hardly any manufacturing system which can cope with all the mentioned requirements, a closer examination is essential.
For that reason, the stages in the product development process should be examined more in detail and with the help of models and prototypes (their importance is already described in section 2.5) an interconnection between the different stages should be created in order to derive significant evaluation criteria.
The target is, to gain a better understanding of the development and manufacturing challenges by means of these criteria. Thus, a meaningful evaluation can be executed. Finally the potential of AM to cope with the previous mentioned trends should be investigated.

3.2 Framework conditions

The product development approach to be considered in the thesis is the systematical approach to the design of technical systems and products according to VDI 2221, illustrated in Figure 3-1. It describes the design process beginning with the clarification of the task, with the consequence of a requirement specification, and ending with the preparation of production and operating instructions, which leads to a complete product documentation as a result. This iterative development approach is generally divided into four phases:

- Phase 1 – Clarification of the task: This includes an analysis, structuring and clear formulation of the task.
- Phase 2 – Conceptual design: This includes the determination and structuring of functions on one hand, and finding principle solutions on the other hand.

- Phase 3 – Embodiment design: This includes the first rough design, combing functions and principle solutions, in order to obtain a first draft.
- Phase 4 – Detail design: This includes the final design under the influence of the production feasibility and material choice.

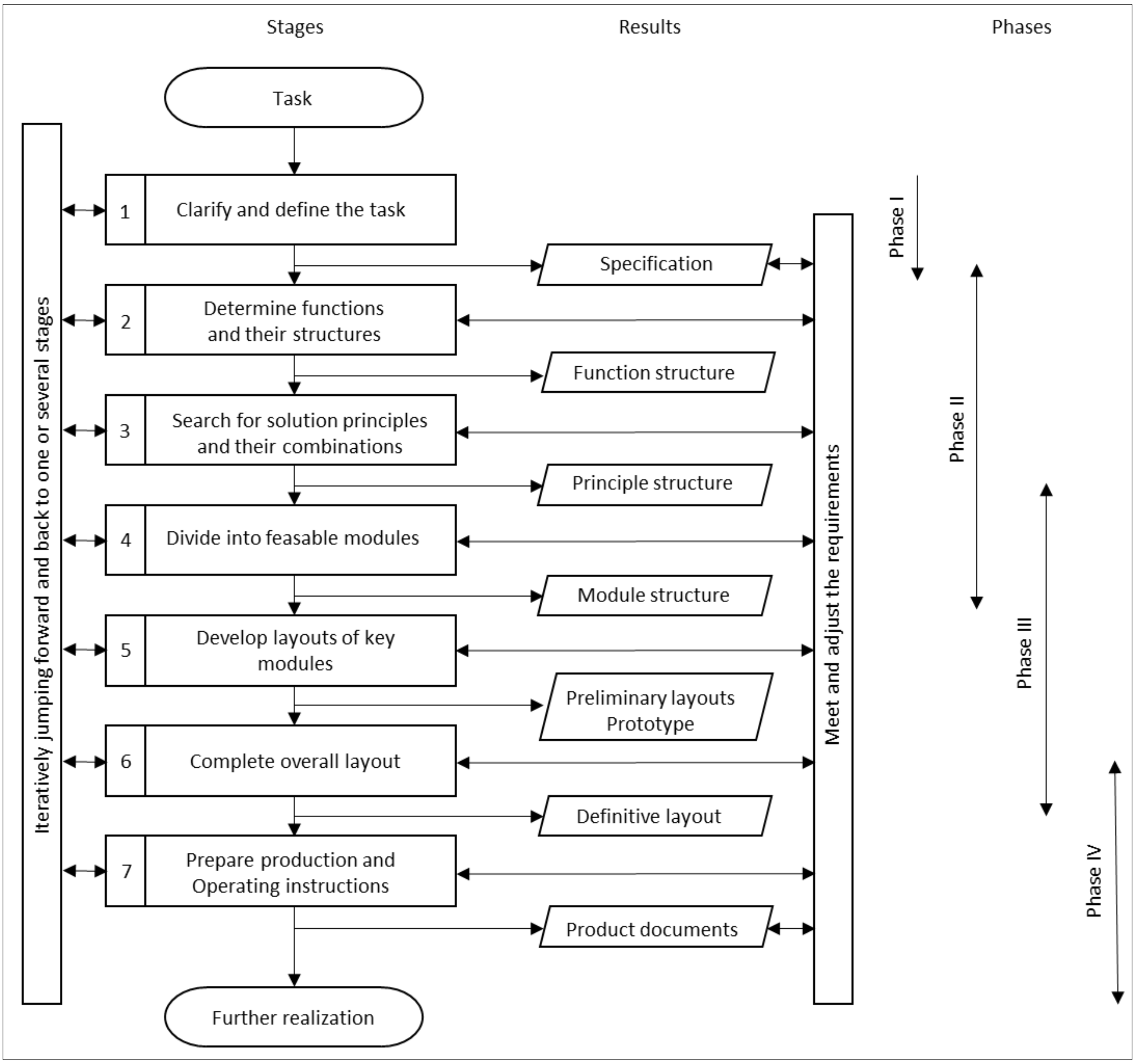


Figure 3-1: General approach to design [VDI93]

As already mentioned in section 2.5, the use of models and prototypes is influencing the product development process according to VDI 2221. Models are usually used in the early development phase. As soon as they contain mechanical-technological functionalities, models are called prototypes. Models and prototypes can be classified according to the definition of the “Verband der Deutschen Industrie Designer” VDID (Table 3-1) and according to the guideline for AM, called

VDI 3404 (Table 3-2). Prototypes and models according to VDID are no prototypes in terms of AM. Table 3-3 shows the relationship between these two definitions and the application levels of AM [GEB07, pp. 254-258].

Table 3-1: Model definition according to VDID [GEB07, pp. 255-256]

Model type	Description
Proportion model	Represents the outer shape and the most important proportions.
Ergonomic model	Decision aid for the technical feasibility.
Design model	Outer shape is equal to the sample.
Functional model	Support to confirm the results from the numerical simulation.
Prototype	Functionality and properties almost equal to specimen but is not produced under series production conditions.
Specimen	Full functionality and properties equal to end product. Produced under series production conditions.

Table 3-2: Model definition according to VDI 3404 [VDI09]

Model type	Description / Application
Concept model	Verifying aesthetic impression of the application and its planned environment.
Geometric model	Verifying of geometry (installation investigation).
Functional prototype	Verifying the (partial) functions.
Technical prototype	Verifying the product in an experiment and a pilot series.
Product	Small series, RM, individual product.

Table 3-3: Classification of models and prototypes [GEB07, p. 257]

Model definition		Application levels of AM	
VDID	VDI 3404		
Proportion model Ergonomic model Design model	Concept model (Solid Images) Geometric prototype	Solid Imaging Concept Modeling	Rapid Prototyping
Functional model	Functional prototype	Functional Prototyping Prototype Tooling	
Prototype Sample End product	Technical prototype Product	Direct Manufacturing Direct Tooling	Rapid Manufacturing

Each type of model has a particular task, in order to evaluate the feasibility of the product for end-use. In the following course of the thesis, the classification of models and prototypes is considered according to VDI 3304. Table 3-4 shows the different requirements of models according to VDI 3404. A concept model, for example, is used for the evaluation of the outer shape. Neither does it need to be loadable, nor does it need to have exact position tolerances.

Table 3-4: Requirements on models according to VDI 3404 [VDI09]

Model type according to VDI 3404	Application: Evaluation of	Proportions	Details	Surface	Mechanical properties	Materials	Building time	Fast availability	Low price	Sustainability	Recycling capability	Reproducibility
Concept model	Outer shape (Three dimensional appearance)	●	◔	◔	○	M	◕	●	●	○	◕	◑
Geometric prototype	Dimensional shape and position tolerances (Assembly)	◕	●	◔	○	M	◑	◕	◕	○	◑	●
Functionality prototype	Single or all functionalities	◔	◔	◔	●	D	◑	◑	◕	◕	◑	●

● = Very important ◕ = Important ◑ = Neutral ◔ = Less important

○ = Unimportant M = Model material D = Design material

3.3 Evaluation method

In order to evaluate strengths and significance of a system or solution a methodical approach is required, which is suitable to evaluate evaluation criteria with different properties standardized. For that reason, various evaluation methods exist. Pahl and Beitz [PAH07] describe an evaluation scheme that includes a value scale according to VDI 2225 and the weighting of values, which is actually common in a benefit analysis. It is recommended that the evaluation should contain qualitative and quantitative values for the evaluation criteria [PAH07, pp. 170-175]. In terms of the thesis, quantitative criteria are avoided, as a strict classification is too extensive, due to the dependency on many factors. The neglect of these quantitative criteria hardly influences the results of the evaluation.

Advantages:

- **Value scale according to VDI 2225**: Since it is difficult to compare the evaluation criteria with each other and finally to gain a useful result out of the evaluation, standardization is necessary. With the introduction of the scale according to the technical and economic evaluation VDI 2225, a consistent evaluation can be achieved, since properties are only known inadequate.
- **Weighting of values**: By means of a weighting, the relevance of the evaluation criteria can be considered and finally a more precise result can be gained.

Disadvantages:

- Depending on the amount of evaluation criteria, the evaluation requires a relatively high effort due the weighting of the values.
- The weighting of the values is mandatory.
- The consistent use of qualitative values for each evaluation criterion can influence the results through subjectivity of the assessor.

Table 3-5 shows a scheme for the methodical evaluation built on the principles according to Pahl and Beitz.

Table 3-5: Scheme for methodical evaluation [PAH07, p. 171]

No	Evaluation criteria	Weighting w_i	Version V_1		…	Version V_j	
			Value v_{i1}	Weighted value wv_{i1}	…	Value v_{ij}	Weighted value wv_{ij}
1		w_1	v_{11}	wv_{11}	…	v_{1j}	wv_{1j}
. . .	. . .	. . .	. . .	. . .	…	. . .	. . .
n		w_n	v_{n1}	wv_{n1}	…	v_{nj}	wv_{nj}
		$\sum_{i=1}^{n} w_n = 1$	Ov_1	Owv_1		Ov_j	Owv_j

As a result that version is judged, which has the highest overall value $Owv_j \rightarrow Max$.

3.4 Influence on the development process according to VDI 2221

Figure 3-2 shows the steps of the product development process according to VDI 2221 including the four phases, described above. It can be also seen that models are used in every stage during the product development. Concept models, geometric models and functional models are used during the design process, whereas technical prototypes are used to test a production system under series production conditions [VDI09]. Furthermore, the relation between the product development process and the key issues of the thesis is illustrated as well.

Influence of customization

As it can be seen in Figure 3-2, the influence of customization takes place at the beginning of the development process and at the end, when the product is going to be produced. Offering a high degree of product variety, often leads to the fact that the customer can bring in his own ideas and imaginations at the very beginning. For this reason, concept models are used in order to obtain an early physical realization and adapt customer requests. Concept models do not meet the product requirements.

Flexibility in the production volume is the quantitative approach of customization and therefore more relevant in the production phase.

Influence of Time-to-market and cost efficiency

As mentioned in section 2.5, time-to-market is a crucial topic and is closely linked with the economic success of a product. It is influenced by the time that is required for product development, as it can be seen in Figure 3-2.

Influence of product design

The actual product design has the most influence on the development process, as it extends across the conceptual, embodiment and detail design phase. During these stages geometric prototypes and functional prototypes are used (Figure 3-2). Geometric prototypes are primarily intended as installation investigation and provide hardly any functionality, whereas functional prototypes do and in addition to that they are formed out of the same material that is present in the end-product. Thus, also requirements on the mechanical strength should be provided by means of a functional prototype. During the design stages design restrictions due to the manufacturing system should be kept in mind.

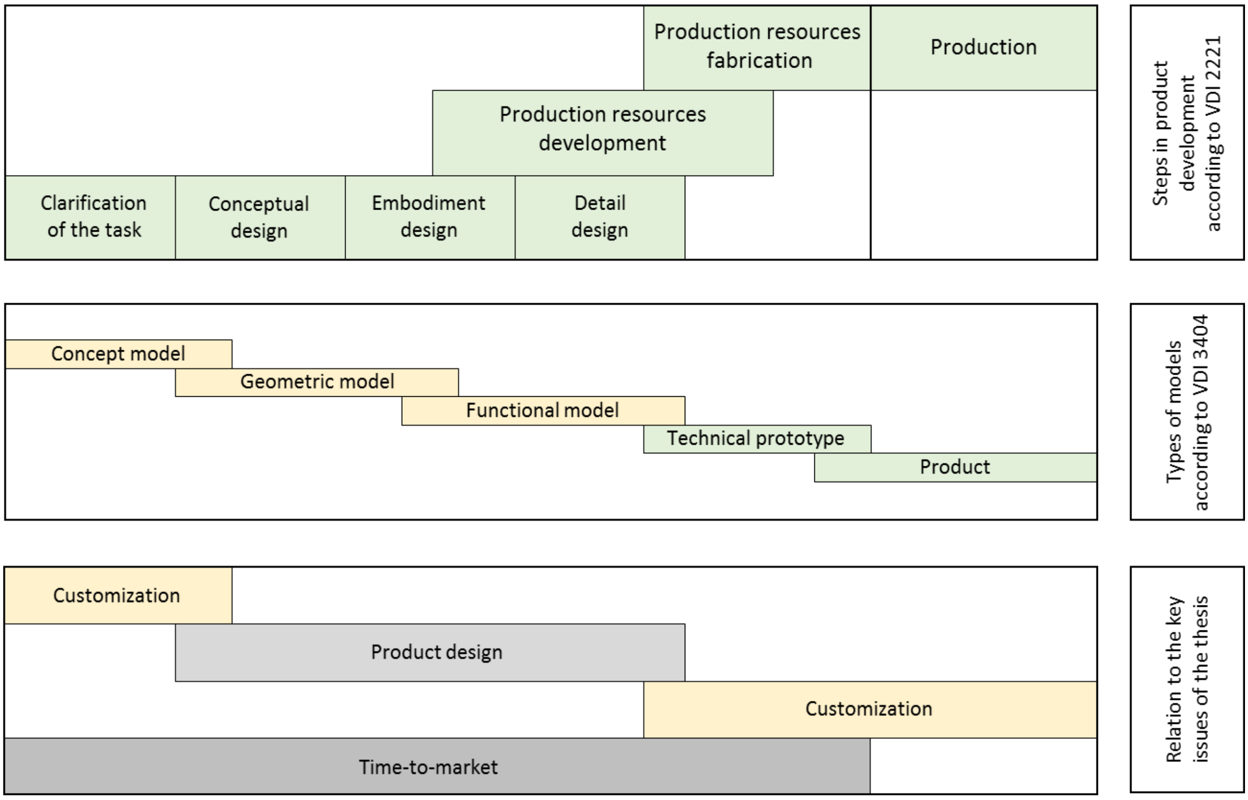


Figure 3-2: Interconnection of the product development and the key issues [GEB07, p. 9]

3.5 Development of evaluation criteria

By means of Table 3-4, which illustrates the requirements of each model or prototype, and Figure 3-2, where the application of these models is shown, requirements on the manufacturing system related to each stage in the development process VDI 2221 can be deducted. These requirements are closely linked with the key issues of the thesis and well suitable as criteria for the later evaluation of manufacturing systems.

Phase 1 – Clarification of the task:

- Product variety

Phase 2 – Conceptual design:

- Accuracy
- Dimensional stability

Phase 3 – Embodiment design & phase 4 – Detail design:

- Design freedom
- Material variety

That some requirements are only related to one kind of model or prototype does not mean that it is less important for other models, but they are first considered in that stage, e.g. accuracy is not only relevant for geometric models, thus in the conceptual design phase, but also for the product itself.

In addition to that, requirements have to be considered, which are not part of the actual product development process itself, but rather part of the production process.

- Flexibility in production volume
- Process time of the manufacturing system
- Accuracy

Table 3-6 shows a summary of the evaluation criteria divided by its influence on the development process and production process.

Table 3-6: Evaluation criteria and their influence

	Influence on development process	Influence on the production process
Evaluation criteria	• Product variety • Accuracy • Dimensional stability • Design freedom • Material variety	• Flexibility in production volume • Process time of the manufacturing system

Product variety

This criterion describes the ability of a manufacturing system to produce a number of different products. The range of product variety begins with non-variety, followed by passive personalization, which takes places in between, up to active personalization and unique parts or components.

- **Non-variety** means that changes neither in the design nor in the material choice of the product are possible.
- **Passive personalization** means that the product responsibility lies with the manufacturer and the customer can bring in his imaginations, e.g. with a variant catalog [GEB07, p. 353].

- **Active personalization** means that the customer implements his imaginations of the product himself [GEB07, p. 355].
- **Unique part** means that each product is influenced by the customer as much as it has a unique characteristic.

Accuracy

The accuracy of a produced part can vary strongly, depending on the manufacturing method. Some methods are not able to operate with a sufficient accuracy in order to meet high requirements. There are cases, where the desired quality can be obtained with post-processing, e.g. reaming after drilling processes in order to obtain mechanical fit. This evaluation criterion contains the consideration of following influences on the quality of the work piece:

- Dimensional accuracy
- Tolerances in shape (Straightness, planarity, circularity, cylindricity, profile of a line, profile of a surface)
- Tolerances in position (Perpendicularity, angularity, parallelism, symmetry, positional tolerance, concentricity)
- Surface roughness

These influencing factors can have an effect on geometric shape, shown in an example of a drilling process (Figure 3-3).

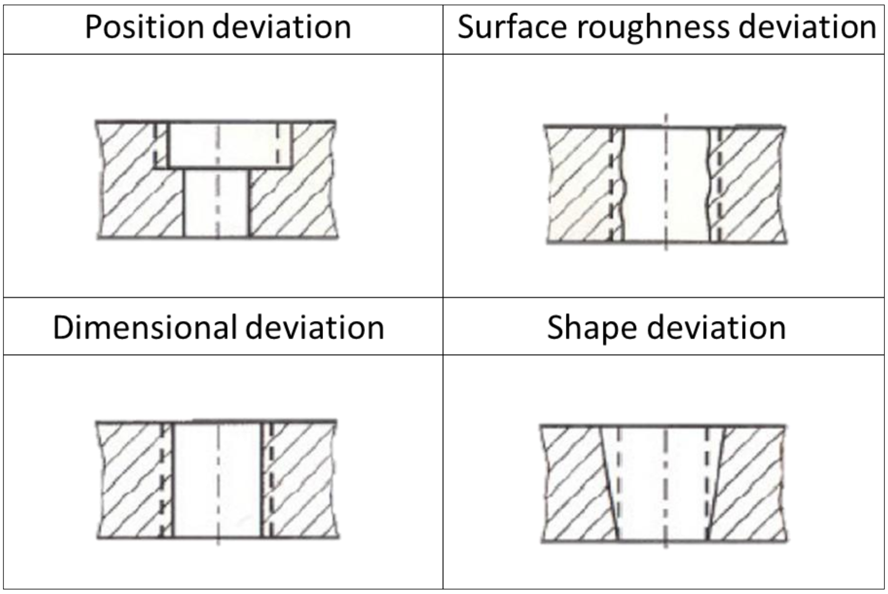


Figure 3-3: Geometric error after a drilling process [KIE55]

The reason for these errors can be caused by

- Inaccuracies of the machinery
- Inaccuracies of the tools

Dimensional stability

Dimensional stability is a property of a material and can be described as the resistance against linear dimensional change due to various influences. Following equation expresses dimensional instability by summing up the linear strains due to the various influences [WOL04, p. 1]:

$$\varepsilon = S\Delta\sigma + \alpha\Delta T + \beta\Delta M + \eta\Delta t + \psi\Delta Q \tag{3.1}$$

It can be seen that dimensional instability is depending on external influences and on the material properties. External influences are:

$\Delta\sigma$ = Stress
ΔT = Temperature
ΔM = Absorbed moisture
Δt = Time
ΔQ = Fluence or radiation

Material properties are included in following constant values:

S = Compliance = 1/E where E = Young's modulus
α = Coefficient of thermal expansion
β = Coefficient of moisture expansion
η = Coefficient of temporal expansion
ψ = Coefficient of radiation expansion

In terms of the thesis, dimensional stability only consideres the influence of heat and stress, as these influencing parameters are most important for the selection of a suitable manufacturing system. Regarding to the dimensional stability, materials can have following directional dependencies [WOL04, p. 2]:

- Anisotropic: Properties are directional dependent
- Isotropic: Properties are directional independent
- Orthotropic: Isotropic in each of three mutually perpendicular directions

Especially manufacturing processes, which rely on phase changes in order to create a part, must be investigated regarding to dimensional stability to heat. Cooling processes after thermoforming (e.g. molding) processes should be considered exactly. Also the consideration of the mechanical strength is important in the field of mechanical engineering. Not every manufacturing method is able to create parts or components that are loadable or loadable to limited extent. However, there are some processing methods that come with the characteristic to strengthen the material due to grain concentration, for instance. Regarding the dimensional stability to stress, this evaluation criterion contains the consideration of:

- Tensile strength

Design freedom

This criterion describes the design freedom that an engineer has in the design phase of the development process. The range of design freedom depends on the particular manufacturing system, or, more precisely, on the tools for creating value or on the process itself. As already described in section 2.6, during the design phase DFM and DFA has to be considered. A distinction has to be drawn between:

- Design of a single component
- Design of an assembly

Range of materials

This criterion interprets the ability of a manufacturing system to process a certain range of materials. There are systems that are only capable to operate with one kind of a material, but there are also those that can fabricate different parts with several materials. Often, only a few process parameters, like process speed for instance, have to be adjusted to the material to be processed.

Flexibility in production volume

Since process planning and scheduling is difficult to predict when high flexibility is required, the manufacturing system should be flexible to demand peaks, which occur regularly or as a single event. A manufacturing system can be very flexible and produce parts whenever required, but can also be very inflexible, e.g. extensive and time-consuming startups.

- **Constant quantity** is the output of continuous production. That often means 24 hours non-stop operations.
- **Batch production** is the production of a small volume of products in a specified short time period [HIT96, p.65].
- **Whenever required** means that the system is very flexible in producing goods when there is a demand for goods. When the demand is zero, the system stands idle.

Process cycle time of the manufacturing system

This criterion is the time of a manufacturing system, which is required to obtain a part. Depending on the manufacturing process, the duration of this time can be caused by different activities, which are necessary in the manufacturing process. There are some differences regarding the definition of the process cycle time depending on the manufacturing method:

- **Cutting processes**

  The cycle time of cutting processes of autonomous working machineries can be expressed with following equation [TSC13, p. 65]:

$$t_z = t_H + (t_{An} + t_{Zu} + t_{Ab} + t_{Ru}) \times i \tag{3.2}$$

t_z = Cycle time

t_H = Main time (Creating value, cutting process)

t_{An} = Start-up time

t_{Zu} = Positioning time

t_{Ab} = Lifting time

t_{Ru} = Return travel time

As it can be seen in equation 3.2, the main influence on the cycle time is caused by the main, start-up, positioning, lifting and the return travel time. The main time, where the actual value adding process takes place, depends on the type of machinery that is used. The following equation is an example for the main time calculation of a milling and lathing process.

$$t_H = \frac{L \times i}{f \times n} \tag{3.3}$$

Following factors are influencing the main time:

L = Total length of the tool

i = Number of cutting steps

f = Feed rate [mm/U]

n = Rotation speed [1/min]

- **Molding processes**

  For molding processes (e.g. injection molding) the above mentioned consideration is not valid anymore, as there are completely different factors, influencing the process time. The main influence factor in injection molding process is the cooling time. It depends mainly on the thickness of the molded part. The following picture (Figure 3-4) shows the process cycle time of a typical molding process [MIC13, p. 71].

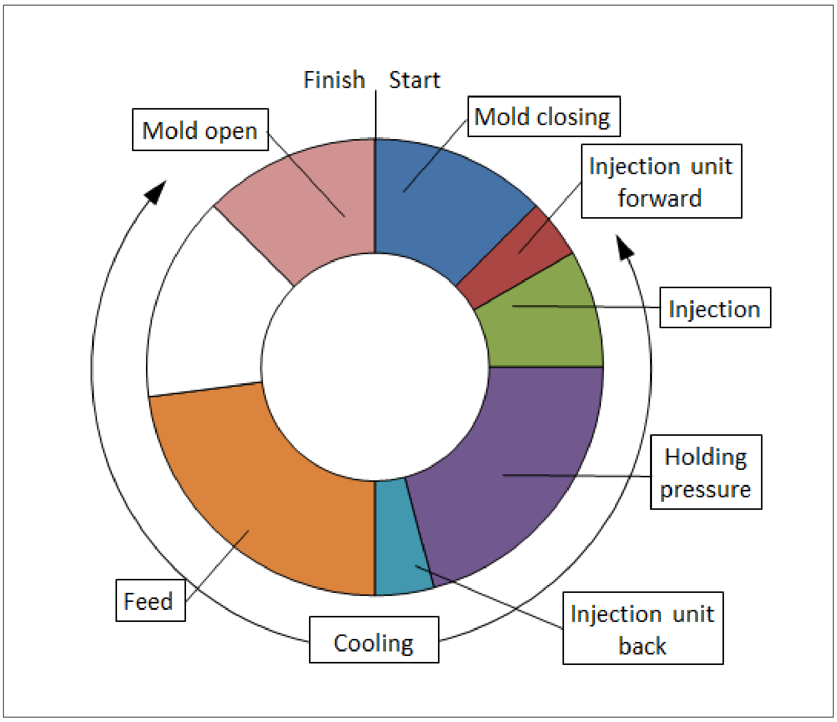


Figure 3-4: Cycle time of a typical molding process [MIC13, p. 71]

Following table shows the ranging scale of the criteria summarized (Table 3-7).

Table 3-7: Ranging scale of the criteria

Criterion	Possible criterion variations (red)	(orange)	(yellow)	(light green)	(green)
Product variety	Non-variety	Slight variety	Passive personalization	Active personalization	Unique parts
Accuracy	Very inaccurate	Inaccurate	Average	Accurate	Very accurate
Dimensional stability	Very low	Low	Average	Good	Very good
Design freedom	Very low	Low	Average	High	Very high
Range of material	Only one special kind of material processable	Only one group of materials processable (e.g. metals or plastics)	Wide range of materials processable to a limited extend	Wide range of materials processable	Every kind of materials processable
Flexibility	Constant quantity	Slight variance of the production volume permitted	Batch production	High variance of the production volume permitted	Whenever required
Process time	Very high	High	Moderate	Low	Very low

3.6 Standardization and ranking of the evaluation criteria

Since it is difficult to compare the discussed evaluation criteria with each other and finally to gain a useful result out of the evaluation, standardization is necessary. With the introduction of a scale according to the technical and economic evaluation VDI 2225, a consistent evaluation can be achieved (Table 3-8).

Table 3-8: Evaluation scale according to VDI 2225 [VDI98]

(red)	0	Unsatisfactory
(orange)	1	Barely acceptable
(yellow)	2	Sufficient
(light green)	3	Good
(green)	4	Very good

In order to get a better view of the importance of the influencing factors and furthermore to put emphasis on the most essential ones, the criteria get different weighting and ranked (Table 3-9).

Table 3-9: Weighting of the influencing evaluation criteria

Product variety	14%
Accuracy	12%
Dimensional stability	13%
Design freedom	18%
Range of material	16%
Flexibility	17%
Process time	10%
Sum	**100%**

1. **Design freedom:** It has the highest importance in the ranking, as it does not only influence DFM and DFA. Manufacturing systems that provide an unlimited design freedom are often able to produce a broad variety of products.
2. **Flexibility:** As already described above, product variety can be achieved with unlimited design freedom as well. Therefore, flexibility in production volume is the most important criterion to evaluate the possible degree of customization.
3. **Range of materials:** It is less important than the previous mentioned, as with state of the art technology it is possible to operate modern systems with almost every kind of materials.
4. **Product variety:** The reason for its ranking is already discussed.
5. **Dimensional stability:** The reason for the weighting is that depending on the used material an outstanding property is not required in most cases. Whether the material meets the specification requirements, or, if not, another type of material must be chosen.
6. **Accuracy:** This criterion has a low impact on the key issues, but can restrict the field of application.
7. **Process time:** This criterion is ranked as last, since it influences the three core issues of the thesis at least.

3.7 Potential of Additive Manufacturing

AM has the potential to increase the performance in manufacturing in terms of reducing the scale effect to a minimum and increasing the flexibility in product design, which easily enables production changeover and customization.

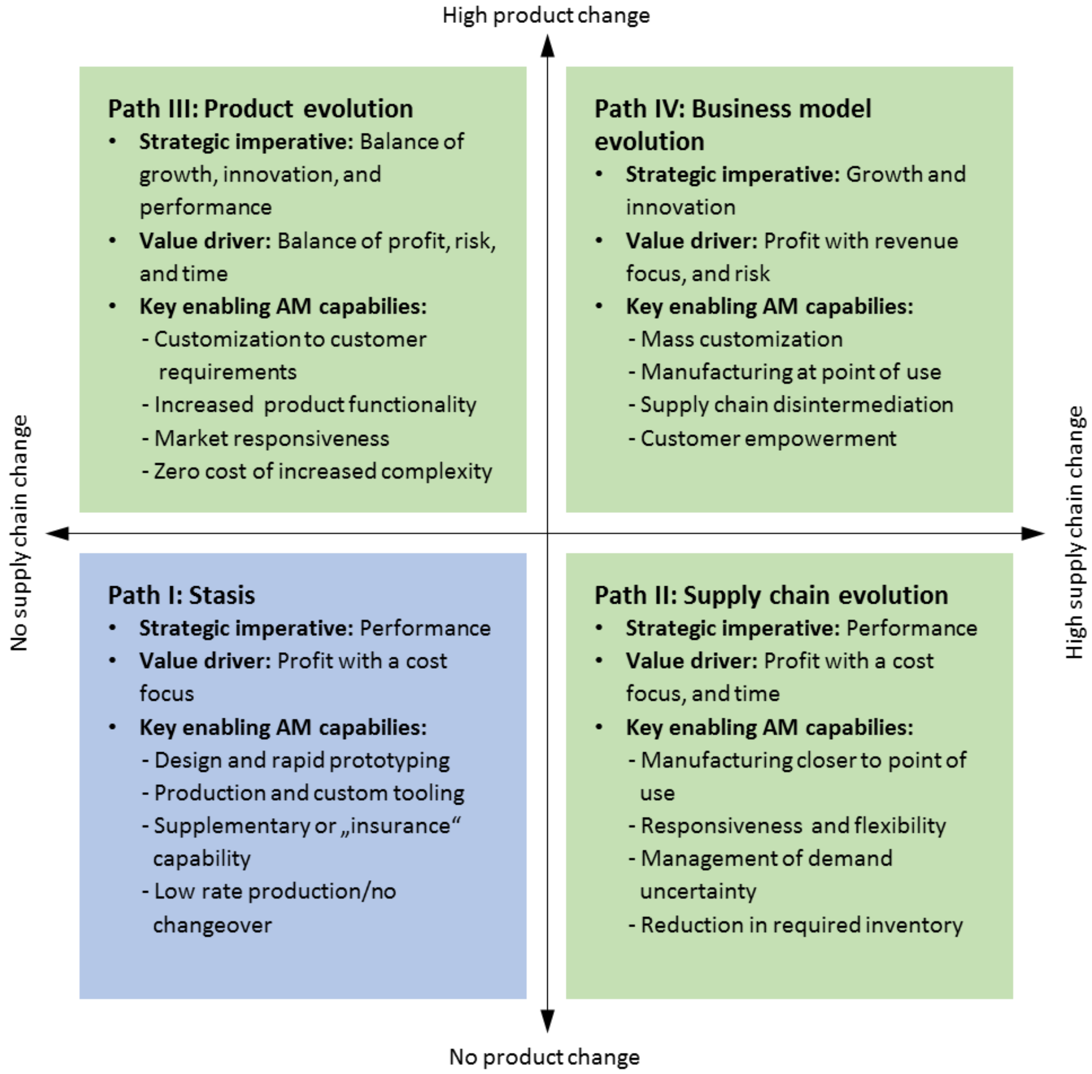


Figure 3-5: Potential of AM [MIC15]

Figure 3-5 shows the use of AM from a strategic point of view. It illustrates four tactical paths that can be deployed across a business. By means of these paths, the product design can be influenced but also the supply chain can be improved [MIC15].

- Path I - Stasis: No radically change of the product or supply chain, but improving current products with existing supply chain by means of AM technology.

- Path II – Supply chain evolution: By taking advantage of the low scale effect, inventory can be reduced, a responsive production can be realized and manufacturing closer to the point of use is possible.
- Path III – Product evolution: Due to increasing flexibility in design, customization to customer requirements can be enabled, increased product functionality can be achieved and increasing complexity is not influencing the costs.
- Path IV – Business model evolution: By taking advantage of both, path II and III, a new business model is realizable.

However, when considering the product design and development, AM has the potential to influence this process significantly. As it can be seen in Table 3-10, the replacement of traditional product design and development by AM supported product development leads to optimized products. This means that the product can be brought to market faster and cheaper but the design of the end product is still limited due to TM. Many industries are starting to make benefit of that. In comparison to that digitally optimal design (DOD) enables totally new products and features, and the improvement of the product design and development process. Additionally DOD has the capability to redesign products easily at low costs and includes the ability of three-dimensional scanning [MIC15].

Table 3-10: Comparison of non-AM, RP and DOD influenced development process [MIC15]

	Product design & development	Manufacturing	End product
Non-AM	Traditional	Traditional	Traditional
Rapid Prototyping (RP)	Additive Manufacturing	Traditional	Traditional (optimized)
Digitally optimal design (DOD)	Additive Manufacturing	Additive Manufacturing	Breakthrough

AM for designing and prototyping

Figure 3-5 shows that AM takes place in the first quadrant path I, known as RP. As already mentioned it supports the traditional product development and as a consequence brings following advantages [MIC15]:

- **Saving time in the development process**, as the fabrication of prototypes, which can be associated with a less time-consuming product development, can be executed faster than with TM.
- **Reducing costs in the development process** due to insourcing and inexpensive prototypes. Latter is the result of producing less scrap by using AM and eliminates the cost intensive creation of layouts, preparation (e.g. CNC programming) and tooling processes, which are usually related to TM.
- **The end product's quality and design can be improved** by a faster creation of prototypes, as designers have the possibility to execute more iterative improvement loops in the development process.

AM for designing, prototyping and production

Digitally optimal design (DOD) enables the tactical paths III and IV and has following advantages [MIC15]:

- **Improved part characteristics** (e.g. complex geometries, varying wall thickness' and low density parts). Example of application: Hinges for engine covers for Airbus, which has the half weight of those that a manufactured with TM [BUL11].
- **Mass customization**. Example of application: Tailored products in the medical and dental industry for individual customers [SNY14].
- **Decreased system complexity**. Example of application: Boing manufactures ducts for so called environmental control systems out of one part, instead of assembling TM manufactured parts [MIC15].
- **Non-traditional sources of design information** (e.g. Three-dimensional scanner). Example of application: The Smithsonian Institution is able to create copies of unique historical parts for local museums and libraries by means of three-dimensional scanning [MAC15].

3.8 Conclusion

The process-model VDI 2221 is a general approach for product development with broad applicability that supports the solution finding in mechanical engineering, software development and process engineering. Therefore, a complex problem is divided into smaller sub-problems in order to facilitate the solution finding and finally combined to an overall solution again. Especially in mechanical engineering, physical models and prototypes support the solution finding process of each sub-problem. By means of models and prototypes, the development process according to VDI 2221 can be optimized in order to cope with the key issues of the thesis. Each model and prototype has specific requirements, which have to be fulfilled to gain meaningful results in the solution finding. In order to meet these requirements as good as possible, requirements for the manufacturing process of these models can be deducted. AM is a relatively new manufacturing method that has the potential to fulfill these deducted requirements and furthermore, optimize the product design and development regarding the three key issues of the thesis, and finally enables the ability to create products for new applications.

4 Methodology

This section deals with the evaluation of different manufacturing systems by means of the chosen and weighted criteria in chapter 3. At the end of this chapter, the different results are summarized and evaluated with a benefit analysis.

4.1 Objective target

The target is to determine a manufacturing system by means of the evaluation criteria, formed in chapter 3. The evaluation should be executed with TM methods and the AM approach. Latter system should show the advantage compared to TM and finally the potential to cope with the key issues of this thesis. Thereby following criteria should be considered and awarded with evalution points (EP):

- Design freedom
- Flexibility in production volume
- Materials variety
- Variety of products
- Dimensional stability
- Accuracy
- Process time

Finally the impact on the development process, due to AM, should be shown and confirm the findings about AM’s potential in chapter 3.

4.2 Framework conditions

In order to evaluate different manufacturing methods, it is necessary to narrow the broad range of TM systems to a few that seem appropriate to meet the requirements. One of them is the injection molding (IM), as it is an efficient system to produce mainly plastic components with complex geometries in series quality. Another system is computerized numerical control (CNC), which is related to a continuous high accuracy. Finally AM is part of the evaluation, as it is a relatively new technology that has its strengths in customization and applicable materials. The manufacturing systems, which are supposed to be evaluated, are defined as followed:

- **IM:** Includes mainly all IM processes with thermoplastics, thermosetting polymers, thermoplastic elastomer, but also with multi-materials.
- **CNC:** Includes all state of the art CNC milling, lathing and drilling processes.
- **AM:** Includes all described AM systems, especially treated in chapter 2.

4.3 Design freedom

As already indicated in section 3.5, a distinction between designing a single component or a whole assembly is made.

Design of a single component

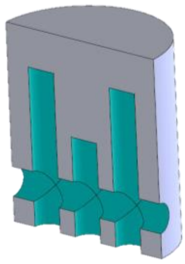
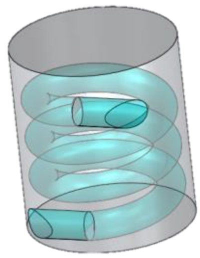
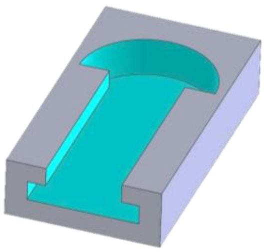
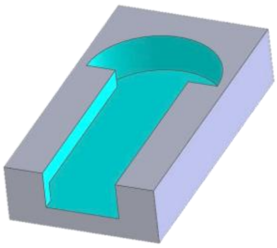
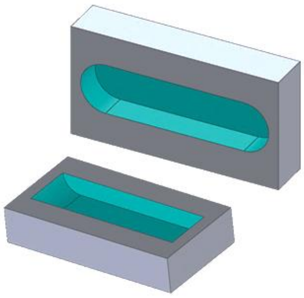
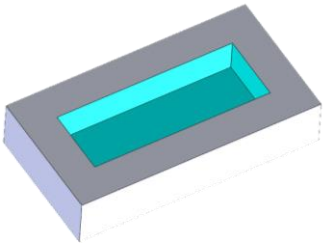
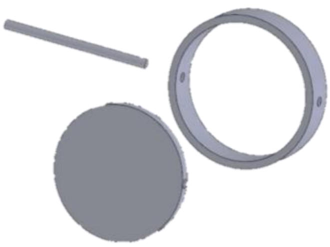
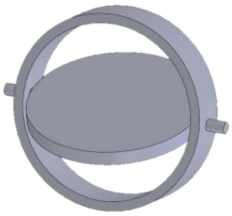
Table 4-1 shows the design features achievable with AM compared with the limitations of TM. For example, AM enables the realization of curvy cooling channels with any profile, which is not possible with conventional machining [GEB11, p. 89]. The production of undercuts often involves problems, especially with CNC. AM can build parts with any kind of undercuts easily without increasing manufacturing costs, by the use of support structures. The use of AM also eliminates design limitations due to the manufacturing process, like mold partitions or draft angles which have to be considered for IM process [GEB11, p. 141]. Particularly noteworthy is the possibility to manufacture parts with integrated kinematic functions out of a single piece [GEB11, p. 109].
Another fact is that the usage of cutting tools, as it is with CNC, brings limitations as well. For example, fabricating a completely angular slot is not possible with CNC-milling, because of the cylindrical geometry of the tool.

Design of a whole assembly

As mentioned before, the use of AM enables the fabrication of parts with integrated kinematic functions. In addition to that, the ability to manufacture integrated assemblies decreases the parts count and finally product complexity from management and production perspective [GEB07, p. 412]. Nevertheless, whole assembly groups are rarely produced with AM. That means, even if there hardly any design restrictions for AM parts, DFA has to be considered. Following issues have to be considered, when manufacturing parts for an assembly group or a whole assembly [HAG03]:

- In most cases the assembly does not only consist of AM parts. Therefore, the design of AM parts has to be adjusted to the TM manufactured parts in order to ensure mounting.
- Design for Maintenance must be considered in most applications.
- AM enables to imbed components within the build. This causes issue regarding recycling, as the assembly is difficult to separate and finally disposal leads to problems.

Table 4-1: Design advantages and features related to AM

Design feature	TM	AM	Explanation
Cooling channels			Instead of straight cooling channels, AM opens the possibility to realize complex channels close to the surface to be cooled.
Undercuts			The left illustrated undercut can be realized with TM, but the second one is very difficult to create with TM.
No design restrictions regarding tools			Any geometry can be achieved without limitations due to the manufacturing process or by the geometry of tools.
Integrated functionality			Single piece in one build with the same functionality as traditional manufactured and assembled part.

As shown in Figure 4-1 with increasing geometric complexity, the costs for parts produced with TM grow exponentially. When using AM, the degree of geometric complexity is not a cost driver. At a certain degree of complexity, the complexity break-even point, AM is the only economic rationally method [MER12].

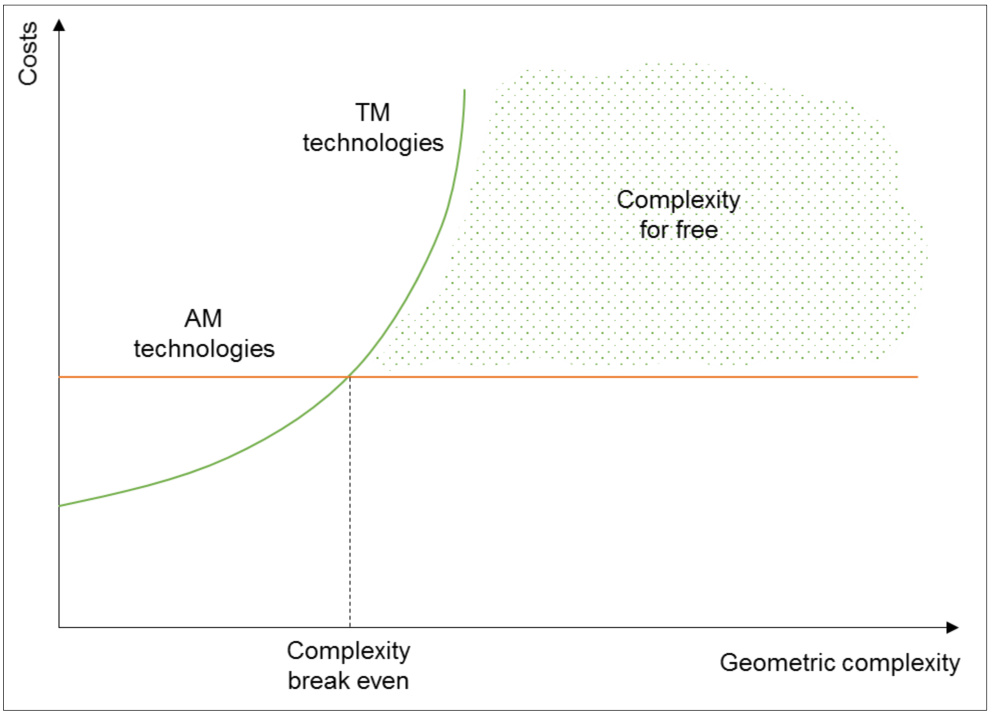


Figure 4-1: Costs of AM and TM related to geometric complexity [MER12]

Evaluation

The design freedom is one of the main advantages of AM, since it is possible to produce almost any desired geometry. As TM processes are always limiting the design possibilities, design engineers can put their whole creativity into the part by the use of AM. Molded parts with complex geometries are realizable, but mold partitions, low material accumulation, draft angles, etc. have to be considered. Also when processing with CNC, designs are limited by the geometry of the used cutting tool. Another important disadvantage of CNC is that material is subtracted and thus, the creation of extensive overhanging parts out of voluminous raw material is very uneconomic and inefficient. Summarized the evaluation results are following:

- AM: Hardly any design restrictions. Every desired shape can be achieved (4 EP).
- IM: Part geometry is restricted due to the use of molds (3 EP).
- CNC: Part geometry is restricted due to the use of tools and the process of material subtraction is limiting the design freedom (1 EP).

4.4 Flexibility in production volume

Flexibility in production volume is very challenging for TM, as they are often connected to economies of scale. This effect cannot be achieved with AM, since fixed costs are independent of the number of the produced parts, but it provides an opportunity for small series of single product manufacturing (Figure 4-2). On the other hand, the slow building speed of the most AM is limiting their usage as an effective manufacturing system. Related to that fact and the lack of the scale effect, AM systems are not suitable for series production [DOU14].

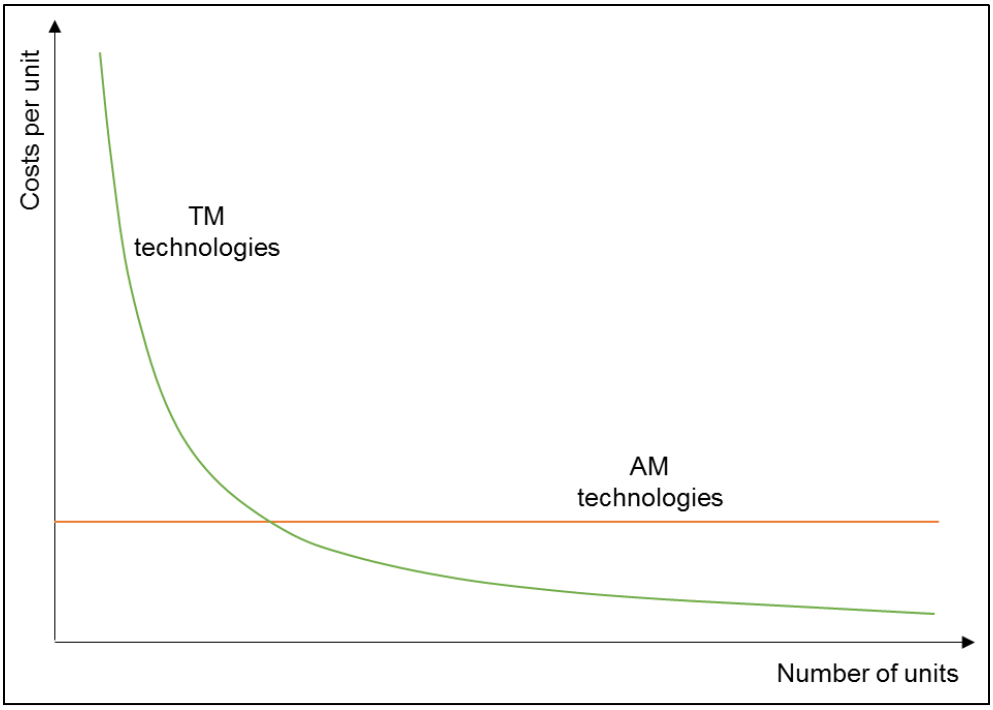


Figure 4-2: Economies of scale TM compared with AM [CON14]

Figure 4-3 shows again the effects of a high volume production on a TM, in this case IM. The tool costs, which are part of the fixed costs, are enormously high, if the system runs for small batch sizes and are decreasing with increasing number of produced units. Usually molds are expensive and therefore IM is not suitable for production of a small number of products. Here, AM points out its strength, as it does not require any tools in order to manufacture a part. As shown in the example in the following figure, only by quantities starting at 100,000 pieces the IM system is more economical than an AM system.

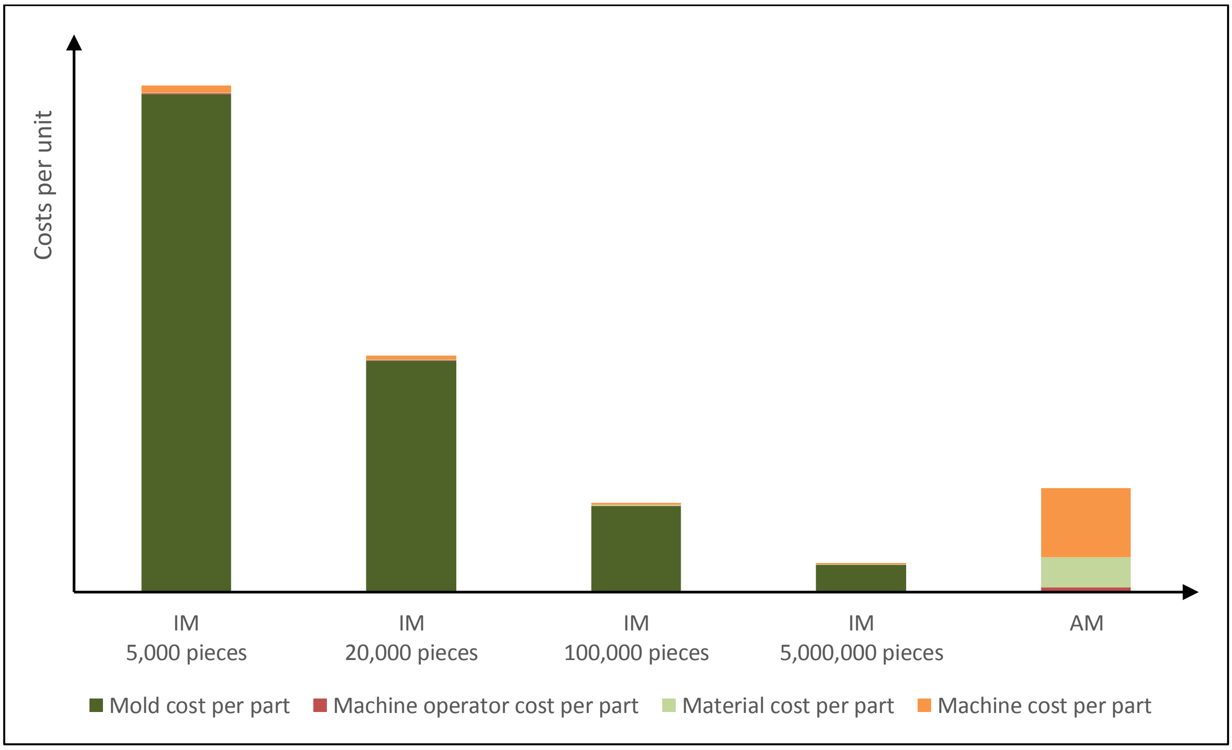


Figure 4-3: Costs of IM and AM related to production volume [DOU14]

Evaluation

AM is a very flexible manufacturing system, which is well suited especially for low volume production, but shows its weaknesses in series production. A major advantage to other systems is that AM does not require tools, which has a positive effect on the fixed costs. CNC systems system reflects a good trade-off between small batch and series production. Depending on the machine type, both strategies are realizable under the acceptable economic conditions. IM is very inflexible as one tool can only be used for one kind of product and furthermore, production volume must be constantly high in order to cover the production costs. On the other hand, the high process speed of IM confirms the suitability for series production. Summarized the evaluation results are following:

- AM: Very flexible and perfect use for small production volume. Not suitable for series production (3 EP).
- CNC: Trade-off between small batch and series production (2 EP).
- IM: Strongly depended on the scale effect. Not suitable for low volume production (0 EP).

4.5 Materials variety

In order to provide a basis for the evaluation of the materials variety of manufacturing systems, the materials have to be evaluated regarding the knowledge about their properties obtained from various investigations (Table 4-2). Following properties are taken into consideration:

- **Physical properties** including mechanical properties (e.g. tensile strength), electrical properties (e.g. electrical conductivity) and thermal properties (e.g. specific heat capacity)
- **Chemical properties** (e.g. corrosion resistance and flammability)
- **Manufacturing properties** (e.g. castability and weldability)
- **Environmental properties** (e.g. toxicity and recyclable)

Table 4-2: Research progress of various materials

Material	Physical properties	Chemical properties	Manufacturing properties	Environmental properties
Metals	++	++	++	+
Plastics	+	++	+	o
Ceramics	+	++	+	+
Silica	o	o	o	++
Biomaterial	-	+	-	o
Wood material	+	o	+	++
Multi-materials	-	-	-	o
++ Very well known	+ Well known	o Known	- Further research required	-- Almost unknown

As it can be seen in Table 4-2, there have been done a lot of investigations about metal material. Thus, their properties are very well known in generally with the exception of a small number of alloys. In comparison to that, the usage of the most multi-material is relatively seldom, as the material properties are almost unknown.

The evaluation of the range of material criteria includes the two most common materials in engineering, plastics and metals, as well as the not less important ceramic and wood materials. Furthermore, parts out of silica sand find technical meaning, as they are appropriate as sand molds for casting processes. Although biomaterials are almost used in medical engineering, the consideration in the evaluation should show the material capabilities of miscellaneous manufacturing systems. Table 4-3 shows the material opportunities and limitations of the three treated manufacturing systems.

Table 4-3: Manufacturing systems with its applicable materials

Material	Manufacturing system		
	IM	AM	CNC
Metals	◑	●	●
Plastic	●	●	●
Ceramics	◑	◑	◑
Sand molds and cores	○	●	○
Paper	○	●	○
Biomaterial	○	●	○
Wood material	○	○	●
Multi-materials	◑	●	○

● = Possible ◑ = Possible to limited extend ○ = Not possible

Injection molding

- **Plastics:** IM is able to process with a wide range of plastic materials, not only thermoplastics, but also elastomers and thermosets are processable [EYE10, p. 192].
- **Metals:** It is possible to manufacture metal parts with the aid of various metal powders. The spectrum ranges from tool steel up to hard metals. In order to produce metal parts, a binder is necessary, which is burned-out afterwards [HEA12, pp. 29-32]
- **Ceramics:** Similarly to the metal fabrication, a binder is required, in order to obtain a ceramic part. In a post-processing step, debinding is executed to obtain the final part in desired quality [STA12].
- **Multi-materials:** IM is able to create multi-materials with the so called multicomponent IM [JOH04, p. 505].

CNC

- **Plastics:** The fabrication of plastic parts with any ordinary CNC system is possible. Only cutting speed needs to be adjusted to the melting point of the particular plastic material, otherwise thermal warping can occur.
- **Metals:** Milling and lathing processes are possible with almost every kind of metal materials.
- **Ceramics:** The production of ceramic components with CNC systems is possible but can lead to challenges, especially in the hard machining of ceramics, as ductility and breaking elongation is very low. For this reason, the proper cutting tool has to be carefully selected [KOL04, pp. 436-437].
- **Others:** CNC enables the creation of accurate parts and components out of any type of solid wood.

Additive Manufacturing

- **Plastics:** Plastics have been the first materials used for AM processes. Therefore, the most AM machineries mainly keep focus on processes with plastic material. The liquid-based additive manufacturing systems SL and Polymer Printing are processing with photopolymers resin materials, such as acrylates and epoxies.
- **Metals:** AM can provide high density parts with complex geometry and mechanical properties close to those of bulk materials as well as full functional multi-parts [YAD10]. Available metal materials are ranging from stainless steel or tool steel, to different alloys, such as TiAl6V4 or AlSi10Mg for instance, up to noble metals, like gold and silver [KRU05, BUC11, KHA2010].
- **Ceramics:** As it is with IM, a ceramic-binder composite is the fundamental mixture to obtain a green part, in order to fabricate pure ceramic parts. Post-processing ensures a burn-out of the binder material [HIM97, AGA96].
- **Others:** Other materials ranges from paper, sand molds and cores up to biomaterials, which opens possibilities to repair human organs [MEL11].
- **Multi-materials:** The main advantage of AM related to the applicable materials, is the possibility of composing a broad range of multi-material parts [GEB11, p. 40].

Evaluation

As shown in Table 4-3, AM brings advantages with a broad variety of applicable materials, whereas IM and CNC systems are restricted regarding the materials variety. The reason for that is the manufacturing process itself. IM processes rely on phase changes of the raw material, which is not feasible with all kind of materials, like paper for instance. Furthermore, metal and ceramic parts are feasible, but binder material is necessary. With the usage of binder material, the realization of full-density parts is not possible. On the other hand, are not all properties of the materials known, which a processable with AM and thus, only applicable to a limited extent. Summarized the evaluation results are following:

- AM: AM systems show great potential to process with almost any materials, even with multi-materials, but often the lack of knowledge about their properties is limiting the field of application (3 EP).
- CNC: Well suited for most applications in engineering. Properties of processable materials are usually well known (3 EP).
- IM: Well suited for plastic part applications and other applications possible to limited extent. (2 EP).

4.6 Variety of products

As already mentioned, product variety is a certain flexibility of a manufacturing system. In particular this means that the system is able to generate different products with the same tools, or at least, the system is performing with a set of tools, which are interchangeable.

Also here, tools are a significant factor that is mainly limiting the degree of product variety. Especially with casting and molding process, design changes are possible to a very limited extend. The change of material in an IM process is very extensive and time-consuming, as the reciprocating screw has to be thoroughly cleaned or replaced, if the molding process should be executed with another kind of material [KOL12, p. 25].

Evaluation

AM provides the ability to produce unique parts in one piece since it does not require tools to manufacture a part. However, the outer dimensions of the part are restricted due to the limited space in the building chamber. State of the art CNC systems are able to cover a broad product portfolio, but at a certain point the possible variety is limited due to the type of machinery. Either the CNC system is combined with a milling machine or with a turning lathe. The latter means that a certain degree of variety is given, as long as the product is rotary-symmetrical. When processing with IM, product variety is almost impossible to achieve, since any changes in the geometry or functionality of the product requires a new mold. Summarized the evaluation results are following:

- AM: A random production of unique products is realizable (4 EP).
- CNC: Passive personalization is possible (2 EP).
- IM: Product variety is very restricted (0 EP).

4.7 Dimensional stability

The dimensional stability is divided into dimensional stability to heat, which is considered especially during the manufacturing process, and dimensional stability to stress of the manufactured part.

Dimensional stability to heat

Especially sintering processes (e.g. SLS) and polymerization processes (e.g. SL) are particularly affected by dimensional instability to heat. SL provides only “green parts”, which are not hardened completely and need a curing subsequently with post-curing ovens after the building process [JAY95]. This post processing can cause shrinkage of the part. Shrinkage is influenced by process parameters like layer thickness, laser power and temperature of the working environment. As already shown in equation 3.1, dimensional stability to heat depends on α, which is a material specific constant, and ΔT. For this reason, the temperature of the working environment is often increased, which leads to a reduction of the laser power and this in terms leads finally to a decrease the temperature difference ΔT. This procedure affects the shrinkage positive [WAN07]. Large amount of shrinkage can cause dimensional instability and warping.

Shrinkage does also occur within IM processes and can be decreased by various process parameters, like mold temperature and melt temperature but also the cooling time influences the shrinkage [ZÖL01].

Subtractive manufacturing methods (CNC) show comparatively hardly any dimensional instability caused by the process.

Dimensional stability to stress

Parts fabricated with AM have anisotropic characteristics. This means build direction is an important process parameter that affects the mechanical properties [LEE07]. Figure 4-4 shows a tensile strength investigation of ABS P400 specimens built with FDM and IM. The stated values in the diagram are the maximum tensile strength before failure occurs. It can be seen that the building direction has a dramatically influence on the permitted tensile strength [AHN02]. Anisotropic character can also be strongly developed though IM due to inaccurate settings of injection speed and melting temperature [REN05]. Investigations have shown that there is no noticeable influence on the tensile strength though milling or lathing [THE08].

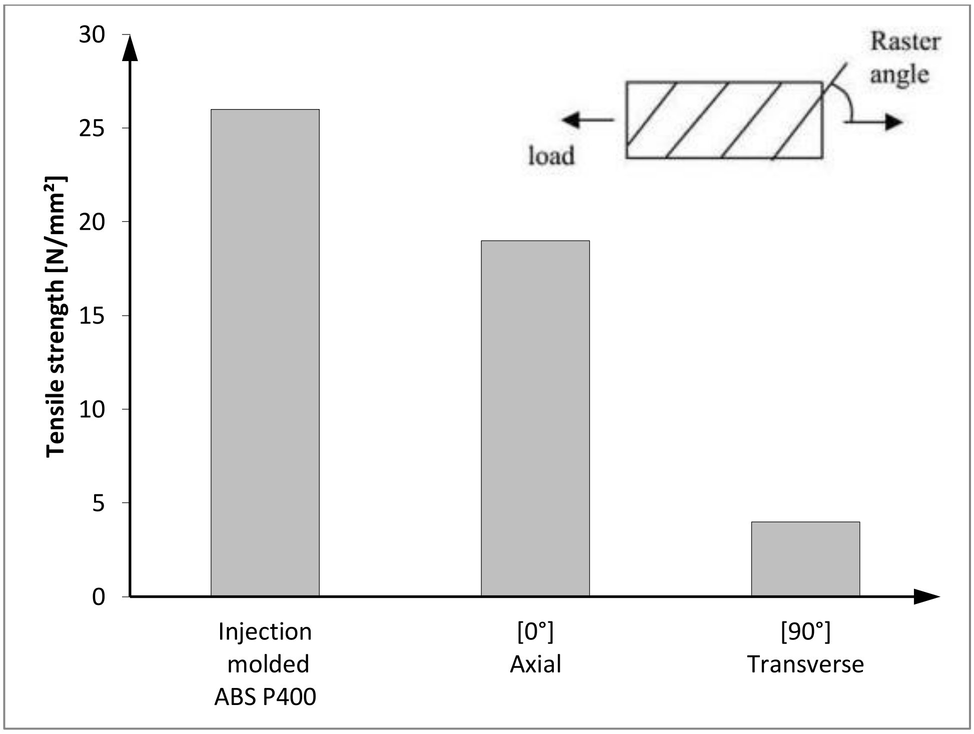


Figure 4-4: Tensile strengths of ABS specimens manufactured with IM and AM [AHN02]

Evaluation

With the use of CNC, materials can be processed without any negative consequences on the mechanical properties, whether the process is milling or lathing. When parts are manufactured with IM machines, good knowledge about the process parameters is required in order to obtain molded parts with acceptable mechanical properties. Regarding AM, anisotropy is unavoidable and thus, loading direction should not be the same as the building direction (Figure 4-5). In this illustration the single layers are exaggerated.

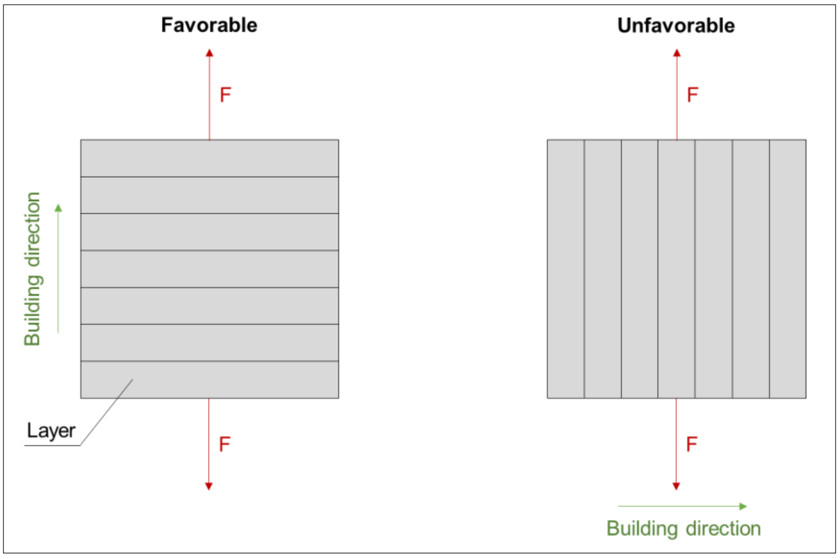


Figure 4-5: Building direction vs. loading direction of AM parts

Summarized the evaluation results are following:

- CNC: The process does not influence the dimensional stability noticeably (4 EP).
- IM: Process parameters influence the dimensional stability (3 EP).
- AM: Anisotropy is unavoidable. Shrinkage can be influenced by process parameters. (2 EP).

4.8 Accuracy

As already mentioned, this criterion contains the consideration of dimensional accuracy, surface roughness and tolerances in shape and position.

Dimensional accuracy and surface roughness

The dimensional accuracy and surface roughness are an essential parameter for manufactured parts. Many fields in engineering require highly accurate parts. Therefore, a manufacturing system is necessary that can cope with that. Table 4-4 shows the dimensional accuracy and surface roughness of IM, AM and CNC.

Table 4-4: Accuracy of manufacturing systems

Manufacturing system	Dimensional accuracy [mm]	Surface roughness [µm]
IM	±0.15 up to ±0.05	0.8
AM	±0.20 up to ±0.13	60 up to 2
CNC	in the micron millimeter range	0.4 up to 0.2

Leading conventional CNC systems can achieve the maximum machine specific state of the art accuracy [KOM14]. This leads to very smooth surfaces with roughness between 0.2 µm for milling machines and 0.4 µm for lathing machines.

The achievable tolerances for IM processes are between ±0.15 mm up to ±0.05 mm and wall thicknesses between 1 mm and 1.4 mm are realizable [SCH02, p. 24].

A typical characteristic of every AM part is the so called staircase effect (Figure 4-6), caused by layer based building principle. The illustration shows the possibility to build a square shaped part, whereas building direction has a massive influence on the quality of the part. The staircase effect is a common error source affecting the surface roughness negatively [CHU15, pp. 203-207]. This leads to a distortion of the desired shape, especially on curved surfaces [PAN03].As a result, surface quality of AM part is negatively influenced by that fact and surface roughness ranging between 2 µm for STL and 60 µm for LOM. The dimensional accuracy is between ±0.13 mm for FDM and ±0.20 mm for SL [CHA02, AHN02, PIC98]. Another issue is the poor reproducibly, as identical parts, which are built under the same conditions, are varying in their dimensional accuracy and properties [BLR09].

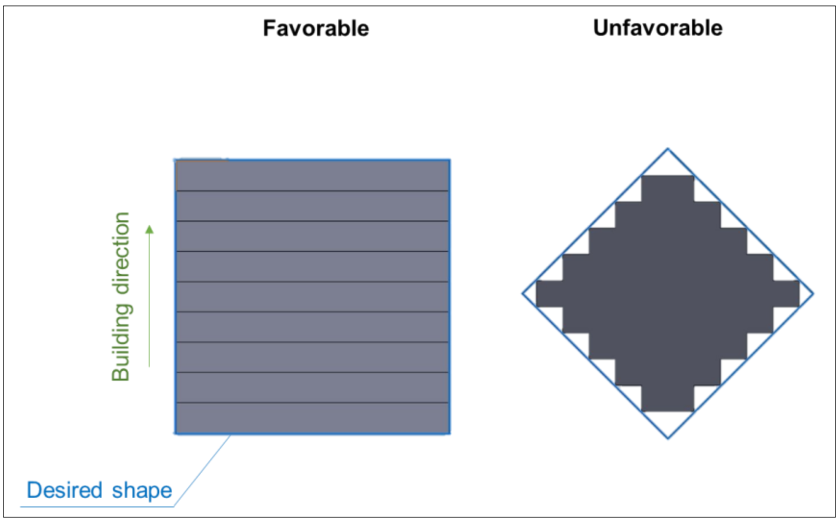


Figure 4-6: Staircase effect caused by AM [PAN03]

Tolerances in shape and position

As geometrical deviations are unavoidable within manufacturing processes, tolerances in shape and position are required to define permitted deviations. Therefore, standards have been introduced for TM, e.g. ISO 2768-1 [ISO89].

Until now, there is not any literature or standard available about geometric tolerances for AM. Although, tolerance specifications exist, they are mostly gained by individual experience but not empirically confirmed.

Evaluation

CNC systems are perfectly suited for highly accurate applications, as they are capable to produce parts with constantly high accuracy and have the ability to meet tight tolerances. With the use of high-class AM systems, an acceptable dimensional accuracy can be achieved. Nevertheless, post-processing is necessary due to the high surface roughness, caused by the staircase effect. Related to TM systems, there are various standards existing for the compliance with tolerances. In opposite to that, there are no proven standardized tolerances for AM systems available. Summarized the evaluation results are following:

- CNC: High dimensional accuracy as well as high surface quality (4 EP).
- IM: Good dimensional accuracy and also a high surface quality are realizable (3 EP).
- AM: Acceptable dimensional accuracy, but post-processing is required. Until now, no standards in terms of tolerances available (1EP).

4.9 Process time

As already described in section 3.5, this criterion stands for the time of a manufacturing system, which is required to obtain a part. A clear distinction between the different definitions of process time has to be made, as every manufacturing system includes various activities, which in terms result into the total time for producing a part.

CNC

The time for producing a part is declared as cycle time, which contains of the start-up time, positioning time, lifting time and return travel time. The main time is the actual time, where the machinery is processing the material and adding value on it. A closer look on equation 3.3 shows that the main time depends on the length the tool has to move, feed rate and rotation speed. The two last in turn depend on:

- The rotation speed depends on the material that has to be processed.
- The feed rate depends on the rotation speed and the tool geometry.

Thus, the main time mainly depends on the geometry which has to be created. Modern CNC systems can perform precise start-ups and positioning in a few seconds.

Injection molding

Here the time for producing a molded part is called cycle time. As it can be seen in Figure 4-7 that the cycle time depends on the wall thickness, as voluminous parts requires more time for injecting and cooling.

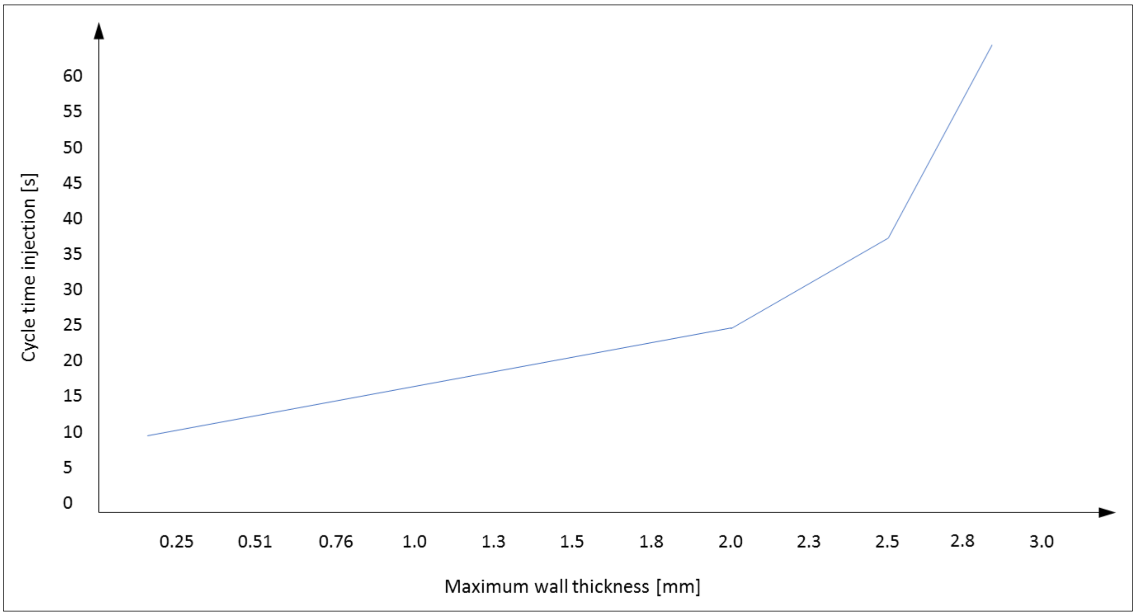


Figure 4-7: Cycle time estimation regarding wall thickness [DOU98, p. 56]

Additive Manufacturing

To obtain one part or assembly, the so called building time is required. The build time depends on the z-height of the product, the part volume and the bounding box. For AM principles that require support structure, such as FDM, the height and volume of this structure has to be considered as well. Following table (Table 4-5) shows an examination about the generation of different parts with SLS by changing the mentioned parameters [ZHA15].

Table 4-5: SLS production parameters and build time [ZHA15]

Part	Z-height [mm]	Volume [cm³]	Bounding box [mm³]	Real build time [h]
1	29.79	54.40	109942.80	2.98
2	54.93	94.22	684636.47	4.30
3	66.88	64.79	144372.98	4.93
4	152.98	187.59	2916396.41	9.49
5	17.02	34.30	60826.13	2.32

Although modern AM systems have the ability to create parts with complex geometries within a short time, the build speed of AM is low and therefore limits its use for high volume production [DOU14].

Evaluation

IM molding system are designed for producing a high volume of parts with complex geometries and therefore, suited for mass production. Also CNC systems are used for mass production for several decades [BER97, p. 144]. Behind this are AM systems, which can create complex geometries without negatively affecting the time for producing parts. Nevertheless, the building time is generally low. Summarized the evaluation results are following:

- IM: Very low cycle time. Cycle time depends mainly on the wall thickness of the part (4 EP).
- CNC: Low cycle time. The more complex the geometry, the longer is the cycle time (3 EP).
- AM: Long build-time. Build time depends on the part height, part volume and the volume of the bounding box (1EP).

4.10 Total results of the evaluation

The result of the evaluation shows that AM is the most appropriate manufacturing system in consideration of the discussed criteria (Table 4-6). Its strengths are the enormous design freedom, which can be achieved with the use of AM, the huge applicable range of materials and the flexibility in small batch and single piece production. Right behind is the CNC system, which has its strengths in producing components with high dimensional stability and accuracy. The main strength of IM is the very low process time, which makes it perfectly suitable for mass production.

Table 4-6: Evaluation of different manufacturing methods

No	Evaluation criteria	Weighting w_i	IM		AM		CNC	
			Value v_{i1}	Weighted wv_{i1}	Value v_{i2}	Weighted wv_{i2}	Value v_{i3}	Weighted wv_{i3}
1	Design freedom	0.18	3	0.54	4	0.72	1	0.18
2	Flexibility	0.17	0	0	3	0.51	2	0.34
3	Range of materials	0.16	2	0.32	3	0.48	3	0.48
4	Product variety	0.14	0	0	4	0.56	2	0.28
5	Dimensional stability	0.13	3	0.39	1	0.13	4	0.52
6	Accuracy	0.12	3	0.36	1	0.12	4	0.48
7	Process time	0.10	4	0.40	1	0.10	3	0.30
		$\sum_{i=1}^{n} w_n = 1$	**15**	**2.01**	**18**	**2.78**	**19**	**2.58**

4.11 Improvement of the product development by AM

Customization, short time-to-market and increasing complexity of the product design are influencing the development process. The results from the evaluation have shown that these challenges can be mastered by AM. Furthermore, they are also confirming the findings in section 3.7.

High degree of Customization

In terms of customization, AM has the capability to provide a broad variety of products easily. Even unique parts can be produced without high effort. As economic of scale does not influence AM, small volumes of products, even single parts can be produced without increasing costs in any way.

Short Time-to-market

Short time-to-market is influenced by the whole product development process. Thus, an optimization of the product development process can decrease the development time, which in terms means the product can enter the market faster. In order to shorten the development time, models or prototypes can be used, as already described in section 2.5. Depending on the manufacturing system used for prototyping, the time to create such a prototype can be more or less time consuming, as most manufacturing methods require a lot of preparation time and time for tooling. Traditional design processes start with a rough concept CAD model in order to obtain the first prototype. Based on the prototype model, further improvements of design and geometry follow as long as it is possible to manufacture the model. Afterwards, tooling and work scheduling have to be executed (Figure 4-8). AM is able to eliminate those steps, since a completely finished CAD model can be directly manufactured with the respective AM system. [HAG03].

High degree of design freedom

AM enables the possibility for engineers to create almost every desired shape without considering DFM and partially DFA as well. Furthermore, assemblies with integrated functionalities in one piece can be achieved. In addition to that, design changes can be realized imminently with AM and does not require any changes in tool design, since AM does not require any tools. Figure 4-8 points out the time consuming tooling steps that come with IM, in order to adapt on design changes.

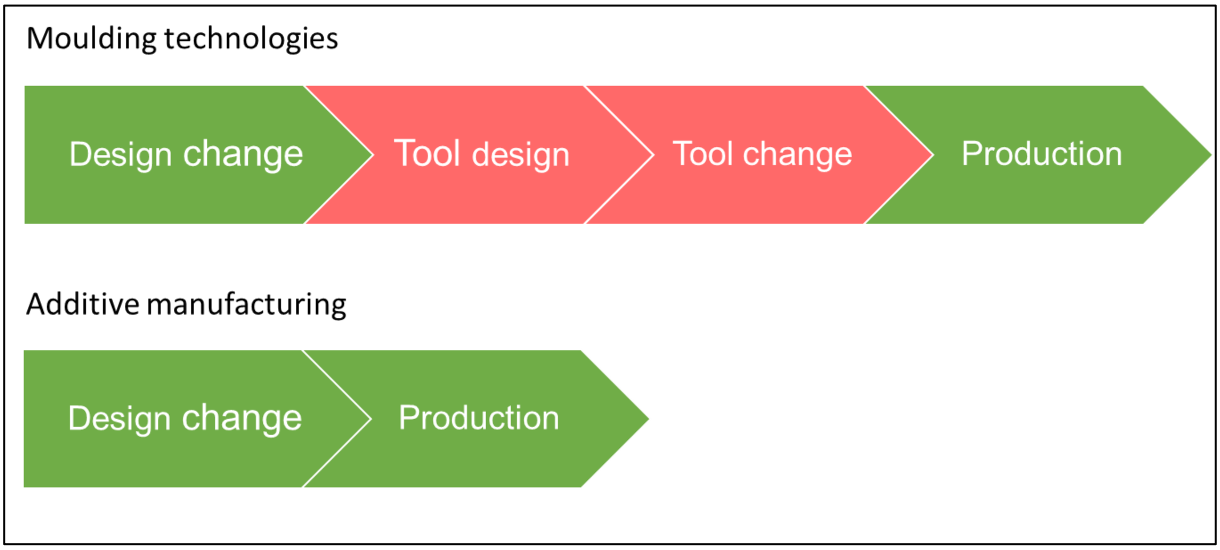


Figure 4-8: Time-to-market when introducing design changes [MAT15]

When AM is used during the product development process, it is called RP (Figure 4-9). The term RM is often used, when the product is going to be realized. As already mentioned in section 3.7, nowadays many industries are taking advantage of RP.

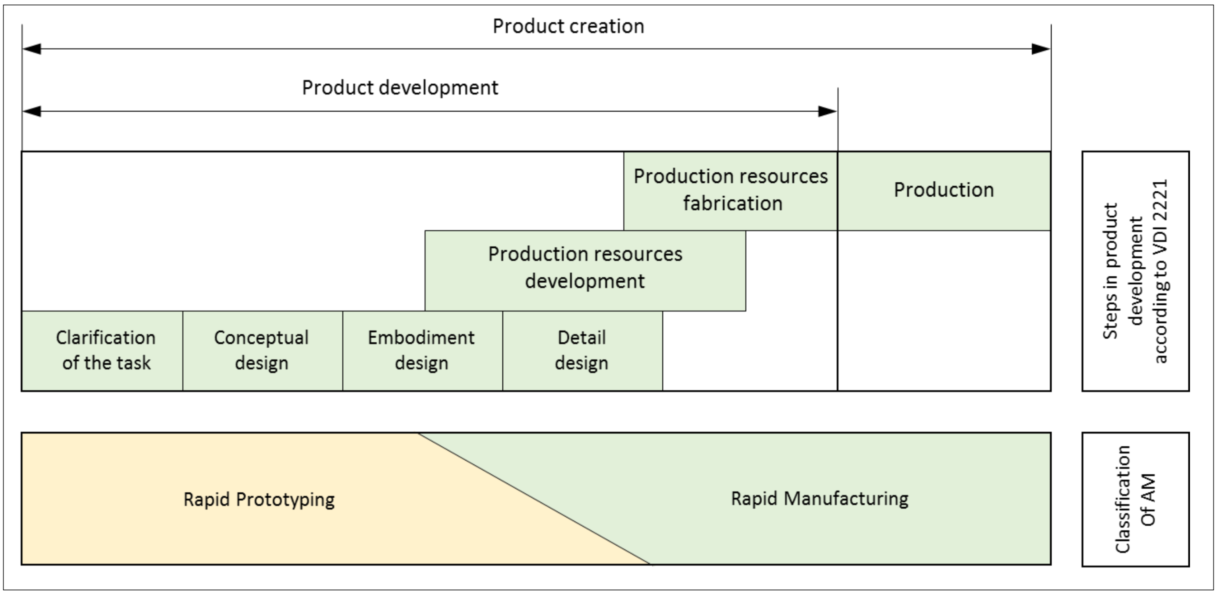


Figure 4-9: Interconnection of the product development and AM [GEB07, p. 9]

In combination with RM, it can open a new business path and significant advantages in product designing and development as well as in production. The so called DOD is already used in some industries (examples have been already described). Nevertheless the manufacture of end-products with AM, contains weaknesses that have to be considered. The evaluation has point out these weaknesses and following main advantages by the use of AM systems (Table 4-7).

Table 4-7: Benefits, weaknesses and potentials of AM

	Influence of AM on development process	AM as manufacturing system
Benefits	• High variety of products can be realized, which enables a fast response on product and design changes. • No tooling and work scheduling necessary. • No consideration of DFM and partially DFA. Realization of integrated functionalities possible. • High variety of processable materials available.	• Very suitable for small volume production. • System complexity can be decreased. • Reduction of manufacturing scrap. • No expensive tools are required.
Weaknesses	• Lack of standards related to geometric tolerances. • Dimensional instability in stress and heat (Anisotropy and shrinkage). • Lack of dimensional accuracy. • Restriction of the outer part's dimensions.	• Missing scale effect leads to the fact that AM is not suitable for mass production. • Slow build speed confirms the infeasibility for high volume production. • Poor reproducibly.
Potentials due to benefits	• Reduction of costs in development process. • Shorter time-to-market. • High degree of customization is possible.	• Reduction of costs in manufacturing. • High degree of customization is possible.

5 Development of a plate tray in consideration of AM

This chapter deals with the systematical approach according to VDI 2221 of creating variations and designing concept models of an innovative plate tray. After evaluation of the different variations, the most suitable concept has been chosen and used for further detailed design. Thereby, the gathered information from the theoretical investigations about a proper manufacturing system has been always kept in mind.

5.1 Initial situation and framework conditions

The company "Ökoservice GmbH" is specialized for renting tableware for catering-services. After the return of the tableware in transport boxes (Dimensions in Table 5-2), the inventory is checked for completeness and possible damages. Then, the dirty tableware is put on a belt conveyor (Dimensions in Table 5-1) that guides the tableware through a washing system. Especially for dishes, this is very challenging, since the plates are stapled in buckets and transported in that way. When checking for completeness, every single plate has be taken out of the bucket and then placed on the conveyor belt. There are two existing variations of the conveyor belt, which are used at the moment. On the one hand, a flat belt for already existing glass, cup and cutlery trays and on the other hand a finger belt, which is mainly used for the dishes. Figure 5-1 and Figure 5-2 illustrate the existing conveyor belt variations.

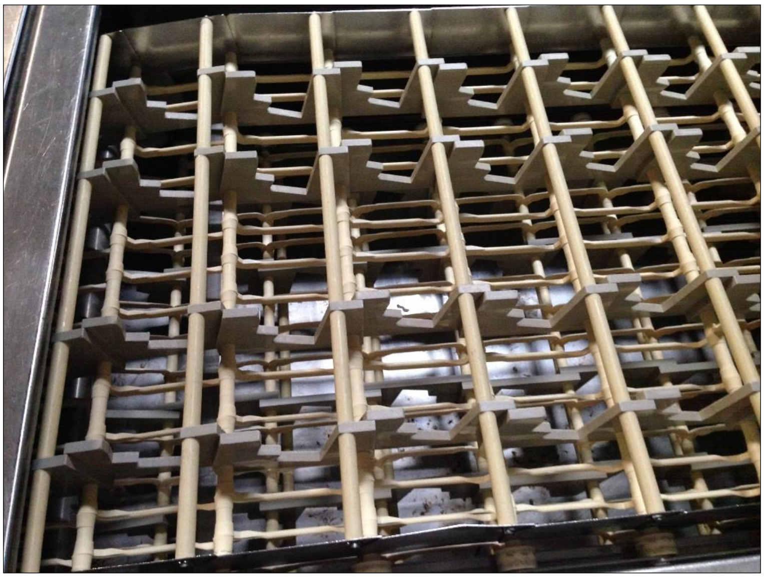


Figure 5-1: Flat conveyor belt

Figure 5-2: Finger conveyor belt

Table 5-1: Conveyor belts' dimensions

	Flat conveyor belt	Finger conveyor belt
Inner width [mm]	550	550
Outer width [mm]	600	600
Distance between horizontal links [mm]	80	80
Distance between vertical links [mm]	125	125
Inclined position of the plates [deg]	-	63

Table 5-2: Transportation box dimensions

Outer dimensions [mm]	600 x 400 x 278
Inner dimensions [mm]	556 x 356 x 276
Usable height [mm]	262
Weight [kg]	2.7

“Ökoservice GmbH” provides three different assortments of tableware, beginning from low budget quality up to porcelain quality (Table 5-3). Since the most frequent requested quality is the low budget quality, the main focus is kept on that product range. In addition to that, the largest proportion of the low budget quality is the dinner plate with a diameter of 245 mm.

Table 5-3: Arcopal low budget quality

	Diameter [mm]	Height [mm]	Weight [kg]
Dinner plate	245	24	0.38
Soup plate	225	36	0.30
Desert plate	195	16	0.26

The target was to find a product solution in order to facilitate the handling of the plates. A tray for transporting a particular set of plates in the already existing transport boxes, was the first idea that deemed suitable, since trays are already used for glasses and cutleries but are not nearly suitable for plates.

In order to realize this target, AM is the manufacturing system that is considered to be used. Therefore, the gained results from chapter 4 should be considered in the development process. Thus, the advantages of AM should be exploited but on the disadvantages that come with AM should be paid attention as well. As already shown in section 4.11, following advantages are:

- High variety of products can be realized
- System complexity can be decreased
- No consideration of DFM
- High variety of processable materials available
- No tooling and work scheduling necessary
- Very suitable for small volume production
- Reduction of manufacturing scrap
- No expensive tools are required

Whereas the disadvantages are following:

- Dimensional instability in stress
- Restricted outer dimensions of the part
- Lack of dimensional accuracy

5.2 Requirement specification

Deducted from the actual situation and the customer expectations, following requirements on the solution principle need to be fulfilled more or less efficiently. The letters in brackets express whether the requirement is essential or desirable.

1. Forces
   - Maximum loadings of 300N (E)
   - Sufficient mechanical strength against deformation under load (D)

2. Material
   - Chemical resistance to dishwashing liquid and rinsing agent (E)
   - Thermal resistance to temperatures up to 90°C in the washing system (E)
   - Food-safe and harmless for health (E)

3. Geometry
   - Maximum height: 252mm (E)
   - Maximum width: 356mm (E)
   - Maximum length: 556mm (E)
   - Plates must be clearly determined in its position (D)
   - Plate tray must be clearly determined in its position (in transportation box) (D)
   - Washing procedure with plate tray must be enabled (E)
   - Avoidance of niches and troughs such that no residual water remains (E)
   - Modularity (D)
   - Handling of 25 plates (D)
   - Handling of 20 plates (E)
   - Fast visual inspection (E)

4. Manufacturing method
   - Realization of complex geometries (E)
   - Few manufacturing steps (D)
   - Usage of standard materials (D)

5. Ergonomics
   - Easy handling when taking out the plate tray (E)
   - Easy handling without the usage of additional tools (E)
   - Low weight of the tray (E)

6. Safety issues
   - No risk of injury due to sharp corners and edges (E)

7. Economic efficiency
   - High durability / low wearing (E)
   - Low development time (E)
   - Low material costs (E)
   - Low tool costs (E)

8. Recycling
   - Simple waste disposal of damaged components (D)

9. Maintenance
   - No maintenance planned (E)

10. Transportation
    - Transportation in already existing plastic box (E)

Formulation of the problem statement

According to a systematical approach described by Pahl and Beitz [PAH07, p.237] and by means of the requirements specification a meaningful problem formulation can be defined.

1. Elimination of desirable requirements.
2. Only consideration of requirements, which include functions and which are essential ones.
3. Transformation of quantitative data into qualitative data.
   - Dimensional stability
   - Maximum dimensions must not exceeded
   - Any geometries should be realizable

- Washing procedure with the whole tray has to be enabled
- Handling of dishes
- Fast visual inspection
- Transportation in existing plastic boxes

4. Extension of recognized meaningful.
   - Dimensional stability
   - Maximum dimensions must not exceeded
   - Washing procedure has to be enabled
   - Handling of dishes
   - Fast visual inspection
5. Formulation of problem solution-neutral.

   Secure transportation of plates in transport boxes, enable washing in one compound and simple visual inspection.

5.3 Function structure

The next step in the development phase is the consideration of the functions and structure of the plate tray by means of the problem formulation above. The function structure combines all essential tasks that the plate tray should perform.

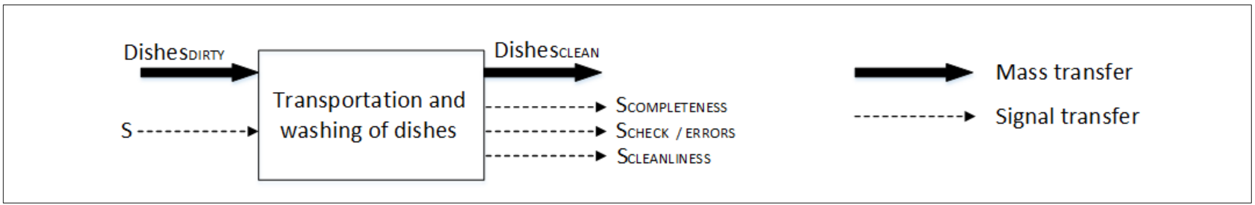


Figure 5-3: Overall function of the plate tray

The overall function in Figure 5-3 indicates the principal tasks. The tray should transport dirty dishes and enable the washing process of those. Furthermore, it should enable to check the completeness, the integrity and the cleanliness, without rejecting the single plates.

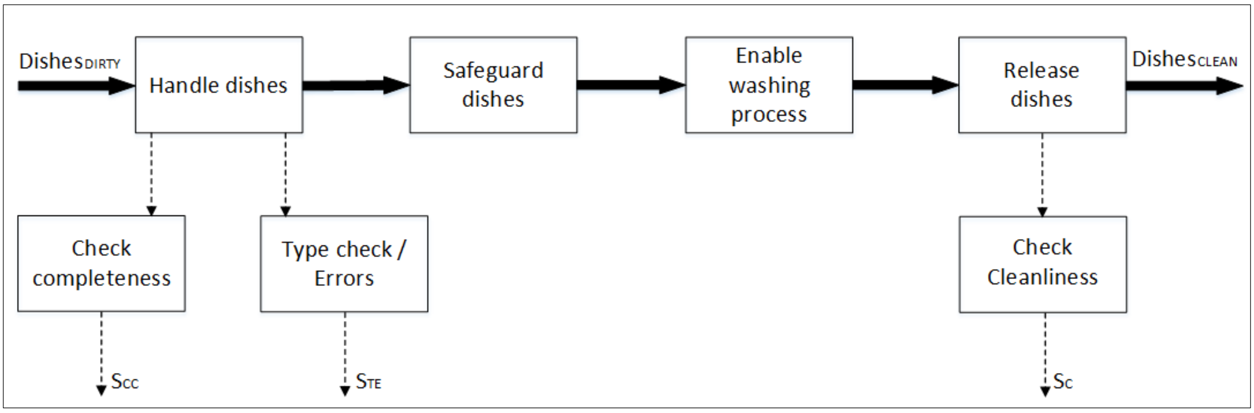


Figure 5-4: Sub functions of the plate tray

A closer look on Figure 5-4 shows the sub functions of the tray. There, the entire functions are more obviously described.

5.4 Principle solution

By means of the function structure and the regarding sub-functions, solution principles can be determined. The result of combining the solution principles is one main principle solution (orange colored line) that is feasible. Table 5-4 also shows that the use of standard components is almost impossible to fulfill the functions in section 5.3. The reason for this is that the product to be developed is a unique product and products with comparable functions are hardly widesread on the market.

Table 5-4: Solution principles

Sub-function	1	2	3	4	5	6
Handle plates	Form fit	Ferro-magnetic	Electro-magnetic	Aero-static	Gravity	
Safeguard dishes	Force fit	Form fit	Ferro-magnetic	Electro-magnetic	Aero-static	Coulomb friction
Enable washing process	Vertical structure of uptakes	Horizontal structure of uptakes				
Check complete-ness	Visual inspection	Mechanical switch	Optical sensors	Weigh	Changing dielectric in capacitor	
Type check / error	Visual inspection	Optical sensors	Weigh	Weigh		
Check cleanliness	Visual inspection					

In order to gain a favorable main principle solution, an evaluation is necessary that is considering the findings from chapter 4. Also here, Pahl and Beitz describe a useful approach, how this evaluation of solution principle can be executed [PAH07, p. 262]. The evaluation table includes various evaluation criteria, which all have to be fulfilled in order that a principle solution is permitted. Following criteria are deducted from the gathered results from chapter 4 and the requirement specification:

- Requirements fulfilled: The requirements from the requirement specification in section 5.2 have to be fulfilled.
- System complexity realizable: Even though, the usage of AM enables a high degree of system complexity, some sub functions cannot be realized.
- Sufficient dimensional stability to stress: As dimensional stability is a weakness of AM, the dimensional stability to stress in order to realize the sub function is restricted.
- Sufficient dimensional accuracy: The required dimensional accuracy of the sub function is restricted.
- Basically realizable: The sub function has to be basically realizable.
- Effort permitted: The effort to realize the sub function has to be permitted.

Table 5-5: Evaluation table of principle solutions

	Requirements fulfilled	System complexity realizable	Sufficient dim. stability to stress	Sufficient dimensional accuracy	Basically realizable	Effort permissible	Comments	Solution excluded
A1	+	+	+	+	+	+	Simple and proven in practice	+
A2	+	-	-	+	+	-	Effort too high and too cost intensive	-
A3	+	+	-	+	-	-	Not realizable	-
A4	+	+	+	+	+	-	Effort too high	-
A5	-	+	+	+	+	+	Does not fulfill the requirements	-
B1	+	+	-	+	+	-	Simple and proven but effort too high	-
B2	+	+	+	+	+	+	Simple and proven in practice	+
B3	+	-	-	+	+	+	Effort too high and too cost intensive	-
B4	+	+	-	+	-	-	Not realizable	-
B5	+	+	+	+	+	-	Effort too high	-
B6	+	+	-	+	+	-	Simple solution principle but effort too high	-
C1	-	+	+	+	+	+	Does not fulfill dimensional requirements	-
C2	+	+	+	+	+	+	Simple and fulfill the requirements	+
D1	+	+			+	+	Meet the requirements and low effort	+
D2	-	+			+	-	Does not fulfill requirements (Visual check)	-
D3	-	-			+	-	Does not fulfill requirements (Visual check)	-
D4	-	+			+	-	Does not fulfill requirements (Visual check)	-
D5	-	-			+	-	Does not fulfill requirements (Visual check)	-
E1	+	+			+	+	Meet the requirements and low effort	+
E2	-	-			+	-	Does not fulfill requirements (Visual check)	-
E3	-	+			+	-	Does not fulfill requirements (Visual check)	-
F1	+	+			+	+	Meet the requirements and low effort	+

With the information gained from the evaluation in table above, permitted solution principles can be combined in order to obtain one clear main principle solution. Table 5-6 shows the favorable main principle solution by combining A1-B2-C2-D1-E1-F1.

Table 5-6: Morphological box

Sub-function	**Solution**					
	1	**2**	**3**	**4**	**5**	**6**
Handle plates	Form fit	Ferro-magnetic	Electro-magnetic	Aerostatic	Gravity	
Safeguard dishes	Force fit	Form fit	Ferro-magnetic	Electro-magnetic	Aerostatic	Coulomb friction
Enable washing process	Vertical structure of up-takes	Horizontal structur of up-takes				
Check completeness	Visual inspection	Mechanical switch	Optical sensors	Weigh	Changing dielectric in a capacitor	
Type check / errors	Visual inspection	Optical sensors	Weigh			
Check cleanliness	Visual inspection					

5.5 Elaboration of various concepts

Out of the gathered information of chapter 5.3 and 5.4, and by means of the requirement specification treated in section 5.2, three different concepts have been elaborated - a wire construction, a pure plastic concept and a hybrid version. The plastic concept and the hybrid model are adapted to suit into the transportation box, whereas the wire construction is an alternative concept for the bucket. In this section, the concepts are investigated due to their mechanical properties and their advantages and disadvantages. The whole calculation report can be read in the appendix.

Concept 1: The wire construction

This concept is a wire based construction, coated with plastic material, to avoid corrosion. The plates are vertically orientated during transportation in the bucket. After the tray is taken out of the bucket via the handle bar, the whole tray can be tilt and placed on the conveyor belt. So, the plates are oriented perpendicularly to the surface of the belt. The plate tray is able to carry 12 plates with dimensions slightly varying from the low budget quality dinner plate.

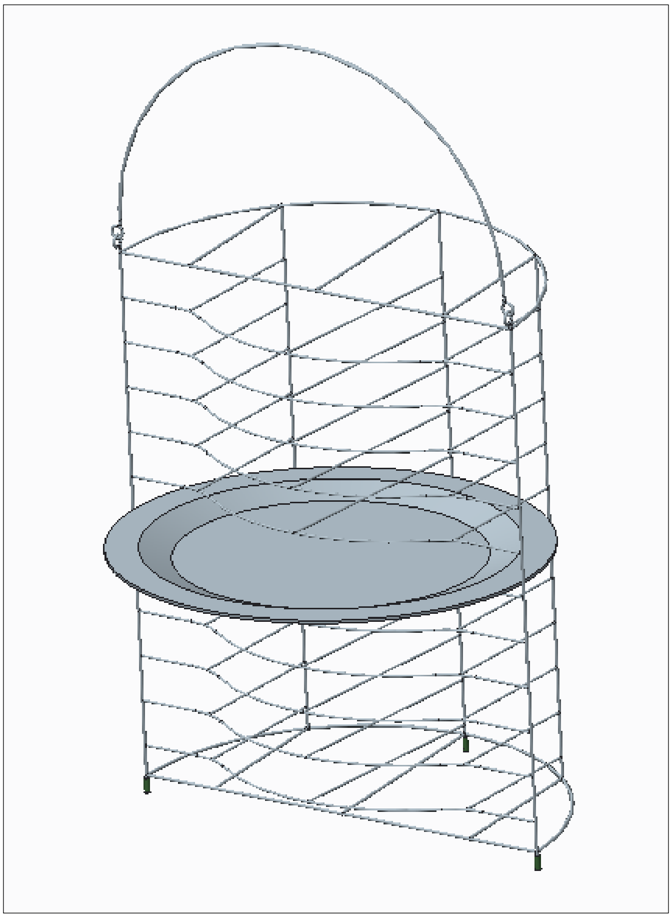


Figure 5-5: Rough 3D CAD model of concept 1

Assumed material for the rough calculations

The whole construction could consist of wire material S235JR, which is coated with Polyamide 12 (PA12). This is essential, to avoid corrosion due to the contact with water and acids. This material decision was made due to the characteristics shown in the following table (Table 5-7). S235JR is very common in almost any fields of engineering and suitable for almost any applica-tions. PA12 is already used for similar applications, especially for commercial dishwasher wire trays. Plastic caps are used to cover the end of the wires, which are in contact with the base of the transport bucket. With the combined used of these three materials, the total weight of the tray is approximately 240 g.

Table 5-7: Materials and their properties used for concept 1

S235JR	PA12
• Relatively cheap • Good machinability and weldability • Sufficiently good mechanical properties • Mechanical properties: $E = 2.1 \times 10^5\ N/mm^2$ $\rho = 7.85\ g/cm^3$	• Very low water absorption • Very good resistance against solvents, lipids and other chemicals • Good workability • Heat deflection up to 115 °C

Due to the choice of S235JR and its good mechanical properties, the maximum bending stress is far below the permissible bending stress. Furthermore, the maximum deflection is almost zero, whether the plate tray is transported via the handle or tilted (Chapter 8).

Concept 2: The pure plastic design

This concept is made out of one part and is designed for transportation in the standard box (600 mm x 400 mm). In order to increase the intake capacity of one transportation box, it is equipped with two plate trays, which are aligned point symmetric. This fact leads to another advantage, as the maximum deflection decreases. This is due to the shorter length of the plate tray in contrast to a design which is inserted into the transportation box lengthwise. One tray has an intake capacity of 10 plates, whose dimensions can slightly vary from the low budget quality dinner plate.

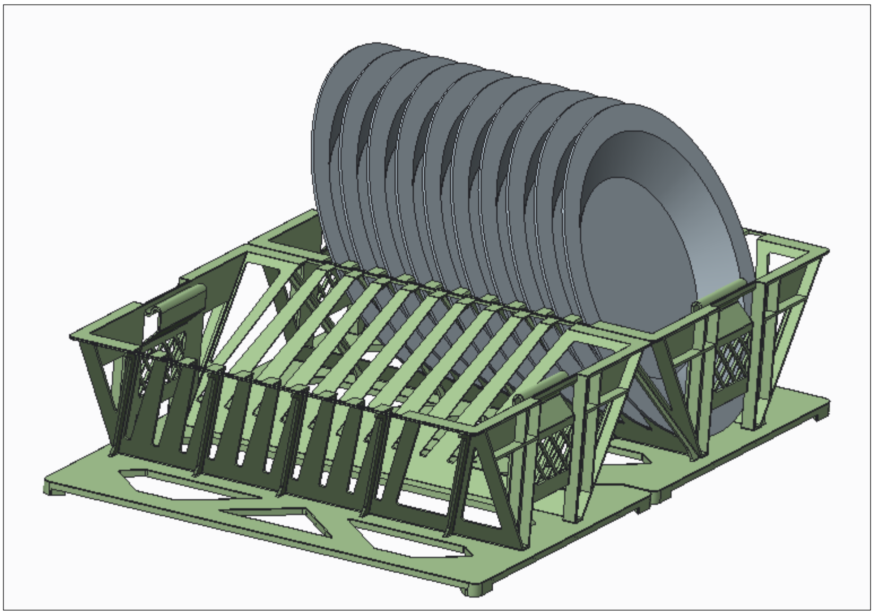


Figure 5-6: Rough 3D CAD model of concept 2

Assumed material for the rough calculations

The whole tray could be manufactured out of high density polyethylene (HDPE). In comparison to concept 1, this design does not contain any loose parts. The reason for HDPE is the high mechanical strength, compared to other plastic materials and the good chemical and thermal resistance. Table 5-8 shows the properties of concept 2. The total weight of concept is approximately 350 g.

Table 5-8: Materials and their properties used for concept 2

HDPE
• High mechanical strength • Resistance against acid, lyes and water • Good machinability • Mechanical properties: $E = 1{,}000\ N/mm^2$ $\rho = 0.95\ g/cm^3$

Even though the mechanical properties are not comparable with those of S235JR, rough calculations reveal that the maximum bending stress is well below the permissible bending stress. Also the maximum deflection is acceptable (Chapter 8).

Concept 3: The hybrid construction

Figure 5-7 shows the concept elaboration 3, which is similar to concept 2 but includes loose parts that have to be assembled first before usage.

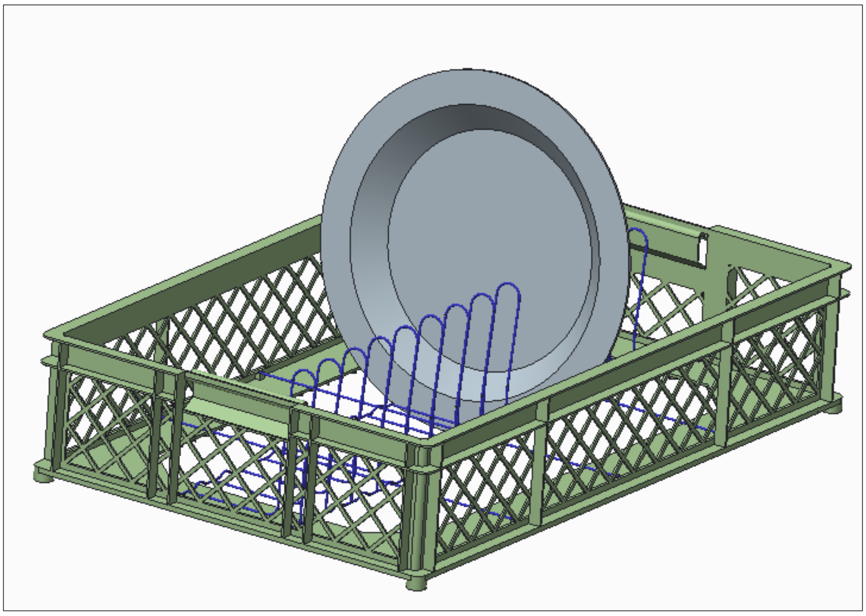


Figure 5-7: Rough 3D CAD model of concept 3

Assumed material for the rough calculations

Concept 3 could be a combination of all materials, which are used in the concepts before. The tray, which carries the plates during transportation and washing process, is formed out of S235JR metal wire material. Similar to concept 1, a PA12 coating protects the metal material against the aggressive washing liquid. The wire tray is inserted in a HDPE plastic-based frame, whose handles guarantee a simple use of the whole construction. The plate tray is able to carry 13 plates with dimensions varying from the low budget quality dinner plate to limited extent. Due to the easy replacement of the wire tray, interchangeability of those is realizable, and the basic concept is useable for other plate types as well. The total weight of this concept is around 570 g.

The combination of S235JR and HDPE leads to a very low maximum deflection. The approximate calculations show that the maximum bending stress lies far below the permissible bending stress (Chapter 8).

Ability of the manufacturing systems to realize the concepts

In order to guarantee the fabrication of the elaborated concept models regarding to the requirement specification, it is becoming apparent that AM is the only suitable manufacturing system. Table 5-9 shows the most important criteria regarding the requirement specification in chapter 5.2 and the suitability of the manufacturing systems, which have been already evaluated in general.

Table 5-9: Evaluation of suitable manufacturing systems for the fabrication

	IM	CNC	AM
Realization of the geometries	◑	◑	●
Material variety	◑	◑	●
Ability for single-part production	○	◑	●
Decreasing systems complexity	◑	◑	●
Economic efficiency	◑	○	●
Tool costs	○	◑	●
● = Very good / well suitable	◑ = Average	○ = Poor / Not possible	

The reason for this particular evaluation is following:

- The realization of the concept's geometries is only partially possible with IM or CNC. Concept 1 is impossible to produce with CNC, as the construction is not able to withstand the cutting forces. IM struggles with the production of concept 2, as it includes undercuts.
- The fact that concept 1 and 3 include a metal wire construction, which is coated with plastic material, reveals the infeasibility of the two considered TM methods.
- The realization of single-part production can be obtained best with AM. As mentioned in section 4.4, CNC is a good trade-off between small batch and series production. IM is not suitable for single-part production, as the production costs cannot be covered by only one part.
- AM is able to decrease the products systems complexity, as it can be built in one piece. As revealed in section 4.3, especially IM is not able to manufacture the tray in one piece, because of undercuts.
- As CNC is a subtracting manufacturing method, especially the production of concept 2 is very uneconomic due to the overhanging design. The reason for this is the high amount of production scrap.

- The tool costs are high, when using IM as a manufacturing system. Tooling is necessary and every change in the product’s design, require changes of the mold design as well. This fact is already shown in section 4.6.

5.6 Evaluation of the concepts by means of a benefit analysis

For the evolution of the concepts, a benefit analysis is used. With the combined use of the scale of the benefit analysis and those of the VDI 2225, different properties are easier to declare.

Table 5-10: Range of scales comparison between benefit analysis and VDI 2225 [VDI98]

Benefit analysis		Guideline VDI 2225	
Points	Description	Points	Description
0	Absolutly unusable solution	0	Unsatisfying
1	Very poor solution		
2	Weak solution	1	Barely acceptable
3	Acceptable solution		
4	Sufficient solution	2	Sufficient
5	Satisfying solution		
6	Good solution with minor deficiencies	3	Good
7	Good solution		
8	Very good solution	4	Very good (ideal)
9	Solution that goes beyond the objective		
10	Ideal solution		

Evaluation criteria

Deducted from the requirements specification, following evaluation criteria are used to make a decision for a proper manufacturing system:

1. **Amount of plates:** Concept 2 has the highest intake capacity, as two trays can be used for one transportation box.
2. **Suitability for conveyor belts:** Concept 2 and 3 are not suitable for the finger belt conveyor, but well suitable for the flat belt. Due to its round shape, concept 1 is suitable for both belt types, but only to a limited extent.

3. **Load of capacity:** Concept 1 has the highest load of capacity, as the total weight of the construction is relatively low. Concept 2 and 3 are almost the same, according to that criterion.
4. **Ergonomics:** The ergonomics of all three concepts are evaluated as almost the same. Concept 1 has the advantage that one person can carry it laterally, without using both hands.
5. **Production complexity:** Although AM is used as a manufacturing system, the production complexity of concept 1 is quite high. The reason for that are the high amount of filigree and overhanging geometry.
6. **Cleanability:** Due to the above mentioned filigree geometry, the cleanability of concept 1 is the highest, but also concept 2 and 3 come with relatively high cleanability.
7. **Material variety:** Concept 2 is based on just one kind of material, whereas concept 1 requires three different materials for realization.
8. **Drain:** All concepts are designed that no residual fluid can remain.
9. **Robustness in handling:** Due to concept 2 has no loose parts and a compact design, its robustness is the highest.
10. **Amount of loose components:** Concept 2 is produced in one piece, whereas concept 1 consists of four loose components, which need to be assembled.
11. **Series maturity:** For series production in future, TM systems are necessary, as already discussed before. At this, manufacturing of concept 1 is relatively complicated, as wires need to be bended and welded. Welding processes for such a filigree construction are usually very cost-intensive.
12. **Modularity:** This is very difficult to realize with concept 1, as the outer dimensions cannot be randomly adjusted to smaller plate dimension. A change of the geometry leads to a failure of the sub-function safeguarding, since the tray may move in the bucket during transportation.

The evaluation, shown in the appendix (Table 8-2), reveals that concept 2 is the most suitable construction, in order to meet the requirements from chapter 5.2. The detailed scale of the values can be read in the appendix as well.

5.7 Detail design and optimization of the selected concept

After the evaluation of the various concepts and the selection of the best suitable concept, the next step was the detailed design process. This process has been executed by means of PTC Creo Parametric 1.0. The basic approach was to improve the design of the concept model in order to eliminate determined weaknesses in terms of mechanical strength and ensure that the degree of cleanability is as high as possible. Furthermore, it must be guaranteed that no residual fluid is remaining. As already included in the concept phase, the construction comes with following features and properties:

- Inclined position with an angle of 67° of the plates, like they are deployed on the finger belt.
- Lug for centering, when combining two trays to form one transportation unit.
- Lug for centering, thus two trays make use of the conveyor belt as good as possible.
- Stable positioning of the dishes in the tray, due to the relatively large distance of the contact points between each plate and the tray.
- The selected material is PA2200, proposed by the company “robotmech Stössl GmbH” that manufacture the tray with their machineries and have the experience with AM applicable materials.

Reduction of material accumulation

The very first step of improvement was the reduction of material and voluminous points. This approach has two reasons:

- Due to the function structure, as the cleanability of the tray is very essential and the less material is surrounding the dirty plates, the higher is the probability that the plates become clean.
- As AM is the used manufacturing system and as mentioned before, the manufacturing costs are only connected with the volume of the product.

Material reduction for weight reasons is not absolutely necessary, as the originally weight of the concept model is relatively low. Figure 5-8 shows a section of both, concept and detailed model, and the executed improvements in terms of volume reduction.

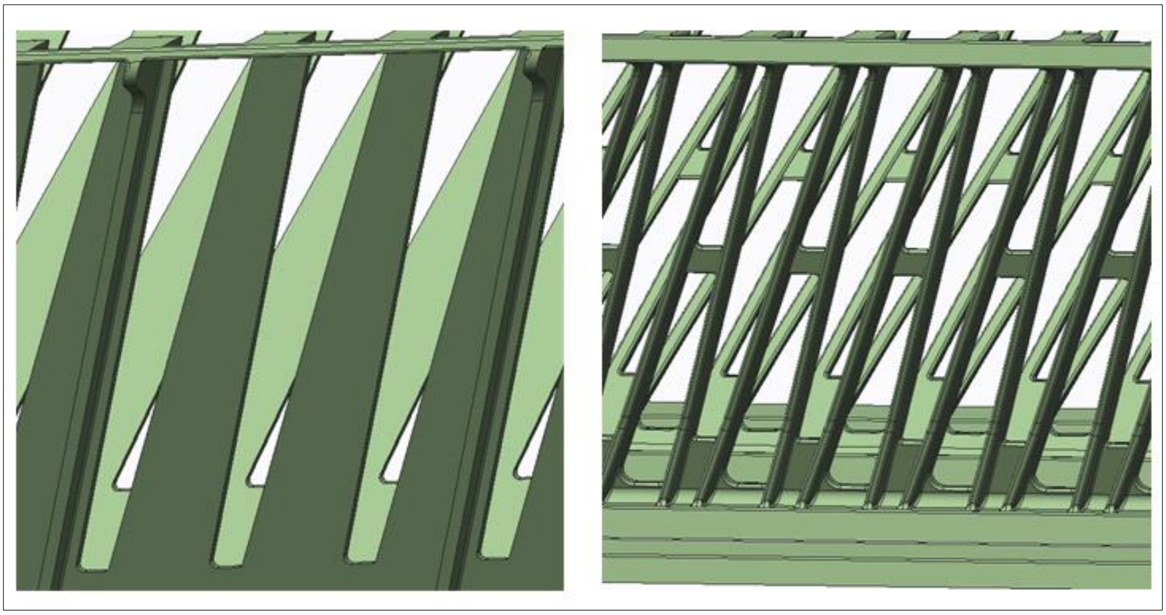


Figure 5-8: Comparison of the concept and detailed model in terms of volume reduction

Inclined surfaces

As it can be seen in Table 8-2, the requirement of low residual fluid is weighted relatively high. Therefore, the construction must guarantee that no fluid remains after the washing process. Inclined surfaces of 1° makes sure that fluid cannot remain in niches, gaps or slots.

Strengthening the base plate with honeycomb structure

This action was a result of the reduction of material accumulation, as described before. A solution had to be found to compensate the decreased mechanical strength due to the material reduction on the base plate. Therefore, the honeycomb structure is well suitable (Figure 5-9). It is a bionic lightweight design approach and has following characteristics:

- High bending stiffness
- Low material accumulation
- Low weight (not absolutely essential for designing the tray)

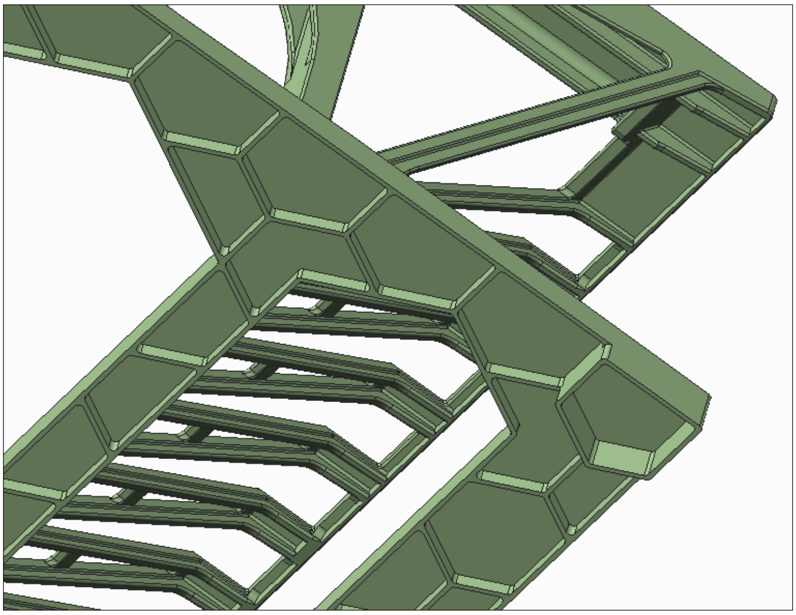


Figure 5-9: Honeycomb structure of the base plate

FEM analysis and optimization

As already mentioned, the reduction of material normally decreases the mechanical strength. Therefore a Finite Element Method (FEM) analysis with Ansys Workbench has been executed, in order to gain a relatively precise statement about occurring stresses and deflections. It can be reasonably assumed that the maximum bending stress and deflection, caused by the loading of the dishes, is at the half of the total length of the tray. Thus, the inserted CAD model can be quartered, to accelerate the computing process.

As already discussed in section 4.7, AM parts have anisotropic behavior. Therefore, building direction should be the same as shown in Figure 5-10.

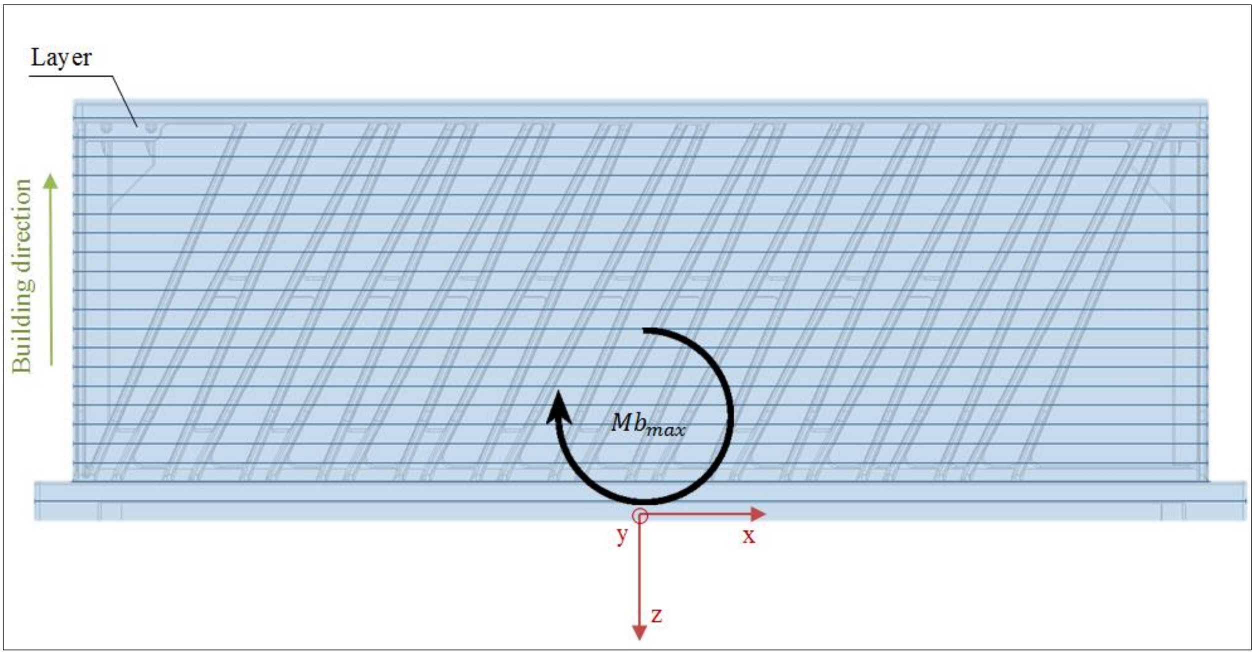


Figure 5-10: Building direction and bending moment concept 2

Figure 5-11 illustrates the overall deformation of the detail designed plate tray, executed with FEM. According to the analysis, the maximum deflection at half of the total length is approximately 4.38 mm. This result shows that the rough calculation in chapter 8 does not vary very strongly, even the complex geometry was not considered in that phase.

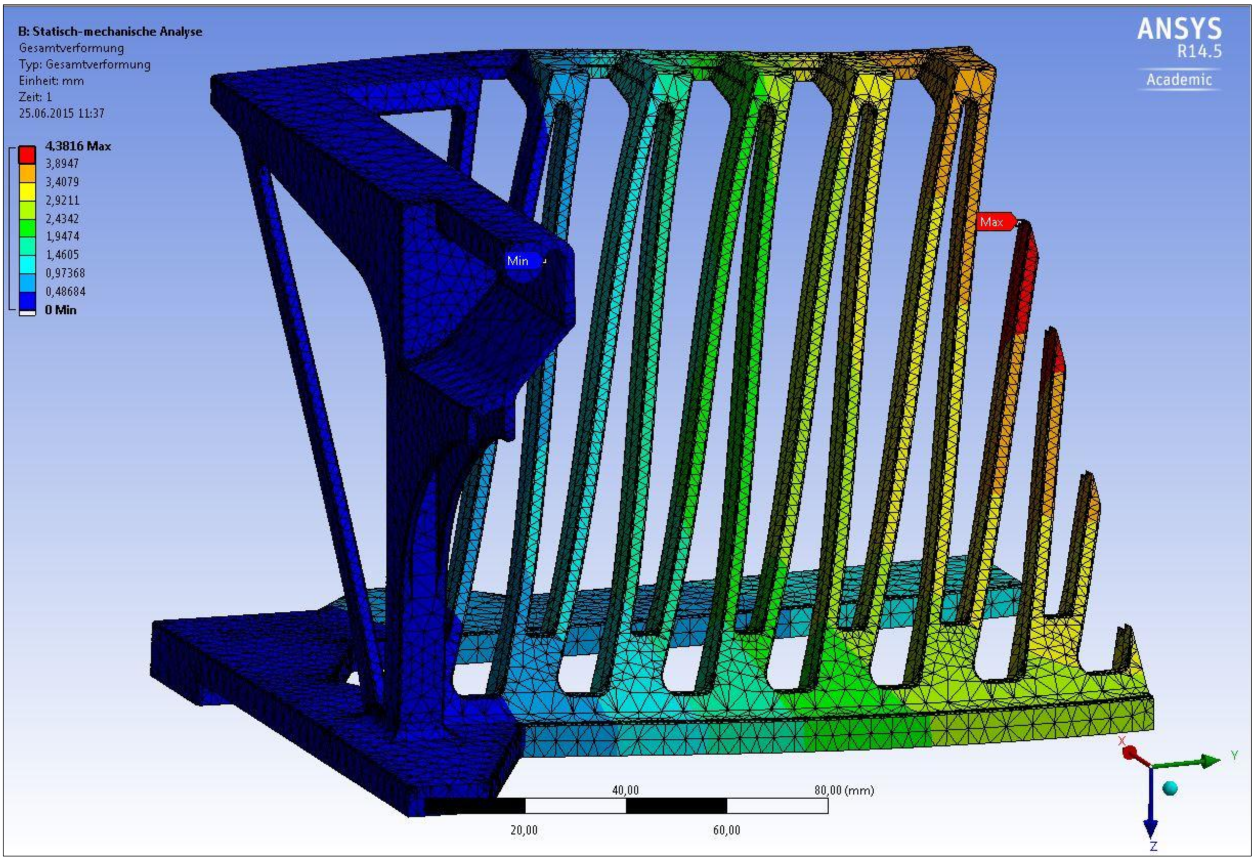


Figure 5-11: FEM analysis after detail designing

In a second improvement step, the cross section, which directly affects the second moment of area, has been strengthened. This action was only possible to limited extent, since changes in the geometry should not affect the cleanability of the tray negatively at all. Figure 5-12 shows the deformed construction with the improved cross sectional area. The circles in red indicate the sections, where improvements have been made, in order to counteract against the bending line. Due to these actions, the maximum deflection has been lowered by 11%.

Further strengthening of the cross sectional area has hardly any noticeable effect on the bending line. Anyway, deformations are acceptable and normal stresses ($\sigma_N = 4.55\ N/mm^2$) are beyond the permissible stresses ($\sigma_{Nperm} = 58\ N/mm^2$) according to the FEM analysis.

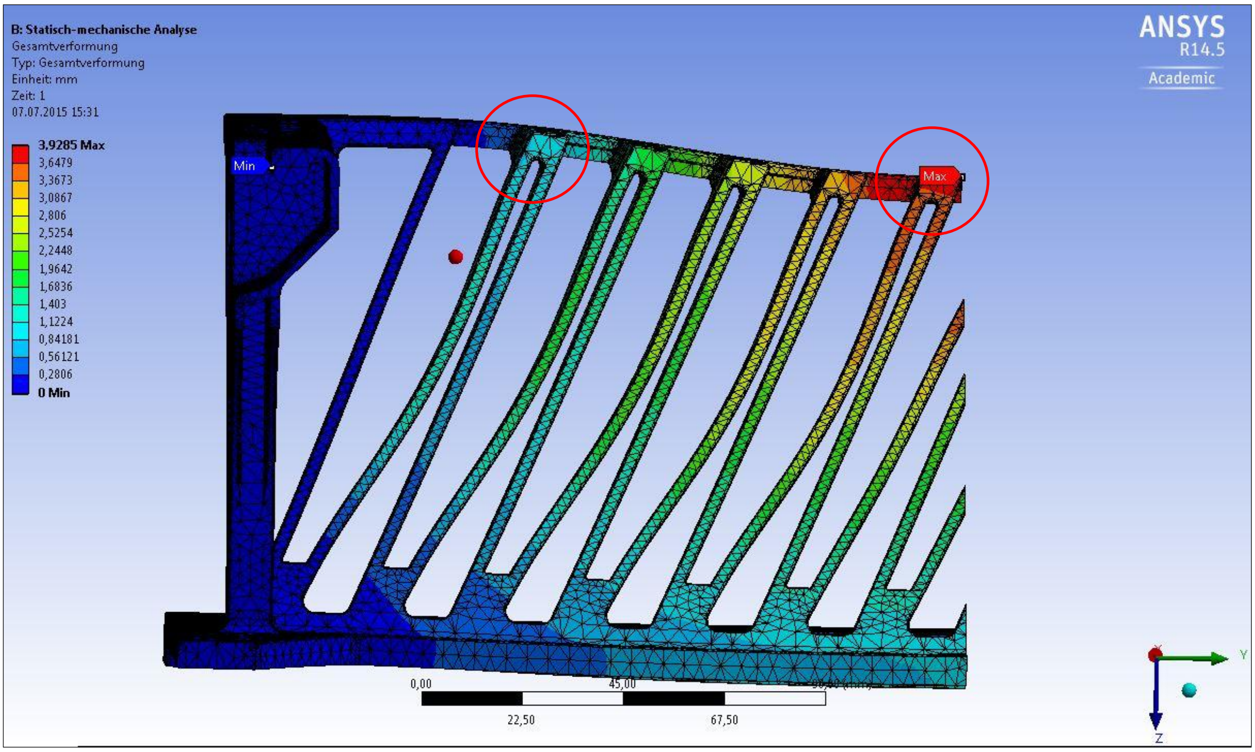


Figure 5-12: FEM analysis after improvement of the detail design

5.8 Fulfillment of the requirement specification

This section reveals how far the particular requirements, declared in the requirement specification in section 5.2, are fulfilled. As already mentioned, each requirement has essential or desired characteristic. In order to implement the realization of the developed product, the essential requirements have to be fulfilled. Otherwise an iteration loop has to be executed until the product fulfills all essential requirements satisfactorily.

Table 5-11: Degree of fulfillment of the requirement specification

No.	Fulfilled	Description
1		*Forces*
1.1	+	Maximum loadings of 300N
1.2	++	Sufficient mechanical strength against deformation under load
2		*Material*
2.1	++	Chemical resistance to dishwashing liquid and rinsing agent
2.2	++	Thermal resistance to temperatures up to 90°C in the washing system
2.3	++	Food-safe and harmless for health
3		*Geometry*
3.1	++	Maximum height: 252mm
3.2	++	Maximum width: 356mm
3.3	++	Maximum length: 556mm
3.4	++	Plates must be clearly determined in its position
3.5	++	Plate tray must be clearly determined in its position (in box)
3.6	+	Washing procedure with plate tray must be enabled
3.7	+	Avoidance of niches and troughs that no residual water remain
3.8	-	Modularity
3.9	--	Handling of 25 plates
3.10	+	Handling of 20 plates
3.11	+	Fast visual control
4		*Manufacturing method*
4.1	++	Realization of complex geometries
4.2	++	Few manufacturing steps
4.3	o	Usage of standard material
5		*Ergonomics*
5.1	+	Easy handling when taking out the plate tray
5.2	++	Easy handling without the usage of additional tools
5.3	++	Low weight of the tray
6		*Safety issues*
6.1	+	No risk of injury due to sharp contours
7		*Economic efficiency*
7.1	+	High durability / low wearing
7.2	++	Low development time
7.3	o	Low material costs
7.4	++	Low tool costs
8		*Recycling*
8.1	o	Simple waste disposal of damaged components
9		*Maintenance*
9.1	++	No maintenance planned
10		*Transportation*
10.1	++	Transportation in already existing plastic box

Table 5-11 shows the degree of fulfillment of the requirement specification, beginning with not fulfilled at all up to optimally fulfilled.

++ = Optimally fulfilled

+ = Well fulfilled

o = Fulfilled

- = Not fulfilled completely

-- = Not fulfilled at all

It can be seen that not every requirement is fulfilled completely, but those that are declared to be essential are at least fulfilled:

- Forces: Dimensional stability to stress is guaranteed.
- Material: The material requirements on chemical resistance, thermal resistance and health compatibility are fulfilled entirely.
- Geometry: Outer dimensions and the determination in position are fulfilled completely. Also requirements on the washing process and the visual inspection are well fulfilled, but modularity and the intake capacity of 25 plates cannot be fulfilled.
- Manufacturing method: Due to the use of AM, complex geometries and few manufacturing steps are realizable easily.
- Ergonomics: The ergonomic requirements are fulfilled.
- Safety issues: The requirements on safety are fulfilled.
- Economic efficiency: AM enables the fulfillment of low development time and tool costs very well. The material costs are not known exactly but it can be assumed that they meet the requirements.
- Recycling: The fulfillment of the recycling requirements is not known exactly.
- Maintenance: The maintenance requirements are optimally fulfilled.
- Transportation: The transportation requirements are optimally fulfilled.

In summary it can be said that the detail design of concept 2 meet the requirements entirely. Potentials for improvements are primarily in increasing the intake capacity of the plates as well as the implementation of modularity.

5.9 Total results and conclusion

Based on the systematic approach for product design and a benefit analysis, a concept has selected for detail designing. The main strengths of concept 2 are the high intake capacity and very good handling. Further advantages are the very low variety of material and amount of loose components, as the tray can be built in one piece.

The improvements made in the detail designing phase are the generous removal of material and strengthening of the model with ribs and struts as far as necessary. Afterwards, a FEM analysis has been executed in order to detect potential for improvement in terms of mechanical strength.

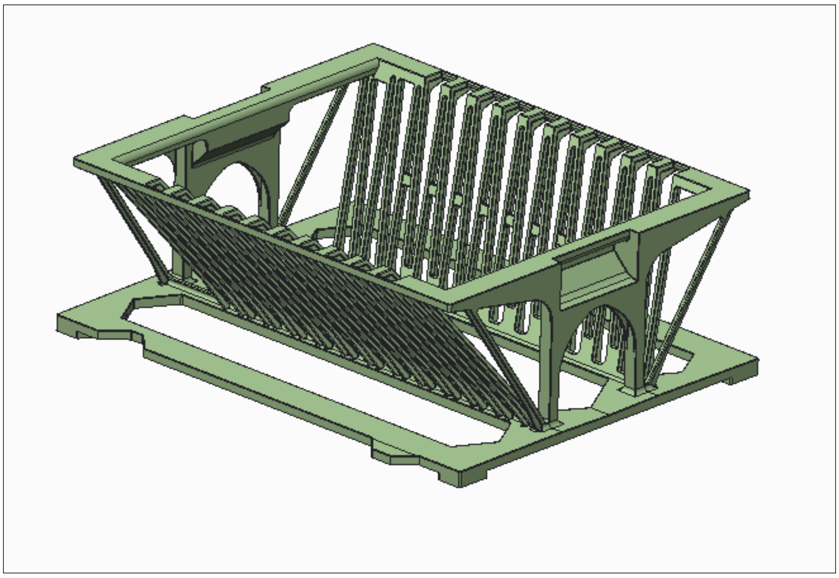


Figure 5-13: Detailed design of concept 2

Figure 5-13 shows one detailed design and Figure 5-14 illustrates a compound of two trays to form a transportation unit with an intake capacity of 20 plates. This transportation unit is suitable for the already used transportation box, with the outer dimension 600 mm x 400mm.

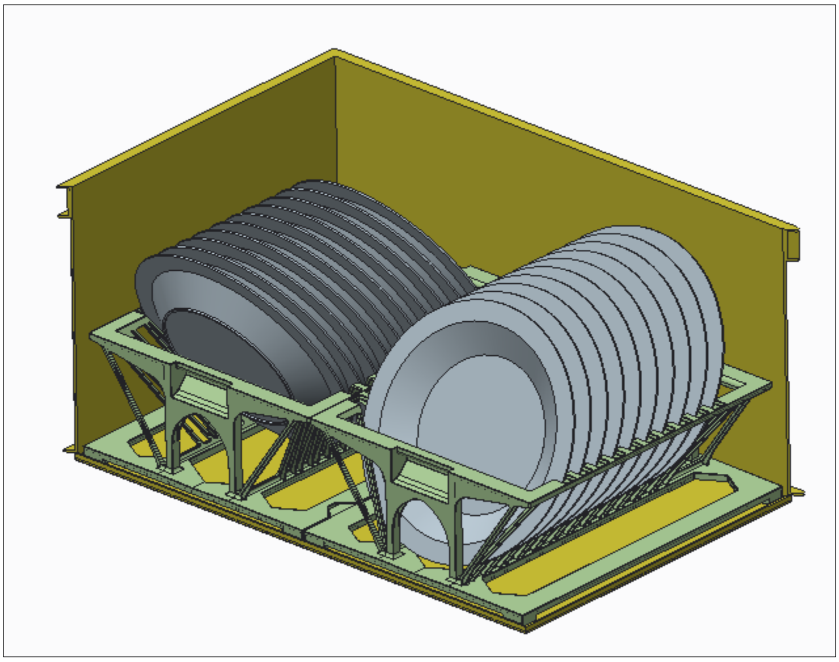


Figure 5-14: Plate tray formed to transportation unit

The framework conditions, in order to develop the plate tray, have been nearly the same as the findings from chapter 2. The plate tray is an innovative product, where hardly any standard components exist. The product design should not be restricted due to the manufacturing product. The same applies to the range of materials. Additionally, the fact that a unique product is going to be produced, a production system is required, which is flexible in production volume. As the findings in chapter 3 and 4 reveal, AM can cope with these tasks. Considering the findings in the practical part, especially in section 5.4, 5.5 and 5.6, leads to the result that AM is the only manufacturing system, which is suitable during the whole product development.

The findings from the theoretical part can be implemented in the product development process as followed:

- Customization: The plate tray is a unique product without standard components, which is only produced in a single quantity. As the results in chapter 4 show, AM is very suitable for small volume production and enables a high degree of product variety.
- Design for manufacture and assembly:
    - High system complexity can be realized, which influences the decision making for realizable sub function in section 5.4. With the usage of AM, hardly any design restrictions during concept modeling and detail designing exist.

    - Almost every materials used in the concept models can be applied, which influences the evaluation of suitable manufacturing systems for the fabrication in section 5.5.
    - From the economic perspective, the fact that AM produces hardly any manufacturing scrap, influences the evaluation of suitable manufacturing systems for the fabrication in section 5.5.
- Time-to-market: Improving the product development according to VDI 2221, as some steps can be eliminated. It is possible to fabricate the product directly after a finished CAD model. This is because no tooling and work scheduling is required, as shown in section 4.11.

Also the disadvantages that are related to AM, are influencing the development process as following:

- The dimensional instability to stress is limiting the possible combinations of sub function in section 5.4.
- The lack of dimensional accuracy is also limiting the possible combinations of sub functions.
- The restricted outer dimensions of the part due to the building chamber has no influence on the development process of the plate tray, as the maximum permissible dimensions of the tray do not present a problem for industrial AM machineries.

Following characteristics of AM have not been considered during the development process in chapter 5, as the manufacturing process itself is not scope of this thesis:

- Slow building speed
- Poor reproducibility

6 Conclusion and Outlook

The increasing demand of alternative products on market and the continuously decreasing PLC due to rising global competition, leads to challenges for the development process and incentives for new manufacturing systems. These are the increasing demand for customization, increasing geometric complexity and faster market introduction, which are difficult to manage for TM systems.

An analysis of these three core issues has pointed out the problems occurring during the product development process with TM systems. For a deeper analysis and a cause study, criteria for manufacturing systems have been deducted from the incentives. Based on these criteria, three different manufacturing systems have been treated and evaluated. On one hand, the IM process, and on the other hand CNC and the emergent AM. Narrowing the field of modern manufacturing systems was essential, in order to allow a more precise discussion and finally a meaningful evaluation. By means of a benefit analysis, AM became apparent as the most suitable manufacturing system that can cope with the challenges mentioned in the problem statement and optimize the development process.

In order to reveal the outcomes of the theoretical element, a practical example in terms of product development in consideration of AM, is part of this thesis. The target was to find a solution for the company “Ökoservice GmbH”, in order to improve the handling of tableware. Therefore, a plate tray has been development by means of the systematical approach for product design VDI 2221. The execution of this methodical approach has led from a requirement specification, agreed upon with the “Ökoservice GmbH”, over a set of various concept models, to a final detail design and solution.

On the basis of the knowledge obtained from the theoretical and the practical part of this thesis, following statements about AM can be made:

Table 6-1: Knowledge obtained from the theoretical and practical part about AM

Knowledge obtained from the theoretical part		Knowledge obtained from the practical part
• Broad variety of applicable materials, even multi-materials. • Design freedom. Every desired shape can be achieved. System complexity can be reduced. • Optimized product development process, as tooling and production scheduling is not necessary. • AM is very flexible and fits perfectly for small production volume, since it does not depend on the economics of scale effect.	⟺	• Every materials used in the concept models can be applied. • No design restrictions during concept modeling and detail designing. Neglecting of DFM and DFA. • Improving the product development according to VDI 2221, as some steps can be eliminated. It is possible to fabricate the product directly after a finished CAD model. • As the product is a unique product (prototype), AM is well suitable.

A closer look on Table 6-1 reflects not only that AM is an alternative to TM, but also influences the product development process. When considering AM during product development, engineers can put much more creativity into the product's design. Furthermore, the use of AM improves the development process and finally leads to a faster market introduction of the product. Additionally, it provides the ability to fabricate single products at economic reasonable conditions.

The latter can be revealed with an example from the automotive industry again. As already described in this thesis, the increasing variety of configurations in the automotive industry leads to new challenges, especially for TM systems. It is often the case that a series is too small and tools are not applicable due to economic reasons. Therefore, Audi produces the front spoiler for the small "RS-series" with the support of SL technology [GEB11, p. 75].

Although AM entails many advantages, it reveals following weaknesses, which are not discussed in detail in this thesis:

- **Dimensional accuracy:** Almost every AM process shows a lack in dimensional accuracy due to the undesired stair case effect, which is unavoidable with the current technologies. Therefore, various post processing approaches exist to insure the surface quality. In addition to that, a lack of standards related to geometric tolerances is limiting the use for applications in engineering.
- **Dimensional stability to stress:** Since AM parts are built layer upon layer, those show anisotropic behavior, which in turn affects the mechanical strength negatively.
- **Ability for series production:** For small batch sizes, the lack of the scale effect is desired, but for larger series, this leads to a production under uneconomic conditions. In addition to that, the process speed of state of the art AM systems is relatively low, which is also the reason that AM is inappropriate for series production at the moment.

Since the acquisition costs for entry-level AM system are already relatively low and machine design is compact, this manufacturing method opens new opportunities in personal fabrication in office spaces. It only requires access to a CAD system, but no special operator skills. As a result, small or even one-man companies are able to create parts with unique requirements at low cost expenditures. Already now, some companies like Airbus and Boing are taking advantage of AM during product development and as a manufacturing system (DOD). In near future, it can be estimated that this could have a dramatically effect on various manufacturing systems and strategies.

7 Lists

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8 Appendix

8.1 Appendix 1 – Published abstract

Abstract

This thesis is dealing with the growing requirements on modern manufacturing systems and their influence on the product development process. Traditional Manufacturing systems often reach their limits due to increasing demand of product variety, decreasing life cycles of products and inconsistent demand of production volume. This leads to a quest for alternative manufacturing systems, which can be adapted in order to cope with that mentioned trends.

Following up on this question, a detailed problem analysis is the base required for a further analysis of different manufacturing systems regarding to their economic efficiency and influence on the product development process and product design. This analysis also considers the emerging Additive Manufacturing. A further measure is a meaningful evaluation to support the decision-making process for suitable systems.

A practical example of a product to be developed and which is linked with almost the identical requirements, as discussed in the theoretical part, points out the influence of a particular manufacturing method on the product development according to VDI 2221.

Zusammenfassung

Diese Arbeit befasst sich mit den immer höher werdenden Anforderungen an Produktionssystemen und deren Einfluss auf den Produktentwicklungsprozess. Oft ist der Einsatz von konventionellen Fertigungsverfahren durch die steigende Nachfrage von Produktvariationen, immer kürzer werdeden Produktlebenszyklus und fluktuierender Nachfrage von Produkten beschränkt. Daher besteht die Aufgabe dieser Arbeit, ein Produktionssystem zu finden, welches an diesem steigenden Trend adaptiert werden kann.

Ausgehend von dieser Frage dient eine detailierte Problemanalyse als Basis für weitere Analysen verschiedener Produktionssystemen bezüglich ihrer Wirtschaftlichkeit und deren Einfluss auf den Produktentstehungsprozess sowie auf die Produktgestaltung. Analysiert wird zudem auch das aufstrebende Generative Fertigungsverfahren. Als Entscheidungshilfe um schlußendlich ein

geeignetes System zu finden, welches den Anforderungen entspricht, dient eine aussagekräftige Nutzwertanalyse.

Um die Erkenntnisse aus der Theorie nochmals zu bekräftigen, umfasst der praktische Teil dieser Arbeit die methodische Entwicklung eines Neuprodukts, welches die zuvor beschriebenen Anforderungen stellt. Als grundlegende Unterstützung des Produktentwicklungsprozesses dient dabei die Richtlinie VDI 2221.

8.2 Appendix 2 – Calculation report

Concept 1: Wire construction for bucket – Mechanical stresses

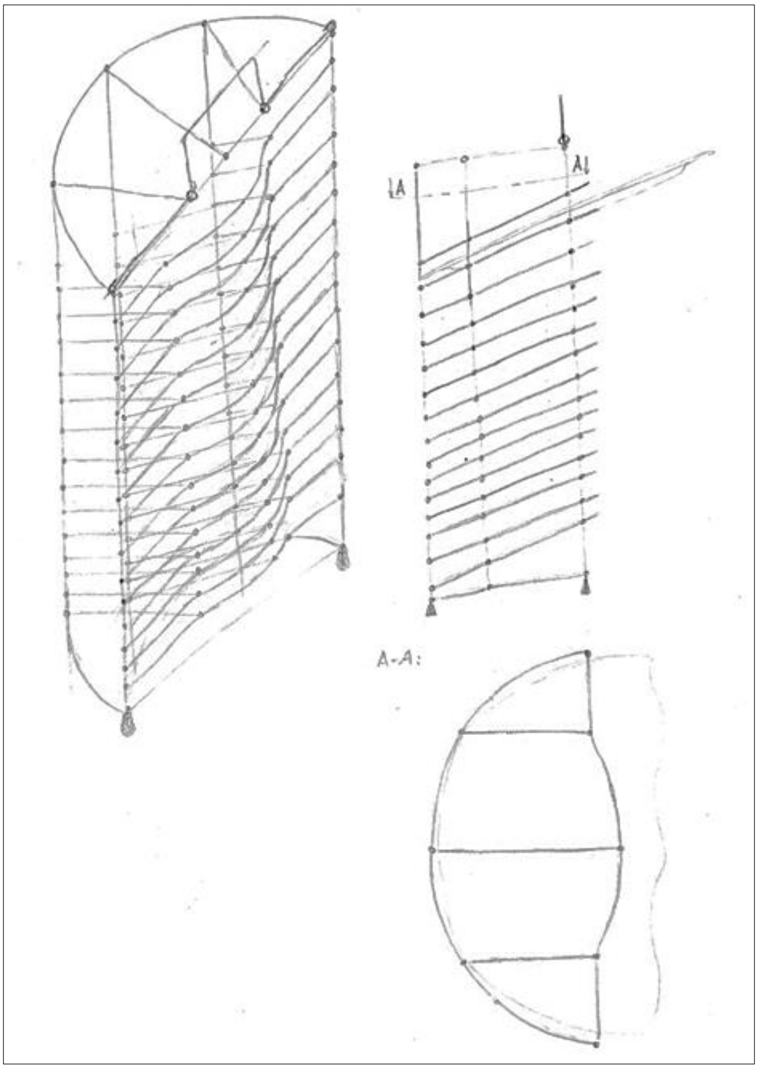

Figure 8-1: Freehand sketch of concept 1

Situation 1:

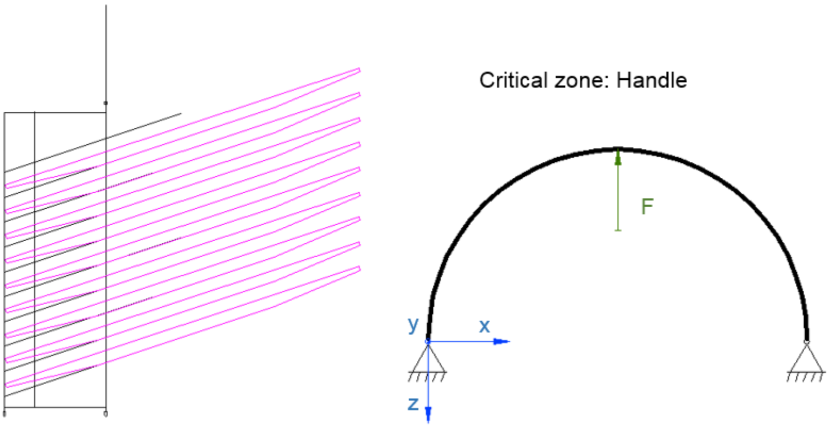

Figure 8-2: Substitute model situation 1 concept 1

Mass plate concept 1:

$$m = 0.4\ kg \tag{8.1}$$

Number of plates concept 1:

$$n = 12 \tag{8.2}$$

Radius of handle concept 1:

$$R = 142\ mm \tag{8.3}$$

Diameter of wire cross section concept 1:

$$d = 3\ mm \tag{8.4}$$

Young's modulus handle concept 1:

$$E = 2 \times 10^5\ N/mm^2 \tag{8.5}$$

Mass force concept 1:

$$F = m \times g \times n = 47.09\ N \tag{8.6}$$

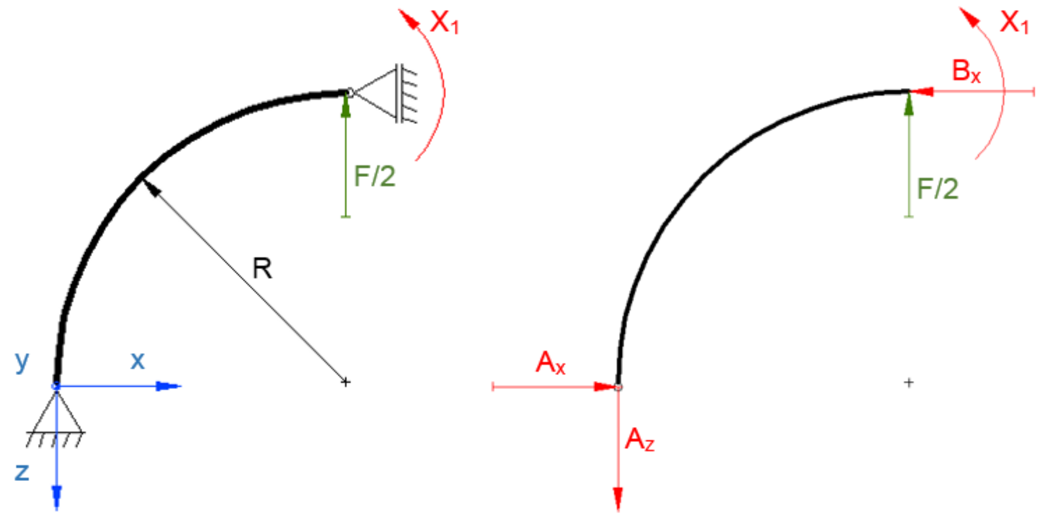

Figure 8-3: Virtual force concept 1

Moment A:

$$\sum M_{(A)} = 0 = B_x \times R + X_1 + \frac{F}{2} \times R \tag{8.7}$$

$$=> \; B_x \times R = -X_1 + \frac{F}{2} \times R$$

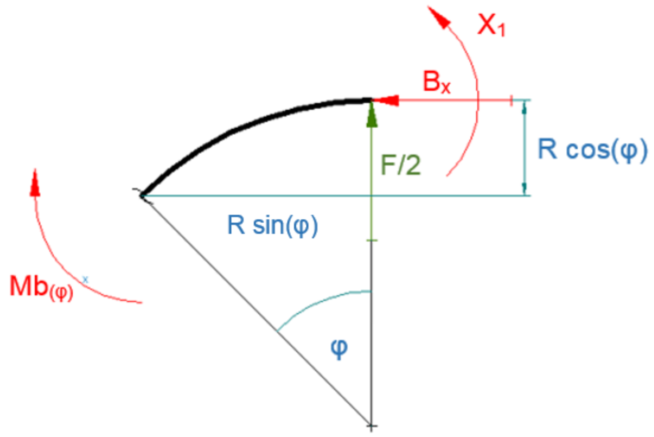

Figure 8-4: Internal forces and moment concept 1

Internal forces and moment:

$$\sum M_{(x)} = 0 = -Mb_{(\varphi)} + X_1 + B_x \times (R - R \times \cos\varphi) + \frac{F}{2} \times R \times \sin\varphi \tag{8.8}$$

$$\Longrightarrow \; Mb_{(\varphi)} = \frac{F}{2} \times R \times (\cos\varphi + \sin\varphi - 1) + X_1 \times \cos\varphi$$

Flexibility method:

Virtual work $g_{1,F/2}$:

$$\delta X_1 g_{1,F/2}^{(0)} = \int_0^{\frac{\pi}{2}} \delta Mb, \delta X_{1(\varphi)} \times \frac{Mb_{F/2_{(\varphi)}}}{EI} \times R \times d\varphi \tag{8.9}$$

$$g_{1,F/2}^{(0)} = \frac{R^2 \times F \times (\pi - 2)}{8EI}$$

Virtual work $g_{1,x1=1}$:

$$\delta X_1 g_{1,X_1=1}^{(0)} = \int_0^{\frac{\pi}{2}} \delta Mb, \delta X_{1(\varphi)} \times \frac{Mb_{X_1=1_{(\varphi)}}}{EI} \times R \times d\varphi \tag{8.10}$$

$$g_{1,X_1=1}^{(0)} = \frac{R \times \pi}{4EI}$$

Total virtual work:

$$g_{1,F/2}^{(2)} = g_{1,F/2}^{(0)} + g_{1,X_1=1}^{(0)} \times X_1 = 0 \tag{8.11}$$

$$\Longrightarrow X_1 = -\frac{F \times R \times (\pi - 2)}{2\pi}$$

Maximum bending moment concept 1 handle:

$$Mb_{max} = -607.435\ Nmm \tag{8.12}$$

Maximum bending stress concept 1 handle:

$$\sigma b_{max} = \frac{Mb_{max}}{W_p} \tag{8.13}$$

$$\sigma b_{max} = 114.58\ N/mm^2$$

Permissible bending stress concept 1 handle:

$$\sigma b_{per} = 270\ N/mm^2 \tag{8.14}$$

$$\sigma b_{max} \leq \sigma b_{per}$$

Situation 2:

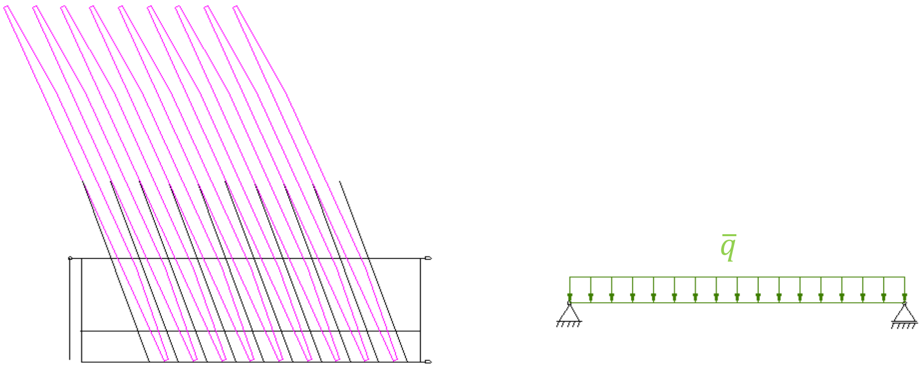

Figure 8-5: Substitute model situation 2 concept 1

Length of tray concept 1:

$$l = 400\ mm \tag{8.15}$$

Diameter wire frame concept 1:

$$d = 2\ mm \tag{8.17}$$

Uniformly distributed load concept 1:

$$\bar{q} = \frac{m \times g \times n}{l} \tag{8.18}$$

$$\bar{q} = 0.118\ N/mm$$

Second moment of area

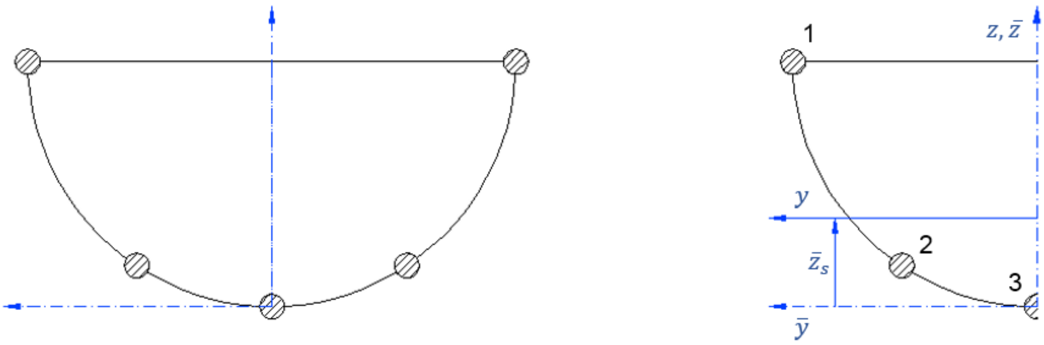

Figure 8-6: Cross section tray concept 1

Center of gravity z-direction concept 1:

$$\sum \bar{z}_s = \frac{\sum A_i \times \bar{z}_i}{\sum A_i} = \frac{A_1 \times \bar{z}_{s1} + A_2 \times \bar{z}_{s2} + A_2 \times \bar{z}_{s2}}{A_1 + A_2 + A_3} \tag{8.19}$$

$$\bar{z}_s = 71\,mm$$

Second moment of area 1 concept 1:

$$I_{\overline{yy}1} = I_{yy1} + (R - \bar{z}_s)^2 \times A_1 \tag{8.20}$$

$$I_{\overline{yy}1} = \frac{d^4 \times \pi}{64} + \frac{R^2 \times d^2 \times \pi}{16}$$

Second moment of area 2 concept 1:

$$I_{\overline{yy}2} = I_{yy2} + \left(\frac{R}{4} - \bar{z}_s\right)^2 \times A_2 \tag{8.21}$$

$$I_{\overline{yy}2} = \frac{d^4 \times \pi}{64} + \frac{R^2 \times d^2 \times \pi}{64}$$

Second moment of area concept 1:

$$I_{\overline{yy}} = 2 \times \left(I_{\overline{yy}1} + I_{\overline{yy}2} + I_{yy3}\right) \tag{8.22}$$

$$I_{\overline{yy}} = 39595.8\,mm^4$$

Maximum bending moment concept 1:

$$Mb_{max} = EIw^{II}_{(l/2)} = \bar{q}_{(x)} \times \left(\frac{l^2}{4} - \frac{l^2}{8}\right) \tag{8.23}$$

$$Mb_{max} = 2360\,Nmm$$

Maximum bending stress concept 1:

$$\sigma b_{max} = \frac{Mb_{max}}{W_y} \tag{8.24}$$

$$\sigma b_{max} = 4.29\ N/mm^2$$

$$\sigma b_{max} \leq \sigma b_{per}$$

Maximum deflection concept 1:

$$w_{max} = w_{(l/2)} = \frac{5\bar{q} \times l^4}{384EI_{\overline{yy}}} \tag{8.25}$$

$$w_{max} = 0.0047\ mm$$

Version 2: Plastic tray out of one piece – Mechanical stresses

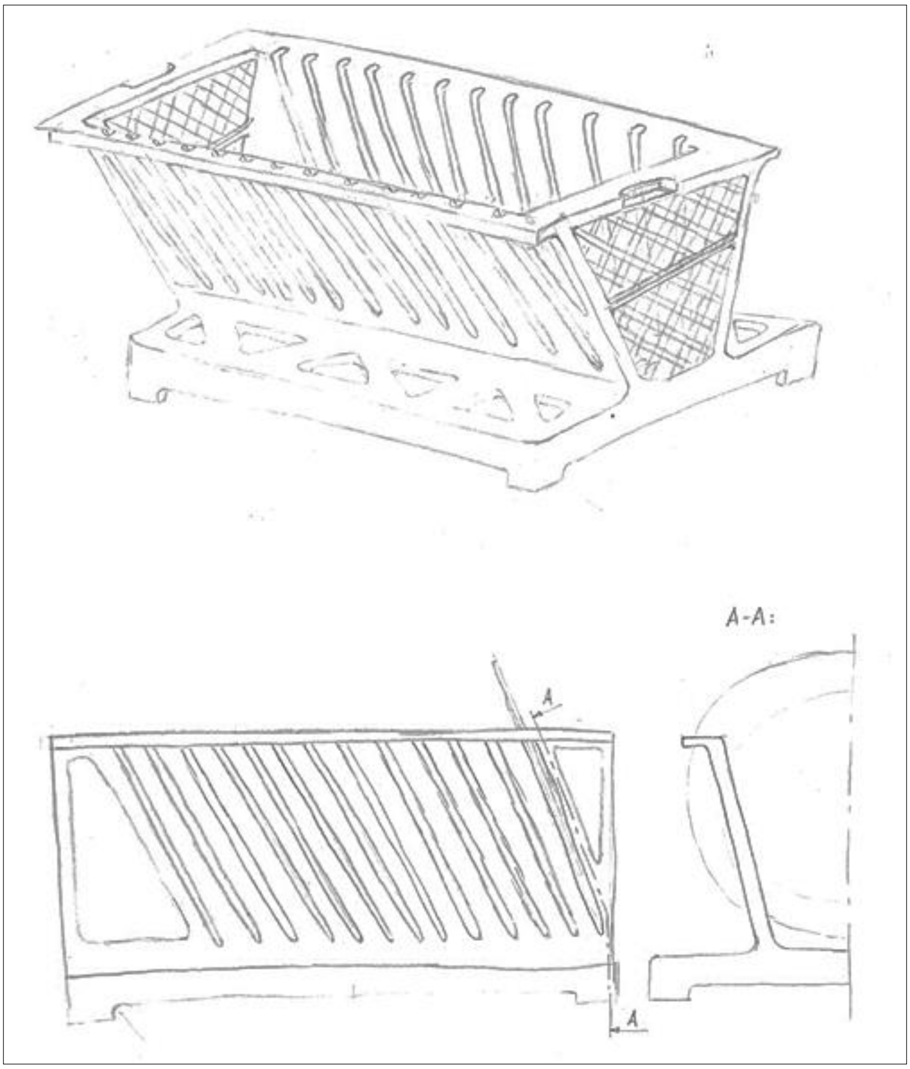

Figure 8-7: Freehand sketch of concept 2

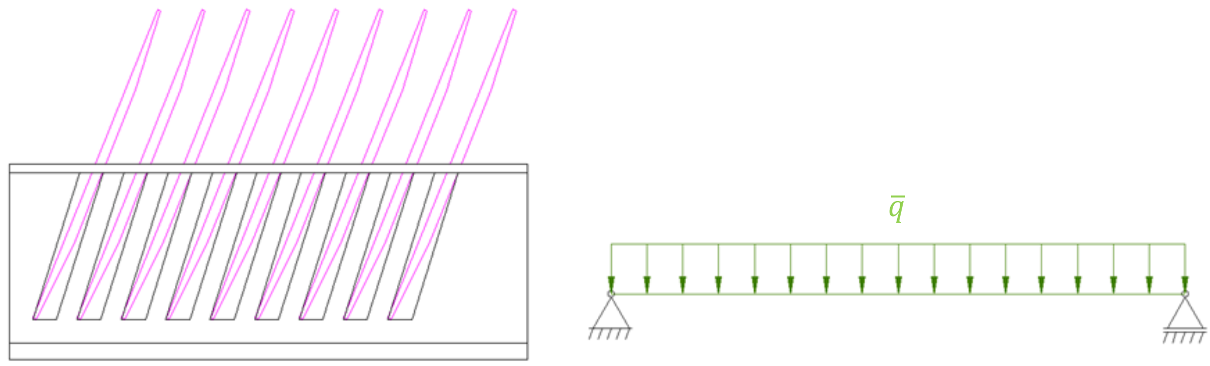

Figure 8-8: Substitute model concept 2

Mass plates concept 2:

$$m = 0.4\ kg \tag{8.26}$$

Number of plates concept 2:

$$n = 10 \tag{8.27}$$

Dimension a concept 2:

$$a = 150\ mm \tag{8.28}$$

Length of tray concept 2:

$$l = 300\ mm \tag{8.29}$$

Thickness b concept 2:

$$b = 5\ mm \tag{8.30}$$

Angle α concept 2:

$$\alpha = 60° \tag{8.31}$$

Uniformly distributed load concept 2:

$$\bar{q} = \frac{m \times g \times n}{l} \tag{8.32}$$

$$\bar{q} = 0.131\ N/mm^2$$

Second moment of area:

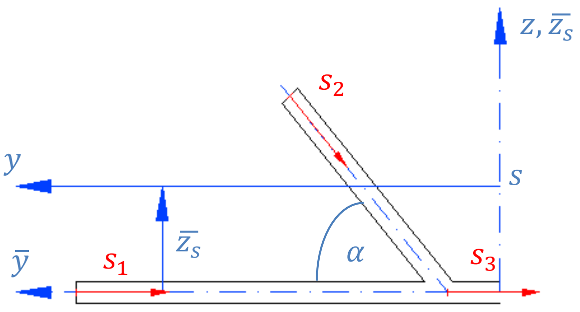

Figure 8-9: Cross section simplified concept 2

Center of gravity z-direction concept 2:

$$\sum \bar{z}_s = \frac{\sum A_i \times \bar{z}_i}{\sum A_i} \tag{8.33}$$

$$\bar{z}_s = \frac{a \times \sqrt{3}}{440}$$

Second moment of area 1 concept 2:

$$I_{yy1} = \int z^2\, dA = \int_0^{\frac{a}{2}} \left(\frac{-a \times \sqrt{3}}{440}\right) \times b \times ds_1 \tag{8.34}$$

$$I_{yy1} = \frac{3 \times a^3 \times b}{387200}$$

Second moment of area 2 concept 2:

$$I_{yy2} = \int z^2\, dA = \int_0^{a} \left(\frac{3a \times \sqrt{3}}{110} - \frac{s_2 \times \sqrt{3}}{2}\right)^2 \times b \times ds_2 \tag{8.35}$$

$$I_{yy2} = \frac{31 \times b}{484000}$$

Second moment of area 3 concept 2:

$$I_{yy3} = I_{yy1} \tag{8.36}$$

Second moment of area concept 2:

$$I_{yy} = \left(I_{yy1} + I_{yy2} + I_{yy3}\right) \times 2 \tag{8.37}$$

$$I_{yy} = 2684.66\, mm^4$$

Maximum deflection concept 2:

at $x = \frac{l}{2}$:

$$w_{(l/2)} = \frac{5q_{(x)} \times l^4}{384EI} \tag{8.38}$$

$$w_{(l/2)} = 5.19\, mm$$

Maximum bending moment concept 2:

$$Mb_{max} = EIw^{II}_{(l/2)} = q_{(x)} \times \left(\frac{l^2}{4} - \frac{l^2}{8}\right) \tag{8.39}$$

$$Mb_{max} = 1473.75\, N$$

Maximum bending stress concept 2:

$$\sigma b_{max} = \frac{Mb_{max}}{W_{yy}} \tag{8.40}$$

$$\sigma b_{max} = 0.873\ \ N/mm^2$$

Permissible bending stress concept 2:

$$\sigma b_{per} = 58\ \ N/mm^2 \tag{8.41}$$

$$\sigma b_{max} \leq \sigma b_{per}$$

Concept 3: Hybrid construction – Mechanical stresses

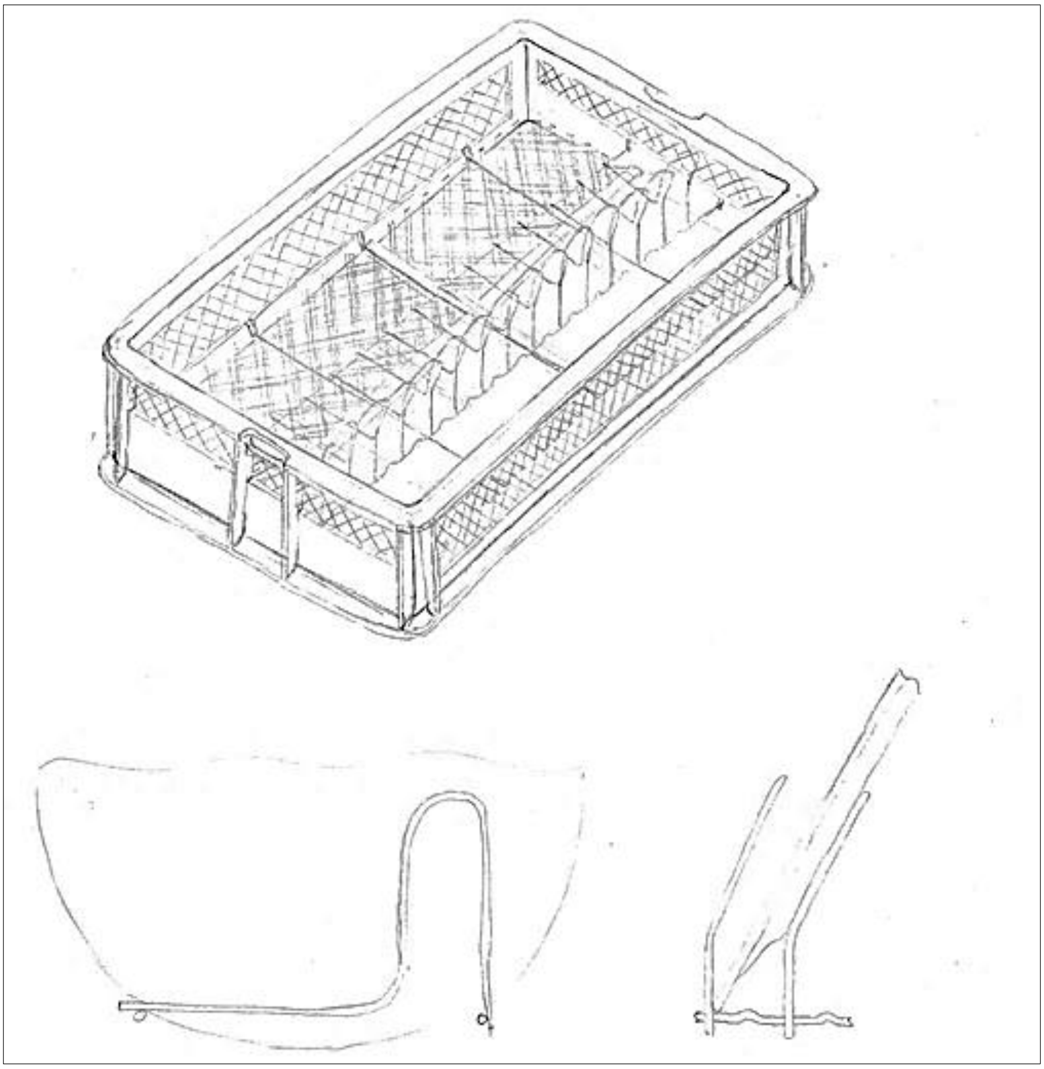

Figure 8-10: Freehand sketch of concept 3

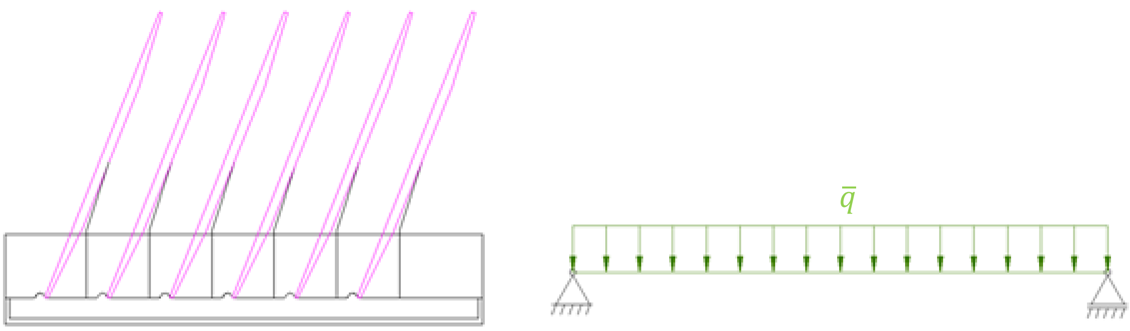

Figure 8-11: Substitute model concept 3

Mass plates concept 3:

$$m = 0.4\ kg \tag{8.42}$$

Number of plates concept 3:

$$n = 15 \tag{8.43}$$

Length of tray concept 3:

$$l = 500\ mm \tag{8.44}$$

Dimension a concept 3:

$$a = 350\ mm \tag{8.45}$$

Dimension f concept 3:

$$f = 20\ mm \tag{8.46}$$

Thickness b concept 3:

$$b = 1\ mm \tag{8.47}$$

Height h concept 3:

$$h = 150\ mm \tag{8.48}$$

Wire diameter d:

$$d = 2\ mm \tag{8.49}$$

Uniformly distributed load concept 3:

$$\bar{q} = \frac{m \times g \times n}{l} \tag{8.50}$$

$$\bar{q} = 0.118\ N/mm^2$$

Second moment of area

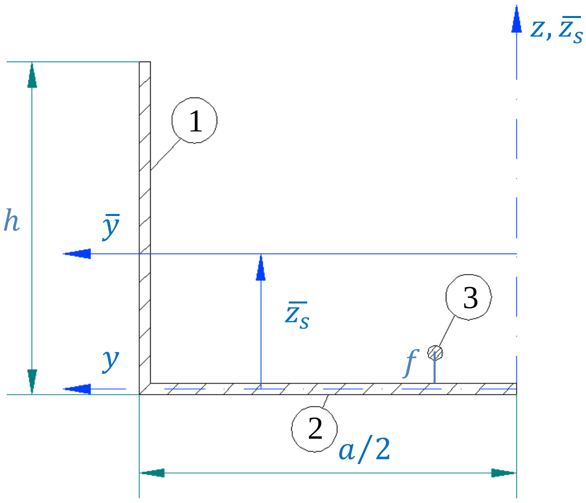

Figure 8-12: Simplified cross section concept 3

Center of gravity z-direction concept 3:

$$\sum \bar{z}_s = \frac{\sum A_i \times \bar{z}_i}{\sum A_i} \tag{8.51}$$

$$\bar{z}_s = 34.55\ mm$$

Second moment of area 1 concept 3:

$$I_{\overline{yy}1} = \frac{bh^3}{3} \tag{8.52}$$

Second moment of area 2 concept 3:

$$I_{\overline{yy}2} = \frac{ab^3}{24} \tag{8.53}$$

Second moment of area 3 concept 3:

$$I_{\overline{yy}3} = I_{yy3} + \bar{z}_{s3}{}^2 \times A_3 \tag{8.54}$$

$$I_{\overline{yy}3} = \frac{d^4\pi}{64} + f^2 \times r^2\pi$$

Second moment of area concept 3:

$$I_{\overline{yy}} = 2 \times \left(I_{\overline{yy}1} + I_{\overline{yy}2} + I_{\overline{yy}3}\right) \tag{8.55}$$

$$I_{\overline{yy}} = 2.26 \times 10^6 \; mm^4$$

Young's modulus:

Cross sectional area consists of two different materials.

Young's modulus HDPE:

$$E_{HDPE} = 1{,}000 \frac{N}{mm^2} \tag{8.56}$$

Young's modulus S235:

$$E_{S235} = 2.1 \times 10^5 \frac{N}{mm^2} \tag{8.57}$$

Young's modulus combined:

$$E = E_{S235} \times V_F + E_{HDPE} \times (1 - V_F) \tag{8.58}$$

$$E = 2010.1 \; N/mm^2$$

Fiber ratio:

$$V_F = \frac{A_F}{A} \tag{8.59}$$

Maximum deflection concept 3:

$$w_{(l/2)} = \frac{5q_{(x)} \times l^4}{384EI} \tag{8.60}$$

$$w_{(l/2)} = 0.0211 \; mm$$

Maximum bending moment concept 3:

$$Mb_{max} = EIw_{(l/2)}^{II} = q_{(x)} \times \left(\frac{l^2}{4} - \frac{l^2}{8}\right) \tag{8.61}$$

$$Mb_{max} = 3{,}687.5 \; N$$

Maximum bending stress concept 3:

$$\sigma b_{max} = \frac{Mb_{max}}{W_{yy}} \tag{8.62}$$

$$\sigma b_{max} = 0.06\ N/mm^2$$

Permissible bending stress concept 3:

$$\sigma b_{zul} = 58\ N/mm^2 \tag{8.63}$$

$$\sigma b_{max} \leq \sigma b_{zul}$$

8.3 Appendix 3 – Benefit analysis of the concepts

Table 8-1: Scale of values benefit analysis

Scale of values		Properties											
Utility paramters	VDI 2225 points	Intake capacity	Suitability for conveyor belt	Load capacity [No. plates/kg]	Ergonomics	Production complexity	Cleanability	Material variety	Drain	Robustness in handling	Amount of components	Series maturity	Modularity (Adaptability)
0	0	1	not suitable for both belt types	4.5	very complicated (risk of injury)	very high	very unclean	very high	very much residual fluid	very low	>10	very complicated	very complicated
1		3		9							>5		
2	1	6	for both belt types suitable to a limited	13.5	complicated	high	unclean	high	much residual fluid	low	5	complicated	complicated
3		9		18							4		
4	2	12	suitable for one belt type	22.5	average	average	moderate	average	moderate residual fluid	average	3	average	average
5		15		27							2		
6	3	18	suitable for both belt types	31.5	good handling	low	clean	low	few residual fluid	high	1	easy	easy
7		21		36							1		
8	4	24	very well suitable for both belt types	40.5	very good handling	very low	very clean	very low	no residual fluid	very high	0	very easy	average
9		27		45							0		
10		30		49.5							0		

Table 8-2: Results of the evaluation according to VDI 2225

Evaluation criteria			Property types		Variation 1			Variation 2			Variation 3		
No.	Criteria	Weighting	Property	Unit	Property p_{i1}	Value v_{i1}	Weighted value	Property p_{i2}	Value v_{i2}	Weighted value	Property p_{i3}	Value v_{i3}	Weighted value
1	High amount of plates	0.15	Intake capacity	#	10	3	0.45	20	7	1.05	13	4	0.6
2	Good suitability for conveyor belts	0.125	Suitability for conveyor belts	-	for both belt types suitable to a limited extent	2	0.25	suitable for one belt type	5	0.625	suitable for one belt type	5	0.625
3	High load capacity	0.025	Load of capacity	#/kg	43.1	9	0.225	25.77	5	0.125	22.65	4	0.1
4	High degree of ergonomics	0.1	Ergonomics	-	very good handling	9	0.9	very good handling	8	0.8	very good handling	8	0.8
5	Low production complexity	0.075	Production complexity	-	high	2	0.15	low	7	0.525	average	5	0.375
6	High cleanability	0.175	Cleanability	-	very clean	8	1.4	clean	6	1.05	clean	7	1.225
7	Low material variety	0.025	Material variety	-	average	4	0.1	very low	10	0.25	low	7	0.175
8	Less residual fluid	0.175	Drain	-	no residual fluid	9	1.575	no residual fluid	8	1.4	no residual fluid	7	1.225
9	High robustness	0.05	Robustness in handling		average	4	0.2	very high	8	0.4	high	6	0.3
10	Small number of loose components	0.025	Amount of loose components	#	4	3	0.075	0	10	0.25	1	6	0.15
11	Simple realization of series production	0.025	Series maturity	-	complicated	3	0.075	easy	7	0.175	easy	6	0.15
12	Simple adaption of modules	0.05	Modularity (Adaptability)	-	very complicated	0	0	average	4	0.2	very easy	8	0.4
	Sum weighting	**1**			**Sum**	**56**	**5.4**	**Sum**	**85**	**6.85**	**Sum**	**73**	**6.125**