Additive Manufacturing: Tools and Methods Supporting Early Adopters in a Focused Implementation

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ADDITIVE MANUFACTURING: TOOLS AND METHODS SUPPORTING EARLY ADOPTERS IN A FOCUSED IMPLEMENTATION

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“Don’t let your biggest dreams
become your biggest regrets.”

— ANONYMOUS

Abstract

Developments in Additive Manufacturing (AM) in the last decades originated a shift from prototyping toward manufacturing applications. Through a *small lot-size advantage* and a *complexity advantage* over established manufacturing technologies, AM demonstrated the capability of enabling for incremental and radical innovation in products and processes. However, despite an affirmed industrial potential, and a modest availability of success stories, AM adopters still face multiple barriers to the implementation, and the adoption rate is reduced. Evidence suggests that the value-adding capabilities of AM are today not enough understood in industry and require further investigation. The purpose of the present research is to provide adopters with tools and methods to structure the AM adoption process, to achieve more focus in the implementation, and to facilitate the direct scoping of value-adding AM applications. Three studies were conducted combining multi- and single- case study approaches to observe the adoption of AM technologies in different industrial contexts. The research proposes:

- a new value-driven framework for the clustering of AM applications, adding a layer of assessment in the scoping of AM applications;
- a novel methodology to assess different manufacturing strategies for high variety component families and quantitatively assess the implications of AM adoption on operational KPIs;
- the implications in the functional domains of R&D, operations, sales and marketing of adopting AM in combination with Agile development methods for the purpose of incremental product launches of hardware.

Overall the thesis identifies five managerial implications for companies in the adoption phase of AM.

Riassunto

I recenti sviluppi nell'ambito delle tecnologie di produzione additiva (TPA) hanno originato una tranizione del loro scopo di utilizzo, dalla sola prototipazione rapida verso applicazioni di produzione di serie. Attraverso vantaggi nella produtione di piccole serie di componenti, e benefici nella fabbricazione di geometrie complesse le TPA hanno dimostrato il loro potenziale nell'originare innovazione incrementale e radicale in molteplici prodotti e processi industriali. Malgrado un affermato potenziale industriale, e un modesto elenco di applicazioni di successo molti nuovi utilizzatori di TPA vedono sorgere diverse barriere nel processo implementazione di queste nuove tecnologie. Di conseguenza, il loro tasso di adozione in ambito industriale rimane ridotto. Ciò suggerisce che il valore aggiunto generato dall implementazione di TPA rimane in ambito industriale tuttora parzialmente incompreso, e necessita ulteriori approfondimenti. La presente tesi mira a fornire metodi per strutturare il processo di adozione di tali tecnologie, e a facilitare gli utilizzatori nell'individuazione di applicazioni ad alto valore aggiunto. La ricerca osserva tre casi di adozione di tali tecnologie e considera l'adozione di tali tecnologie in ambito industriale. La tesi propone:

- un metodo per il raggruppamento di casi d'uso di tecnologie di fabbricazione additiva, e l'identificazione di possibili aree di appicazione a valore aggiunto in ambito industriale;
- una metodologia per la valutazione e il confronto di differenti strategie produttive, nel caso della fabbricazione di famiglie di componenti con alto numero di varianti, e la stima delle loro implicazioni su variabili operazionali;
- una serie di implicazioni nelle funzioni di ricerca e sviluppo, operazioni, relazioni con la clientela e marketing nel caso dell implemen-

tazione di TPA in combinazione con sviluppo "Agile" per ragiungere il lancio incrementale di prodotti sul mercato.

In conclusione la ricerca individua cinque implicazioni manageriali per le imprese che approcciano l’adozione di TPA.

Acknowledgement

After a long and intensive period, today is the day: writing this note of thanks is the finishing touch on my dissertation. It has been a period of intense learning for me, not only from a scientific perspective, but also on a personal level. Writing this dissertation has had a big impact on me. I would like to take some time and reflect on the people who have supported and helped me so much throughout this important period.

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Publications

During the course of this study, the following publications were produced:

Filippo Fontana, Daniel Omidvarkarjan, Daniel Temperli, and Mirko Meboldt (2019). “An Additive Manufacturing Enabled NPD Process Model for Incremental Product Launch of Hardware”. In: *Computers in Industry*. Submitted

Filippo Fontana, Christoph Klahn, and Mirko Meboldt (2018). “Value-driven Clustering of Industrial Additive Manufacturing Applications”. In: *Journal of Manufacturing Technology Management*, JMTM–06–2018–0167

Filippo Fontana, Enrico Marinelli, and Mirko Meboldt (2018). “Selection of High-Variety Components for Selective Laser Sintering: An Industrial Case Study”. In: *Industrializing Additive Manufacturing - Proceedings of Additive Manufacturing in Products and Applications - AMPA2017*. Cham: Springer International Publishing, pp. 238–251

Christoph Klahn, Mirko Meboldt, Filippo Federico Fontana, Bastian Leutenecker-Twelsiek, and Jasmin Jansen (2018). *Entwicklung und Konstruktion für die Additive Fertigung - Grundlagen und Methoden für den Einsatz in industriellen Endkundenprodukten*. Würzburg: Vogel Business Media

Ralph Rosenbauer, Filippo Fontana, Heidi Hastedt, Thomas Luhmann, David Ochsner, Dirk Rieke-Zapp, and Robin Rofallski (2018). “Advantages in Additive Manufacturing for a Medium Format Metrology Camera”. In: *Industrializing Additive Manufacturing - Proceedings of Additive Manufacturing in Products and Applications - AMPA2017*. Cham: Springer International Publishing, pp. 296–307

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Mirko Meboldt and Filippo Fontana (2016). *Additive Fertigung in der industriellen Serienproduktion: Ein Statusreport*. Tech. rep. AM Network

Contents

Abbreviations

AM	Additive Manufacturing
CAGR	Compound Annual Growth Rate
CAD	Computer Aided Design
CEO	Chief Executive Officer
CNC	Computer Numerical Control
CTP	Catalyst Turboprop
DfAM	Design for Additive Manufacturing
ERP	Enterprise Resource Planning
FDM	Fused Deposition Modelling
GPS	Global Positioning System
IPL	Incremental Product Launch
MTO	Make to Order
MTS	Make to Stock
NPD	New Product Development
NPL	New Product Launch
OEM	Original Equipment Manufacturer
OFP	Order Fulfilment Process
OPS	Operations
PA	Polyamide
PDM	Product Data Management
SCM	Supply Chain Management
TPU	Thermoplastic Polyurethane
SKU	Stock Keeping Unit
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SME	Small Medium Enterprise

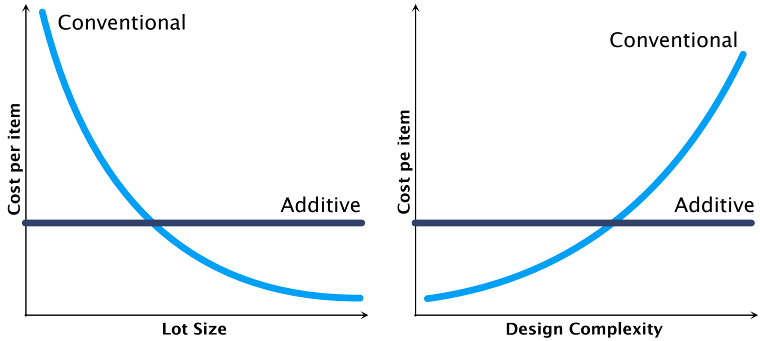
SUS	System Usability Scale
UAV	Unmanned Autonomous Vehicle
VP	Vice President

1 Introduction

It was 1984, when Charles Hull presented the world his invention, the world the first stereolithography 3D-printer (Hull, 1984). Since that achievement, and in more than 30 years, the realm of Additive Manufacturing (AM) has grown at an important pace (Wohlers Associates, 2017). AM development in the last decades has been characterized by the invention of new printing processes, an overall increase in process reliability, a surge in availability of production grade materials and enhancements in equipment productivity (Gao et al., 2015; Gibson et al., 2010; Ngo et al., 2018). Through such improvements, AM technologies shifted from prototyping toward manufacturing applications and gained industrial relevance (Bak, 2003; Campbell et al., 2012; Gibson et al., 2010). The term AM today represents a vast ecosystem of technologies, that can be ordered in seven major categories (Gibson et al., 2010):

- vat photopolymerization
- material jetting
- binder jetting
- material extrusion
- powder bed fusion
- sheet lamination
- directed energy deposition

All AM technologies share the capability of seamlessly transforming a digital CAD file into a physical object, enabling an unprecedented connection between the digital and the physical world. Through AM, companies can establish fully digitalised process chains, where products are treated as digital files and can be modified, individualised or moved over long distances at very reduced transaction costs, up to the latest point of manufacturing. The layer by layer approach of AM enables for two very often discussed advantages.



(a) small lot-size advantage **(b)** complexity advantage

Fig. 1.1: two fundamental characteristics of additive manufacturing

Figure 1.1a shows, that the manufacturing costs for additive manufacturing are in a first approximation independent from the level of output. Evidence for this property has been demonstrated for several AM process under efficient production conditions (Hopkinson and Dicknes, 2003; Ruffo, Tuck, et al., 2006). The property holds because first, AM machines can manufacture different designs simultaneously, and second, no special tools or moulds are required. This characteristic determines an increased flexibility of AM technologies compared to other manufacturing processes, and can have important implications on supply chains.

On the other side, Figure 1.1b shows that the complexity of a design has less, or ideally no effect on manufacturing costs (Gibson et al., 2010; Holmström et al., 2010; Weller et al., 2015). For other manufacturing technologies, an increase in design complexity leads to a surge in the amount of operations necessary to manufacture a part. Features such as undercuts, hollow bodies and lattices are in most cases even impossible. AM, despite a set of process specific design rules, delivers unprecedented structures. It allows creative engineers to increase the performance of products (in terms of mass, energy consumption, heat exchange, . . .), and to simplify assemblies by merging components into monolithic designs.

AM can reduce the overall amount of components required to manufacture complex parts. However such advantages come at the cost of reduced surface quality, and coarse tolerances which sometimes require costly post-processing steps.

Small lot-size advantage and complexity advantage of AM have raised opposed views in literature regarding their full validity. As a matter of fact both properties have been criticised in their ideal formulation. Despite that criticism, the author believes these two properties summarize in a first approximation the essence of AM value. When these two properties are exploited effectively, they can enable independent:

- product advantages, whereas the performance of a product in use is directly affected;
- process advantages, whereas the processes applied to create a given product are improved.

1.1 Characteristics of AM Innovation

The study of these unique advantages has led to the consideration of AM as an ecosystem of technologies with an highly disruptive character. It is not a surprise that with such a potential, AM has been designated as one of the pillars of the much hyped Industry 4.0 (Dilberoglu et al., 2017) concept and also addressed as a revolutionary driver of the fourth industrial revolution (Hopkinson, Hague, et al., 2006; World Economic Forum and A.T. Kearney, 2018). This section, contextualises the expectations, and discusses through real use-cases the characteristics of AM innovation.

The global market of AM in the last decade consistently sustained a yearly double digit growth. Projections in Figure 1.2 estimate the reach a global market size of over 24 billion EUR by 2022. Figure 1.3 shows the degree of AM technology readiness in different industries, and reports the most common drivers for industrial adoption. Frost & Sullivan (2016) reports the following fastest growing AM industry verticals:

- aerospace, with a compound annual growth rate (CAGR) of 26% between 2015 and 2025;

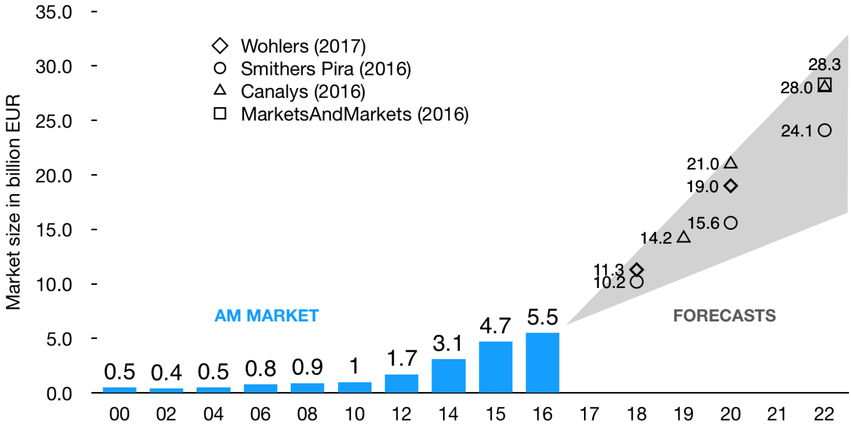


Fig. 1.2: Global additive manufacturing market size between 2000 and 2016 (in billion EUR) and forecasts until 2022. Extended from Langenfeld (2017).

- medical, expecting a 23% CAGR from 2015 to 2025;
- automotive with a 34% CAGR between 2015 and 2020.

It is therefore interesting to analyze how these industries could achieve innovation through the application of AM. Hence, to better understand the degree of triggered innovation, the author proposes two examples from the medical and aerospace industries.

The hearing aid industry together with the dental sector, represent two of the first large scale applications of AM. The hearing-aid industry is considered today one of the most mature use-cases of the technology, and has been subject of the study of scholars (Oettmeier and Hofmann, 2016; Sandström, 2016). The industry is often mentioned as a benchmark to understand the impact that AM can trigger in process chains. The manufacturing of individual hearing devices has shifted in the last decades from a completely manual process, whereas one single technician used to craft an entire device; to a fully digitalised process chain involving many specialists (Oettmeier and Hofmann, 2016). Before the advent of AM, technicians used impressions of the patient's ear channel to manually mold and assemble an individual device, in a slow process subject to unsatisfactory error-rates. Today, the shape of a patient's ear channel is digitalised through 3D-scanning of precise silicone impressions, or directly by means

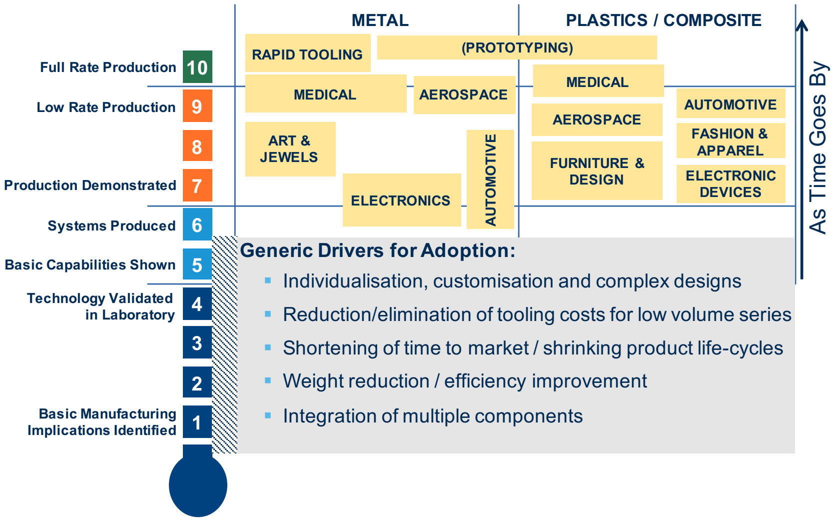


Fig. 1.3: Degree of AM readiness in several adopting industries and related drivers for adoption. Adapted and extended from Eisenhut and Langefeld (2013), with the knowledge provided by Wohlers Associates (2017).

of special scanning device. The entire design of an individual hearing-aid device and the whole planning of its assembly happens digitally, through specialised software (Meboldt and Biedermann, 2018). AM machines manufacture the individualized shell of the devices and specialists directly assemble these right-after. The hearing aids are delivered to the patient within five days from the order (Meboldt and Biedermann, 2018). The industry is still experiencing incremental innovation in manufacturing and process technology, with an ongoing transition from plastic to metal AM (Meboldt and Biedermann, 2018). Sandström (2016) mentioned the following advantages of implementing AM for the manufacturing of hearing aids.

- Industrialization of a labour intensive process previously characterized by quality problems and difficult to standardize.
- Significant increase in productivity and reduction in lead times.
- Possibility of storing individual shells digitally, thus enabling ubiquitous access (in case of repairs, re-orders).

Fig. 1.4: Example of a AM hearing aid. Top left, silicone impression of the hearing channel. Bottom left, a hearing aid with a clear AM manufactured shell. Right, hearing aid in place. Coustesy of Sonova AG from Meboldt and Biedermann (2018).

- Increase in comfort and acoustic performance due to increased geometrical freedom.
- Improvements in health and safety of technicians due to avoidance of exposition to toxic fumes characteristic of the old casting process.

In terms of production networks, AM adoption had conflicting implications in the industry. Where some players decided to relocate the manufacturing process, and centralise production in off-shore sites; others relied on a decentralised model, based on regional centres.

GE is a renowned pioneer in the field AM. The company identified metal AM as a key technology to pursue its strategic goals, and started with significant investments in the early 2010s . GE acquired established AM system manufacturers and leading service providers to integrate manufacturing capacity and expertise. In the aerospace industry, GE presented several technology showcases, and installed AM parts in the power units of new-generation airliners (Kellner, 2015). One of the latest engineering showcases is the Catalyst Turboprop (CTP) engine. CTP represents the entirety of improvements achievable through AM in a product. According to data released by the company, CTP achieves 10% more power at altitude, 20% improved fuel economy, and requires 30% less maintenance, compared to other engines of the same category (Kellner, 2018). Engineers could achieve such improvements in performance thanks to a significant reduction in engine components from 855 to just 12 (Kellner, 2018). The engine is currently in the certification process is expected to hit the market in 2020 (Kellner, 2018). Despite the innovation potential at the product, the CTP case also highlights the steep learning curve that companies face when introducing AM. In fact, it took GE about a decade of development in metal AM to establish a significant application such as CTP.

Both examples, as well as other industrial use-cases (Meboldt and Biedermann, 2018; Meboldt and Fontana, 2016) underline a significant innovation potential in the operations (OPS) and new product development (NPD) of a single focal firm. Hence, in an industrial context, AM has a proven track record of enabling for incremental or radical innovation in products and processes, mostly within the boundaries of a single focal firm and shows less of a disruptive and revolutionary character at the industry-wide level (Sandström, 2016; Steenhuis and Pretorius, 2017).

1.2 Challenges of Adopting AM for Industrial Manufacturing

Despite affirmed industrial potential for radical and incremental innovation, and a modest availability of success stories, AM adopters still face multiple barriers to implementation, and thus the adoption rate is reduced.

Researchers investigated the barriers toward implementation of AM at the firm level. A summary of major studies in this context is provided in Table 1.1. Challenges are often categorized according to the following factors: strategic, technological, organisational, operational and supply chain related (Mellor et al., 2014). The most important challenges encountered by AM adopters include:

Tab. 1.1: Summary of literature about challenges and barriers to AM adoption

	Method	**Findings**	**Research Gap**
Ballardini et al. (2018)	Multi Case study approach based on seven semi-structured interviews with experts from representative companies in the field.	AM application is restricted by technological limitations, structural industry limitations and patent law uncertainties.	Deepen the understanding of business- and patent-related factors influencing AM-produced spare parts market in Europe.
Deradjat and Minshall (2017)	Multi Case study based interviews with six companies in the dental sector.	Implementation challenges vary according to implementation phase, technology maturity, and company size. AM enables for the achievement of pure customisation.	Understanding dynamics by which companies achieve successful implementation of AM in mass customization.
Flores Ituarte et al. (2016)	Desk research combined with thorough case-study analysis and a survey. Interviews conducted with multiple representatives and decision-makers from the case company. Survey with 15 respondents.	The results highlight the considerable barriers to transferring AM technology to engineering applications.	Analyze transferability of AM systems in product development activities. Ongoing need to present case research in order to explain effective ways to overcome the barriers to AM transferability.
Martinsuo and Luomaranta (2018)	Multi case study approach with 21 managers and researchers from 17 companies.	Challenges vary according to firm position in supply chain. Larger scale benefits are likely to be achieved if the majority of the supply chain adopts AM technologies.	Understand AM adoption challenges in the specific context of SMEs.
Mellor et al. (2014)	Single case study approach based on a successful AM adopting company. Conceptual framework driving the analysis including strategic, technological, organisational, operational and supply chain factors.	The study delivers a formative structural model of AM implementation process. The study identify several supportive statements as evidence for the validity of the proposed research framework.	The research is driven by a lack of socio-technical studies about the implementation process of AM.
Ngo et al. (2018)	Comprehensive review of literature	The study presents the current state of materials development, and lists the main processing challenges.	Focus on technical aspects.

C1 Inability to identify suitable applications, including parts for AM. Risk of engaging in manufacturing of parts resulting more expensive and inferior in quality. (Ballardini et al., 2018; Martinsuo and Luomaranta, 2018).

C2 Lack of clear strategy for adoption (Martinsuo and Luomaranta, 2018; Mellor et al., 2014).

C3 Determination of cost-advantages and lack of calculation models (Ballardini et al., 2018; Martinsuo and Luomaranta, 2018; Mellor et al., 2014; Ngo et al., 2018).

C4 Skepticism about materials availability, part quality and durability (Flores Ituarte et al., 2016; Martinsuo and Luomaranta, 2018; Mellor et al., 2014; Ngo et al., 2018).

C5 Inaccessibility of a full, single digital process chain from designer to machine operator, due to lack of integral software and dedicated smart interfaces. (Deradjat and Minshall, 2017; Martinsuo and Luomaranta, 2018)

C6 Lack of knowledge about design for additive manufacturing (Flores Ituarte et al., 2016; Martinsuo and Luomaranta, 2018).

In general, outside the context of pioneering industries, a relevant portion of the examples of AM applications today are the result of a technology push approach. Many system providers, AM companies, software vendors and enthusiasts showcase process capabilities by means of products that are far from a positive business case. Although the technology push approach is essential to ensure advancements in the technology and gather a deep understanding of the process, it often delivers results that are far away from the market. As an example, just because it is possible to 3D-print a plastic car, it neither means that it is economically sustainable, that a market for such cars exists, nor that an organization can create value through that. Hence, although a technology push approach is necessary to build up knowledge and understand the limits and the context of application of AM, it often fails in solidly establishing it in companies. To deeply root AM inside the technological portfolio of a company, and enable its long-term survival, it is necessary to achieve a self sustaining condition through positive business-cases. However, vthe industrial adoption of AM is still characterised by an abundance of inventions, where only a few of these show the prerequisites for becoming real innovations.

1.3 Statement of Research Vision

In section 1.1 the author discussed the suitability of AM for industrial applications, and highlighted its potential for radical and incremental innovation at the firm level. In section 1.2 the author further summarized the major challenges faced by early adopters and therefore limiting the rate of adoption of AM in industry. The section further mentioned the drawbacks a technology push approach in the development of AM applications, resulting in a plethora of inventions, but subject to a reduced rate of sustainable innovation. This argument serves as evidence for the fact that the value-adding capabilities of AM in an industrial context are today not enough understood and require further investigation. The purpose of the present research is therefore to provide early adopters with tools and methods to structure the AM adoption process, to achieve more focus in the implementation, and to facilitate the direct scoping of value-adding AM applications. The novel theories proposed through this thesis aim at enabling AM adopters to early achieve positive business-cases. In particular, the research addresses the challenges C1,C2 and C3. The work raises the following three overriding research questions, which drive the design of all studies included in this dissertation.

RQ1 *How can new adopters be supported in the identification of viable AM applications?*

The scoping of suitable applications, thus avoiding the risk of engaging in suboptimal applications is a current challenge for AM adopters. Here the focus should be set on the direct identification of value-adding applications, to avoid a technology push approach. Tools and methods to support the scoping of value-adding AM applications should be developed through the qualitative analysis of applications with positive business cases.

RQ2 *What is the value and what are the implications of AM adoption?*

The second research question investigates the impact of post-AM implementation. Owing to the evidence that the largest impact is obtained at the single-firm level, the research undertakes such a perspective. The question can be addressed through both qualitative and quantitative methods. A qualitative analysis can be performed in combination with the results of the previous question. The application of quantitative methods demands instead for the consideration of representative *ad-hoc* case-studies with multi operational scenario analysis.

RQ3 *How should new adopters structure the implementation process?*

The last question aims at understanding the adoption process by collecting evidence from successful implementation projects. The analysis is expected to contribute novel theories and provide meaningful insights and recommendations for early adopters.

1.4 Scientific Contribution

Three studies were conducted to address the research questions above. Owing to the explorative nature of the research, and to observe the adoption of AM technologies in industrial context, an approach combining of multi- and single- case study analysis is selected (Yin, 2013). A short overview of each study, including purpose, relevance and a summary of the results is provided below.

Study 1 — Value Driven Clustering of Industrial AM Applications

The first study investigates and structures the possibilities of adding value through AM technologies in a focal firm value chain. The study further provides an overview of post-adoption implications on the focal-firm established processes for each identified domain of feasible application. The topic is of high relevance as it contributes novel theories addressing the challenges faced by industrials in the identification and prioritisation of AM applications.

The qualitative study applies a multi-case study approach to collect empirical evidence from successful adopters of AM. The authors introduce a value-chain framework constituted of a new product development process and an order fulfilment process to pinpoint the value adding characteristics of AM. Data is collected from interviews with AM adopters from the Swiss and central European region in the medical and industrial manufacturing industries.

The full publication is included in section 2.

Filippo Fontana, Christoph Klahn, and Mirko Meboldt (2018). "Value-driven Clustering of Industrial Additive Manufacturing Applications". In: *Journal of Manufacturing Technology Management*, JMTM–06–2018–0167

The applied value chain model together with the identified value-adding clusters are reported in Figure 1.5. The research identifies seven domains in a focal-firm value chain where AM can create unprecedented value. Implications on surrounding processes for each domain are also studied.

Study 2 — Selection of High-Variety Components for Selective Laser Sintering

The second study delivers a quantitative assessment of the benefits of implementing AM in the case of high-variety manufacturing. It develops an algorithmic approach to optimise the manufacturing strategy of an high-variety component family. The study is relevant as it contributes to the literature of AM component selection, and provides a quantitative estimation of achievable lead time reduction and savings in manufacturing costs in the case of reproducing an existing component geometry with AM.

Our analysis is based on a single case-study from a global manufacturer of packaging machines. The research first develops an algorithm for manufacturing costs estimation based on empirical data from the case

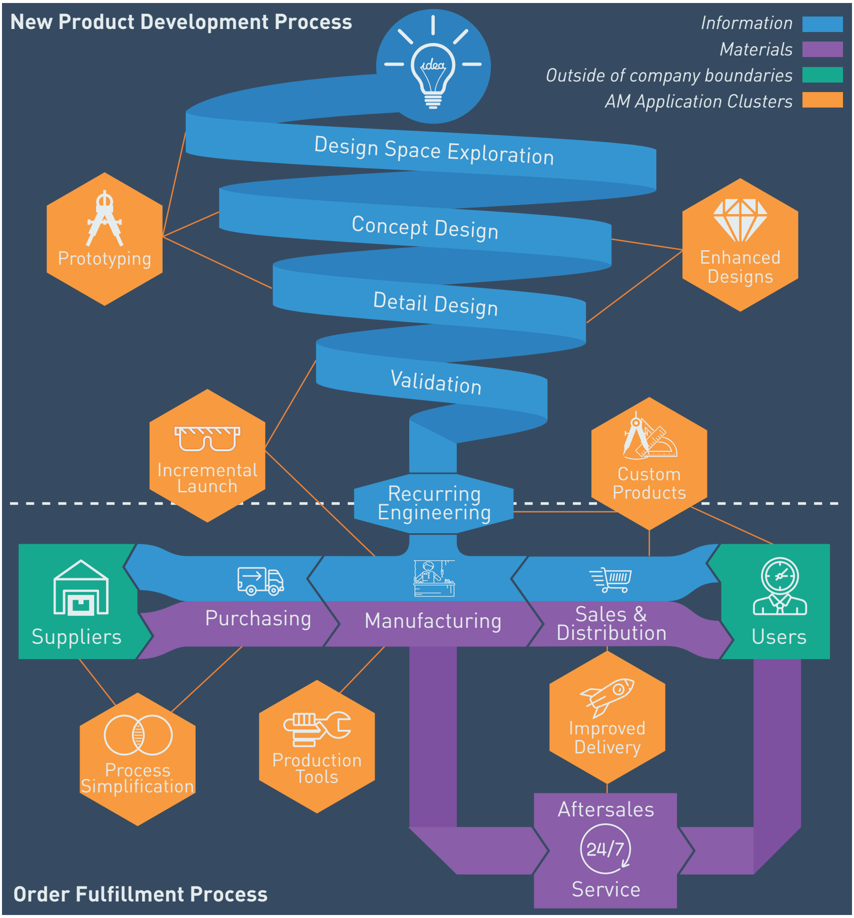


Fig. 1.5: Overview of the value-driven clustering model presented in Study 1. Each value adding cluster is discussed in section 2.5.

company, and compares lead-time and manufacturing costs under different operational scenarios.

The full publication is included in section 3.

Filippo Fontana, Enrico Marinelli, and Mirko Meboldt (2018). “Selection of High-Variety Components for Selective Laser Sintering: An Industrial Case Study”. In: *Industrializing Additive Manufacturing -*

Proceedings of Additive Manufacturing in Products and Applications - AMPA2017. Cham: Springer International Publishing, pp. 238–251

Study 3 — An AM Enabled NPD Process Model for Incremental Product Launch of Hardware

The last study investigates how companies can combine agile product development methods with AM to achieve risk reduction in new product launches. Results of the study identify the interplay between AM and agile for the purpose of new product launches as a novel field deserving the attention of further research.

The authors consider in a longitudinal study the case of a manufacturer of medium-format cameras, which combined AM and agile to enter a new and unexplored market.

The study delivers a twofold analysis. First, data collected over three years about AM implementation in the company is analysed to assess the technology development process. Second, a suitable NPD process model for combining agile with AM for the scope of new product launches is presented.

The full publication is included in section 4.

Filippo Fontana, Daniel Omidvarkarjan, Daniel Temperli, and Mirko Meboldt (2019). "An Additive Manufacturing Enabled NPD Process Model for Incremental Product Launch of Hardware". In: *Computers in Industry*. Submitted

2 Value Driven Clustering of Industrial Additive Manufacturing Applications

2.1 Abstract

Purpose – A prerequisite for the successful adoption of additive manufacturing (AM) technologies in industry, is the identification of areas where such technologies could offer a clear competitive advantage. The present publication investigates the unique value-adding characteristics of AM, defines areas of viable application in a firm value chain, and discusses common implications of AM adoption for companies and their processes.

Methodology – The research leverages a multi-case-study approach and considers interviews with AM adopting companies from the Swiss and central European region in the medical and industrial manufacturing industries. The authors rely on a value-chain model comprising a new product development (NPD) process and an order fulfilment process (OFP) to analyze the benefits of AM technologies.

Findings – The research identifies and defines seven clusters within a firm value chain where the application of AM could create benefits for the adopting company and its customers. The authors suggest that understanding the AM process chain and the design experience are key to explaining the heterogeneous industrial maturity of the presented clusters. They further examine the suitability of AM technologies with agile development techniques to pursue incremental product launches in hardware. It is clearly a field requiring the attention of scholars.

Originality/value – This article presents a value-driven approach for use-case identification and reveals implications of the industrial implementation of AM technologies. The resultant clustering model provides guidance to new AM adopters.

2.2 Introduction

New technologies find their way into real-world value chains where they offer a leap forward in terms of value creation. Production technologies are no different than others and follow the same adoption patterns. In fact, companies adopt new manufacturing technologies only if their implementation generates a substantial increase in productivity or if it provides an unprecedented competitive advantage (Conner et al., 2014; Reichstein and Salter, 2006; Schrettle, 2013). It has been previously demonstrated that innovation in process and equipment technology can sometimes provide improved quality, shorter delivery cycles, lower inventory levels, and shorter product development cycles. It can enable unprecedented products, reduce economies of scale, enrich the offered product portfolio, and allow more customer specials (Skinner, 1984).

Evidence supporting these statements is particularly common for additive manufacturing (AM) technologies. In their first adoption, AM technologies found vast application in prototyping (Campbell et al., 2012). AM made it possible to physically realize and visualize product concepts beyond virtual representations (e.g., CAD) in a simple and economic manner. The implementation of AM for prototyping purposes allowed the adopting companies to validate products early and avoid costly mistakes. Further-more, adopters of AM prototyping technologies could compare the performance and feasibility of different design alternatives and ease the selection of the most suitable variants for further development (Lopez and Wright, 2002).

In recent decades, industry has manifested a growing interest in AM technologies and their broader adoption, mostly in prototyping, and has attracted new investments, therefore increasing the innovation pace of the AM ecosystem (Wohlers Associates, 2016). A subsequent surge in the number of available AM technology improvements (i.e., process reliability and improved availability of production-grade materials) has pushed them ever more toward industrial production (Bak, 2003).

In this context, this article investigates the unique value-adding characteristics of AM, justifying its broader adoption in industry. Through this contribution, the authors elucidate the underlying motives driving the industrialization of AM technologies and their increasing adoption for serial manufacturing purposes. Manufacturing companies considering the introduction of AM face two fundamental questions. The first is how to determine the potential applications within their company to generate value. The second is how to understand the implications of AM adoption on established processes. Companies addressing these questions undergo long-learning cycles, and require time, effort, and experimentation to obtain results.

If a firm lacks a structured approach in the implementation of AM by failing to correctly scope suitable opportunities in its value chain, a successful and timely implementation might be compromised. In this work, the authors suggest that a value-driven approach to the identification of AM application domains and its introduction will increase the likelihood of success, as it proved beneficial in the circumstances of other managerial challenges (Slywotzky, 1996). In this context, the paper investigates the following research questions:

RQ1. What are the elemental domains of a focal-firm value chain where AM can be applied to generate unprecedented value?

RQ2. What are the implications of AM adoption in the identified elemental domains?

To address these questions, Section 2 reviews the relevant literature in the domain of AM management. In Section 3, the authors introduce a value-driven conceptual framework leveraged for the analysis of the case interviews, describe the selected case-study approach, and introduce the methods employed for data collection. Section 4 reports the results of the study in the form of seven recurring clusters of value creation, presenting the identified value generated in implementation as well as for a few implications. Section 5 highlights the contribution of the present work to the existing literature, and Section 6 provides final considerations.

2.3 Literature Review

Relevant studies have been identified in four distinct research streams of the AM management literature: AM value, barriers to AM implementation, impact of AM implementation, and identification of AM suitable parts and applications.

2.3.1 AM Value

Previous studies showed that AM technologies offered the largest advantages in terms of enabling unprecedented freedoms of design, and provided greater manufacturing flexibility. Two fundamental proper-ties were recurrent in the literature, providing the source of many advantages achieved by the implementation of AM. Such fundamental properties are the manufacturing complexity advantage and the small lot-size advantage (Berman, 2012; Holmström et al., 2010; Mellor et al., 2014; Petrovic et al., 2011). In literature, manufacturing complexity advantage is often referred to as “complexity for free” (Eisenhut and Langefeld, 2013; Gibson et al., 2010; Weller et al., 2015). However, scholars had already demonstrated the existence of a relationship between increasing design complexity and increasing manufacturing costs (Pradel et al., 2018).

Regarding manufacturing complexity advantage, the layer-by-layer characteristics of AM processes enable the achievement of highly complex geometries with few limitations imposed by technology-specific design rules (Baumers, Tuck, et al., 2011). Engineers can leverage the manufacturing complexity advantage to provide customers with more efficient, more lightweight, more functional, and more customized products (Ahuja et al., 2015). When compared to other manufacturing technologies, AM shows a lower increase in total cost with increasing design complexity (Hague et al., 2004). Nevertheless, post-processing activities can be a major driver for increasing overall manufacturing costs for AM, especially at high degrees of complexity (Baumers, Dickens, et al., 2016).

Regarding small lot-size advantages, the absence of tooling, equipment changeover, and product-specific set-up procedures make AM favorable over other manufacturing processes for low-volume series, up to lot-size one (Tuck, Hague, Ruffo, et al., 2008). Pioneers in the AM domain can achieve cost reductions in the manufacture of high-variety component families (Fontana, Marinelli, et al., 2018). The implementation of AM technologies in a company directly influences its value-adding processes. Two processes are often directly influenced by such an implementation: the new product development (NPD) process and the order fulfilment process (OFP). Several scholars have identified and described how the fundamental properties of AM can enable unprecedented value creation in NPD and OFP. Such value enablers are summarized in Table 2.1 and are further described below.

Tab. 2.1: AM value enablers in a generic firm value chain.

	New Product Development Process	**Order Fulfilment Process**
Complexity Advantage	Function driven product design (Gibson et al., 2010; Klahn, Leutenecker, et al., 2015; Vignat et al., 2012; Yadroitsev et al., 2007)	Integral product design (Türk, Kussmaul, et al., 2016)
Small Lot Size Advantage	Facilitate test driven, iterative development (Lopez and Wright, 2002)	Reduce barriers to product variety and Just In Time (Ballardini et al., 2018; Deradjat and Minshall, 2017; Fontana, Marinelli, et al., 2018; Ghadge et al., 2018)

First, in the domain of NPD, the manufacturing complexity advantage enables engineers to apply function-driven product design (Gibson et al., 2010; Klahn, Leutenecker, et al., 2015). Through function-driven design, engineers have the opportunity to focus on the function of the designed components, rather than on their manufacturability. Thus, engineers can integrate design elements and features that are not manufacturable by means of other manufacturing technologies (Vignat et al., 2012; Yadroitsev et al., 2007).

Second, the small lot-size advantage in NPD enables test-driven, iterative development. Via iterative development, engineering teams can economically manufacture several test versions of a product and drastically increase the communication and understanding of the designed system (Lopez and Wright, 2002). The approach enables new development paradigms based on rapid design iterations and is driven by physical testing instead of by meticulous planning.

Third, in OFP, the manufacturing complexity advantage enables value creation through the application of integral designs. Integral designs allow manufacturers to achieve their desired functionality with a reduced number of parts. With the application of integral design, complex monolithic designs enable the substitution of assemblies (Türk, Kussmaul, et al., 2016). This approach reduces the need for assembly, simplifies manufacturing processes, and potentially streamlines related supply networks.

Lastly, the small lot-size advantage in OFP reduces the barriers responsible for surges of manufacturing costs in the case of high-variety and just-in-time manufacturing (Fontana, Marinelli, et al., 2018). With smaller lot-sizes, companies can achieve more responsiveness in production, reduce delivery lead times, lower inventories, and establish operational prerequisites to address individual customer needs (Ballardini et al., 2018; Deradjat and Minshall, 2017; Ghadge et al., 2018).

2.3.2 Strategic Challenges and Barriers to AM Adoption

Previous publications in the domain of AM innovation identified elements of incremental, radical, and disruptive AM technologies (Steenhuis and Pretorius, 2017). To capitalize on the innovation potential of AM, companies must overcome several adoption challenges. Hence, for successful adoption, companies should learn how to reconfigure and adapt to AM (Khorram Niaki and Nonino, 2017). Several papers tackle these issues and propose studies on the challenges and the barriers towards the implementation of AM and propose ways for companies to overcome these limitations.

Some scholars have described the challenges of implementing metal AM, arising in the specific case of mass customization (Deradjat and Minshall, 2017). Their study leveraged a case-study approach with six companies from the dental industry and drew attention to the challenges in the domains of corporate strategy, technology, operations, organizations, and external factors faced by adopters. The identified challenges included a limited degree of automation offered by software, high costs of post-processing, and high costs for equipment maintenance and set-up. The authors concluded that the implementation challenges varied from case to case according to the implementation phase, the degree of technological maturity, and company size.

Other researchers applied multi-case studies to deepen the understanding of business- and patent-related factors influencing the adoption of AM for spare-parts manufacturing purposes (Ballardini et al., 2018). Their studies confirmed the applicability of AM for spare-parts manufacturing, but further highlighted restrictions posed by technological limitations and introduced structural industry limitations and law uncertainties as challenges to implementation. They further highlighted the risk for firms inadvertently approaching suboptimal AM applications, then engaging in the manufacturing of parts with inferior quality, being more expensive than other methods. Thus, this paper highlights the relevance of studies deepening the methods and practices for scoping AM applications.

A multi-case-study approach, using collected data from 21 interviews from 17 companies has been leveraged to understand and describe AM adoption challenges in the specific context of small-to-medium size enterprises (Martinsuo and Luomaranta, 2018). Their study confirmed previously identified challenges, such as a lack of knowledge of AM design and skepticism of material availability, quality, and durability of AM parts. It further highlighted the dependency of the challenges upon the position of the firm in the supply chain. A notable challenge emerging from their study, reported by original equipment manufacturers (OEM), is the difficulty in the identification of suitable applications for AM.

2.3.3 AM Adoption and Impact of Implementation

Another relevant research stream in the AM management literature describes the AM adoption process and addresses the impact of implementation. In this domain, scholars have investigated the post-implementation effect to the organization, proven processes, supply chains, and operations. Ghadge et al. (2018) undertook a system-modeling approach to simulate and explore the impact of AM deployment to aircraft spare-parts inventory management. The study revealed that the responsiveness introduced by AM had beneficial effects on the mitigation of high-inventory risks, on the increase of service levels, and on the reduction of downtime costs. Rylands et al. (2016) studied the introduction process of AM within companies' operations and described the related impact on business. Their research applied a case-study approach analyzing the cases of two AM adopters. Their contribution highlighted the effect of shifting value proposition and creating new value streams for the adopting company.

The impact of AM in mechanical engineering and medical industries was explored with an online survey approach (Muir and Haddud, 2017). There, the authors investigated the potential impact of AM on inventory performance and customer satisfaction in the spare-parts supply chain. In this setting, AM technology was found to positively influence inventory performance, mitigate supply risks, reduce the impact of sudden surges in demand, and reduce stock obsolescence.

Another comprehensive study on supply management processes and components systematically investigated the impact of AM technology usage in customized-parts production (Oettmeier and Hofmann, 2016). They performed an empirical analysis via a multi-case-study approach of two companies in the hearing systems industry. Their paper identified important implications in the domains of flow management, supplier relationship management, order fulfilment, customer relationships, and returns management. Whereas other contributions in this stream focused strongly on describing implications in SCM and operations, this publication was the first to include important observations related to product development. Interviewees reported the influence of AM in an earlier integration of customer feedback in product development and the impact on internal communications. This consideration highlighted a current gap in the literature and stressed the need for further research considering not only the environment of supply chain and operations, but also the perspective of AM adoption on the new product development process.

2.3.4 Identifications of Parts and Applications for AM

Several industries have experienced major barriers to AM implementation via the difficulty to identify promising AM applications (Martinsuo and Luomaranta, 2018). Scholars have addressed this issue by investigating the common industry sectors of AM adoption and by proposing decision-support tools, frameworks, and methods to ease the scoping of parts and applications suited for AM.

In the domain of component identification, a top-down approach to systematically identify AM-feasible spare-parts was proposed in the context of the aviation industry (Knofius et al., 2016). The component search strategy relies on an analytic hierarchical process, and the proposed method was validated with a single case-study. The method relied on data available in common company databases, such as: logistic key performance indicators , supplier information, inventory figures, and parts geometries to rank candidates based on their expected feasibility for AM processes. The method was suitable to assess a large spare-part portfolio and was used to identify about 1,000 economically and technologically feasible parts for AM manufacturing. Other scholars suggested a bottom-up search strategy based on a combination of workshop concepts and a scoring method using multi-criteria analysis (Reiher et al., 2015). The study proposed a 3- stage selection process based on the assessment of economical, functional, geometrical, operational, and manufacturing process-related characteristics of the parts. However, search strategies based on screening and assessment of existing components could limit the scope to mere manufacturing technology substitution or the re-engineering of already existing components and assemblies. Hence, it might prevent the full exploitation of AM potential on a larger scale.

Conner et al. (2014) leveraged a key-attribute analysis framework to provide a detailed map of possible application domains for AM technologies. The framework relied on three product dimensions: geometrical complexity, manufacturing volume, and degree of customization. It provided a reference system to categorize potential AM applications in eight regions. Other scholars have investigated promising industry sectors for AM application (Guo and Leu, 2013; Petrovic et al., 2011). They reported aerospace, automotive, biomedical, and energy sectors as common adopters of AM technologies.

The analysis of prior publications in this subsection shows that extant literature considered the search of possible AM applications at the component-level or described AM adoption at an industry-wide level. This highlights the need for further research at a firm-level. Furthermore, the review of literature highlights a lack of value-driven approaches. Therefore, researchers should investigate the domains of a company value-chain, where AM could be leveraged to enhance value creation. The results of the entire literature review performed by the authors reveals a literature gap best summarized by the following three statements:

- The identification of the right AM applications represents a challenge especially for OEMs, and the issue should be further investigated.
- Despite NPD and OFP being the two processes where AM shows the greatest potential for value creation, there is a lack of studies jointly considering AM impact on both NPD and OFP.
- There is a need for literature undertaking a value-driven approach to the identification of application domains of AM at the firm-level.

2.4 Methods

2.4.1 Value-Driven Conceptual Framework

This research analyzes value creation through AM technologies in the context of a generic focal-firm value chain. The authors use a holistic approach to analyze the benefits originating from AM implementation in both NPD process and OFP. The model considers a focal-firm with an internal research and development unit and managed operations. The firm is assumed to source raw materials and semi-finished products from a network of suppliers and to supply its customers (not necessarily the final users) as shown in Figure 2.1. This presented value-chain framework comprising NPD and OFP describes a relevant portion of the lifecycle of a product within and beyond the boundaries of the focal-firm, and is thus key for deepening the understanding of the implications of AM.

On the upper part of Figure 2.1, the NPD process ensures that new ideas and business opportunities are converted into marketable products and services. This process is executed one-time for the introduction of a new product or product family and is often a rather fuzzy process (Heck et al., 2016). The development of new products entails a certain degree of uncertainty. Therefore, the process includes several design iterations, feedback loops, and validation steps that converge towards meeting user requirements. Requirements set by users include haptics, functionality, durability, and other criteria, and often evolve to adaptive requirements. The speed of production and number of new products that can be brought to the market, given a certain amount of resources or capital, is a direct driver of total NPD efficiency Swink et al., 2006. Shareholders often manifest their interest in the reduction of the development time or in the increase of NPD throughput to increase profitability. When new products are ready for the market, the development team hands over the output of the development project to manufacturing. During this phase (i.e., product launch), operations develop and establish standards, procedures, quality control routines, and continuous improvement techniques. The long-term recurring OFP begins, and products are distributed to the final users. Depending on the product and its characteristics, after-sales and reverse logistics processes are sometimes established to guarantee customer support.

Regarding value, scholars of several research streams have provided several definitions (Khalifa, 2004; Sanchez-Fernandez and Iniesta-Bonillo, 2007; Srivastava et al., 1999; Van der Haar et al., 2001). For this research, the authors restrict the definition of value to include the actors of the above introduced value-chain framework. AM implementation can thus influence value creation and create benefits for both the focal-firm and its customers. Therefore, we provide definitions for value for the focal-firm and value for the customer. Value for the focal-firm includes improvements that increase the profitability of the company. Thus, it either reduces costs

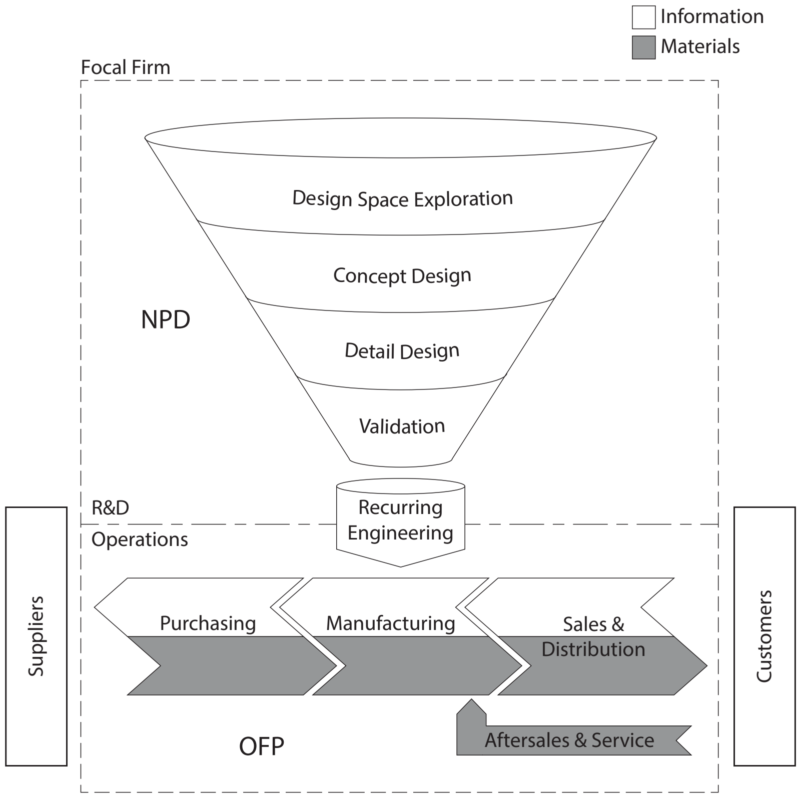


Fig. 2.1: The proposed model of a generic focal-firm value-chain.

by making the processes more efficient or reduces the materials cost because of reduced consumption, or it increases revenue because of increased sales price or quantity. Value for the customer is anything that increases customer willingness to pay for a product. Here the authors define it as the increased efficiency of the product in use, increased product quality, and the achievement of better service (e.g., delivery lead times) as perceived by the customer. Efficiency of the product in use can be described as the reduction of total costs of ownership for the customer (Klahn and Fontana, 2017).

2.4.2 Research Design and Selection of Respondents

To address the research gaps listed in Section 2, the authors leverage a case-study approach. Owing to the explorative nature of the research and the interests of the authors in contributing novel theories, a case-study approach has been selected (Eisenhardt, 1989; Yin, 2013). Both the current lack of literature and the need for observing the issue in common circumstances suggest the selection of a qualitative case-study method (Eisenhardt, 1989; Meredith, 1998). A multiple-case-study approach is thus applied to increase external validity, owing to the availability of multiple cases (Stake, 1995; Voss et al., 2002).

As the basis for data collection, the authors leveraged a network provided by the “Swiss AM Expo 2016,” the largest Swiss professional fair for additive manufacturing with about 70 exhibitors showcasing applications representing the entire central European market. To address the gap, the authors focused on firms recurrently applying AM technologies in the context of series production. To ensure industrial relevance, companies engaging in art, research and education, architecture, construction, jewelry, and software development were dropped from the initial sample. Furthermore, companies directly engaging in the development of AM products with their own managed operations were preferred to fully grasp the influence of AM on both NPD and OFP. Institutions with whom the authors have already engaged in professional relationships, or where the authors previously performed research activities were excluded from the list of candidates for the sake of avoiding confirmation bias and conflicts of interest. Finally, the focus was set on selecting cases representative for a wide spectrum of industrial sectors, from companies of varying size to specifically targeting better-established industry applications. It was assumed that the choice of domains where AM was already established contributed to the completeness of the analysis. Cases regarding one-time experiments, preliminary technology developments, and early-stage adoption of AM were deliberately excluded from the sample. The final set includes seven case studies, summarized in Table 2.2. An in-depth description of the selected cases and of the companies is available in the literature (Meboldt and Fontana, 2016).

Tab. 2.2: Background information on the selected cases.

Case	Product	Company Size	Industry	Interviewees	Respondents Positions	Sourcing Strategy	AM Technology	Units per year
Case A	Vibratory bowl feeders	Medium	Automation, Industrials	3	CEO AM Services Supplier: Head of R&D AM Services Supplier: Executive VP	Buy	SLS	1–10
Case B	Dental aligners	Medium	Dental, Medical	3	Executive VP Medical Treatment Specialist AM System Supplier: Manager	Make	SLA	>1,000
Case C	Surgical cutting guides	Large	Medical	3	Department Head Surgeon AM Services Supplier: Engineer	Buy	SLS, FDM	n.a.
Case D	Tramcar lightbox indicator gears	Large	Transportation	2	Engineer AM Supplier: Head of Production	Buy	SLS	100–1,000
Case E	Injection molding feeding device	Medium	Electronics Manufacturing	2	Engineer AM Supplier: Head of Production	Buy	SLS	1–10
Case F	Structural inserts for UAV frame	Large	Geospatial, Aerospace	2	Manager AM Supplier: Engineer	Buy	SLS	100–1,000 frames
Case G	Structural components for ergonomic exoskeleton	Small	Orthopedics, Ergonomics	2	CEO AM Services Supplier: Business Development	Buy	SLM	10–100

2.4.3 Data Collection and Analysis

This research employs semi-structured interviews with managers, engineers, suppliers, and practitioners closely related to seven additively manufactured products. The authors conducted interviews with 17 people from several functions related to the same case, thus enabling triangulation and the collection of more perspectives and increasing the overall reliability of the study (Patton, 1987). All case interviews were conducted on-site by the same researchers with expert representatives from the focal-firm and their closest AM suppliers. Interviewing sessions were further combined with site visits and product showcases.

Owing to the heterogeneous background of the interviewees and the diverse industrial sectors represented in the sample, the authors leveraged a generic and open-ended interview outline. Thus, the outline was employed as an opener for further discussion, where the interviewees were given the chance to provide further insights, or endorse statements from other sources. All interviews covered the following central aspects: an introduction of the respondents and their business relationship, a description of the implemented AM case, the circumstances under which the project was initiated, the chances of creating unprecedented value in the focal-firm and for its customers observed in both NPD and OFP throughout the project, and implications and effects on the focal-firm activities after AM implementation. All interviews were recorded and processed with the help of software specialized in the analysis and coding of recordings for the purpose of qualitative research (Nijmegen: Max Planck Institute for Psycholinguistics, 2018; Wittenburg et al., 2006). The relevant parts of the interviews were transcribed, allowing for an in-depth analysis of the data. Secondary data was collected from publicly available documents about the companies, site visits, notes from the authors, and product showcases.

The collected data was analyzed in three distinct phases. In the first phase, the authors focused on each interview recording to isolate discussions and statements related to the value added by AM. Transcriptions of all relevant portions of the interviews were performed. In the second phase, the authors performed a cross-case analysis to identify recurring patterns of value creation, to define a coding strategy, and to compile the value-adding clusters with single statements. In the third phase, the recordings were analyzed to isolate and transcribe all discussions about the implications observed for each identified cluster. The authors conducted most of the interviews in German. Results were translated to English for the sake of documentation. During the translation process, the authors transcribed as accurately as possible the original German statements. Therefore, the form of the translated statements might not fully respect English grammar. The analysis identified 51 statements about unprecedented value obtained from the adoption of AM and the implications in the observed firms' value chains. To enable more in-depth discussions of the investigated research questions, the results of the study were reported in the form of a cross-case analysis (Yin, 2013).

2.5 Results

Research identified seven elemental domains within a firm value chain where the application of AM could create benefits for the adopting company or for its customers. These are listed with major findings in Table 2.3. In each application cluster, the authors identified direct effects caused by the application of AM and consequences of implementation on other surrounding activities.

2.5.1 Prototyping

Prototyping simulates physical artifacts intended to reproduce a portion or the entirety of characteristics of a final product to test and validate during development. Despite three decades pioneering AM, interviewees reported prototyping as a relevant value-adding application domain. According to interviewees, the direct advantages of adopting AM in prototyping lay in the ability to perform quick design iterations and to therefore compare the feasibility of different design approaches. An interviewee, responsible for the development of case A reported,

> *Adaptations can be achieved very quickly . . . to manufacture such precise sliders, we should perform a test, so that we*

Tab. 2.3: Summary of identified value adding clusters.

Cluster	Direct AM Effect	Implications on focal firm
Prototyping	• Quick iterations over different design and concepts • Trial versions with other non-series-like materials, to test product features • Visualise important product characteristics not captured in CAD	• Faster time-to-market • Ensuring that design will perform correctly in production conditions • New Patterns of collaboration and team dynamics in the product development team (Agile, Parallelization)
Enhanced Designs	• Design follows the function. Reduced focus on the manufacturing constraints • Design practices aiming at weight reduction • Design practices aiming at integration of functions	• Design impacts the performance of the product once in use (energy consumption, throughput, ergonomic, usability, . . .) • Design impacts the performance of the manufacturing process and improve production of the product (variation, assembly time, quality, . . .)
Incremental Product Launch	• Flexibility to update the design even after selling of first unit • Avoidance of lock-in in tools and molds	• Learning from customer feedback reduces uncertainty for entry in unexplored markets • Smooth transition between product generations • Requirement of new business models for selling the product
Custom Products	• Increasing convenience and simplicity of manufacturing • Reduced transaction costs in digital domain (data can be stored, transmitted, accessed, modified at any-time and at very reduced cost) • Single point of storage of information, including meta-data • Hard-coded error detection, and quality assurance gates	• Drastic increase of productivity in the manufacturing of individual products • Often require the combination with a fully digital process chain • Increasing challenges in traceability • Late physicalization of products
Improved Delivery	• Cost efficiency for small lot sizes, even in high variety • Saves waiting caused by absence of specific equipment changeover • Suitability for spare parts with reverse engineering	• Reduction in delivery lead times and in costs • Operation with less stock due to enhanced responsiveness
Production Tools	• Economic production of molds or tools for indirect processing • Fast accessibility, reduced downtime	• Reduction of error rate, especially in combination with manual operations. Improvement of process stability, ergonomics. • Increasing overall throughput and cycle time
Process Concentration	• Reduction of total process steps • Elimination of handover and of waiting time between separated process • Transition from several fragmented manual manufacturing steps to one integral manufacturing process	• Better scalability due to, one-time design overhead • Substitution of manual work as a major driver of profitability • Possibility of extending the portion of in-house value creation • De-skilling / Re-skilling, reduction of skill barriers for workers

have an idea of how the process performs, and then maybe adapt some measures . . . Here, one could manufacture more versions of the part, . . . and then test them all.

Via prototyping, adopters can reproduce important characteristics of the final product and therefore gather new perspectives and insights on their design or scoped systems. These are not offered by means of other techniques (e.g., CAD), even without applying the final production-like materials. The interviewed engineer from Case E further stated,

. . . and this is for the purpose of validating automation. In order to run the first trials, we made a plastic version.

furthermore, from the medical industry, a surgeon in charge for the design of Case C stated,

allows us a complete new perspective . . . , that we cannot obtain with conventional 2D imaging technologies. (AM)

According to interviewees, the adoption of AM in NPD in the field of prototyping has three major implications. First, they report a change in the collaboration and team dynamics in NPD from a plan-driven set-up to a more agile-driven approach. An engineer from Case E stated,

We recently observed that, [during the development of a conventional tool manufactured by means of CNC, we had to . . . sit together to ensure everything works. It's not possible to test a lot as we do [here with AM]. There, [in the conventional case] we have to really discuss together in team and rely on our expertise. With AM we do not need a lot of help from the collaborators. It works best to test! . . . In teams, we have to sit together and discuss less.

The teams define interfaces, parallelize development tasks, rely on testing, and therefore achieve more efficiency with NPD. Compared to the development of conventionally manufactured tools, where the team must extensively rely on the expertise of all members and discuss each feature of the mold to avoid costly errors. In the case of AM, engineers can work in parallel, and they have shorter sessions together for interface definition and integration of independently developed elements. Second, physically testing the performance of the designed system allows for the reduction of uncertainty, flaws, and errors in both production and the final system. A surgeon from Case C reported,

> *A big part of increasing importance is this 3D planning, from this we derive all such . . . models. Here it is possible to create for example prototypes . . . and actually test how these perform. Are these applicable? Do they work in the available entryway? These are all domains where this technology plays an important role!*

Therefore, highlighting the feasibility of prototyping technologies for the validation of the designed system helps verify its usability by simulating real production conditions. Third, interviewees reported the feeling of an increase in the pace and speed of NPD, thanks to the other findings mentioned above. The CEO of the company from Case G reported,

> *I mean, 3D printing is quite flexible and it helps obviously, you don't want to spend time trying to sort of make something. If you lose the time window you are done. . . . First you ask people [to manufacture a test system, and they reply:] uhm. . . four weeks, five weeks using CNC. And then we start to see, 3D printing takes about a week or even less.*

This can relate directly into faster time-to-market for the developed products.

2.5.2 Enhanced Designs

AM's capability of generating complex and unprecedented structures is well-understood and documented in literature (Bletzinger and Ramm, 2001; Glasschroeder et al., 2015; Hague et al., 2004; Horn and Harrysson, 2012; Huang et al., 2014). In the application cluster of enhanced designs, companies can leverage this AM process capability with the creativity of engineers to enhance the functionality of the product. By leveraging design for AM practices, engineers can follow an approach where the function of the designed system directly defines its shape, and the conceptualization process is freed up from many manufacturing constraints. Engineers can leverage such properties to achieve substantial mass reductions, especially in the aerospace sector (Emmelmann et al., 2011). Scholars have identified three features allowing the reduction of the weight of parts: bionic design, lattice structures, and thin-walled structures (Orme et al., 2017). According to interviewees, engineers can also pursue functional integration. The head of research and development from Case A stated,

> *We try to integrate as many functions as possible in the bowl. This means, air ducts, vacuum ducts to hold the part steady, or to blow them away and such things; also transition elements. . . . If we leverage this art of functional integration, then the process is faster.*

Functional integration can achieve incorporation of mechanical functions, fluid and thermodynamic functions, or electrical functions (Glasschroeder et al., 2015). Leveraging weight reduction and functional integration in the design and engineering of components has important downstream implications in the focal-firm value chain. First, interviewees reported that such design measures could impact product performance once in use. Here, in the scope of Case A, functional integration reduced changeover time. The CEO of the Case A focal-firm reported,

> *Changeover time is of course much smaller. Two screws, and the bowl is changed. Usually [speaking of conventional feeders] no blue-collar workers in the line can change and calibrate the bowl feeders. When we apply several different formats in a line, let's say two or three, then these have to be changed and calibrated by specialized workforce. When these are set-up with just two screws [as the case of AM feeders] and two pins, then anyone can make the changeover. And this is of increased interest, and also speed is increased.*

However, this is not the only case where improvements of the product in use could be achieved. Scholars have reported improvements in terms of efficiency, usability, and mass (Gibson et al., 2010; Huang et al., 2014; Klahn, Leutenecker, et al., 2014; Oettmeier and Hofmann, 2016). Second, interviewees reported the influence of design for additive manufacturing on the manufacturing process of the product. An engineer in the domain of Case F reported,

> *So, what is nice there, is that the connection pieces they have an internal structure that, ... makes sure we can glue the carbon rods easily together. ... we came up with a solution with a sort of glue channels, where we inject glue in one hole, and it's a sort of trap. ... Furthermore, we know that we have a specific amount of glue added, and will always be the same on every connection point. And it's also a kind of quality check. We know that if we inject the glue, and it comes out on the other end of the threads, we know that it's secure and it's holding together.*

Here, the design complexity can be leveraged to ensure quality in complex assembly operations, improve cycle time, or simplify labor intensive assembly steps. Therefore, it can positively influence the production process and the product.

2.5.3 Incremental Product Launch

With incremental product launches, a company leverages AM to reduce the uncertainty and increase the speed of a new product launch. Incremental product launch finds an application at the interface between NPD and OFP at the market-launch step. To pursue incremental product launch, a company relies on a test-driven, iterative product development approach, where product increments are frequently released and validated by lead customers on the market. The feedback from early adopters can be used to fine-tune the product until a stable design is reached. Through this approach, the uncertainty of NPD can be reduced, time-to-market can be shortened, and product-to-user fit can be optimized. The interviewees saw the biggest advantage of AM in this domain in the possibility of updating the design, even after commercialization without incurring major cost penalties. Therefore, in the absence of tooling lock-in. The team of engineers supporting Case F focal-firm reported,

> *The biggest advantage that they have by using AM, is that they can make several iterations of an existing product . . . and in that way, they could launch the product, but they can still change the design ongoing. They can make changes because they didn't have any mold, or tools that were specifically made for producing the parts.*

Through this approach, the central implication on NPD is its ability to integrate customer feedback earlier in the loop.

> *They sell a drone to their customer and in that way, the customer gives feedback. Yeah, I would like to add something to the GPS tracker, something extra to the model, and they make a new iteration . . .*

Therefore, companies can continuously adapt the product to the evolving needs of the market or can learn more quickly when addressing a new market niche. Interviewees reported the lack of distinct product generations in the case of incremental product launches. Instead, there was a smooth transition or evolution of the product.

> *So that was the biggest advantage. They don't take a lot of stock of these drones, so they can continuously improve their designs and immediately once the design has been improved, they can get it into the manufacturing process. The purpose for them is to keep continuing product development to smoothly go from version A to version B.*

The novel approach of iteratively releasing and updating products has commonalities with patterns known in the field of software. However, in the case of hardware, such an approach poses major challenges on the pricing model, the supply chain, and the communications with the customers. In fact, customers are usually reluctant to buy products that are going to be updated soon. To successfully apply such an approach, companies may need to profoundly alter their business models and move towards a more service-centric or pay-per-use model.

2.5.4 Custom Products

Customization is defined as the alteration of product characteristics, the modification of a product model, or even the one-time design of a product from scratch to specifically meet the individual needs of a customer. In the field of customization, the major advantage of AM can be found in the tool-less batch fabrication of lot-size-1 components, where, because of AM implementation, companies experience an increasing convenience and simplicity in manufacturing. Practically, if products share a common material, the build envelope of a machine can be filled with different 3-dimensional models with no additional efforts in set-up, and the batch manufacturing process can be started. Thus, if different product variants fit into a machine, these can be manufactured in the same job. In the domain of customization, AM is the direct effect of extending the digital process chain to the point of manufacturing. Digital information can be stored at one single point of access and shared by all actors in the value chain. The executive vice president of the company producing the Case B product stated,

> *The dentist can load the digital model in his practice account, . . . and we collect the data from there. We get a notification from the system once he uploaded his data. We download the dataset with pictures, scanned 3D models, x-ray and a so-called treatment plan. Meaning, the planner thinks about how he wants to handle the case, which steps in what order, what should be the end result so that the teeth are correctly positioned . . . Such information is sent to us together with the 3D scan.*

Digital models can be transferred, modified, and re-worked with much lower transactional costs and increased speeds in the digital domain compared to their physical counterparts. Digital work-flows applied to the generation of specific customer variants can be standardized and programmatically coded. Therefore, the underlying process can be executed with built-in gates for quality assurance. From Case C,

> *. . . information is standardized, so that nothing can be forgotten, and so that the process is executed in the right order. This is also as a source of security for the patient, to ensure that the final result is reproducible from patient to patient.*

Furthermore, from Case B,

> *The software provides us the possibility to move the teeth only within a certain feasible range in each step. In this way, the force applied to the tooth is not too high. Too large forces can lead to the loss of the tooth.*

Owing to the digital process chain, adopters of AM experience an increase in productivity in the field of customization. The medical treatment specialist from Case B reported,

> *the more I invest on this digital process chain, . . . the faster it gets. And in the same time the doctor was able to address 10 cases, he is now able to deal with 20.*

It is also clear from the interviews that AM adoption in this domain is often the consequence of the pre-existence or the compatibility of fully digitalized process chains.

> *One result is the usage of such surgical cutting guides, which also are born from the trend, that today surgeons rely more and more on 3D planning. Also, in other cases . . . not only in our clinic. It's a routine to rely on 3D planning, and a logical consequence that such surgical guides are manufactured [using AM].*

Such statements highlight the fact that AM technologies, for customization, must be integrated in already digitalized chains. Otherwise, multiple switching between the digital and the physical domains can impede the full exploitation of benefits. Most productivity increases are therefore achieved when products are manufactured at the latest point possible in the process, thus applying most changes and necessary adaptations digitally.

2.5.5 Improved Delivery

AM can be applied in operations to improve and streamline the process of delivering goods to customers. When applied within the OFP, AM can impact the planning of manufacturing operations and the execution of the delivery orders. The process of delivering physical goods to a customer usually involves the managing of information flow, material handling, production, packaging, inventory, and transportation. Applications of AM in this domain can influence the efficiency and speed of the order fulfilment process. (Fontana, Marinelli, et al., 2018) demonstrated that the application of AM in the case of small lot-sizes and high-variety manufacturing could substantially reduce the per-item cost and improve delivery lead times. At an operational level in manufacturing, improvements offered by AM are facilitated by the batch manufacturing of lot-size 1 items combined with the absence of equipment changeover. This unique feature can drastically reduce the impact of fixed manufacturing costs on the total per-item manufacturing costs. Interviewees report a particular suitability of AM processes for the manufacture of spare-part components, especially with reverse engineering. The AM supplier and manufacturer of Case D states,

> *The business unit maintenance and repair contacted us in relation to non-availability of a spare part. They provided us with an original part, . . . but no drawings and no CAD. The problem was that the supplier went out of business, as typical. The supplier was located in Eastern-Europe. . . . The first iteration was delivered in 5 days. The verification required then 3–4 weeks, because the part was tested on the real vehicle.*

Regarding the impact on established processes, interviewees reported an increase in the speed of sourcing and a reduction of costs for low-volume series compared to machining. Here, the engineering team from Case E reported,

> *It is impossible with conventional manufacturing to achieve the same lead times as here. I would say as a rough estimate it takes three times as much conventionally. . . . Costs are for sure lower than a factor eight to ten.*

Interviewees also mentioned the potential of AM implementation in the reduction of stocks and works-in-process because to the increased responsiveness of the process. The service provider and manufacturer of unmanned aerial vehicle frame inserts disclosed,

> *I think stock-wise there is a big advantage. They don't have a stock, they have a few frames, and they know when there are several ones running in production.*

This suggests a more pull-oriented set-up in production.

2.6 Production Tools

Production tools include all the shape-giving devices that can be applied during the manufacturing of a product (e.g., molds). As an example, from Case B, a vacuum forming process is performed with the help of AM produced molds.

> *The 3D printed model is then used in a vacuum forming device, where sheets with different thickness are formed.*

Second, production tools include non-shape-giving devices, such as jigs and fixtures used to ease manual operations during production, assembly and quality control. From Case F,

> *You can use the technology to build a quality fixture for measuring the frames, so when we assemble the frames . . . , we assemble them on 3D printed, or partially 3D printed fixtures, in order to keep track of the tolerances and the exact dimensions of the frame.*

Jigs and fixtures are specially designed so that large numbers of components can be machined, assembled, verified, transported, and positioned identically. Via the use of such devices, better ergonomics, quality, and repeatability is achieved during assembly. Production tools conventionally require complex and time-consuming steps to be produced and are often manufactured in lot-size 1. AM offers several possibilities to speed up sourcing and lower the costs of such devices. In Case E, an interviewee reported,

> *We manufactured this soldering jig quickly. That's always very practical, because if I try to machine these geometries, the part ends up very complex and expensive. [With AM] in one or two days, the parts are delivered.*

AM can be applied to the manufacturing of production tools for the processing of components made of metal (Bassoli et al., 2007), polymers (Ahn, 2011; Levy et al., 2003; Rännar et al., 2007) and composites, such as carbon fiber reinforced polymers (CFRP) (Türk, Triebe, et al., 2016).

2.6.1 Process Concentration

In the domain of process concentration, AM technologies can be applied to reduce the total number of steps needed to manufacture a product, assembly, or component. Thanks to the manufacturing complexity advantage, multiple complex features can be achieved in one or a few manufacturing steps. The head of research and development of Case A supplier disclosed,

> *Milled bowls had to be purchased, at least the raw work-piece and then further processed in house. . . . Now we can integrate all of this in the first SLS manufacturing step. That is an advantage.*

Interviewees reported that the substitution of manual-labor steps could be particularly beneficial for profitability. From Case A, *The more manual work is needed to manufacture a conventional bowl feeder, and the more we are able to substitute this manual work with an AM process, the more it gets profitable. Here we usually talk about weeks of manual work in a conventional bowl feeder.*

The reduction of process steps has a twofold effect on the total cycle time. The processing time of the excluded operations is subtracted, and the waiting time between the excluded steps is gained. Therefore, process concentration can achieve major reductions of total cycle time. This shows the potential to profoundly alter the supply networks of products. Shorter process chains are less complex, and thus easier to operate. Therefore, there is demand for integration in a single company. As mentioned in the Case-A interview,

Very important, the value chain grew. Before, they used to outsource many milled parts, and now they are able to perform much more in house. The value-adding in house increased extremely.

When deploying AM for process concentration, design represents a significant part of value creation. However, once a design is available, it can be digitally reproduced at much reduced cost.

Today much more happens in CAD, and manufacturing a second bowl was a challenge. . . . When one need to manufacture a second bowl, in the conventional case, even if the same person is manufacturing it, then he needs the same time as the first one.

In simpler terms, more automated processes have implications for employees. The substitution of process steps with AM requires substantial re-skilling of the workforce towards machine operations, but it also allows for de-skilling in the case of simpler and automated process chains. An example was given in the case of dental aligners,

The staff is trained on the digital method and most of them are able to take scans. There is the new possibility of delegating *within the practice to more unskilled labor such as assistants, and the check-up visits are also much faster.*

2.7 Discussion

With the first research question the authors addressed the question, “What are the elemental domains of a focal-firm value chain where AM can be applied to generate unprecedented value?” Compared to other studies addressing the identification of feasible applications for AM (Conner et al., 2014; Guo and Leu, 2013; Knofius et al., 2016; Reiher et al., 2015), and focusing on component identification driven by product characteristics, or on describing the industry-wide sectors of application, the present publication delivers an analysis at the firm-level. The authors contributed the proposed clustering model by extending the propositions suggested by previous research. The development of AM implementation strategies by identifying the benefits of AM, with the creation of new assessment criteria for AM manufacturing, was previously proposed as a key issue to ease the implementation of AM (Martinsuo and Luomaranta, 2018). The current formulation of the clustering model contributes to this domain and provides guidance to new adopters of AM technologies in two distinct ways. First, it enables a systematic approach to the evaluation of potential applications. By leveraging the clusters and their definition, companies can analyze and evaluate step-by-step which application domain shows the greatest potential, given the company’s offered products and established processes. Chances are that the screening can highlight one or more application clusters that are particularly attractive for the company to start with. Second, once such clusters are identified, adopters can focus their resources to accomplish value creation and can therefore select existing parts or engage in the development of new designs for AM. Regarding the targeted cluster, it can therefore achieve more effectiveness in the implementation project. This second aspect contributes in the mitigation of the risk of inadvertently engaging in the manufacturing of components resulting more expensive or inferior quality goods, as previously highlighted by scholars (Ballardini et al., 2018). This adds a new layer in the assessment process.

Tab. 2.4: Identified instances of value statements and their distribution among clusters and case study.

			Prototyping	**Enhanced Designs**	**Incremental Launch**	**Custom Products**	**Improved Delivery**	**Production Tools**	**Process Concentration**
Case A	Vibratory bowl feeders	Automation, Industrials		2					6
Case B	Dental aligners	Dental, Medical				9		1	1
Case C	Surgical cutting guides	Medical	2			3		4	1
Case D	Tramcar lightbox indicator gears	Transportation					4		
Case E	Injection molding feeding device	Electronics Manufacturing	3		1		3	1	1
Case F	Structural inserts for UAV frame	Geospatial, Aerospace	1	1	3		1	1	
Case G	Structural components for ergonomic exoskeleton	Orthopedics, Ergonomics	2						
		TOTAL	8	3	4	12	8	7	9

The results further highlight that clusters are not mutually exclusive to particular products. As shown in Table 2.4, from a single interview focusing on a specific product, value-adding statements belonging to different value-adding clusters were identified. This suggests that a single product can be optimized for and therefore leverage value-adding elements from different domains. However, existing component selection strategies undertake approaches focusing on the identification of parts residing in a narrow subset of the whole potential application spectrum identified by this study. A clear example is the fact that both the top-down Knofius et al., 2016 and bottom-up approaches (Reiher et al., 2015) target the identification of components residing in the scope of the improved delivery and enhanced designs clusters. Thus, this finding suggests that a certain relationship might exist between an application cluster and a suitable method for component selection. To be more precise, each cluster or group might have a certain component screening procedure, resulting in more effective scoping. Therefore, the introduction of a new layer given by the clustering approach at the firm-level contributes to AM component identification streams by highlighting the need for the further development of component search strategies tailored to the other AM application domains.

The second research question asked, “What are the implications of AM adoption in the identified elemental domains?” Here the results confirm some of the impacts previously identified by other publications. This paper extends previously identified implications of AM adoption in NPD (Oettmeier and Hofmann, 2016), especially in the application domains of prototyping and incremental product launches. In these settings, the study confirms both changes of communication in engineering teams and the earlier occurrence of testing and validation during the development process. Our study further adds insights at the customer relationship level, where interviewees confirmed a growing importance of integrating customer feedback early during the product launch to reduce uncertainty. It identifies a rather smooth transition between product generations for AM adopters. These two aspects suggest that, to some extent, agile development techniques for hardware might be best suitable in combination with AM technologies at this stage of NPD, specifically for incremental product launch. The study reveals that this interplay requires further investigation. In the domain of custom products, our study highlights the importance of pre-established digital process chains to automate the customization process prior to manufacturing. This result agrees with previous findings, where the degree of automation in software was identified as an important challenge of AM implementation (Deradjat and Minshall, 2017).

Other studies listed knowledge-related barriers to the implementation of AM (Martinsuo and Luomaranta, 2018; Mellor et al., 2014), suggesting AM-specific training or experimentation to internalize such knowledge. However, once the technology was established in production, our study identified an impact on de-skilling or re-skilling of employees in the domain of process concentration. Hence, our work highlights that some tasks leveraging highly automated AM enabled process chains can be executed by operators with lower degrees of specialization. Such evidence confirms patterns already seen in cases of computer integrated manufacturing (Agnew et al., 1997), highlighting their relevance for the domain of AM.

Shifts in value creation identified in a previous study (Rylands et al., 2016) were confirmed in the domain of process concentration, where interviewees reported a substantial growth of in house value creation, after the introduction of self-operated AM machines. Furthermore, previous studies investigated the effect of technological maturity on the implementation aspects of AM (Deradjat and Minshall, 2017). The results of our study provide evidence of different degrees of application maturity in the various identified AM application clusters. Some clusters, such as prototyping and production tools, are widely applied in industry (Wohlers Associates, 2016), and their implications are well-understood. Clusters (e.g., enhanced designs and improved delivery) have been demonstrated in pioneering applications and are currently growing in adoption at larger scales (Emmelmann et al., 2011; Fontana, Marinelli, et al., 2018; Holmström et al., 2010; Sirichakwal and Conner, 2016; Türk, Kussmaul, et al., 2016; Türk, Triebe, et al., 2016). However, clusters such as process concentrations, custom products, and incremental product launches are described in the literature, but need to be further understood to disclose their full potential at an industrial level. Whereas further research and *ad hoc* studies are required, as a first attempt to explain such heterogeneous degrees of application maturity among the identified clusters, the authors suggest two dimensions: the degree of understanding of design for AM and the degree of expertise in the AM process chain.

Figure 2.2 shows the prerequisites for applying AM in a specific value-adding cluster according to the above introduced aspects. As the figure shows, applications for prototyping and for production tools do not require a profound understanding of the entire AM process chain or an advanced know-how in AM design. They rather replicate conventional designs and leverage existing supply chain models. Hence, these clusters present minor barriers in the implementation and could spread in industry earlier than other, more demanding clusters. On the contrary, value-adding clusters, including custom products, incremental product launch and process

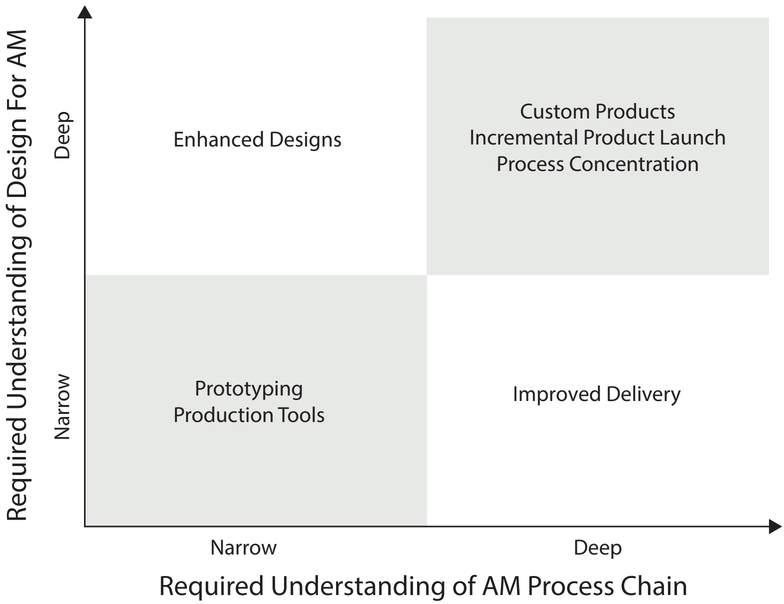


Fig. 2.2: 2-Dimensional portfolio showing prerequisites for adoption of AM in a specified cluster.

concentration are positioned in the upper end of the portfolio. These application domains are the ones demanding the most advanced knowledge in AM, mastering of the process chain and, in some cases, even requiring new business models to be successfully implemented. Therefore, such applications lag in industrial adoption and present the largest implementation challenges. Value-adding clusters, such as enhanced designs and improved delivery, require only a major focus of either process chain or design for AM. It can therefore be positioned in-between.

The study further provides some insights about the priorities of different industry sectors regarding the adoption of AM. In fact, the cases presented in this study can be split into two overarching categories: industrial manufacturing and medical. Cases A, D, E, and F are part of industrial manufacturing, whereas Cases B, C, and G are part of the medical category. By observing the distribution of statements found in the interviews reported in Table 2.4, further insights can be understood. First, all the statements related to the cluster, "custom products," are mentioned by companies in the medical category only. Therefore, industry-wide efforts towards achieving specific solutions are facilitated by establishing fully digitalized process chains (Deradjat and Minshall, 2017; Oettmeier and Hofmann, 2016). Second, statements related to the clusters of enhanced designs, incremental launch, and improved delivery are mentioned only by companies residing in the industrial manufacturing category, and they appear to be a priority. Lastly, application clusters of prototyping, production tools and process concentration show that statements mentioned by companies reside in both categories.

2.8 Conclusion

Regarding the industrialization of AM technologies, newly adopting companies demand tools and methods to structure the technology adoption process. The identification of high-potential fields of application and the awareness of the implications of AM adoption on the focal-firm level are of central interest to scholars eager to facilitate the spread of AM technologies in industry. This publication leveraged a multi-case-study approach to identify, define, and describe seven value-adding clusters, where AM technologies could be applied by a focal-firm to create unprecedented value. The study further draws attention to several implications of AM technology adoption in both NPD and OFP.

The present work contributes to the body of knowledge of AM management in the specific domains of application identification, AM adoption, and impact of implementation. Contrary to other seminal works in the field (Achillas et al., 2015; Conner et al., 2014; Muir and Haddud, 2017; Reiher et al., 2015), the present publication undertook a value-driven approach, and jointly considers both the operations and the product development functions of a focal-firm. The publication further postulates the suitability of AM technologies in combination with agile development techniques to achieve incremental product launches of hardware. The authors highlighted the need for further research addressing the dynamics of incremental product launch.

As a pioneering work in the domain, this study has some clear limitations. These include a geographically local sample of observed case studies. Despite Switzerland being oft-reported among the most competitive and innovative countries in the world (Schwab et al., 2017) and is therefore a representative country for research in innovation matters. The observed case studies were selected from a restricted geographical area, and may, therefore, not be fully representative of the global ecosystem. Second, a larger sample of case studies might be necessary to perform a solid validation of the presented clustering model to ensure its completeness and resilience. A further limitation is the strong single technology focus. Despite SLS being one of the most mature technologies for industrial applications, and therefore widely employed, it is necessary to perform further investigations to ensure the validity and completeness of the results of this study for other AM technologies.

Further work is not only limited to more case studies, but can also conceptualize specific methods and processes leveraging the clustering model to provide procedures for structuring the process of introducing AM. In this direction, the interplay between value-adding clusters and cluster-specific methods for business-case considerations can be developed. Furthermore, component search strategies dependent on the specific definition of clusters can be considered. The authors identified a different degree of application maturity and suggested two dimensions to explain the differences of adoption rate. This interplay could be also further investigated and verified with *ad hoc* studies.

3 Selection of High-Variety Components for Selective Laser Sintering: An Industrial Case Study

3.1 Abstract

The tool-less manufacturing of lot-size one components by means of Selective Laser Sintering (SLS) can enable companies to enhance their manufacturing flexibility. Especially in the case of high variety manufacturing, companies adopting SLS can potentially reduce order lead times and manufacturing costs. This paper introduces a methodology suitable to assess different manufacturing strategies for high variety component families and leverages a case study from a global manufacturer of packaging machines to show the implications of AM adoption. The case study quantifies the reduction of both manufacturing costs and order lead time in the case of a component with a large amount of possible variants. In the case study, two possible operational strategies for the manufacturing of such with SLS are identified. In a first strategy, SLS adoption can be focused on optimising the specific volume-unit operating cost for producing all component variants, and thus obtain a total manufacturing cost reduction of up to 17% compared to the current conventional set-up. As a second strategy, SLS can be employed for the improvement of service quality. By focusing on the reduction of order lead times over the whole component family, this can be reduced by 48% compared the incumbent set-up. The trade-off among the two strategies is explained with the introduced concept of aggregated lot size.

3.2 Introduction

Additive Manufacturing (AM) encompasses a set of production technologies allowing to create physical objects starting from digital models (Gibson et al., 2010). Selective Laser Sintering is an AM process for the production of polymeric components (Schmid, 2015). Compared to other AM processes, SLS shows the major advantages of not requiring support structures, and of enabling higher throughput (Petrovic et al., 2011). SLS achieves very similar mechanical properties to the ones obtained by injection moulding (Goodridge et al., 2012; Wong and Hernandez, 2012). For these reasons, SLS is often the AM process of choice for the production of polymeric series components (Meboldt and Fontana, 2016).

AM technologies in general have seen an increased adoption in manufacturing (Wohlers Associates, 2013). The work (Campbell et al., 2012) identifies industrial adoption of AM technologies in Aerospace, Automotive and Medical industries. The proliferation of AM technologies in the manufacturing ecosystem (Wohlers Associates, 2013), has given rise to interest of scholars, with regard to to the implications such technologies have on firms operations. The work (Oettmeier and Hofmann, 2016) leverage a case studies approach and interviews, to show that AM can reduce the trade-off between scale and variety, in the domain of highly customised products. They furthermore conclude that, adopters of AM achieve unprecedented flexibility by producing batches of customer tailored products. In (Liu et al., 2014) the impact of SLS deployment on the aircraft spare parts supply chain is investigated. The authors identify applicability of SLS especially for the manufacturing of spare parts with low average demand. The study shows that AM adoption can reduce inventory along the entire supply chain, however effects on costs are not quantified. The work (Holmström et al., 2010) presents a case study focusing on the manufacturing of an environmental control system for a military aircraft by means of SLS. The contribution identifies that, the deployment of SLS technology can lead to a simplified and less complex supply chain set-up. The same case study is further leveraged by (Khajavi, Partanen, and Holmström, 2014) to provide quantitative insights about operating costs for AM in scenarios with a different degree of decentralization.

The manufacturing costs for AM are investigated by (Ruffo, Tuck, et al., 2006) among others. The contribution shows that the cost structure of SLS is dominated by machine costs in a first place, followed by material costs. It further defines the inverse relationship between manufacturing costs and build chamber utilization. Findings suggest that unit costs of additively producing components quickly drop and stabilize to a certain value, with increasing filling of the machine chamber. The work (Lindemann et al., 2012), investigates the cost structure for the manufacturing of metal parts with Selective Laser Melting (SLM). The contribution argues, that optimisation of the SLM process chain can lead to 50% reduction in manufacturing costs. AM implications in the domain of operations (Tuck, Hague, and Burns, 2006), and especially for the efficient production of spare parts have been identified by some scholars scholars, as introduced above. Industrials also attribute vivid interest to the topic, often with strategic commitment of top managers (Cohen, 2014). However applications in the industry are nowadays not widespread, and positive business cases are rare. Companies are still struggling in the mainstream adoption of additive manufacturing for the manufacturing of high variety components. Few scholars address this novel field of research in a quantitative manner. This contribution addresses this gap, and investigates the improvements, that SLS can enable for companies operating in the domain of high-variety manufacturing. The authors therefore formulate the following two research questions to be answered:

RQ1. Which specific variants of a given high-variety component should be produced with SLS?

RQ2. What are the benefits, that SLS can offer in terms of cost and lead time reduction?

3.3 Methods

The present work uses a case study approach, collecting data from a global manufacturer of machines for food processing with a portfolio of around 800’000 active Stock Keeping Units (SKUs). The project team performed an heuristic component search, combining process expertise about SLS together with several key functions from the company including engineering, service and business development. While conducting the portfolio analysis, the team first set the focus on finding products with an inefficient, intricate and costly order processes, and only in a second phase evaluated technical feasibility with SLS. The component search identified lugs as the subject of the case study.

Lugs are customer specific wear components mounted on a series of roller chains, moving food units along the machine track, for packaging purposes. The lugs portfolio shows an high extent of variability. A customer specific lug variant is shown in Figure 3.1. Requirements set on lugs include: resistance to wear, reduced mass, and use of food grade material. Lugs are currently made out of PA6, however tests performed by the company showed that Laser Sintered PA12 also fulfils all application requirements. Customer specific variants of lugs are engineered, depending on food

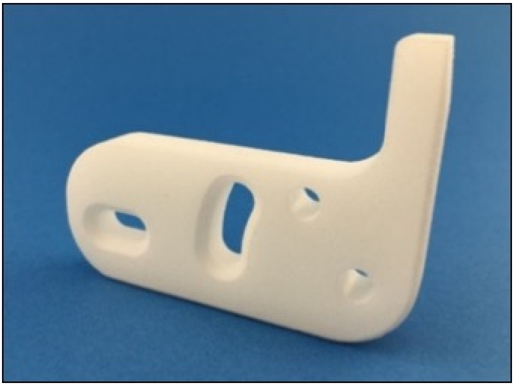


Fig. 3.1: Customer specific lug variant, manufactured in laser sintered PA12.

processing format requirements and machine type where the component is mounted on. Data has been collected for 392 lug variants from the company ERP and PDM systems, covering a time-frame of five years from year 2011 to 2015. Collected data is introduced in Table 3.1.

The consolidated demand of lugs has been stable over the considered five years time-frame. On average only 31 units of a given variant are produced in a given year. Considering all product variants, the average

Tab. 3.1: Variant specific data collected from company PDM and ERP information systems.

	Description	Unit	Descriptive Statistics					
			μ	median	σ	min	max	NAs
m_i	Mass of the a finished lug unit	g	21.57	20.00	14.41	3.00	211.00	5
v_i	Actual material volume of a given lug variant	cm^3	19.88	17.86	13.13	3.19	188.39	0
c_i	Manufacturing cost per unit of manufacturing one specific variant i, includes direct material costs, direct labour costs and work-center rates.	CHF	25.21	21.66	13.11	2.97	75.00	0
o_i	Order or manufacturing lot-size for lugs ordered from internal or external suppliers in year 2015	units	52.70	37.00	58.88	3.00	570.00	47
$N_{i,y}$	Average amount of units of variant i produced in year y. Data collected for five years from 2011 to 2015. The descriptive statistic considers the average over five years.	units	30.11	14.00	67.68	0.20	$1'034.80$	0
T_i	Order-lead time for delivery of lug variant i to the company from supplier.	days	24.83	28.00	4.04	14.00	36.00	271

manufacturing cost per unit produced amounts to about 20 CHF. Two dimensions define the possible manufacturing set-ups for lugs: stock management policy and production site. The stock management policy is decided according to the amount of units historically sold for a given variant. Variants showing stable and relatively high demand are produced in a Make-to-Stock (MTS) configuration. In MTS, inventory is held for the variant, and customer orders are fulfilled from stock. Variants with sporadic and relatively lower sales are produced in a Make-to-Order (MTO) configuration. In MTO, the product is either manufactured from raw materials or adapted from a semi-finished version kept in stock, upon the issue of a customer order. Lugs manufactured from a semi-finished product are usually processed in house, whereas manufacturing of variants with no parent version is usually outsourced. When lugs share a similar geometry, the company can use common parent versions to reduce the complexity of the process chain and increase its responsiveness. In the current set-up, only 15 variants are manufactured in a MTS configuration, but these few variants account for 23% of the consolidated unit production. All other lug variants show very reduced per variant sales, and are therefore produced in a MTO configuration. Distribution of variants and units produced according to the above discussed dimensions are shown in Table 3.2. Currently, delivery lead time for lugs, depends on production location, supplier and stock management policy.

Tab. 3.2: Characterisation of lug portfolio according to production site and stock management policy.

	In-house	**Outsourced**
MTO	47 (12%)	330 (84%)
MTS	4 (1%)	11 (3%)

(a) Distribution of product variants.

	In-house	**Outsourced**
MTO	1'601 (14%)	7'428 (63%)
MTS	122 (1%)	2'651 (22%)

(b) Distribution of average yearly total units manufactured.

This research compares the current situation of producing the product portfolio, with other new scenarios, where SLS is introduced. The reader shall notice that these new scenarios do not necessarily imply the additive production of all lugs variants, but rather a combination of conventional and SLS manufacturing. In order to clearly distinguish variants conventionally produced from the ones manufactured with SLS, a strict notation is defined. Let us consider a lug variant i in the set of all variants considered in this study $\mathcal{L}$. For a given scenario we denote $\mathcal{C}$, where:

$$\mathcal{C} \subseteq \mathcal{L}$$

as the subset of variants produced with current manufacturing technologies, and $\mathcal{S}$ with:

$$\mathcal{S} \subseteq \mathcal{L}$$

as the subset of variants produced by means of SLS. Furthermore, we define, that in a given scenario a product variant i can only be produced either conventionally or with SLS, and therefore following statements apply.

$$\mathcal{C} \cap \mathcal{S} = \emptyset$$

$$\mathcal{C} \cup \mathcal{S} = \mathcal{L}$$

3.3.1 Operating costs for conventional production

The authors define the total operating costs for conventionally producing variant i, in year y as:

$$\mathrm{TC}^{\mathrm{C}}_{i,y} = \mathrm{MC}^{\mathrm{C}}_{i,y} + \mathrm{OC}^{\mathrm{C}}_{i,y} + \mathrm{IC}^{\mathrm{C}}_{i,y}$$

whereas $\mathrm{MC}_{i,y}$ are total manufacturing costs, $\mathrm{OC}_{i,y}$ are total order costs and $\mathrm{IC}_{i,y}$ are total inventory costs for corresponding lug variant i in year y.

$\mathrm{MC}^{\mathrm{C}}_{i,y}$ is computationally obtained form the manufacturing cost per unit c_i and the amount of units produced $N_{i,y}$, as follows.

$$\mathrm{MC}^{\mathrm{C}}_{i,y} = c_i \cdot N_{i,y}$$

$\mathrm{OC}^{\mathrm{C}}_{i,y}$ are estimated through a per-order fee k^{C}, heuristically defined by the company. An order fee of $\mathrm{CHF}100$ is applied for each order issued for outsourced components, and a fee of $\mathrm{CHF}50$ is applied to each order of in-house produced variants. Hence, total order costs depend on order lot-size, total units produced, and production location.

$$\mathrm{OC}^{\mathrm{C}}_{i,y} = \frac{N_{i,y}}{o_{i,y}} \cdot k^{\mathrm{C}} \quad \mid \; k^{\mathrm{C}} = \begin{cases} 100\,\mathrm{CHF} & \forall i \in \mathrm{Outsourced} \\ 50\,\mathrm{CHF} & \forall i \in \mathrm{In-house} \end{cases}$$

Total inventory costs are computed and apply only for MTS variants, or in the case of MTO variants with a parent version kept in stock. Computations are performed as follows:

$$\mathrm{IC}^{\mathrm{C}}_{i,y} = \overline{S}_{i,y} \cdot c_i \cdot \zeta \quad | \; \overline{S}_{i,y} = 0.75 \cdot o_{i,y}$$

where $\overline{S}_{i,y}$ is the average stock level and ζ is the inventory rate. The average stock level is assumed to be 75% of the order lot-size using a common order point technique (Schönsleben, 2016). This value includes a 25% safety stock. The average inventory level of a variant is consequently multiplied by the holding costs per variant. We assume an inventory rate ζ of 13% which includes a 9% capital expenses and a 4% warehousing cost. These rates have been suggested by the company, and are applied for internal financial calculations.

The average total operating costs for producing lug variant i over the considered time period can therefore be computed as follows.

$$\overline{\mathrm{TC}}^{\mathrm{C}}_{i} = \frac{1}{5} \sum_{y=2011}^{2015} \mathrm{TC}^{\mathrm{C}}_{i,y}$$

This value can be further divided by total amount of lugs produced during the observed time period for a given variant, and by the actual material volume of the lug variant v_i.

$$\overline{\mathrm{tc}}^{\mathrm{C}}_{i} = \frac{\overline{\mathrm{TC}}^{\mathrm{C}}_{i}}{\overline{N}_i \cdot v_i} \quad | \; \overline{N}_i = \frac{1}{5} \sum_{y=2011}^{2015} N_{i,y}$$

The volume specific average operating costs per variant unit are therefore obtained. This value and its distribution shown in Figure 3.2 can be used as a baseline for comparing the current manufacturing set-up, with other possible production scenarios based on the adoption of additive manufacturing.

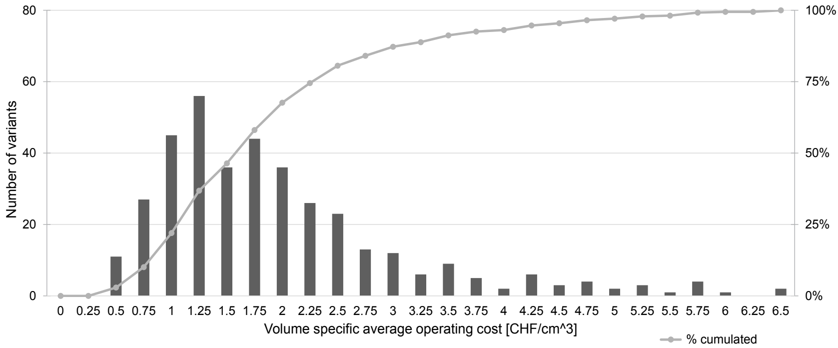


Fig. 3.2: Volume specific average operating cost distribution of lug variants produced conventionally.

3.3.2 Operating costs for SLS production

Analogously to the previous section, the authors define the average total operating costs for SLS produced variant i, as follows.

$$\overline{\mathrm{TC}}_i^{\mathrm{SLS}} = \overline{\mathrm{MC}}_{i,y}^{\mathrm{SLS}} + \overline{\mathrm{OC}}_i^{\mathrm{SLS}}$$

Inventory costs do not apply for SLS parts as these are produced in a MTO configuration only. Manufacturing costs per variant unit i in the case of SLS manufacturing $\overline{\mathrm{MC}}_i^{\mathrm{SLS}}$ assume a constant, volume specific manufacturing cost for SLS ν.

$$\overline{\mathrm{MC}}_i^{\mathrm{SLS}} = \nu \cdot v_i \cdot \overline{N}_i$$

The reason behind this assumption is that manufacturing costs with SLS do not depend on part specific geometry, but rather on how the SLS equipment is operated (Ruffo, Tuck, et al., 2006). Order costs in the case of SLS manufacturing are differently as from the current situation. With SLS it is more convenient to consolidate small orders of different lug variants, even of lot size one, into a single manufacturing job and then release a larger order (Ruffo and Hague, 2007). For this purpose the concept of aggregated lot size is introduced. Aggregated order lot size a is defined as the minimum amount of lugs not necessarily of the same variant, required to release a manufacturing order. The research assumes, that an order is released, as soon as this trigger value is reached. Therefore, average per year order costs for variant i can be expressed as:

$$\overline{\mathrm{OC}}_i^{\mathrm{SLS}} = \frac{\overline{N}_i}{a} \cdot k^{\mathrm{SLS}}$$

where a can be arbitrarily defined by planners. The decision on how to set a, has important implications on the overall order costs, as well as on customer order lead-time. We can define the mean maximal order lead time for SLS $\overline{T}_{\max}^{\mathrm{SLS}}$ as follows.

$$\overline{T}_{\max}^{\mathrm{SLS}} = \frac{a}{\sum_{i \in \mathcal{S}} \overline{N}_i} \cdot 365 + \mathrm{T}^{\mathrm{SLS}}$$

This value estimates the amount of time the company waits, in the worst case, when placing an order for a lug unit. The value is obtained by adding the mean time between SLS orders to the delivery lead time for SLS $\mathrm{T}^{\mathrm{SLS}}$. The formula further highlights the trade-off between cost of orders and lead-time, proportional the parameter a.

Hence, the volume specific average operating costs per variant unit are obtained for SLS produced variants as follows.

$$\overline{\mathrm{tc}}_i^{\mathrm{SLS}} = \frac{\overline{\mathrm{TC}}_i^{\mathrm{SLS}}}{\overline{N}_i \cdot v_i}$$

The research considers two possible outsourcing approaches for the production of lugs with SLS: market and partnership. An in house approach has been discarded a priori, as the production of all variants in the considered portfolio with SLS, would imply an average capacity utilisation of a small industrial SLS system of 6% per year[1]. At this capacity utilisation level, operation of SLS equipment is not cost efficient.

In the SLS Market approach, the company relies on a different supplier on the marketplace for each order. Here, a per order fee of 100 CHF together with a volume specific manufacturing cost of 1.50 $\mathrm{CHF}/\mathrm{cm}^3$ are

[1] An EOS Formiga P110 was used as a reference system for capacity utilization calculations

assumed. In a partnership approach, the company commits to sourcing from a single supplier, and therefore can achieve a reduced per order fee of 60 CHF as well as a reduced volume specific manufacturing cost of 1.30 $\mathrm{CHF/cm^3}$, thanks to higher negotiation power and consolidation of larger volumes. Assumptions for volume specific manufacturing cost are based on quotes collected from suppliers, and are in line with values proposed by (Baldinger et al., 2016). All approach specific assumptions are reported in Table 3.3. The reported cost per order k^{SLS} relies on estimations performed together with managers from the company.

Tab. 3.3: assumptions for considered outsourcing approaches

	SLS Market	**SLS Partnership**
Order lead time $\mathrm{T}^{\mathrm{SLS}}$ [days]	5	5
Volume specific manufacturing cost ν [CHF/cm^3]	1.50	1.30
Cost per order k^{SLS} [CHF]	100	60

3.3.3 Observed Optimisation Scenarios

The research considers two optimization scenarios targeting distinct parameters. First, a cost minimizing production strategy is addressed. Here, we observe the optimal combination of variants produced conventionally, and variants produced with SLS, such that the total operating costs for offering the entire product portfolio to customers is minimal. Therefore, we define for this scenario the sets $\mathcal{C}_1$ and $\mathcal{S}_1$ as follows.

$$\mathcal{C}_1 = \{i \in \mathcal{L} \mid \overline{\mathrm{tc}}_i^{\mathrm{C}} \leq \overline{\mathrm{tc}}_i^{SLS}\}$$

$$\mathcal{S}_1 = \{i \in \mathcal{L} \mid \overline{\mathrm{tc}}_i^{\mathrm{C}} > \overline{\mathrm{tc}}_i^{SLS}\}$$

The research observes the effects, caused by the introduction of SLS, on the average total operating costs for managing the entire portfolio.

$$\overline{\mathrm{TC}} = \sum_{i \in \mathcal{C}} \overline{\mathrm{TC}}_i^{\mathrm{C}} + \sum_{i \in \mathcal{S}} \overline{\mathrm{TC}}_i^{\mathrm{SLS}}$$

Tab. 3.4: Implications of aggregated lot-size a on machine powder bed filling of a small SLS production system.

Lot-size $\mathbf{a}$	**Machine filling**
26	One horizontal layer
52	Two horizontal layers
182	Half machine chamber
364	Entire machine chamber

Calculations in the cost minimisation scenario furthermore must ensure, that the company can experience at least the same order lead time as the one offered in the current production scenario. To be on the safe side, and ensure the meeting of customer demand the targeted maximal order lead time for SLS has to be lower than 21 days.

In a second scenario, the research observes the costs for improving the service quality over all lugs variants. Target is therefore, to reduce the order lead time from customer perspective, hence applying the most responsive order fulfilment combination. We therefore observe the average total operating costs for managing the entire portfolio, where all MTO variants are produced with SLS. Here, MTS variants are still produced conventionally, as these can be delivered immediately to customer from stock. For this scenario, the sets $\mathcal{C}_2$ and $\mathcal{S}_2$ are defined as follows.

$$\mathcal{C}_2 = \{i \in \mathcal{L} \mid sm_i = MTS\}$$

$$\mathcal{S}_2 = \{i \in \mathcal{L} \mid sm_i = MTO\}$$

3.3.4 Definition of aggregated lot-size

Decision about setting the aggregated lot-size a has crucial implications on the results of the case study. The choice of a not only influences directly the order costs, but must also comply with the assumptions for efficient equipment operation. For the computation of the optimization scenarios, the values presented in Table 3.4 apply. Predictions are based on test jobs performed on an EOS Formiga P 110.

Tab. 3.5: Results of calculations for the cost minimization production strategy in both outsourcing approaches.

SLS Market

Lot-size a	$\|\mathcal{S}\|$	$\overline{T}^{\mathrm{SLS}}_{\mathrm{max}}$	$\Delta\overline{\mathrm{TC}}$
26	149 (40%)	10	CHF −24′590 (09%)
52	179 (47%)	11	CHF −30′139 (12%)
182	194 (51%)	24	CHF −34′857 (13%)
364	200 (53%)	41	CHF −35′865 (14%)

SLS Partnership

Lot-size a	$\|\mathcal{S}\|$	$\overline{T}^{\mathrm{SLS}}_{\mathrm{max}}$	$\Delta\overline{\mathrm{TC}}$
26	210 (56%)	8	CHF −39′182 (15%)
52	223 (59%)	10	CHF −43′792 (17%)
182	231 (61%)	21	CHF −47′296 (18%)
364	232 (62%)	36	CHF −48′016 (19%)

3.4 Results and Discussion

Results of the calculations for the cost minimization scenario are reported in Table 3.5. Results show cost reductions compared to the baseline total operating costs in all computed approaches. Reductions span from a minimum of 9% up to a maximum of 19% depending on selected parameters. However, for both outsourcing approaches SLS Market and SLS Partnership, solutions related to aggregated lot-sizes of $a = 182$ and $a = 364$, show order lead-time values equal or longer than the current situation, and should therefore be discarded. An aggregated lot-size of $a = 52$ provides feasible results in both observed outsourcing scenarios. A detailed comparison of both outsourcing approaches for $a = 52$ is depicted in Figure 3.3. As the figure shows, in such cost minimization scenario 46% of product variants are produced with SLS in the market outsourcing approach, and 51% of the variants are produced with SLS in the partnership outsourcing approach. In both outsourcing approaches, no MTS variant has experienced a manufacturing technology switch to SLS. This highlights an already cost effective production of MTS variants. Evidence

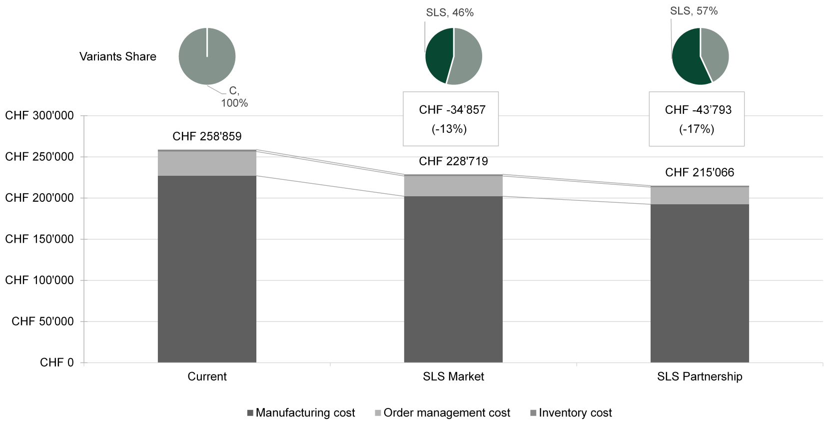


Fig. 3.3: Comparison of resulting total average operating costs for managing the entire lugs portfolio, in the case of an aggregated lot size $a = 52$.

for this is further supported by a volume specific average operating cost per MTS lug unit of $0.62 \mathrm{CHF}/\mathrm{cm}^3$ in the current scenario. Therefore, in this particular case study, SLS is not a cost effective substitute for MTS variants. Hence, the case study provides evidence for the fact that, components with stable, predictable and relatively high demand are optimally produced conventionally. Furthermore, calculations show, that inventory costs even in the current scenario account up to a very reduced portion of the total costs. The reduction of inventory enabled by SLS is often theorised as one of the possible major advantages of introducing this technology. However, by applying the cost structure defined earlier, the present case study shows that, inventory costs hardly have an impact on total operating costs. This low magnitude of inventory costs can be explained by the consideration of capital expenses only. The inclusion of other hidden costs such as obsolescence might have an impact on the presented figures.

Calculations furthermore show, that SLS has rather a considerable impact on reducing order management costs and manufacturing costs. Lower order costs are achieved through the effects of the aggregated orders, whereas manufacturing costs are reduced by the more variable nature of the SLS cost structure. MTO components conventionally produced show a cost structure largely dominated by fixed-costs originated in frequent equipment set-up and changeover. Such fixed costs are less pronounced in the case of SLS. Further savings from the reduction in complexity in the case of a full switch to SLS might be also of relevance. In the current scenario, lugs undergo different processing routes, and are made of different materials. The manufacturing of all lugs with SLS can reduce this complexity by having one manufacturing process and one material for all variants.

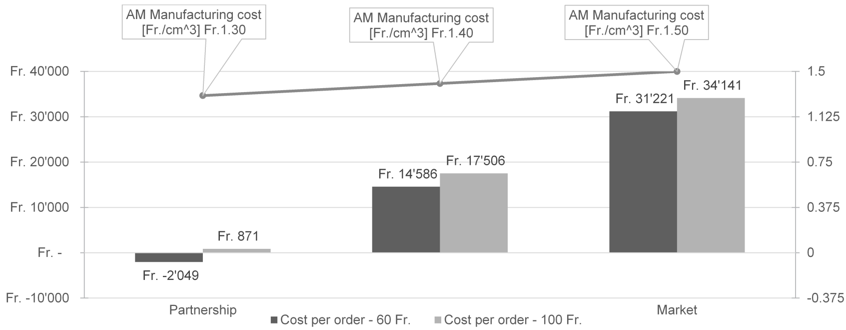


Fig. 3.4: Difference of total yearly average operating costs for producing the entire lug portgolio between the conventional and the SLS scenarios. Positive values imply lower costs in the conventional set-up.

Results for the service improvement scenario are reported in Figure 3.4. The figure shows the difference between the total operating costs in the current scenario and the ones where all MTO lugs are produced with SLS. Varying assumptions of order fees k^{SLS} and volume specific manufacturing costs ν apply. Calculations show that, producing all MTO lugs with SLS is CHF 34’141 more expensive than the current baseline, when applying market outsourcing assumptions. In this case, the aggregated lot size equals $a = 124$ and the maximal order lead-time is equal to 10 days. However, by considering the SLS partnership outsourcing approach, computed total costs are similar to the ones in the current baseline. Here, the same aggregated lot-size of $a = 124$ and maximal order lead-time of 10 days as above apply. This implies that, a reduction of the maximal order lead-time by 52% can be achieved when producing all MTO lugs additively under SLS partnership outsourcing assumptions, without penalties in total operating costs.

Results show that SLS can be profitably employed in manufacturing, without performing of component redesign, and without the need of owning equipment. However, the re-design of SLS produced variants according to SLS process specific optimization criteria, can further extend the cost savings and further reduce the manufacturing costs (Atzeni et al., 2010). Furthermore, after performing redesign, even more variants might be eligible for manufacturing at a lower cost with SLS than in the current situation. Automation of the order process might also have an impact on reducing the order management costs. For this purpose, a solution including a web configuration portal, where customers can configure and release orders for their specific variants can be of interest. Other possibilities for reducing the order lead time could be to implement shipping of products directly from the SLS provider to the customer, without the need of transiting through the company.

3.5 Conclusions

The present study provides quantitative results supporting the conclusion that, SLS can enable substantial efficiency improvements for companies operating in the domain of high-variety manufacturing, even without performing component redesign.

With regard to the first proposed research question, the computation and comparison of volume specific average operating costs per variant unit, as defined in this paper, represent a sold basis to algorithmically identify component variants to be produced either with SLS or conventionally. The procedure applied in this work is directly applicable to other high variety component families.

Concerning the second research question addressed in the paper, the proposed model describes the major trade-off encountered in the case of outsourced SLS production, between total operating costs and order lead-time. The critical parameter underpinning this trade-off between time and cost is represented by the definition of the aggregated order lot size. For the specific case of lugs, the paper identifies two counter-posed operating strategies, feasible for either cost reduction or improvement of order-lead time. Calculations performed for the lugs case show that, either an operating cost reductions of 17% or an order-lead time improvement of 52% can be achieved when introducing the SLS manufacturing technology.

Limitations of the study include the fact that, the computations are performed based on the arithmetic mean of the produced units over five years. Therefore, effects of volatility in produced units and in demand are not fully captured by the model. To overcome this limitation, a more sound statistical approach is required. The case study further excludes a make approach a priori, as the conditions for efficient in-house production are not given. However, it can be of interest to capture how in-house production would affect the total costs compared to the presented outsourcing approaches. Furthermore, results are highly dependent upon the definition of the exogenous aggregated lot size a. Hidden costs of inventory are further not considered, in the presented cost structure. Further attempts to include such hidden costs of inventory management of high variety components are much required.

The lug case represent a very specific component, and the possibility to generalise results based on this example is limited. Validity, and range of improvements for other high variety components have to be further investigated. Further effects on the process chain, provided by the introduction of a web based product configuration, allowing the customers to directly order parts with custom dimensions shall be further investigated.

Despite the simplicity of the approach, the case study provides valuable insights about the influence of the most important parameters, and provide decision makers with a set of tools to compare different operating strategies.

4 An AM Enabled NPD Process Model for Incremental Product Launch of Hardware

4.1 Abstract

New product launches (NPL) are critical phases, subject to high uncertainty and with important implications on the success or failure of products on the market. Incremental product launches (IPL) combine additive manufacturing technologies and Agile product development techniques to mitigate the risks of NPL. The present publication investigates how companies can combine Agile product development techniques with additive manufacturing technologies to achieve IPL, as well as how companies should reconfigure their internal processes to support IPL. The paper leverages a single-case study approach based on data collected over a three years collaboration with a swiss manufacturer of medium format cameras for videography and photography. The company established an IPL approach to enter a new and unexplored market. The paper describes a hybrid NPD process model combining agile with plan-driven NPD suitable to achieve IPL. It further identifies a close relationship between process and product improvements in the implementation of AM for IPL named rolling bottleneck. Through these findings, the authors contribute to the body of knowledge of NPD methods and management of AM.

4.2 Introduction

The launch of a new product represents a critical phase in product lifecycle and should be managed with attention. The outcome of a New Product Launch (NPL) has important implications on the success or failure of the product on the market (Hultink et al., 1997; Veryzer, 1998). NPL is a phase generating high costs for the introducing company (Benedetto, 1999; Bowersox et al., 1999). In a NPL, companies are exposed to high risks and subject to uncertainty. A critical issue is the understanding of how the market will respond to the new product (Calantone et al., 2011; Cooper and Kleinschmidt, 1987; Hitsch, 2006). In NPD, uncertainty has two faces, a technological perspective dealing with how a product should be implemented, and a market perspective addressing what features should be delivered (Stacey, 2003; Zimmerman et al., 2000). Extensive market research and forecasts are important in a NPL (Barczak et al., 2009; Bowersox et al., 1999), however due to uncertainty in demand estimation and customer response, mitigation and responsiveness are key elements to succeed (Cui et al., 2011; Hitsch, 2006). Companies failing to achieve a short-time to market suffer a direct impact in terms of lost sales, and leave room for competitors to enter the market (Cohen et al., 1996).

Additive Manufacturing (AM) technologies belong to the realm of direct digital manufacturing technologies, and allow for the layer by layer fabrication of parts (Gibson et al., 2010), in high variety (Fontana, Marinelli, et al., 2018), and without the need of tools and product specific set-up operations (Tuck, Hague, Ruffo, et al., 2008). AM is employed in prototyping, and enables for advantages in NPD (Campbell et al., 2012). The implementation in prototyping allows to validate products early and avoid mistakes in manufacturing. Engineering teams leveraging AM can compare the feasibility of different design alternatives and select of the most suitable variants for further development (Lopez and Wright, 2002). The adoption of AM in NPD favors a paradigm change from a plan-driven set-up to a more agile-driven approach; allows for the reduction of uncertainty due to test-driven development; and positively impacts the speed and pace of NPD (Fontana, Klahn, et al., 2018).

However, AM is in most cases employed only within the boundaries of R&D, and when NPL is initiated, AM is abandoned in favor of more established manufacturing technologies. This switch introduces undesired drawbacks. The design of the product must be frozen, to allow for tooling, and introduction of design specific production routines. At this stage, changes in design are not possible any more or come only at very high costs. Hence, flexibility is lost through a switch in manufacturing technology, and it becomes hard for companies to timely react to first customers feedback and revise the product, to fine tune it and ensure a better product to market fit.

In the realm of software development, it is a common practice to apply agile and iterative development methods to release early versions of products, sometimes even with known design flaws or bugs, which enable developers to collect feedback on usability and acceptance of the final product. Engineers can therefore react, and improve the code (MacCormack et al., 2001). Agile methods proved to be suitable in the mitigation of uncertainty, for the launch of software products, and might enable the same advantage when applied to hardware developments.

Latest improvement in AM technologies shifted them from prototyping-only applications to series manufacturing. Incremental product launch (IPL) emerged as an innovative application of AM with the potential of overcoming drawbacks of conventional NPL in hardware (Fontana, Klahn, et al., 2018).

The concept of IPL, represented in Figure 4.1, stems from the combination of AM and agile development methods, and promises to postpone, or even avoid the technology switch seen in NPL. IPL promises to mitigate the uncertainty of a NPL, by introducing more responsiveness, and might increase the chance of earlier achieving a product to market fit (Benedetto, 1999; Restuccia et al., 2016). To better investigate IPL, the following research questions are addressed:

RQ1 How can companies combine AM technologies and Agile development techniques for the purpose of achieving IPL in hardware?

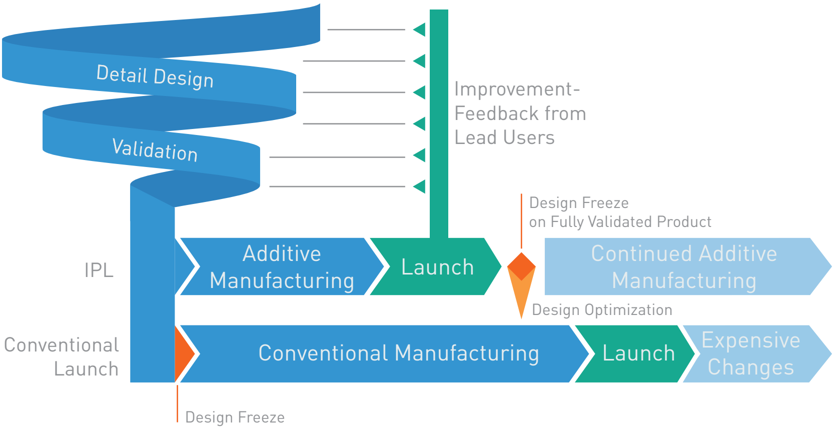


Fig. 4.1: Conceptual process representation of the IPL approach vs. a conventional product launch

RQ2 How should companies reconfigure their internal processes in support of IPL?

4.3 Theoretical Background

Technology intensive industrial sectors experience the shortening of product lifecycles. This sets new challenges for the speed and frequency of NPL (Minderhoud and Fraser, 2005). Markets experience fragmentation in niches, and players who can deliver tailored and validated products have higher chances of success (Schilling and Hill, 1998). Companies face increasing complexity in NPD, and NPD practices are often fragmented and outsourced toward external partners (Minderhoud and Fraser, 2005). In technology intensive domains, NPD is shifting from a fully integrated process towards an ecosystem of partners and suppliers (Minderhoud and Fraser, 2005). Previous work introduced two layers of a NPL: a strategic layer, related to product innovativeness and target group: and a tactical layer focusing on traditional elements of the marketing-mix (Bowersox et al., 1999; Cui et al., 2011; Guiltinan, 1999; Talke and Hultink, 2010).

The research considers two counter-posed NPD approaches: Plan Driven NPD, and Agile NPD. Plan driven NPD methods are common in industry, especially in hardware development. An example is the stage gate model (Cooper, 1990; Cooper, 2014; Cooper, Edgett, et al., 2002). It represents a linear approach from idea generation to product launch. Commitment to the project (resources and financials) is renewed at each step in a so called a go/no-go gate. After each gate, a new phase characterized by a narrower scope and increased total costs begins. Plan-driven methods focus on estimation and prediction, and therefore rely on meticulous planning. Planning minimizes the amount of iterations required to deliver a final product. Plan driven methods are suitable for predictable environments, where user requirements can be easily described and documented early on. Plan driven methods are limited, when dealing with higher degrees of technological, market and product uncertainty (Cooper and Sommer, 2016). Under uncertainty conditions, plan driven methods lack of flexibility and allow for late changes only in exchange of high costs.

One of the first industries addressing the shortcomings of plan driven methods was the software development industry. Agile development techniques found their way into software development between the late 1990s and the the beginning 2000s. Agile is characterized by an iterative development approach. It aims at increasing speed and flexibility in development (Sommer et al., 2015). The goal is to rapidly deliver value to customer and ensure enough flexibility and responsiveness to mitigate the effects of uncertainty. Feedback acquisition and user involvement play an important role in the agile process. The learnings collected from how users interact with early versions of the product influence the planning of next development steps. SCRUM is a widespread agile process commonly applied in software development (Schwaber, 2004). SCRUM leverages short development iterations called sprints to deliver shippable product increments to customers in short time intervals, called sprints. Product requirements are listed in a so-called product backlog, a living list of all product features that might or might not be implemented in the final product. For each sprint, a set of features is prioritized and implemented with the aim of delivering a shippable product increment at the end of the time-boxed phase. Extensive communication among team members is enforced through several routines. Daily stand-up meetings inform all participants about development status and ongoing issues. At the beginning of each sprint, in a sprint planning meeting the team reviews the product backlog, and selects features that will be implemented in the upcoming iteration. At the end of each sprint a retrospective observes the last development session and introduces process improvement measures, to refine the adopted methods and tools. SCRUM leverages three key roles: A product owner (voice of the customer, responsible for the product backlog), the development team (consisting of the engineers and technical staff working on the implementation of product features) and the scrum master (coach, responsible for the correct application of the scrum framework).

AM was shown to have several implications in NPD. Most of these stem from its suitability for the rapid manufacturing of prototypes (Bak, 2003; Campbell et al., 2012; Gibson et al., 2010). AM technologies have been employed to improve ergonomics in the case of handheld video-games in an agile manner (Lopez and Wright, 2002). The study showed how AM technologies enabled to rapidly achieve working products, test their functionalities and characteristics with lead users, and finally perform design changes according to user feedback. Although this approach was applied within the boundaries of R&D, and not for products actually sold on the market, the paper highlighted the potential of delivering early prototypes to lead users to collect feedback and influence development activities. An approach to mitigate risk of new product launches through the application of direct-digital manufacturing was previously proposed in literature (Khajavi, Partanen, Holmström, and Tuomi, 2015). The research relied on incremental sheet forming to speed-up the manufacturing of tools for conventional manufacturing methods, and therefore reduce the upfront investment on a NPL. The contribution concluded that postponement of conventional tooling to later after the launch provides a time slot where management can understand market dynamics and react upon. The interplay between Agile development methods and AM technologies has been identified by scholars under the name of IPL as a field deserving the attention of researchers (Fontana, Klahn, et al., 2018; Jiang et al., 2017). In IPL, previous research envisioned a smooth transition between product generations, and the disappearing of clearly separated product versions in favor of frequent releases of product increments (Fontana, Klahn, et al., 2018). Products were identified to remain for longer periods in a rather "beta" phase, with frequent modifications, as often seen in the case of software (Jiang et al., 2017).

The performed literature review highlights a lack of studies investigating the combination of Agile development techniques with AM technologies for the purpose of IPL in hardware. Owing to the latest advancements in AM, there is the need of addressing a NPL where AM technologies are used in both prototyping and series manufacturing, therefore completely avoiding a manufacturing technology switch. This approach allows to capture meaningful insights on how Agile techniques can be employed in the context of IPL.

4.4 Methods

The authors selected a single case study approach to address the research gap. Owing to the explorative nature of the research and the interests of the authors in contributing novel theories, a case-study approach has been preferred (Eisenhardt, 1989; Yin, 2013). Both the current lack of literature and the need for observing the issue in natural circumstances support the selection of a qualitative case-study (Eisenhardt, 1989; Meredith, 1998). The research follows an inductive approach (Smith, 1998), as it leverages observations to formulate explanations and descriptions. To ensure construct validity, the authors relied on multiple sources of evidence, combined in a chain of evidence, and allowed key informers to review and challenge reports and findings. Internal validity has been ensured through the discussion of competing explanations with research colleagues, as well as employees of the case company.

The choice of the case company is due to its unique characteristics and pioneering efforts in IPL. Since the findings are based on contemporary events, these are generalizable to theoretical propositions (Yin, 2013). Data has been collected over three years from a Swiss company developing high-end photography and videography solutions. The authors observed several new product development projects, in combination with the related introduction on the market. The authors tracked the company's development activities by means of: development diaries, project tracking spreadsheets, periodic participant and non-participant observation, participation to meetings, discussions and interviews with employees and suppliers, analysis of CAD development time-lines, analysis of product backlogs and agile boards. The authors observed the development sprints and the related lead user testing sessions of different product generations. The evolution in products were related to measures applied in the key functional units of R&D, Operations and Sales & Marketing (Olson et al., 2001; Srivastava et al., 1999).

4.5 Description of Case Company

The case-company is a small Swiss manufacturer of medium format cameras counting at 8 Full Time Equivalents (FTEs) at the time of writing. Its reduced size ensures a flat hierarchical structure, fosters fast internal communication and enables for rapid decision making. The classic camera systems produced and distributed by the company are highly modular. Modularity allowed the company to provide different camera setups, and therefore offer variety and customization. The company traditionally leveraged conventional high precision machining technologies outsourced to few manufacturing partners, and operates an international network of distributors.

The initial adoption of AM was driven by the need of economically manufacturing products in small lot sizes, as this was a major limitation with machining technologies. Soon the company realized a broader potential defined by three additional elements. First, customers manifested an increasing interest for individualized niche solutions in the domains of photogrammetry and research. Second, faster release cycles and innovation pace in electronics (mostly sensor technology) set new pressure on lifecycle of products. To remain innovative, the company felt pressure to increase reactivity and shorten time to market. Third, the emergence of video as a new and unexplored market for the company, requiring a new product to be developed, introduced and validated. All three factors together demand for an increased responsiveness in NPD. Previously employed machining technologies required an average manufacturing lead time of twelve weeks, therefore preventing a-priori the achievement of the required responsiveness. The company started introducing AM back in 2015. Through observation of results, the implementation was broken down into one preliminary phase and four product phases. Figure 4.2 summarizes the products phases.

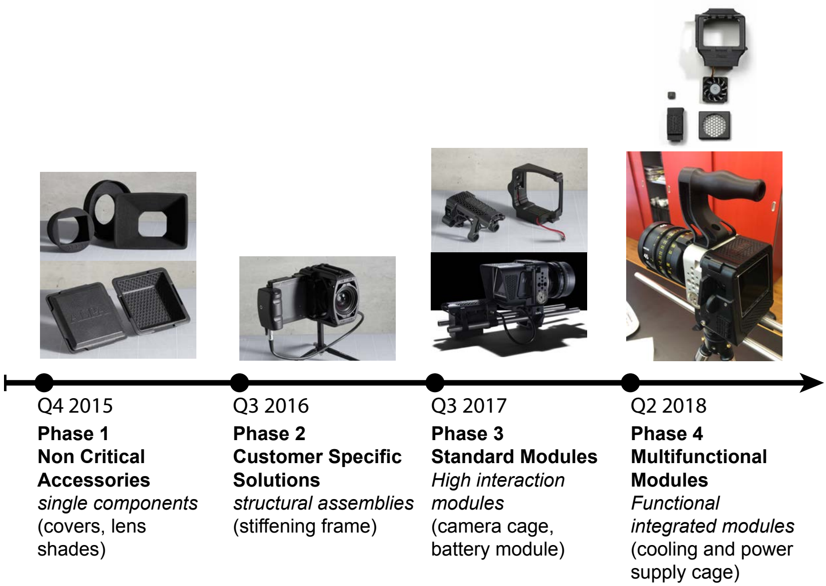


Fig. 4.2: Overview of major development phases and related products

In phase 1 the company addressed non-business-critical accessories such as covers and lens shades. Covers are made of rigid plastic (PA12) and are used to protect the camera. Lens shades are made of TPU 80, a flexible, rubber like material, preventing light to enter and scatter in the lens, deteriorating contrasts. Such parts present reduced dimensional requirements, but demand for high haptics and finishing requirements. For acceptance, the users must perceive surfaces as high quality.

Phase 2 dealt with the development of a customer specific camera for application in metrology (Hastedt et al., 2018; Rosenbauer et al., 2018).

Here an existing product was reinforced with an AM external frame, to enable for photogrammetric applications. The stiffening frame is made of several additively manufactured parts assembled together around the camera. This application introduced strict requirements in terms of dimensional accuracy and demanded for new methods for fastening the components. The product was the first including functional features such as hinges for a focus lock.

Phase 3 addressed the development and introduction of the company's first videography system on the market through the IPL approach. For this purpose, two standard modules had to be developed and validated on the market. A cage for the camera back including power supply, and a battery compartment for the use of the camera with long lasting videography batteries. Both modules represent critical elements of the product due to frequent user interaction. On top of the requirements already addressed in previous products, these systems include an increased amount of functional integration such as basic electrical functions, quick release features, snap-fits, hinges, interfaces to conventionally manufactured components, as well as features for backlash clearance.

In phase 4 the company aimed at updating its videography solution in a second iteration by introducing a thermal management functionality in the cage. Lead users reported the overheating of the camera sensor after long takes. The company decided to improve the module by including an air-cooling solution in the cage, which increased again the overall complexity of the additively manufactured product. This implied the development of control electronics, integration of switches for interaction with the user, new interfaces and the consideration of noise and vibration aspects induced by a fan.

4.6 Results

The first subsection reports the analysis of phases 3 and 4, and explains the process model adopted by the company for the purpose of IPL. The second subsection delivers an analysis of all five phases, and explains how internal processes were reconfigured to implement IPL.

4.6.1 Realizing IPL by Combining AM and Agile

IPL sets new requirements in NPD in terms of predictability and responsiveness to change. Predictability is required to manage the product interfaces between different subsystems within a single product. Responsiveness, on the other hand, enables to mitigate uncertainty. The adopted process model employs a balanced mix of plan-driven and agile techniques. The pace in development is given by the frequent alternation between development sprints and user testing sessions. The plan-driven and agile phases are executed at two separate layers. On the upper level we find an overarching, plan-driven frame, that we call strategic layer. On the lower level, and framed by the strategic layer, we find a multitude of agile loops, that we call tactical layer.

The results highlight two fundamental challenges of applying agile in hardware: first a limited fragment-ability of product features and interfaces; and second the existence of restrictions in deployment lead time. Owing to the first, physical products cannot be entirely fragmented, decoupled and modularized. They are always subject to some extent of interdependence and tight coupling with other subsystems. Therefore, it is not possible in hardware to ensure that design changes to one particular module is not affecting others. Second, the time span required to deploy AM prototypes is still much longer than, for example, in deploying software. Physical items require logistic planning for manufacturing, delivery, handling, post-processing and other special efforts, which are inexistent in the realm of software. Such aspects set clear constraints on the minimum length of sprints achievable.

The strategic layer deals with decision and management of product features which need to be implemented in the next sprint. The strategic layer addresses the issue “what should be developed” and is dominated by a plan-driven approach. The strategic layer, depicted in Figure 4.3, represents the macro process from ideation up to product launch and is reviewed, questioned after each sprint, by taking into consideration the novel learnings from user testing and customer feedback from last product releases. In the sprint planning the team reviews the backlog, and critically edits it with the novel knowledge collected. The team decides whether to

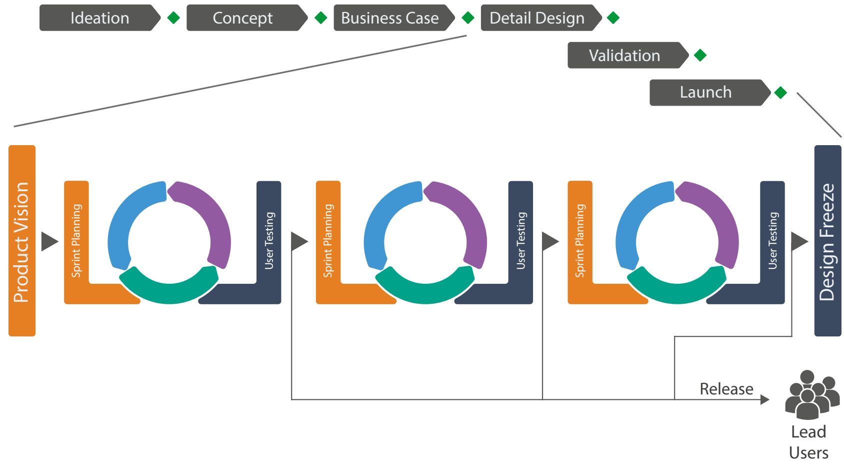


Fig. 4.3: Strategic layer of the NPD process model as employed by the case company

persevere in the given direction and therefore implement more functions, or whether to take a step back and re-implement or remove suboptimal solutions or features not important for the user. After the user testing session, the company considers the possibility of releasing the product increment to the public based on the outcomes of user testing.

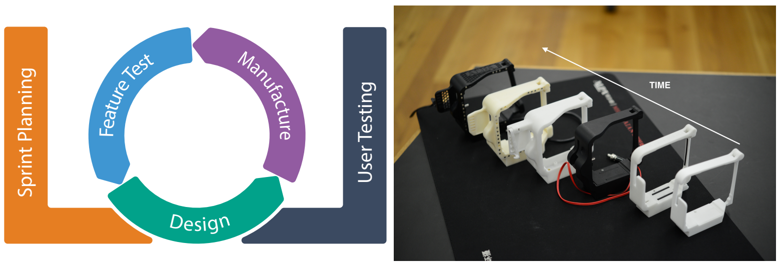


Fig. 4.4: On the left Tactical layer of the NPD process model as employed by the case company. Right, six iterations of a cage design.

The tactical layer, denoted by the design, manufacture and feature test loop in Figure 4.4, governs the intra sprint activities. It focuses on how a particular product feature is practically implemented at the product. It deals with a narrow scope and focuses on delivering a product increment for user testing. The tactical layer handles the actions needed within a sprint and is dominated by agile methods. In the alternation between tactical and strategic layer, the focus should be set on maximizing the value per sprint.

4.6.2 The transformation process to IPL

The introduction of this NPD process model has implications on the company's processes. Aside of NPD, supporting functions need to be streamlined and fine-tuned to allow for a faster execution of the tactical sprints, and to provide the right information for decision making in the strategic layer. Supporting processes need to be adapted to keep up with the fast-paced environment of development iterations, and to support the unpreventable trial and error process needed to achieve working AM designs. The following subsections report the implemented process improvement measures in each key functional domain.

Tab. 4.1: Summary of applied process improvement measures

	R&D	**Operations**	**Marketing & Sales**
Phase 0	DfAM Basics (CAD System, function driven design)	Selection of suppliers with right technologies and process chain	Verify customer acceptance for AM products
Phase 1	Fine tuning of manufacturing parameters (aesthetics, haptics, dimensional accuracy) through close collaboration with suppliers	Establish routines for first orders (quality controls at source)	feeding customer insights to R&D directly. For newly introduced products service is moved directly under R&D control
Phase 2	Introduction of structured functional testing to achieve desired tolerances in fastening and fitting	Labelling of parts to track variants in supply chain	Capturing single customer requirements
Phase 3	Introduction of tactical and strategic layers and IPL	Automation of order process, from CAD to delivery	Feedback acquisition through structured user testing (SUS, Kano Model)
Phase 4	Methods to document and reuse design elements, coordination with other systems (electronics)	Synchronization of AM and other component orders (electronics, third party systems)	Refinement of business model to promote acceptance of frequent product upgrades

R&D

In research and development, the preliminary phase 0 focused on integrating the basics of Design for Additive Manufacturing (DfAM) to design parts for the Selective Laser Sintering (SLS) process. The company first focused on understanding SLS specific design best practices such as minimal wall thicknesses, powder removal, minimal feature sizes, air gaps. In support of DfAM, the company adopted a cloud-based CAD system, allowing for ubiquitous sharing of designs, and offering short release cycles for new functionalities. The system facilitated collaboration among R&D and with suppliers, by allowing collection of feedback and commenting of part designs directly from a web interface.

In phase 1 the company investigated different process chain set-ups, to identify the most feasible process and finishing combinations for its parts. The goal was to understand the relationship between manufacturing process parameters, haptics and aesthetics of finished parts. Furthermore, the company started experimenting on how to optimize manufacturing costs through design.

In phase 2, the higher complexity of the product underlines the necessity of joining several AM manufactured parts, and achieving the first functional elements. The achievement of precise tolerances and functional parts (such as hinges) with AM requires the controlled variation of several design parameters and structured testing to isolate working designs. Due to lack of design guidelines and reproducible tolerances on different AM machines, the company introduced structured feature testing, whereas critical portions of the system were made independent and manufactured in several sizes to spot which parameters achieve the best results. Figure 4.5 provides examples of such testing approaches.

Feature testing breaks down the product in single features (or functions), and tests these independently. Therefore, the process allows for parallelization in the long and repetitive process of finding the correct manufacturing parameters for a particular AM design, and its optimization.

Fig. 4.5: On the right several hinges manufactured with different parameters for the purpose of feature testing. On the right, a low fidelity test bench for the feature testing of a snap fit durability.

The introduction of IPL required a review of the whole NPD process to achieve shorter innovation cycles. The company saw as a natural extension to the newly implemented design approach heavily relying on practical testing and validation, in the domain of Agile development principles. R&D hence started experimenting with the introduction of development practices, tools and routines borrowed from SCRUM. In particular product backlog and user stories were directly adopted. Furthermore, the company introduced structured user testing, as a method to gather quick feedback on the results of concluded development sprints, and in the planning of next development phases. The company achieved a sprint length of about two months.

Phase 4 revealed that feature testing forces the company to perform several iterations in order to achieve working designs. The company realizes that many design features are similar to other previously applied in earlier products. The company should therefore ensure that learnings from previous designs are standardized and are accessible in future projects. Hence, engineers note a growing need for documentation of design features together with their partial parameterization. Through modularization of design elements, these can be reapplied in CAD with reduced efforts in functional testing. Such recurring solutions are required in fastening, integration of electronics and moving elements. The company addresses the development of a feature book to ensure the persistence of design knowledge in future projects.

Operations

In the functional domain of operations, phase 0 was dedicated to the testing and selecting suppliers with suitable process chains. The company experimented with several supplier to achieve the necessary process, material and finishing combination. The company established solid collaborations with two SLS suppliers, and collected a first understanding about error rates, delivery lead times and costs of AM parts.

In phase 1 the company focused on obtaining stable quality, tackling issues in supply such as warping, and dimensional fidelity. To ensure quality at source, the company collaborated with suppliers to introduce special jigs for the verification of the manufactured parts at the source. The supplier together with the company could hence adapt the manufacturing process accordingly, and therefore compensate for variations.

In phase 2, the introduction of functional testing posed new pressure on the supply chain of AM parts, as these drastically increased in quantity and frequency. The surge in orders set new requirements on traceability and demanded an easy solution to track parts. The company introduced a labelling system, where variants IDs are directly engraved in CAD models and printed on the parts. This simplified the identification of working designs.

In phase 3 the introduction of time-boxed sprints originated a further surge in the frequency of orders. The fact that AM requires several iterations and simultaneous ordering of slightly different designs, makes the management of orders and the avoidance of errors a challenge. A resilient order process with the following characteristics is required:

1. Speed: the delivery of test parts should be accelerated so that sprints are shorter and working designs are achieved faster
2. Accuracy: the process should prevent manufacturing errors, and precisely deal with slight variations of the same product
3. Transparency: it should early provide reliable estimations and updates about lead times, manufacturing costs so that designers can plan their work accordingly.

4. Supplier agnostic: should avoid the lock-in on a single supplier.
5. Automated: it must require few resources in the execution and in the maintenance.

The company therefore developed a fully integrated order management system for AM parts, covering the entire process from cost estimation and ordering in CAD (custom plug-in), up to tracking of deliveries and reconciliation of invoices. The software automatically compiles an order backlog which is managed directly by the suppliers. The developed order interface implemented in CAD is shown in Figure 4.6

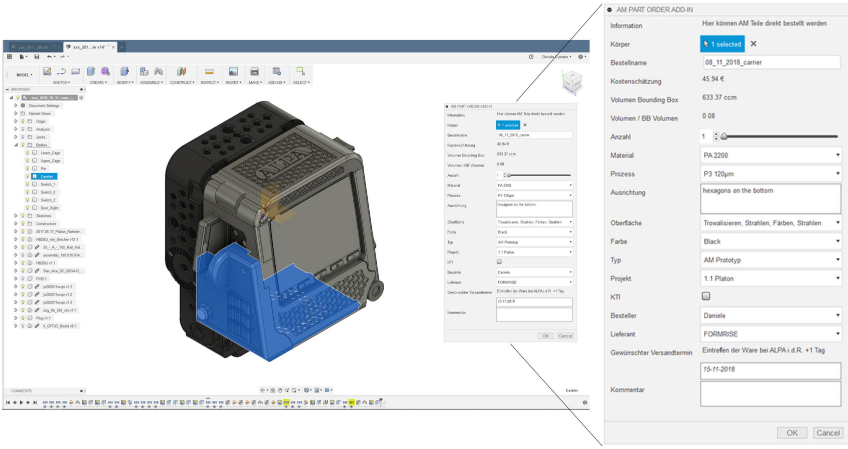


Fig. 4.6: User interface of the custom ordering plug-in developed by the company

In phase 4 the integration of thermal management functionalities required further electronics functionalities. Managers had to ensure that lead times of internally and externally developed components were synchronized, thus avoiding the hindering of the agile development loops and ensuring timely releases of product increments. The company had to accelerate the development and procurement of externally sourced systems to keep up with the speed introduced by AM. For this purpose, prototyping services for electronics were introduced, and some third-party systems were partially modified with the use of AM, or even substituted by mock-ups for the purpose of earlier testing.

Marketing & Sales

In the functional domain of marketing and sales, phases 0 and 1 were dedicated to the learning of minimal requirements for customer acceptance of AM parts. The manufacturing of lens shades and covers helped the company to understand under which conditions the customers were ready to accept AM parts. The company applied an open communication strategy, and informed the customers about the advantages the company could offer in terms of customization and solutions that would have been uneconomical with other technologies, due to the small lot sizes. The company focused on communicating the technological advantages for both final users and the company itself. In the first phase a direct link between customers and R&D was established for AM projects currently developed by the team. A direct link ensured an unaltered feedback from lead users to R&D.

In phase 2, through the development of a customer specific product for a niche market the company learned how to capture individual user requirements. This not only involved the product and its finishing, but was extended to methods for the selection of features considered important by the users and which should be implemented first.

In phase 3, the introduction of recurring user testing sessions set the necessity of collecting user feedback in a structured and comparable way between sprints. The company introduced tools for the standardized assessment of user testing, such as the system usability scale (Bangor et al., 2008; Brooke, 1996; Brooke, 2013), as well as considered the feasibility of a web system to enable the collection of variant specific feedback of released systems in a systematic way. The company further introduced improved methods for the analysis and prioritization of functions desired by the users. For this purpose, the Kano model (Kano et al., 1984; Sauerwein et al., 1996; Xu et al., 2009) was introduced.

In phase 4, the company encountered the need of refining its business model, to better promote the acceptance of frequent product releases by customers, as well as to encourage lead users in providing feedback. This transformation is still ongoing at the time of writing; however it might lead

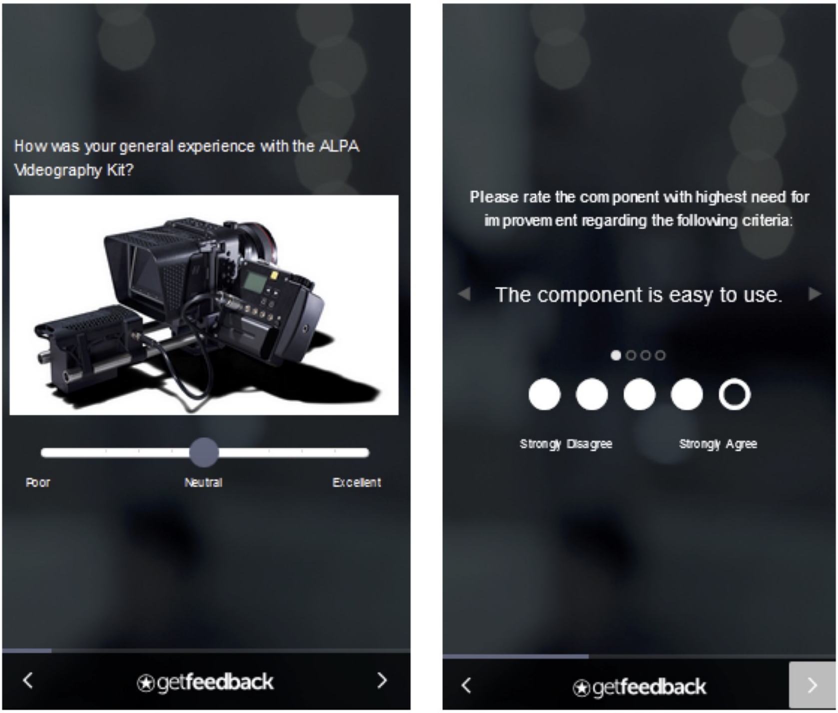


Fig. 4.7: Web tool for the acquisition of user feedback about usability and functionality of the released systems.

to servitizaztion, and toward the adoption of a rather lease or pay-per-use centric model.

4.7 Concluding Discussion

The research contributes to the body of knowledge of AM management, and new product development. Owing to the first research question, the presented hybrid process confirms elements previously described in literature (Cooper, 2014; Cooper and Sommer, 2016). In the specific context of AM, this paper reveals feature testing as a necessary method to achieve working AM designs and to compensate for the lack of interoperable design guidelines for different AM machines or AM system providers. It further extends the scope of previously defined tactical and strategic layers of NPL (Bowersox et al., 1999; Cui et al., 2011; Guiltinan, 1999; Talke and Hultink, 2010) to include the dynamics of hybrid development. The hybrid process model confirms the applicability of agile tools such as product backlog, time-boxed sprints and their suitability for hardware development. The research further highlights two clear limitations of IPL, given by limited fragment-ability of product features and restrictions in deployment lead time.

With regard to the second research question, each phase is characterized by slight increases in product complexity. The company encountered new challenges that had to be addressed in the functional domains of R&D, operations and marketing & sales. In order to progress to more advanced applications of AM, necessary process improvement measures in the functional domains had to be completed. The authors name this effect rolling bottleneck, and summarize its dynamics in Figure 4.8.

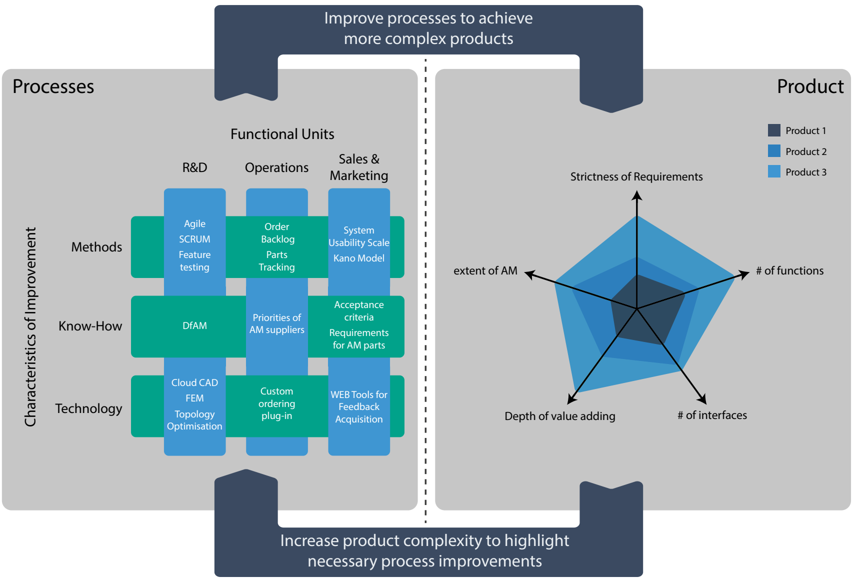


Fig. 4.8: Process and product aspects of a *Rolling Bottleneck*

In parallel to commitment of resources to product development, the company had to dedicate efforts to the development of process improvements in all three functional domains. These aimed at the resolution of bottlenecks, that were hindering the progress of AM implementation. However, the issue can be observed also from the other perspective, whereas controlled increases in product complexity at regular intervals, allowed the company to highlight necessary improvement steps in all three functional domains. The concept of rolling bottleneck therefore shows two critical dimensions. A product dimension serves for highlighting current bottlenecks in processes. A process dimension where improvements need to be implemented to proceed toward more complex product applications. The role of management in this delicate interplay is the control of these slight increases in complexity at the product level, and the subsequent observation for identification of required process improvements. The product dimensions are assessed between the sprints, particularly in the phases of user testing and sprint planning. The ultimate goal of the process dimension is the smoothing of the execution of agile tactical loops. According to observations, the authors propose five dimensions defining the overall product complexity and which should be gradually increased by managers. These are represented on the right side of Figure 4.8 and shortly discussed hereafter.

- Strictness of requirements indicates the amount of technical challenges necessary to meet them. Strict requirements in terms of tolerances, haptics, surface quality and finishing, require more complex process chains to be met.
- The number of functions relates to the amount of mechanical thermal, electrical and ergonomics functions that need to be integrated in a product, assembly or component.
- The number of interfaces is proportional to the number of components or systems the observed element is connected to.
- Depth of value adding is defined by the amount of value-adding clusters as defined by (Fontana, Klahn, et al., 2018) targeted in the product.
- Through extent of AM we indicate the portion of AM manufactured parts, with respect to the entire observed product.

All these dimensions define the degree of complexity of an AM part, as visually represented by the blue area of the polar chart in Figure 4.8. Process improvement happens in three functional domains and its characteristics are represented on the left side of Figure 4.8. The case-study shows that process improvement was achieved through the implementation of new methods, the integration of novel know-how and the adoption of new technologies in the form of tools.

The study presents several limitations. The process model, and its implementation strategy resulted suitable in the case of a small company, characterized by a flat hierarchical structure fast internal communication and rapid decision making. It is necessary to understand under which conditions the presented process model can be applied to larger organizations, distinguished by larger inertia and more rigid structures. The characteristic of the product further supported the application of IPL. The videography system subject of phases 3 and 4 of the case study is a B2B videography product, whereas the industry is not new to the practice of renting equipment. Further work is also required to validate the concept of rolling bottleneck as an approach to the introduction of AM technologies. Despite the limitations, this exploratory study delivers insights about a viable method to achieve and perform IPL.

Conclusion and Outlook | 5

The present chapter, reports the individual contribution of each study to the overall purpose of the thesis; and summarizes the overall learnings in the form of five managerial implications. The chapter closes by discussing necessary future work.

5.1 Conclusion

The three studies included in the present work contribute at a different level of detail to the overriding research questions. The depth of analysis of each study is summarized in Table 5.1. Where Study 1 provides a comprehensive analysis over the entire value chain at a strategic level, studies two and three focus more on an operational and process level and therefore show a narrower scope.

Tab. 5.1: Type and depth of analysis of each study

	Study 1 (Fontana, Klahn, et al., 2018)	**Study 2** (Fontana, Marinelli, et al., 2018)	**Study 3** (Fontana, Omidvarkarjan, et al., 2019)
Focus of Analysis	Strategic Level	Operational	Processual
Entity of Investigation	Entire value-chain	High-variety component family	Combination of Agile and AM in new product launch
Type of study	Qualitative	Quantitative	Qualitative

From a hierarchical perspective, Study 1 frames the scope of Studies 2 and 3. It provides a definition of the value adding clusters of *Improved Delivery* and *Incremental Product Launch*, which are then investigated more in detail in the other studies.

Tab. 5.2: Contribution of each study to the overriding research questions

	Study 1 (Fontana, Klahn, et al., 2018)	**Study 2** (Fontana, Marinelli, et al., 2018)	**Study 3** (Fontana, Omidvarkarjan, et al., 2019)
RQ1 — How can new adopters be supported in the identification of viable AM applications?	Seven clusters for value adding AM applications	Method for the selection of cost-effective components in a high-variety component family	
RQ2 — What is the value and what are the implications of AM adoption?	Direct effect and implications of AM adoption on focal-firm established processes	Quantitative estimation of lead-time and cost reduction potential of AM in a high variety component family	Rolling bottleneck in Operations, R&D, Sales and Marketing
RQ3 — How should new adopters proceed in the implementation of AM?	Systematic approach in the screening of potential applications at the strategic level		NPD process model for IPL Staggered increase of product complexity

The contributions of each study to the overriding research questions are listed in Table 5.2. The first research question asked how can new adopters be supported in the identification of viable AM applications. Study 1 proposes seven clusters where AM technologies can be applied to generate value. The clustering model contributes by adding a new layer of evaluation at the firm level in the screening of potential applications. It therefore directly addresses the challenge C1 of identification of suitable AM applications and mitigates the risk of engaging in manufacturing of parts resulting more expensive and inferior in quality. Study 2 contributes to answering the question at a more operational level. The study identifies volume specific average operating costs per variant as a viable tool to algorithmically identify cost advantageous components in high-variety component families.

The second research question asked what is the value and what are the implications of AM adoption. All the presented studies contribute at different levels in answering this question. Study 1 identifies the basic implications am AM implementation in NPD and OPS for each proposed value-adding cluster. The study further highlights IPL as a construct demanding for further investigation. An inhomogeneous degree of industrial maturity for applications in different value-clusters is further identified. Study 2 provides a quantitative estimation of possible cost and lead time reduction, when applying AM for the purpose of high variety manufacturing. The study highlights the aggregated lot-size as a control parameter to manage the trade-off in manufacturing between lower manufacturing costs and shorter delivery lead times. Study 2 directly addresses challenge C3 by providing novel tools to calculate the total operating costs in the case of high-variety component families. Study 3 contributes to the research question by identifying the rolling bottleneck effect with implications in the functional areas of R&D, Operations and Marketing & Sales. Study 3 addresses challenge C5 by presenting a custom built software solution to automate the ordering and tracking of AM parts.

The third and last research question asked how should new adopters proceed in the implementation of AM. Study 1 provides the tools to structure a preliminary screening process, by listing potential domains of application in the firm value-chain. These elements address directly challenge C2, and enable managers to develop a clear implementation strategy, thus narrowing down the scope of application. Study 3 highlights the interplay between process dimension and product dimension in the implementation of AM technologies. The study shows how slight increases in product complexity are necessary to identify and improve surrounding processes processes. The increase in process performance allows the subsequent targeting of more complex applications at the product, and the cycle can start over again. The study further proposes a NPD process model to achieve incremental product launch in hardware, and highlights the importance of feature testing.

The overall contribution of the thesis is best summarized in form of the following managerial implications, which apply for early adopters.

- The successful adoption of AM technologies requires systemic innovation affecting processes, functions and the structure of a focal firm.
- The initial scope for applications shall be driven by the systematic analysis of value adding potential in the context of the adopting firm.

- Simple applications entirely realized are the key to develop the competences necessary to employ AM in a sustainable manner.
- Optimal implementation scenarios require the combination of AM with conventional manufacturing technologies.
- Search for applications sees improvements in process chain of equal importance as improvements at the product. The scoping of value adding AM applications requires the weighted observation of both factors.

5.2 Outlook

This thesis highlights several domains where further research is necessary. The clustering model presented in Study 1 can be leveraged to direct further work. One domain is the conceptualisation of methods in each cluster to address and calculate business cases. Each value-cluster promotes specific motives for adoption, and might therefore be suitable to direct the development of tools and methods for business case calculation. A similar effort can be done for component search strategies, whereas cluster are used to develop specific component identification methods for each domain. Study 1 further theorizes a different degree of application maturity and suggested two dimensions to explain the differences in adoption rate. This aspect demands for validation and further *ad hoc* studies.

Study 2 deliberately avoids the consideration of an in-house make approach for the manufacturing of high-variety components. However, by considering larger high-variety component families, where more manufacturing capacity is required to keep up with orders, a make approach could represent a viable approach, and should therefore be investigated. The case of high variety components manufacturing could also benefit extensively by the further digitalisation of the process chain and the inclusion of a web product configurator. The effects on lead-times and costs under such conditions are of high interest and should be deepened.

The concept of rolling bottleneck introduced in Study 3 is of high interest and its dynamics should be further investigated. New investigations are required to confirm its validity also for other companies and applications. Furthermore, the suitability of the proposed NPD process model for incremental product launch should be investigated, especially in the case of larger organizations, other industry verticals, and for products with different characteristics.

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