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How Additive Manufacturing Platforms are Digitizing the Manufacturing Value Proposition

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HOW ADDITIVE MANUFACTURING PLATFORMS ARE DIGITIZING THE MANUFACTURING VALUE PROPOSITION

Research Paper

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Abstract

Digital platforms are established in business ecosystems with primarily non-tangible value creation (e.g., social networks, entertainment, software). All partners of a platform usually benefit from network effects. The digitization of physical products and processes drives industrial platformization, so manufacturing companies increasingly establish digital manufacturing platforms. The impact of digital manufacturing platforms on value creation in the manufacturing industry is of great interest. A highly promising technology for emerging production platforms seems to be Additive Manufacturing (AM), which enables economical manufacturing of small batches, individualization, and high flexibility in production. This study examines the relation between platform providers and related platforms in the AM field. A literature review and a subsequent cluster analysis of AM platforms are the two pillars of our research design to identify five patterns of platform-based value creation in digital manufacturing. The discussion of the resulting value creation patterns highlights implications for platform business model design by manufacturing companies and knowledge on digital platforms.

Keywords: 3D printing; Clustering; Manufacturing as a Service; Value proposition

1 Introduction

Digital manufacturing platforms build an integral part of ecosystem formation. Backed by the vision to order any industrial component online – in a process as simple as ordering a custom-printed shirt. Behind the shiny online order service, manufacturing companies with diverse profiles collaborate in flexible and dynamic production networks to distribute the production process across the boundaries of individual companies, aiming for optimization, e.g., cost reduction or flexibility in the production of small batches (Freichel et al., 2022; Helo et al., 2021). The organization of work in such dynamic networks can be fostered through digital industrial platforms, whichact as digital infrastructure, steering interactions between demand and production actors, enriching them with complementary innovations, and forming manufacturing ecosystems (Freichel et al., 2022; Pauli et al., 2021; Weking et al., 2020; Jacobides et al., 2018). In essence, ecosystem actors are attracted by optimization gains and/or innovative business opportunities.

Both, optimization and business innovation, are enabled by Additive Manufacturing (AM) through digitalization and automation of manufacturing processes. AM highly relies on digital product models, which can be simply processed via information systems. Prior research confirms that AM is among the highly digitized technologies integrated into the manufacturing process landscape by heterogeneous companies (Floren et al., 2021). Generic product creation is another important aspect of AM technology. Complex geometry could be seamlessly produced with a single manufacturing system; aside some (optional) post-processing, there is no need for complex processing sequences (c.f., section 2). Hence, AM bolsters several business potentials for manufacturing firms, such as optimization of supply chains through digitalization, disruption of traditional manufacturing processes, and diffusion of digital manufacturing platforms to orchestrate the manufacturing process (Friedrich et al., 2022; Hiller et al., 2020; Hämäläinen and Ojala, 2015). Consequently, the increasing degree of digitalization in the manufacturing context stimulates the diffusion of AM platforms (Hiller et al., 2022; Rong et al., 2020).

The disruptive potential of AM platforms (Baiyere and Salmela 2015; Henfridsson and Bygstad 2013) indicates that bridging the boundaries of digital platforms and AM is far from trivial. Understanding how value propositions manifest when AM and platforms are combined, poses a problem for researchers. Besides, manufacturing firms struggle with such business model changes through disruptive innovations such as AM and platforms (Sarvari et al. 2018; Grünert and Sejdic 2017). Hence, despite the recent research on digital manufacturing platforms (Pauli et al. 2021) and AM business models (Freichel et al. 2021), further research on systematizing the value propositions in manufacturing firms at the intersection of AM and digital platforms is needed. Eventually, insights from researching value creation on AM platforms aim to add to the body of knowledge on manufacturing platforms in general.

It is known that one of the main mechanisms of platforms utilize network effects, leading to winner-takes-all dynamics in platformized markets, increasing the dominance of a platform provider in a platformized domain (Rietveld and Schilling, 2021; Gawer, 2020; Giessmann and Legner, 2013). Although AM platform providers can be considered focal companies in their production networks since they can design their own platform and subsequently leverage value creation, the fragmented market (Freichel et al., 2021) suggests that none of the AM platforms occupies a dominant position in the domain. On the one hand, this indicates that existing platform providers have not yet been able to achieve platform leadership (Gawer and Cusumano, 2002). On the other hand, there is a heterogeneity of existing platform types in AM. This phenomenon seems sufficiently interesting to empirically analyze the different AM platform business models and identify patterns in the platform value creation offered for several reasons. Research into the patterns of platform-based value creation can help to understand industrial platformization better based on the example of the AM domain. Friedrich et al. (2022) explicitly see the establishment of AM platforms as a decisive foundation for competitive advantages, while the actual state of research on how to establish digital manufacturing platforms remains limited.

We sense that manufacturing companies must embrace a significant adaptation of their internal processes of stable supply chain relationships and align them to platform dynamics (Sterk et al., 2022), which will result in the depreciation of gained capabilities from a positive interplay of business processes and technologies. Thus, to build platform business models, organizations need to change their value-creating processes and acquire new capabilities in terms of AM technology, especially in terms of platform design and ecosystem governance (Sterk et al., 2022; Marheine and Petrik, 2021). Despite the positive development of the research stream on platform ecosystems (Rietveld and Schilling, 2021), prior conceptual research on platforms was not dedicated to certain domains (Gawer, 2020), whereas empirical research mainly examined business-to-consumer domains (e.g., mobile operating systems and app stores) (Kathuria et al. 2020). Accordingly, despite the importance of the generic conceptualization of the value facilitated by digital platforms (Gawer, 2020; Cusumano et al., 2019), the impact of domain specifics, such as AM, on the platform value proposition remains underexplored. In addition, extant research often focuses on established platform leaders with a dominant market position (Hein et al., 2019), while research lacks on emerging platforms (Sterk et al., 2022) as well as investigations of the concept of digital platforms together with the ecosystem and value proposition (Marheine and Petrik, 2021). Various manufacturing platform providers abandon their platform business models in early phases that are characterized by competition for overlapping customer segments, and a short timeframe for platform establishment (Liu et al., 2022; Pidun et al., 2020).

Therefore, we conclude that more research is needed on the diverse aspects and fragments of platform ecosystem establishment and ask: *How can AM platforms be differentiated based on the patterns of their value creation?*

To answer this question, we conducted a two-step process. First, we performed a systematic literature review to conceptualize AM platforms. The goal is to understand the key dimensions suitable for characterizing AM platforms (see section 3). In the second step, we classify empirical data from web searches of the existing AM platforms into these key dimensions. Eventually, we reveal patterns of platform-based value creation. Our study identified four distinctive AM platform clusters and derived five patterns for the value proposition of manufacturing platforms.

The purpose of our study is twofold. First, the results support realizing platform-based value creation in manufacturing. Second, the results offer descriptive insights into how distinctiveness can be achieved during the platform design. These findings aid practitioners and scholars in understanding how to improve the strategic positioning of platform business models in domains (Durand and Haans, 2022; Weiller and Neely, 2013) where the winner-takes-all state has not occurred yet (Dattée et al., 2018).

2 Platforms for Manufacturing Ecosystems and Additive Manufacturing

The shift of value creation towards ecosystems, facilitated by digitalization, offers manufacturing companies the possibility of servitizing industrial processes integrating complementary third-party value creation. In this context, the transactional exchange is supplemented by intelligent services, which can evolve into digital service business models, allowing manufacturing companies to escape commoditization traps (Huikkola et al., 2022; Matzner et al., 2021). Therefore, the paragraphs provide an overview of platforms for manufacturing ecosystems in general and AM platforms in particular.

Modern manufacturing companies rarely act alone, as they are usually integrated into complex networks spanning individual organizations. These value creation networks are changing the formerly linear value creation chains and are increasingly taking on a dynamic character. This is expressed by the shift from long-term framework agreements to flexible temporal agreements and can, for example, compete with other organizations of the same network. In this way, organizations' roles in dynamic networks also change over time (Heimburg and Wiesche, 2022), with them the inter-organizational business relationships. These dynamic and multilaterally firm interactions also influence the resulting products or services (Adner, 2017). The value added in the products or services created across organizations becomes ecosystemic due to the complementary value contributions (Jacobides et al., 2018). The value proposition created by multiple organizations determines the interdependence of the organizations in the network, which is why the alignment of the actors in manufacturing ecosystems also plays a significant role (Adner, 2017). Given that, manufacturing ecosystems are structured networks of organizations that evolve together to create superior value propositions based, for example, on innovations or digital services (Sjödin, 2019).

Compared to conventional production processes, for instance, milling or casting, AM is highly digitized: the production process depends on digital models – such as CAD models and production parameters. Furthermore, AM offers nearly unlimited freedom of design and high production flexibility, as layers of materials are applied without time-consuming and rigid retooling (Friedrich et al., 2022; Hiller et al., 2022). Consequently, AM is said to have various disruptive potentials for industrial value creation (Floren et al., 2021; Piller et al. 2015), and empirical examples such as the value creation transformation by AM in dental products or hearing aids prove the disruptive potential of AM (d'Aveni, 2015).

Accordingly, AM is also seen as the technology by manufacturing companies to expand the traditional business field and gain competitive advantage, especially by exploiting the high level of digitization of

AM in building platform-based value creation (Friedrich et al., 2022; Freichel et al., 2021; Hiller et al., 2020). These AM platforms utilize the integrated platform concept of Gawer (2014) and Cusumano et al. (2019). Platforms can be differentiated according to their value contribution and the definition of a primary value contribution (Gawer, 2020). Transaction platforms act as intermediaries and foster exchange between platform users. One example are electronic marketplaces, which reduce transaction costs by shortening the order placing time. Innovation platforms provide a technological basis that enables the development of innovative complements (Hein et al., 2020). For instance, operating systems promote innovation in the form of applications dependent on the operating system's technology components.

A common mean of both platform types is the utilization of IT to connect different actors, e.g., through the logic of supply and demand, whether to conduct a commercial transaction or to bring together a complement developer with a paying user. Furthermore, external actors are a significant aspect of platform concepts. The platform users enable the platform provider to generate competitive advantages from network effects. Accordingly, platforms function as a part of the digital infrastructure for dynamic business networks, also known as ecosystems (Cusumano et al., 2019; Jacobides et al., 2018). The platform provider plays a central role in a platform ecosystem. It is his responsibility to design of the platform architecture. Often, he also is in a position to define the ecosystem conditions to maximize the platform value for the third-party providers to capture (Cusumano et al., 2019). Applied to production and AM, platforms act as two-sided markets by connecting a network of manufacturing suppliers with customers via a digital platform. Such platforms act as intermediaries, offering the flexibility to use AM capacities for the demand side (Friedrich et al., 2022; Freichel et al., 2021). In practice, such a platform-based value delivery model for production resources is also known as Manufacturing-as-a-Service (MaaS) (Adamson et al., 2017; Ren et al., 2017).

Although digital platforms and ecosystems are closely intertwined in manufacturing, considering these two concepts would be incomplete without the value proposition. While Adner (2017) speaks only of the manifestation of a focal value proposition, the value proposition in platform-based ecosystems in the industrial context must be considered more differentiated. Empirically analyzed cases of platform leadership show that platform providers become those companies that provide a focal value proposition to a value system (e.g., a smartphone operating system) (Shipilov and Gawer, 2020). Ecosystem actors contribute value to the platform provider's solution (Schreieck et al. 2022; Hannah and Eisenhardt, 2018). This is unrealistic for ecosystems in a business-to-business context such as AM because all platform-using organizations engage in value quantification and expect adequate counter-value (Matzner et al., 2021; Hinterhuber and Liozu, 2018). Organizations do not start using the platform and become platform ecosystem actors without a sufficient value proposition. Thus, it is important for a platform provider not only to understand which collaborations are needed to realize the value proposition (Sjödin et al., 2019; Adner, 2017) but also to plan the value proposition of its own platform for each user group (Gawer 2020). It is the platform providers' strategic decision to define the value proposition, which depends on cooperation, coordination, and integration between different organizations (Kretschmer, 2020). AM platforms in manufacturing context may improve the customers' procurement process by reducing the efforts to find suitable manufacturing partners (e.g., for small lot sizes) and enabling mass customization. In addition, AM platforms enable manufacturing resource sharing for the manufacturing partners, improving their utilization (Simeone et al., 2020; Weking et al., 2020).

3 Conceptualizing Additive Manufacturing Platforms

To understand how the platform concept is used to integrate AM in industrial value creation and to identify key dimensions for characterizing digital platforms we conduct a systematic literature analysis according to Brocke et al. (2009). Hence, only peer-reviewed publications with a business context reporting on the platformization of the manufacturing industry with the objective of AM integration were sought to analyze platform value creation and identify the characteristics of AM platforms for cluster analysis. The overview of search conditions and results is given by Tab. 1. The ACM Digital library was chosen due to the focus on computing and information technology. This would cover the field of digital plaforms. The AIS eLibrary was chosen for its focus on information systems (IS), which exactly points out the field of research we locate this research paper. For the emphasis on engineering and AM ScienceDirect was chosen as a third database. We purposely focused on the search term "Additive Manufacturing" to only include the industrial use of the often-mentioned synonym 3D printing. All hits were checked for relevance by machting the scope of our research and the research conducted in the papers. This was done by title and abstract. The full text was analyzed when the decision on possible inclusion or exclusion in terms of relevance was not obvious.

Database	**Search**	**Hits / Relevant hits**
ACM Digital (Title-Keywords-Abstract)	"Platform" AND "Additive Manufacturing"	8 / 0
AIS eLibrary (Title-Keywords-Abstract)	"Platform" AND "Additive Manufacturing"	83 / 9
ScienceDirect (Title-Keywords-Abstract)	"Platform" AND "Additive Manufacturing"	371 / 9
Inclusion criteria: Access available, in English, peer-reviewed journal or conference papers **Exclusion criteria:** Access not available, not in English, book chapters or basic papers		

Table 1. Overview of the literature review

The 18 relevant hits of the literature review were analyzed from two perspectives on the one hand, of which area of observation of AM the papers were built on, and on the other hand, which AM artifact was designed. We followed the inductive category formation by Mayring (2014) to analyze different dimensions within the perspectives mentioned below and shown in Tab. 2.

Identified Dimension	Freichel et al. 2021	Freichel et al. 2019	Friedrich et al. 2022	George et al. 2021	Hiller et al. 2022	Hiller et al. 2020	Kyriakou et al. 2017	Liu et al. 2021	Pahwa et al. 2018	Pfähler et al. 2022	Qian et al. 2019	Rudolph and Emmelmann 2017	Simeone et al. 2020	Stavropoulos et al. 2021	Stein et al. 2019	Strulak-Wójcikiewicz and Bohdan 2021	Wirth and Thiesse 2014	Wu et al. 2022
Area of Observation of AM																		
Process			x	x	x	x				x	x	x	x	x			x	
Potential		x	x		x	x	x	x	x			x	x		x	x		
Value creation	p		d		e			p	p	e	p			p	p		p	p
Designed AM Artifact																		
Ecosystem					x	x												
Value chain				x		x					x			x			x	
Workflow			x	x					x		x	x		x		x		x
Value creation & Services	x		x			x	x	x		x	x		x				x	x
IS- Architecture		x						x	x		x	x			x	x		

Table 2. Relevant hits of the literature review and their classification (general relation (x) & dimensions of value creation, i.e., ecosystem (e), platform (p), domain-specific (d)).

By analyzing the literature, it became clear that none of the relevant references classified different kinds of AM platforms. Singular business model examples like an AM marketplace (Freichel et al., 2021; Wirth and Thiesse, 2014) or the added value from open design (Liu et al., 2021; Kyriakou et al., 2017) could be observed. This confirms the research gap for this paper.

The literature review provides a basis for deriving characteristics to classify AM platforms, which we refer to as dimensions. A fundamental similarity in most papers regarding the area of observation is that it contains a process view. This reflects in the identified designed artifacts that also refer to processes – with strategic focus as the value chain and concerning operations as workflow. Therefore, we identify the *business process* as a key dimension for the characterization of AM platforms.

Regarding AM technology, viewpoints are two-folded. Two publications examine aspects related to specific AM technologies. Whereas the majority of research investigates AM technologies from a more abstract perspective. In addition to AM-related technologies, IT-related technologies are of importance as well. This is shown by the multiple IS architectures and data model artifacts in the literature sample. For this reason, the *technology* dimension covers AM and IT aspects for further AM platform analysis.

Even though a few papers take an ecosystemic perspective on AM, the need for different partner types within an AM ecosystem seems relevant for a holistic view of AM platforms (c.f., section 2). We consider this consistent with the previously described interdependence of platforms and ecosystems. Therefore, the *partner network* dimension addresses the foundation of ecosystem-related aspects of AM platforms.

Finally, the *value* perspective is the last dimension that could be derived from the literature. The area of observation of multiple papers is based on the value dimension of platforms. From the papers' designed artifact perspective (see Tab. 2), various services and business models could be observed.

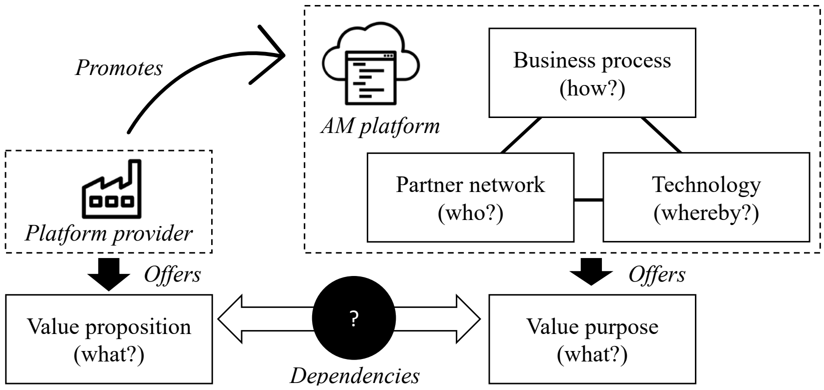

Figure 1. Research Framework for AM platforms.

Integrating the knowledge on digital platforms and AM platforms, we define five dimensions to characterize value creation of AM platforms as depicted in Fig. 1. The value dimension is divided into two dimensions, which are described as follows:

- *Value proposition* of the platform provider: In line with existing business model literature, the value proposition is seen as a business model key element (Al-Debei and Avison, 2010; Endres et al., 2019). We see the value proposition as "A way that demonstrates the business logic of creating value for customers and/or to each party involved through offering products and services that satisfy the needs of their target segments" (Al-Debei and Avison, 2010).
- *Value purpose* of the platform: This concept incorporates the offering of the AM platform, which could include physical products or digital services (Müller and Buliga, 2019). A value purpose might deviate from the above-mentioned value proposition, which is broader and related to the platform provider.

The three remaining dimensions are:

- *Business process*: It is essential to look at all processes (Hein et al., 2020; Müller and Buliga, 2019; Endres et al., 2019) to understand platform-based value creation, as this dimension incorporates the manufacturing process steps supported by the platform.
- *Partner network*: This dimension includes the platform's manufacturing partners and other partners. This aspect gains importance in the business model literature (Al-Debei and Avison, 2010) and platform literature (Schreieck et al., 2022; Endres et al., 2019).
- As mentioned above, the *Technology* dimension includes AM technologies and the needed IT and is seen as a key resource for the generation of the value proposition (Osterwalder et al., 2005).

This research framework for AM platforms, consisting of five dimensions derived from the central literature on platform ecosystems, AM platforms, and business models, serves as the foundation for the following research.

4 Findings on Digitized Value Propositions of AM platforms

The dimensions for AM platforms (c.f., section 2) are the foundation to this analysis process which starts with data gathering that is described below. It proceeds with a clustering process, according to Backhaus et al. (2021), that includes data preparation (i.e., selection of cluster variables), clustering and cluster evaluation (c.f., section 4.1), and ends with interpretation of results (c.f., cluster description in section 4.1 and patterns in section 4.2).

In May 2022, we performed a two-step data gathering from LinkedIn, an international social network for professional networking, which also offers firms an advertising environment for self-presentation. In the first step, we identified 77 companies that declare offering AM platforms (search keywords: “additive manufacturing platform”, “3d printing platform”, “additive manufacturing marketplace”, “3d printing marketplace”, remark: “3d printing” was included since practitioneers does not necessairly distinguish between AM and 3d printing in comparison to the scientific literature). In the second step, we systematically screened the websites of the identified AM platform companies to decide if they provide products or services related to IT-enabled AM platforms. For this purpose, we performed a content analysis of all the subpages of their website and searched for the previously defined five dimensions of an AM platform. If this is the case, their business activities are categorized according to their website. Finally, 41 companies formed the sample of AM platforms that was subject to further investigation. Three researchers from our team conducted this content analysis independently and discussed the different evaluations at the end to reach a consensus.

According to the self-description of the companies, the sample could be characterized as follows (see diagrams in Fig. 2). The majority (33 companies, 80%) of the examined companies were founded within the last decade. Almost half of the sample (20 companies, 49%) have ten or less employees, followed by the segments of 11-50 and 51-251 employees (13 companies, 32% / 5 companies, 12%). Main locations of the companies are USA (15 companies, 37%), and EU (14 companies, 34%), of which most are located in the Netherlands (4 companies, 10% of the overall sample). Concluding the first step of data gathering, the sample consists mainly of small- and medium-sized emerging companies in Western countries.

The quantification of AM platforms based on their web presences (second step) was done by two researchers independently for each company and consolidated in a discussion in cases of discrepancies. Finally, we developed the following operationalization for the initial categories (c.f., section 2.2):

- Regarding platform providers five value propositions could be classified: Physical AM part covers manufacturing providers which produce physical AM parts. *Digital AM part* includes service providers that develop or refine (parts of) digital models for AM production (e.g., simulate or design). *Software* contains companies that develop AM-specific software (e.g., CAD software). *Service* includes service providers for supplement services that does not directly result in a digital AM part (e.g., AM-specific consulting). *Hardware and supplies* cover companies that produce or trade AM hardware or supplies (e.g., material).
- In contrast to the value proposition, the value purpose of the AM platform could be different, resulting in five slightly different classes: *MaaS* describes platforms that provide decentralized AM production services. *Development of digital AM part* stands for platforms that provide product model-related activities (e.g., marketplaces for 3D models). This also covers data management solutions (e.g., “digital warehouse”). *Software development* describes platforms that enable partners to contribute software modules (e.g., via documented interfaces). *Other AM-related services* accumulate all other services to engage in AM, such as analytics and optimization of (business) processes. *Hardware marketplace* describes platforms that trade AM-related hardware (e.g., 3D printers, spare parts, or material).

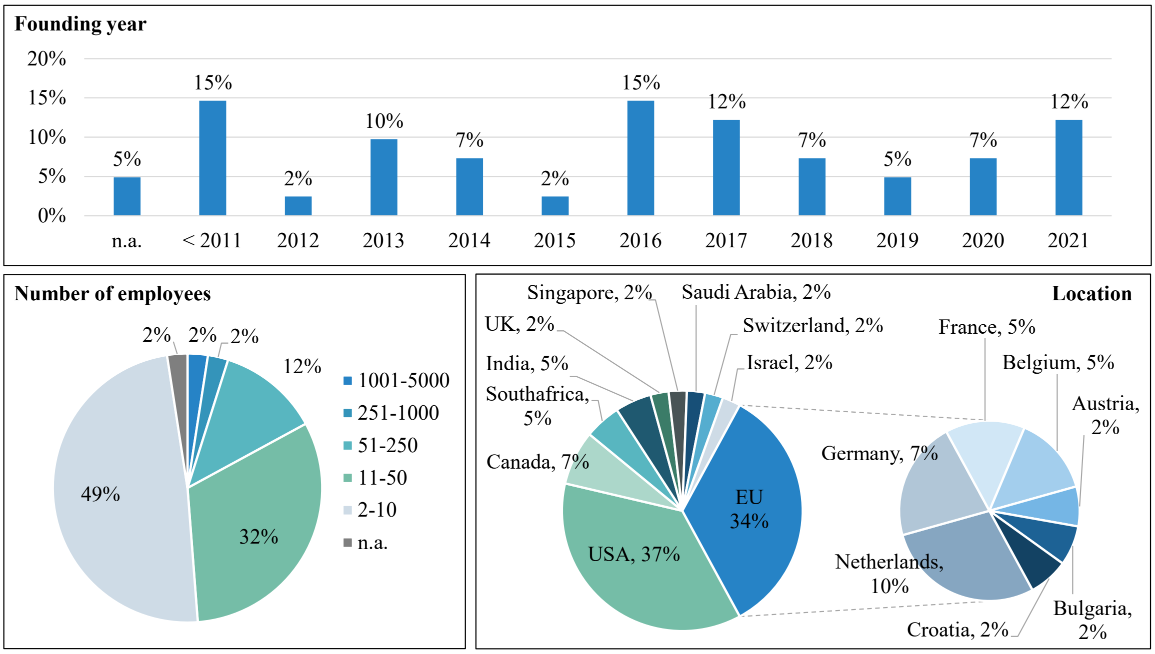

Figure 2. Characterization of the sample (n = 41).

- In terms of platform collaboration, the presence of *partner networks* is indicated by actively promoted partner acquisition (e.g., partner lists, web sections "join the partner network", and registration as a partner). A dependent characterization is whether or not the partner network contains manufacturing partners (partners apply AM in their production).
- Regarding the technology dimension, *AM* and *IT* are distinguished according to their direct or indirect application/value contribution. For instance, explicitly named AM processing techniques are indications of a direct application of AM. IT-related services like simulation or AI-based order matching are indications of a direct IT value contribution.
- Six business (sub)processes covered by the platforms could be identified. *Product development* covers product conceptualization and design, resulting in a digital AM part. *AM pre-processing* includes the preparation of a digital AM part for production (e.g., arranging build batches). *AM processing* results in a physical AM part (half-finished product). *AM post-processing* covers all necessary activities to finish the physical AM part (e.g., surface finishing). *Order fulfillment* aggregates the three activities, AM pre-processing, AM processing, and AM post-processing, into a black box process with a digital AM part as input and a physical AM part as output. All *secondary activities* (e.g., procurement) are aggregated into separate categories.

The complete sample is represented by binary variables expressing whether the value exists (1) or does not exist (0). Subsequently, we identified four different clusters of AM platforms (c.f., subsection 4.1) that allow us to derive patterns of AM value propositions of AM platforms (c.f., subsection 4.2).

4.1 Analysis of AM platform data sample

Data preparation, cluster analysis, and cluster evaluation were performed in SPSS 27. In preparation of the cluster analysis, we identified two highly correlated variables (AM pre-processing and AM processing) which are merged into one variable (Pearson's r = 1). Furthermore, we excluded two outliers (method: single linkage with Euclidean Distance for binary variables).

The clustering on the remaining 39 cases is performed using Ward's clustering method (distance measure: Euclidean Distance) and a validating step with the Two-Step Clustering algorithm with Log-Likelihood in SPSS. We choose a hierarchical agglomerative approach using Ward's algorithm because it performs well for detecting unspecified numbers of clusters and its reliability in terms of cluster recovery of different sizes. Two-Step Clustering is chosen for the validation step because it can detect the optimal number of clusters and works with binary scaled variables (Backhaus et al., 2021). The elbow criterion implies forming four clusters which is confirmed by the results of the Two-Step Clustering (Backhaus et al., 2021). There are slight differences in classification between Ward and Two-Step (3 cases), which is made transparent in Tab. 3, and the cluster size (n_{Ward} / $n_{TwoStep}$) but does not change the overall cluster characterization.

The description of the clusters below is based on evaluating homogeneity (F-measure) and Standardized Mean Difference (SMD, or t value) as proposed by Backhaus et al. 2021 (c.f., Tab. 3). F-measures greater than 1.0 indicate a higher variance of a variable within a cluster in comparison to the sample. Whereas SMD shows underrepresentation (negative) or overrepresentation (positive) of the variable in comparison to the sample (Backhaus et al., 2021).

Cluster 1 (n_{Ward}=11 / $n_{TwoStep}$=11): One-stop AM as a Service

The first cluster is the only cluster that is fully identical in both clustering methods. Platform providers' value propositions within this cluster are categorized into physical AM parts (e.g., AM production providers). Platform value objectives in this cluster mainly focus on MaaS without proposing further services – neither the *development of digital AM parts* nor *other AM-related services*. The partner networks of this cluster are targeted at manufacturing partners. Regarding process coverage, all platforms in this cluster promise customers a seamless and one-stop order fulfillment process.

An exemplary AM platform of this cluster provides detailed information about available AM processes and materials as well as additional production capabilities (i.e., vacuum casting, CNC milling, etc.). Furthermore, they present their global manufacturing partners with key metrics. A prominent button for online quotation is a low entry point to the order fulfillment process. The ordering itself starts with the selection of manufacturing technology and a file upload.

Cluster 2 (n_{Ward}=12 / $n_{TwoStep}$=11): IS-driven AM platforms

Platform providers within this cluster come from the software business. The associated AM platforms are based on the value objectives MaaS and services in terms of the development of digital AM parts as well as other AM-related services. Therefore, the related partner networks mostly consist of different manufacturing organizations but not to the same extent as in Cluster 1. Accordingly, the AM application is mostly indirect, whereas IT has a direct impact. The process coverage of the platforms is ambiguous and could be in product development or secondary activities.

A suitable representative of this cluster is a platform that provides services like production on demand or a digital warehouse. Consequently, this platform offers additional services, e.g., identifying parts with AM potential. The platform promotes the overall benefits for business processes, e.g., minimized lifecycle costs, and reduced downtimes through on-demand spare parts supply. Customers could access the services via a web account.

Cluster 3 (n_{Ward} =8 / $n_{TwoStep}$=10): AM-focused Services

The third cluster is the most heterogenous of the sample (c.f., amount of F-measures > 1 in Tab. 3). The same applies to the platform providers' value propositions, which mainly offer engineering (AM process related) services for either physical or digital AM parts. As in the two clusters mentioned before, the value objectives of the platforms are focused on enabling MaaS. Compared to the first cluster, what strikes is the higher share of direct AM application on the platforms, matching physical AM parts (i.e., value proposition of platform provider) and platform value objective (i.e., MaaS). In particular, AM pre-processing and AM processing are the processes mainly covered by the platforms of this cluster.

Due to the heterogeneity of this cluster, two examples are chosen for illustration. The first example of this cluster provides software for streamlining AM pre-processing and processing. The application integrates with solutions of a wide range of AM-related process coverage (e.g., printer communication or quality assurance). These applications are offered as a cloud-based platform to customers. The second example, is a platform that offers a wide range of applications, i.e., the configuration of mechanical parts (gears) or individualization of products. All applications are integrated into the online platform where the customer could directly order the parts.

Cluster 4 (n_{Ward} =8 / $n_{TwoStep}$=7): AM-suppliers with IS background

The last cluster appears fuzzy since most variables indicate an underrepresentation of values. It contains platform providers whose value proposition is mainly based on software, and some cases in this cluster also provide hardware and supplies. The platforms are mainly characterized by not having a distinct value objective; in contrast, neither they provide MaaS, nor other services. Therefore, the partner networks of the platforms do not include any manufacturing partners, and AM application has only an indirect impact. Some platforms provide value objectives in terms of a hardware marketplace.

Adequate examples for this cluster are a powder-providing platform (material supplies for AM application) and a service provider that provides sets of AM production parameters for certified materials. Both act as marketplaces that offer support for AM applications from different sources.

		Homogenity (F-values) F-values > 1 in red								Standardized Mean Difference (SMD) Releveant values bold, F-value > 1 grey							
	Cluster	C1		C2		C3		C4		C1		C2		C3		C4	
		W	2S	W	2S	W	2S	W	2S	W	2S	W	2S	W	2S	W	2S
Platform provider: value proposition	Physical AM part	0,92	0,92	0,35	0,00	1,13	1,13	0,00	0,00	**0,76**	**0,76**	**-0,57**	**-0,74**	0,55	0,50	**-0,74**	**-0,74**
	Digital AM part	0,00	0,00	1,32	0,79	1,87	2,03	1,09	1,25	-0,38	-0,38	0,11	-0,11	0,36	0,51	-0,01	0,04
	Software	1,31	1,31	0,00	0,00	1,29	1,34	0,60	0,69	-0,38	-0,38	**0,62**	**0,62**	-0,75	-0,48	**0,34**	**0,31**
	Services	0,66	0,66	1,07	1,10	0,50	0,72	0,00	0,00	-0,46	-0,46	0,35	0,27	**0,93**	**0,78**	**-0,82**	**-0,82**
	Hardware and supplies	0,00	0,00	0,00	0,00	1,72	1,37	2,94	3,27	-0,28	-0,28	-0,28	-0,28	0,18	0,09	0,64	0,77
Platform: value objective	Manufacturing as a Service	0,00	0,00	0,00	0,00	0,00	0,00	0,83	0,00	**0,46**	**0,46**	**0,46**	**0,46**	**0,46**	**0,46**	**-1,79**	**-2,11**
	Developemt of digital AM parts	0,65	0,65	0,33	0,36	1,13	1,06	1,06	1,13	**-0,76**	**-0,76**	**0,70**	**0,69**	-0,13	0,07	0,12	0,01
	Software development	0,00	0,00	2,08	1,25	1,72	2,44	0,00	0,00	-0,28	-0,28	0,33	0,05	0,18	0,46	-0,28	-0,28
	Other AM-related services	1,03	1,03	0,61	0,66	0,50	0,72	0,50	0,58	-0,09	-0,09	**0,85**	**0,82**	**-0,57**	**-0,42**	**-0,57**	**-0,54**
	Hardware marketplace	0,00	0,00	0,00	0,00	0,00	0,00	3,68	3,92	-0,28	-0,28	-0,28	-0,28	-0,28	-0,28	1,10	1,30
Partner network	Active network promotion	0,00	0,00	0,00	0,00	2,84	2,47	1,32	1,51	0,33	0,33	0,33	0,33	-0,89	-0,64	-0,07	-0,13
	Manufacturing partner	0,00	0,00	0,35	0,69	1,13	1,18	0,00	0,00	**0,74**	**0,74**	**0,57**	**0,36**	-0,55	-0,29	**-1,32**	**-1,32**
Technology	AM application (direct/indirect)	1,25	1,25	0,00	0,00	0,98	1,22	0,00	0,00	-0,51	-0,51	**0,66**	**0,66**	**-0,95**	-0,63	**0,66**	**0,66**
	IT application (direct/indirect)	1,30	1,30	0,43	0,46	1,46	1,36	0,64	0,73	0,24	0,24	-0,39	-0,37	0,55	0,32	**-0,30**	**-0,26**
Process coverage	Product development	0,00	0,00	0,98	1,03	1,08	1,12	1,08	1,15	**-0,82**	**-0,82**	**0,51**	0,45	-0,07	0,18	0,43	0,32
	AM pre-processing & processing	0,00	0,00	1,16	0,96	0,55	0,44	0,55	0,63	**-0,70**	**-0,70**	0,17	-0,13	**1,13**	**1,19**	**-0,44**	**-0,40**
	AM post-processing	0,00	0,00	0,00	0,00	3,68	3,20	0,00	0,00	-0,28	-0,28	-0,28	-0,28	1,10	0,83	-0,28	-0,28
	Order fulfillment	0,00	0,00	1,09	1,05	1,10	1,10	0,51	0,00	**0,78**	**0,78**	-0,07	0,04	0,02	-0,03	**-0,99**	**-1,25**
	Secondary activities	0,00	0,00	1,46	1,50	0,69	0,55	1,47	1,57	-0,54	-0,54	0,44	0,52	-0,25	-0,31	0,34	0,46

W: Ward method; 2S: Two-Step
Overrepresentation of 'no' or 'direct' (Coding 0) is indicated by negative SMD values.
Overrepresentation of 'yes' or 'indirect' (Coding 1) is indicated by positive SMD values.

Table 3. Cluster evaluation.

4.2 Patterns for AM Value Creation

Identification of patterns for AM value creation on AM platforms is based on two dimensions related to the value creation of the platform provider and the platform of the clusters. Regarding the platform provider delimitation of value proposition in physical (i.e., physical AM part because hardware and supplies are not dominant in any cluster, c.f. C1 and C4) and non-physical (i.e., digital AM part, software, and services) seems suitable. Likewise, the value objectives of the clustered AM platforms suggest a distinction between whether the value objectives contain MaaS. Consequently, patterns could be identified regarding the variables of the five dimensions of AM platforms (c.f. section 3 and Tab. 3). The results are five different patterns (P1-P5) structured in Fig. 3 and described below. The first two patterns are related to a physical value proposition of the platform provider (tangible AM parts) and a value objective of AM platforms that offers MaaS.

<u>P1 – Attract partners</u>: The attraction of partners with the same background as the platform provider (AM production) for integration into the network is a key pattern in C1. This pattern could be achieved in different ways. A common approach is to visibly seek for new partners on the landing page (e.g., contact form or special registration forms for partners).

This might generate additional manufacturing capacities and unlock a wider range of production technologies. Both effects scale the network. Therefore, a high degree of expertise in the same discipline (i.e., AM production) could lead to efficient collaboration and flexible production. Each manufacturing partner broadens its potential customer base. A downside of this pattern might be a power asymmetry between the platform provider and AM production providers, who compete on the same offerings.

P2 – Aggregate main service: It is noticeable that platforms in C1 do not specify diverse AM-related services but aggregate a one-stop order fulfillment service. Therefore, the second pattern focuses on a central service to the customer (i.e., MaaS) combined with holistic process coverage. The platform provider's leading mainly originates from two circumsatnces: Firstly, his knowledge about value creation based on tangible AM-parts and knowhow of AM application. Secondly, his superior process integration approach among multiple ecosystem partners, enabling an intra-organizational manufacturing process based on AM technology.

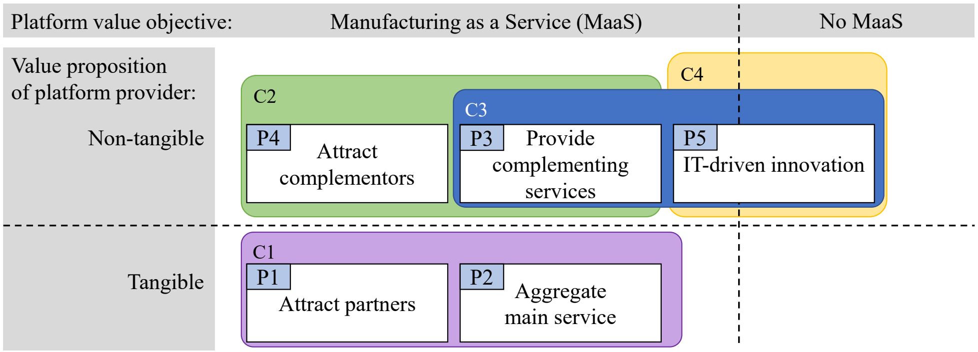

Figure 3. Patterns for value creation on AM platforms with root clusters (C1-C4).

The following two patterns are derived from clusters that provide a value objective based on MaaS with a non-physical value proposition of the platform provider.

P3 – Provide complementary services: In terms of different categories of value proposition and various covered AM activities of the platform, complementary service offering is observed. These services express the heterogeneity of the platform and the possibility of bundling the strength of different partners into a value objective. Furthermore, these services could be provided/requested separately, i.e., automatic part generation, lightweight optimization, and on-demand production services. The following pattern P4 aligns with that.

P4 – Attract complementors: Interdisciplinary network partners (e.g., software-related platform providers that enable different AM service providers) collaborate mainly as complementors. These partners tend to depend strongly on each other, whereas direct competition between the platform provider and the partner network participants is not evident. For instance, on-demand production requires know-how in AM production technology, production planning, and capacity management.

Eventually, the specific IT backgrounds of platform providers (non-physical), regardless of the MaaS value objective on the related AM platform, constitute the last pattern.

P5 – IT-driven innovation: Specific value contribution by innovative IT applications is another characteristic of AM platforms. This pattern heavily relates to whether the AM platform provider is related to a non-physical value proposition. The direction to IT-driven innovation is probably a part of the seed in the incubation phase of such platforms. As a result, interdisciplinary platforms with complementary services promote innovative IT capabilities (e.g., Machine Learning for production planning).

Possible implications at the business model level, as well as implications for platform theory in general, are the subject of the discussion in the following section.

5 Discussion and Implications

Coping with the increasing digitalization of industrial processes, many industrial organizations without knowledge of platform business models experience challenges. While, on the one hand, platform business models hold new potential for digital services or new revenue streams for manufacturing companies, they also require a complete realignment of business processes. Against this background, the achieved classification of AM platforms, including the related patterns to position the platform in a competitive market, guide decision-makers in manufacturing organizations. In particular, the results offer orientation in the strategic decision about establishing a platform business model coupled with the AM domain entering.

The results enable practitioners to analyze if the manufacturing and business processes and the controlled IT and AM capabilities of their companies can be linked to one of the identified patterns to estimate what is missing for the realization of the clustered platform business models. In particular, our study shows how the different AM platform types can facilitate industrial value creation and what the industrial firms need to transform their value proposition by incorporating disruptive IT innovations such as AM platforms. Extant research has already identified how valuable the pattern-based innovation process can be (Drewel et al., 2020). Organized in a catalog, patterns can help practitioners without in-depth knowledge of critical determinants during the business model ideation to close business-related knowledge gaps and understand value mechanisms faster (Drewel et al., 2020). Hence, our results support practitioners in comparing their value creation with the identified patterns, supporting business model innovation. Furthermore, our results contribute to a theoretical perspective of platform business model innovation. Schoormann et al. (2021) revealed how reflection theory could be useful in business model design activities. The theory implies that a business model designer uses other experiences to get inspiration for solving new problems to perform design activities (Schoormann et al., 2021; Daudelin, 1996; Schön, 1984). In our context, decision-makers of manufacturing organizations could face multiple difficulties. They could stem from either process reconfiguration to enable MaaS or complementary AM-related services for customers, opening the platform for external partners, or sustaining an active partner network. Hence, our results can be used to extend the library of patterns on disruptive transformation of value creation through AM platforms, supporting decision-makers' inspiration.

The applied systematical screening of AM platform websites helps to understand the particular state of the industrial platform application. First, we discover that AM platforms, which often support MaaS, exploit information asymmetries. Prior research describes how creating transparency is one of the curating activities of platform providers, which increases the trust in the platform ecosystem and positively affects the value proposition (Cusumano et al., 2019; Sklyar et al., 2019). Nevertheless, our study reveals that several AM platforms (except the marketplaces for hardware in cluster 4) do not provide transparency, hiding the participants of the production networks or prices. This observation leads us to the assumption that the innovation of the production process may well outweigh transparency as an incentive to use a platform. Second, platforms are known to evolve towards hybrid multi-sided platforms (Trabucchi and Buganza, 2022), a phenomenon we also notice in the AM domain. According to our sample, AM platforms can start with a portfolio of manufacturing processes, enabling MaaS, and expand it with complementary digital services such as product design, engineering, inventory management, certification, or digitally processed intellectual property protection in the sense of patenting the AM products. Third, we also see a lack of business models based on modular software architectures to foster complementary innovations, which are conceptualized as innovation platforms (Cusumano et al., 2019), such as the enterprise ERP systems or IIoT platforms supporting AM or operating systems for 3D printers (Arnold et al., 2022; Sarker et al. 2012). Initially, we identified some firms providing similar software solutions, which can be understood as innovation platforms (Cusumano et al., 2019). However, after evaluating the initial set, we excluded such AM software providers as outliers, as they do not pursue a platform business model and only license this software to others. Thus, owners of such software have a traditional software licensing business model, which can, however, enable other companies to become innovation platform providers. This finding has implications for the positioning of platform business models in the niche in which there is still hardly any competition. In addition, it shows that modular, expandable operating systems for printers with a high degree of openness and an integrated transaction platform in the form of an industrial app store (Petrik et al., 2022; Gawer, 2020;) are still missing and can become the subject of further research in the AM domain.

In addition, from a theoretical perspective, our study contributes to the platform-related body of knowledge. Our findings offer new insights into the platform bundling strategy and the platform distinctiveness (Liu et al., 2022; Henfridsson et al., 2018) of platform business models under competition (Durand and Haans, 2022). The empirically discovered patterns of platform value propositions represent different points of distinctiveness for AM platform providers. Given the presence of overlapping customer groups of platforms to reconfigure manufacturing through AM or MaaS, the results help to find market niches where new AM platforms with untapped value offerings might capture value. The specific characteristics of distinctive AM platform business models support the strategic positioning (Weiller and Neely, 2013) of the platform business model, where platforms are conceptualized as open-ended value landscapes. As demonstrated on the example of the AM domain, this happens predominantly by creating distinctive value propositions and value objectives on the platform. These two determinants are crafted by the combination of (1) IT value creation, (2) AM technologies and the resulting (3) process innovations, (4) partner network, and (5) mastering the necessary AM and IT technologies. The derived patterns indicate that a multidimensional view on the intertwined configuration of the five dimensions impacts the platform distinctiveness.

6 Conclusion, Limitations and Outlook

The results provide a starting point for more in-depth analyses of the optimal degree of distinctiveness, especially since three clusters of a supposed homogeneous AM platform business model, focusing on enabling MaaS, were uncovered and rounded off by two more distinct clusters. A future in-depth empirical study with representatives of the identified platform providers would also provide further insights into the platform bundling strategy. In particular, insights that are not discoverable via content analysis of websites, such as specific boundary resources for partner networks, capabilities, value capture mechanisms, and the influence of competitors' AM platforms for building entrepreneurial heuristics. This would also allow us to contribute to the influence of IS (AM platforms) on developing heuristics in platform establishment (sustainable platform establishment). Hence, the main limitations of our work arise from the analyzed data sample. Firstly, the single-sourced search for AM platforms on LinkedIn may not include every AM platform provider, especially from the non-English hemisphere. Therefore, the dataset and thus also the identified clusters and patterns do not claim to be complete. Secondly, the data sample is mainly based on the self-description of the companies on LinkedIn and their website. Accordingly, the companies' self-disclosures may also be exaggerated, e.g., promotion of platform-based services that are hardly offered or not actually implemented, yet.

Furthermore, the generalizability of our results should be reflected. Focusing with AM only one specialized domain, may restrict the transferability of the value proposition patterns to other domains. In the context of production process innovation, the identified value proposition patterns can nevertheless help in business model development, following the principles of reflection theory. In this context, the patterns, understood as experiences or heuristics of platform providers from the AM domain, nevertheless support the reflection processes in the design of platform business models, especially in the transformation of production companies that may lack knowledge of platform establishment (Schoormann et al., 2021; Drewel et al., 2020).

However, further investigation of the identified clusters is needed to derive business model archetypes and, for example, to complement the work of Weking et al. (2020) with a focus on the peculiarities of the AM domain and the platform establishment within it. Besides, when targeting the implementation of AM platforms, our findings also provide a foundation for a research avenue on organizational capabilities that are supported by the discipline of enterprise architecture management. Following this avenue, enterprise architecture management must be adapted accordingly to ensure platform ecosystem establishment, supported by a beneficial interplay of business processes and technologies (Lachenmaier et al., 2018).

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