Matching Supply and Demand in Collaborative Additive Manufacturing

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Abstract. *Due to an increasing individualization of products, additive manufacturing is often seen as a solution to cater for more sophisticated customer requirements. In order to fulfill customer needs, manufacturers have to rely on collaboration to distribute risk and improve the utilization of their resources. In this paper, we used qualitative interviews to define requirements for a marketplace that allows the automatic exchange of additive manufacturing capacities. From these requirements, we derived a conceptual model that matches orders to sales offers while taking specific product requirements, such as quality, into account. Additionally, we implemented a demonstrator to evaluate the model with potential buyers and sellers of additive manufacturing capacities. Our research showed that most requirements could be implemented in a marketplace. However, we could show specific limitations for particular requirements.*

Keywords. Additive Manufacturing • Sharing Economy • Sharing Capacities • Production Networks

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1 Introduction

Manufacturing industries face increasingly sophisticated customer demands, dynamic markets, and cost pressure. In a globalized and digitized business environment, these challenges question established strategies and business models. Current trends like *Industry 4.0* or *Internet of Things* influence and alter production concepts. Maintaining lead times, capacity utilization, and delivery times with demanding target values constitute a further challenge for the companies' operational processes. Their production capacity essentially determines manufacturers' ability to meet these changes and challenges. A key factor for the competitiveness of manufacturers is to overcome the trade-off between availability and production capacity-related costs (Schuh et al. 2017). A high number of orders which cannot be fulfilled by available capacities results in delays or non-fulfillment of orders with negative consequences on sales and profits. In this case, companies are forced to react flexibly. They can either internally use other machines or production capacities to meet customer demands or outsource to external suppliers. Underutilization, in contrast, imposes the risk of fixed costs that cannot be fully covered. This leads to the question of an ideal number of production machines to meet fluctuating capacity needs, a high number of variants, and varying quantities. Investments in additional production facilities, which are intended to cover temporary peaks in demand as a buffer, reduce a company's profitability if the resulting costs and capital commitments cannot be fully compensated on both revenue and financing perspectives.

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Furthermore, the integration of intra- and inter-organizational structures is gaining importance. Due to increasing specialization and the focus on core competencies, the competitiveness of today's companies is not limited to individual companies or a few linear supply chains, but mostly to highly specialized value creation networks (Basole et al. 2018). In addition to numerous positive effects, a high level of cooperation and collaboration results in direct and indirect dependencies between stakeholders and participants in value creation networks, which may cause single points of failure (Li et al. 2015).

Complex material flows characterized by short delivery times are supported and controlled by integrated information systems (Schuh et al. 2017). *Industry 4.0* scenarios require seamless integration within the manufacturing environment of industrial companies, as well as inter-company business processes through advanced information and communication technologies. Integrated data sets, e. g. of production capacities, delivery times, or quantities, for performing scheduling activities are provided by information systems for production planning (Chen 2007). Despite various company-specific functionalities of these software systems, there are still significant deficiencies regarding the ability to react to unexpected situations, especially in a collaborative network between multiple participants (Schuh et al. 2017).

By integrating available data into a platform for production capacities, information, e. g. on the type and current availability of machines, dimensions, costs, and prices, can be provided. Thus, supply and demand for production capacities can be connected, enabling manufacturing companies to adapt to dynamic market conditions by offering or sourcing production capacities to other market participants. Furthermore, this fosters collaboration, communication, and the coordination of distributed stakeholders. It allows potentials for increasing efficiency, e. g. in terms of capacity utilization, ability and time of delivery, flexibility, transparency, trust, costs, and capital commitment. Integrating business information systems on an intra- and especially inter-organizational level is, therefore, of both operational and strategic importance.

In this paper, we seek to design an IT artifact for matching production inquiries and sales offers on an e-commerce platform for additive manufacturing capacities. Based on the principle of the *Sharing Economy*, the aim of *Sharing Production* is to link supply and demand on a platform, thus enabling the use of free production capacities for third parties. Therefore, the platform operationalizes data from multiple manufacturers. It provides the basis for reducing risks caused by a lack of orders. A flexible reaction to various fluctuations in demand may be improved. Against this background, we seek to yield improvements in various dimensions, such as performance, quality, and costs.

Well-known examples in B2C environments showing evidence of successful operations of platforms for brokering capacities in different application scenarios are companies such as Uber for transportation or Airbnb for housing (Cusumano 2015; Oskam and Boswijk 2016).

In contrast to traditional manufacturing, additive manufacturing disrupts the industry, as it allows manufacturing highly differentiated products with minimal setup costs. Therefore, it is more flexible and subject to fewer constraints (Petrick and Simpson 2013; Stein et al. 2019; Thiesse et al. 2015). Hence, the production technology of additive manufacturing provides the optimal starting point for this research problem. It allows us to build a proof of concept and a foundation for similar solutions addressing other industries' requirements or production technologies.

The contents of this paper extend previous work (Freichel et al. 2019) by providing more details and grounding on the requirements, extending and enhancing the developed model, implementing and testing the model and providing further material in the appendix. To structure our work and emphasize its focus, we define the following research questions (RQ):

1. What are the requirements for a marketplace that enables manufacturers to exchange additive

manufacturing capacities and how can they be categorized?

2. How can a model be designed that matches purchase inquiries and sales offers based on the requirements?
3. How can we realize a practical implementation of a marketplace for production capacities and evaluate it based on the model?

To answer these research questions, we structure this study as follows: we present related work on platforms and collaborations in supply networks in the subsequent Sect. 2. We describe the applied research methodology of Design Science Research and an interview study in Sect. 3 and present requirements for capacity exchange as result of our interview study in Sect. 4. These are subdivided into 4.1 *Business Requirements* and 4.2 *Technical Requirements* with four categories *Quality*, *Material*, *Technology*, *Intended Use* and *Post-Processing*. Subsequently, we integrate our findings and build a conceptual model for the matching of purchase inquiries and sales offers in Sect. 5. The practical implementation and scenario-based evaluation of a prototype marketplace is described in Sect. 6. Ultimately, Sect. 7 concludes this study with a summary of findings, limitations, and future research potentials.

2 Foundations and Related Work

We position our research at the intersection of the following topics in information systems research: decentral coordination and collaboration, sharing platforms, and capacity-sharing in additive manufacturing.

The concept of *Collaboration* in value-added networks or supply networks as one approach to connecting manufacturers is gaining increasing importance for companies to realize continuous performance improvements (Grigoriev et al. 2017). It is characterized by sharing information, knowledge, risk, and profits (Mentzer 2000). Companies' high demands can be met by collaboration to leverage strategic economies of scale, specialization, integration, and cost and time efficiency (Chen et al. 2017; Logan 2000; Soylu et al. 2006).

The extended approach of *Shared Value* as well as the ongoing trend of sharing rather than owning goods described by *Sharing Economy* leads to a rethinking and reorganization of established business activities (Porter and Kramer 2019; Stephany 2015). New technologies and business models, as well as increasing networking between actors, are changing markets, reducing transaction costs, and creating opportunities to bring together suppliers and consumers. In this process, products are augmented or replaced by services. The exchange of these services can be implemented through various (internet-based) business models.

Electronic Platforms are used to realize e-business activities. While e-procurement contains purchasing and e-shops sales activities, e-marketplaces are used to exchange products and services by connecting buyers and sellers (Bailey and Bakos 1997). We focus on a digital marketplace for connecting suppliers and buyers of additive manufacturing capacities. Building a platform for collaborative additive manufacturing requires profound knowledge about corresponding production processes, configurations, as well as influence factors.

In general, *manufacturing* defines an industrial production process, describes the way in which something is made, and specifies it in geometric and material terms (Fritz and Schulze 2008). The terms production and manufacturing are often defined as synonyms in literature and practice. Manufacturing can be seen in a functional sense as a special form of production or in the institutional sense as a department in a company in which the production process takes place. While manufacturing mainly comprises the production of physical goods, the creation of services or information, as well as rights in addition to output factors, is usually assigned to the concept of production (Schuh and Schmidt 2014).

Manufacturing technologies described with the term *3D printing* have gained increasing attention in the last years, despite the fact that the development started in the 1980s (Carver et al. 1990; Fudim 1988; Sachs et al. 1990). Although the term *3D printing* has gained common acceptance, it only describes one way within the variety of processes belonging to the field of additive manufacturing. Additive manufacturing processes use digital models that are converted into layer models and add material in layers to obtain a desired object (Atzeni and Salmi 2012; Gibson et al. 2015; Petrovic et al. 2011). Although not replacing traditional production methods in all sectors, additive manufacturing represents a revolutionary process in the range of production methods and enables new applications that offer promising possibilities for industry (Holweg 2015). Economic factors such as quantity, cost, complexity, or processing time of the parts as well as technological factors such as product size, mechanical properties, quality characteristics, functionality, or quality standards are factors influencing the choice of production methods.

In this study, we assume that the platform participants already obtained knowledge about the suitability of additive manufacturing. Therefore, the decision was made before using the platform and will not be considered there. As a basis for this study, we performed an in-depth analysis of technical documentation for additive manufacturing machine types, which we summarize in the following. The findings serve as a conceptual foundation of clustering the multitude of additive manufacturing technologies, machine types, and suitable characteristics.

Tab. 3 in the Appendix provides an overview of all relevant additive manufacturing processes. Literature doesn't use a uniform structure for classifying the detailed technologies. One reason may be the tremendous technological development speed in recent years and a high level of uncertainty about future trends. Hence, the technologies are sorted alphabetically and assigned to the process classes according to DIN EN ISO/ASTM 52900 as well as to the three categories liquid-material process, free-space process, and powder-bed process (DIN 2015). Although all manufacturing processes are based on the general manufacturing steps already explained, they differ for example in terms of how the respective layers are manufactured and bonded and which material is processed.

The processed materials are grouped into the material groups ceramic, plastic, metal, and wax. For example, synthetic resins such as epoxy resin belong to the group of plastics. If other materials are possible for processing, they are grouped under the heading “others” due to their lack of relevance. Synonyms of the detailed technologies can be found in one table field. The categories and ISO process classes of additive manufacturing technologies listed in Tab. 3 in the Appendix are shortly discussed as the basis for the matching. Advantages and disadvantages, as well as areas of application of the respective technologies, are not relevant for this work since the e-commerce platform is not intended to serve as a decision-making device for additive manufacturing processes for the time being.

Liquid-material processes or Vat (Photo) Polymerization according to DIN EN ISO/ASTM 52900 describe the selective solidification of liquid materials by UV radiation (DIN 2015). The liquid-material processes differ in the type of contouring and generation of the radiation. All technologies require support structures, which are already added in the 3D CAD model and, for instance, fix overhangs and temporarily unconnected areas (Gebhardt et al. 2016). The processes of polymerization show limitations due to the processing of polymers and resins, which are limited in their strength. The technologies are, therefore, primarily suitable for prototype production (Bikas et al. 2016).

Free-space processes include three process classes named material extrusion, material jetting, and sheet lamination for plastics as well as direct energy deposition for metals (DIN 2015). Free-space processes produce parts in free space, for instance on a printing bed. Material extrusion comprises technologies that directly deliver liquid or previously melted material through extruders, usually in the form of wire (filament). The material bonds with the underlying layer and solidifies rapidly by cooling (Bikas et al. 2016). Material jetting refers to additive manufacturing processes, which – similar to conventional inkjet printers – spray melted material under the control of fine nozzles (Bikas et al. 2016). Sheet lamination describes manufacturing technologies for building up components layer by layer from paper or plastic. The sheets, e. g. foils or plates of the building material, are cut by laser or knife and joined together by adhesive bonding, ultrasound, soldering, or diffusion welding (Gebhardt et al. 2016).

Powder-bed processes, which process plastics, share some similarities. Powdery material, which is located in the powder-bed, is glued, lasered, or hardened at the points where the component has to be formed. Subsequently, after lowering the building platform, it is again covered with a layer of powder by the amount of one layer thickness. As a result, the part is created by repeating the connection of the powder particles and the individual layers, while the surrounding loose powder can serve as supporting material for some technologies (Gebhardt et al. 2016).

3 Research Methodology

The following section introduces the research methodology. The first subsection describes the design science research (DSR) methodology used to construct the model. Artifacts constructed with DSR have to be adapted to the needs of their environment. To ensure practical relevance, we conducted an interview study with experts from the field. The methodology of the interview study is described in Sect. 3.2.

3.1 Design Science Research

The structure of this work follows the methodological approach of DSR. According to Hevner et al. (2004), DSR pursues the goal of creating new and innovative artifacts and thus solving real human and organizational problems. Artifacts are objects created by humans for a practical purpose encompassing constructs, models, or methods (Wieringa 2014). The main objective of this work is to develop a conceptual model and matching process for additive manufacturing capacities. For this reason, the paradigm of DSR is chosen as a method and design concept for this paper. The model to be designed can be classified as a second level contribution of DSR, which leads to the opportunity to abstract and develop the design theory within it (Baskerville et al. 2018).

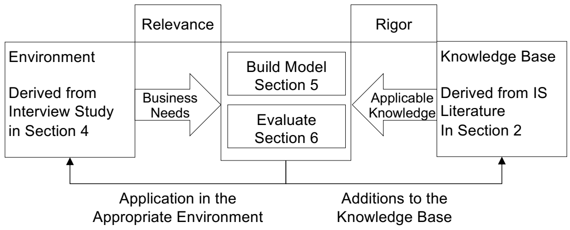

Figure 1: Design Science Research (based on Hevner et al. (2004))

We utilized the DSR framework by Hevner et al. (2004) to ensure *relevance* and *rigor* in of the developed model. The relevance was ensured by interviewing practitioners, that specified their business needs. The relevance cycle was completed by providing a prototypical implementation based on the model developed in this paper. To ensure rigor, we derived a broad knowledge base from IS literature as well as engineering literature. Finally, we completed the rigor cycle by sharing our results with the scientific community. The framework is summarized in Fig. 1.

The DSR process we chose follows the guidelines established by Peffers et al. (2007). The complete process of DSR consists of six steps and is displayed in Fig. 2.

The first step is the *problem identification and motivation*, which have already been discussed in Sect. 1. The second step is to define the *objectives of a solution*. For this step, we conducted a qualitative study among experts, which is described further in Sect. 3.2. The result of these interviews is a set of requirements that are summarized in Sect. 4. We use the data collected through the interviews to *design a model*, that enables matching products to additive manufacturing machines. This is the core of this paper and is described in detail in Sect. 5.

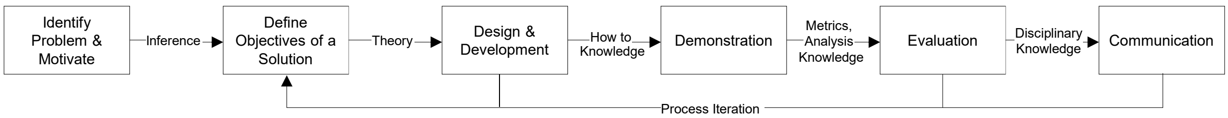

Figure 2: Process of Design Science Research (based on Peffers et al. (2007))

To *demonstrate* the model, we implemented a prototype based on the conceptual model. This is the fourth step in the design science process. We used the implementation to *evaluate* our model as the last step of this paper to verify the applicability and feasibility of our solution. For the evaluation we chose a scenario-based evaluation (Hevner et al. 2004). For this, two scenarios were chosen to be performed on the implemented platform. One from the buyer side and one from the seller side. The implementation and evaluation are described further in Sect. 6.

If there is a need for improvements, the process returns to the design step and is repeated from there. If the artifact fulfills the requirements, Peffers et al. (2007) proposes an additional step, the *communication* of the results in scholarly or professional publications.

3.2 Interview Study

To determine the requirements for the conceptual model, we employed a quantitative research design based on expert interviews. We rely on an explorative research approach that integrates the perceptions and opinions of multiple stakeholders with extensive knowledge and experience in the domain of interest. In the following section, we describe the selection of interview partners, the design of the semi-structured questionnaires as well as the procedures performed for data collection and analysis.

Selection of Interview Partners

We selected interview partners as experts from the following groups: (1) *potential buyers of additive manufacturing capacities*, (2) *potential sellers of additive manufacturing capacities*, (3) *producers of machines for additive manufacturing* and (4) *platform providers*. The interviewees all have knowledge about IT and management concepts as well as additive manufacturing technologies. We did not restrict the interviews on companies that already use additive manufacturing, but also those who intend to use it in the future.

We chose experts and companies according to market position as well as experience with additive manufacturing and e-commerce platforms. Additionally, we considered companies from different industries and of different sizes.

The final set of interviewees consists of experts from three companies from each of the two groups of potential buyers (buyer A, buyer B, buyer C) and sellers (seller A, seller B, seller C), two manufacturers (manufacturer A, manufacturer B), and one platform operator (platform operator A). We had to restrict the interviews to only one platform operator since the market of additive manufacturing platforms is very restricted.

Questionnaire Design

The questionnaires were group-specific and semi-structured. Each questionnaire contained basic information about the topic and guidelines for the interviewees as well as the questions themselves.

The questions can all be answered openly to provide the opportunity to include emerging concepts and ideas (Edwards and Holland 2013; Paré 2004). Besides essential, factual, or direct questions that address the key topic of this study, so-called *throw-away questions*, introductory, and structuring questions were used to guide the interview progress.

After introducing the interviewees to the topic, we started the interview with two questions about their educational and work background to allows us to conclude their knowledge of the topics and, therefore, the quality of their answers.

The following section of the questionnaire contains two general questions that set the topic and prepare the interviewees for the following, more complex questions. These questions ask about potential benefits, challenges, and risks of exchanging additive manufacturing capacities.

The third part varies with each expert group. Manufacturers and platform operators are asked about their portfolio of additive manufacturing technologies and machines, as well as the decisions behind the characteristics of the technologies and machines. Buyers and sellers of capacities are asked about their internal and external production capacities, and whether they are willing to participate in a sharing platform.

In the fourth section of the questionnaires, the manufacturers and platform operators have to provide information about the machines they use and offer, such as target groups and industries, applications, and covered product categories. The buyers and sellers of production capacities have to provide information about the required manufacturing processes and characteristics that they use to distinguish processes and machines.

The last part of the questionnaire for platform operators concerns the necessary attributes to match products and additive manufacturing processes. The buyers and sellers are asked about the characteristics of additively manufactured products, such as the used material and size of the products.

Data Collection and Analysis

In the following section, we describe the data collection and analysis procedures we applied in our study. To ensure that the questionnaire was understandable, well-structured, and of reasonable length, we conducted a pilot study with two independent researchers (Berg 2001). We applied only minor changes to the final questionnaire we used for the interviews.

Even though personal interviews are recommended for best results, we conducted the interviews by phone due to the geographical segregation of the interview partners (Berg 2001). The interview partners were asked for consent to record the interviews, which were, therefore, documented as audio recordings.

We applied the data analysis process, as suggested by Kuckartz (2014). In the first step, we transcribed the recordings literally, adapted the sentence structure, deleted filling words, and anonymized the final transcript.

For the analysis, we coded the transcripts, which allows us to break down relevant information into keywords. To do so, we analyzed the frequency of certain keywords and their synonyms to determine suitable codes and sub-codes. Finally, we grouped the codes into categories and checked whether all relevant questions were covered by codes. The coded information could then be used to derive the requirements for capacity exchange.

4 Requirements for Capacity Exchange

In this section, we present requirements for a capacity sharing marketplace. By introducing the requirements in different interdependent categories, we answer RQ1.

In previous work, the data analysis of the interviews yielded 371 coded text passages relevant for this research. This analysis is carried out by means of a category-based evaluation (Kuckartz 2014). Within categories, we define requirements for the process of developing the matching and thus exchanging additive manufacturing capacities via an e-commerce platform. The text passages were restructured for this paper to highlight the interdependencies of the requirements. In addition to *business requirements*, the passages are grouped into five categories of *technical requirements* (1) quality, (2) additive manufacturing technologies, (3) material, (4) intended use and (5) post-processing.

Besides the five main categories of technical requirements, *connection categories* are added. *Connection categories* contain statements that could not be assigned to a single category, or statements which showcase dependencies between main categories. For example, one connecting category is called *Quality–Material*, short *QM*. Quotations are numbered according to their appearance in the interviews and partly mentioned in the following text. Cited quotes and further related statements are classified in an overview table (see Tab. 4 in the Appendix). Properties and attributes that are included in the conceptual model are shown in italic letters.

4.1 Business Requirements

We obtained an appropriate result of four business requirements within the framework of the interview study, which are presented in the following.

Requirement 1: Additive manufacturing processes for plastic materials must be evaluated for exchanging manufacturing capacities in a first step, as these are most frequently used in practice.

One of the codes contains selected additive manufacturing technologies represented by subcodes. According to the experts, processes for plastics are most frequently used in an industrial context. The companies named the technologies Stereolithography (SLA), Binder Jetting/3D Printing (BJ/3DP), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Multi Jet Fusion/High-Speed Sintering (MJF/HSS), Multi-Jet Modeling/PolyJet (MJM/PJ) and Digital Light Processing (DLP)(PS1, PS2, PS3, PS4, PS6). Experts have described these as standard technologies. The material group plastics represents the largest group of materials for additive manufacturing and is, therefore, the first material category to be considered (Gebhardt et al. 2016; Statista GmbH 2021). Furthermore, the subcode plastics implies that buyers A, B, and C mainly manufacture plastic products. The focus on the material group plastics could thus be decided.

Requirement 2: Additive manufacturing processes for metal materials must be included in a second step due to high relevance in industrial production.

Following the manufacturing processes for plastics, experts attribute high importance to Selective Laser Melting (SLM) as manufacturing technology to process metals (PS5). Among the interviewees, manufacturer B describes the advantages of the SLM process in particular detail: "On the one hand, there is a large variety of materials that can be processed. You can process almost all types of metals that can be pulverized. On the other hand, the devices are relatively flexible in their settings for different parameters" (TM8, TM9). This was assigned according to the material group *metals* through codes and should be included in further research due to its relevance. Metals are especially interesting for stable and light structures such as bionic structures, as these parts can be produced with very thin walls on metal printers (UM5).

Requirement 3: There is increasing potential for small series as well as series production in additive manufacturing. Therefore, the attribute *quantity* must be included in this analysis.

In a first step, the subcodes *prototypes*, *customized production*, *spare parts*, *small series* and *series production* are used to determine the purpose for which additively manufactured products are used. According to the experts, the products are mainly used as prototypes, individual production, and spare parts. According to buyers A and C, platform operator A and seller C, there is increasing potential of small series and series production. Manufacturer B has evolved from its original focus on prototype types to a manufacturer of additive production equipment for the production of functional components. Buyer B only focuses on individual production, which is in the focus of the company's business model. Both manufacturer A and seller A build spare parts or individual products for their own requirements for additive production machines. Small series and series production are often related to quantities. For example, platform operator A applies small series for quantities of 10 to 100 parts, while buyer A suggests that additive manufacturing is beneficial even when producing more than 100,000 parts.

Requirement 4: The platform should match production jobs based on *costs* and *prices* as well as production *capacity* and *times*.

Production costs and time are one criterion for selecting additive production devices in comparison to conventional production processes and constitute an important requirement for the platform.

One relevant code of category (1) *characteristics of additive manufacturing technologies and machines* is costs. According to buyers B and C, the current production costs are one criterion for selecting additive production devices in comparison to conventional production processes. A distinction is also made between additive manufacturing processes with regard to acquisition costs as well as manufacturing and material costs. While manufacturer A describes the FDM process as the most cost-effective (PS4), some processes have a comparably high material consumption or material cost (TC3). In general, there is always a trade-off between the quality of the final product and costs. Seller A states that for prototypes, they "use a mixture of material features and price" for their decision (UM2). Costs and price mechanisms were included in the present work. However, in further work, a distinction can be made between material costs/prices, production costs/prices, and delivery costs/prices.

While "mostly the factor costs differentiates technologies‘, speed is another important influencing determinant (TC4). Seller A and manufacturers A and B distinguish between machines according to their speed/production time (T3), e. g. influenced by the size of the print head or the number and strength of the lasers in the SLM process (T10, T14). Buyer C considers speed to be an important factor in the purchase of additive manufacturing capacities (T2). The relevance of the delivery time was emphasized according to buyer B: 'For us only the delivery time of products is relevant. Of course, it depends on the priority of the order. Normally we need our products within two weeks" (TC2). Likewise, buyer C attaches importance to a certain speed. Buyer A emphasizes that they often choose suppliers with the shortest production time (TC1). No distinction was made for buyer C between production and delivery time (T2). Since production speed is dependent on the used technology, material, and quality in the sense of layer thicknesses and therefore requires a comprehensive analysis for comparability, separate research should be carried out in this respect. The dates indicated for buyers are the sums of production and delivery times.

We summarized these requirements in Tab. 1.

Table 1: Summary of Business Requirements

No.	Name	Definition
REQ 1	Plastic Materials	Additive manufacturing processes for plastic materials must be evaluated for exchanging manufacturing capacities in a first step, as these are most frequently used in practice.
REQ 2	Metal Materials	Additive manufacturing processes for metal materials must be included in a second step due to high relevance in industrial production.
REQ 3	Application Area	There is increasing potential for small series as well as series production in additive manufacturing. Therefore, the attribute *quantity* must be included in this analysis.
REQ 4	Costs and Capacity	The platform should match production jobs based on *costs* and *prices* as well as production *capacity* and *times*.

4.2 Technical Requirements

Following the definition of general business requirements, technical requirements can now be discussed. The classification of requirements by category is shown in Fig. 3. As mentioned at the beginning, the five categories *Quality (Q)*, *Material (M)*, *Additive Manufacturing Technology* (short: *Technology (T)*), *Intended Use (U)* and *Post-Processing (P)* can be distinguished. These are represented as the vertices of the pyramid in Fig. 3. The edges / dependencies are *connecting categories*. Quotations are placed at the corresponding edges of the pyramid. Again, quotations are partly mentioned in the following text and classified in an overview Tab. 4 in the Appendix.

Requirements that are associated with the category *quality* are requirements that determine the quality of a product that is produced with additive manufacturing technologies. The categories *material* and *technology* specify requirements that influence the choice of materials or manufacturing technology, respectively. Requirements that define the matching logic based on the purpose-of-use of the manufactured product are grouped in the category *intended use*. Finally, all requirements regarding the finishing of the product, that do not directly deal with the additive manufacturing process are summarized in the category *post-processing*.

Quality

In the interview study, the category quality turns out to be one of the most important factors for trading additive manufacturing capacities. Several factors influence the quality of an additively manufactured product. Platform operator A outlines some dependencies: "[...] It is unclear what certain products are intended to be used for, how durable they have to be, and whether they have to fulfill certain specifications, which in return depends on the technology, printer or material." (Q8). The results of the surveys show that experts use the term *quality* in different contexts. Buyers A and B use *quality* to describe the product's outer appearance, e. g. its geometry or surface finish. Buyer B mentioned that using "[...] the conventional manufacturing technology in the past caused the problem of products looking injected. With the liquid-material process, you often see the seam, with the powder-bed process, the products look qualitatively better." (QT2). The outer appearance changes depending on the accuracy. Buyer A defines accuracy as a crucial point for defining quality in additive manufacturing (Q1). In the following requirements, contexts are explained in more detail.

Requirement 5: The attribute *quality* has to be considered in the context of the characteristics *material* and *layer thickness* due to the large number of dependencies.

Experts highlight *quality* as an important criterion, which depends significantly on the material, manufacturing technology, post-processing, and intended use. Sellers A and B, as well as manufacturer B, use the term *quality* in relation to materials and manufacturing technologies, especially layer thickness (Q4, Q5). Furthermore, attributes like strength, elongation at break, heat resistance, or biodegradability are used to define material properties rather than product or quality properties for this work.

Requirement 6: To define the required *quality*, details about the *intended use* have to be specified.

Seller B, as well as platform operator A, place the intended use of a product in connection with a correspondingly required quality (Q8). Sellers A, B, and C consider it necessary to be aware of the purpose of a product or its category. Often it is not possible to identify which products they manufacture. In this case, a request from the customer is necessary to be able to decide which production process is suitable for the respective application of the product in order to achieve the highest possible quality. Therefore, the factor *quality* must be defined differently for different purposes. For example, a prototype has different quality requirements (low) compared to a functional component (high). In this regard, buyer A mentions quality in connection with the

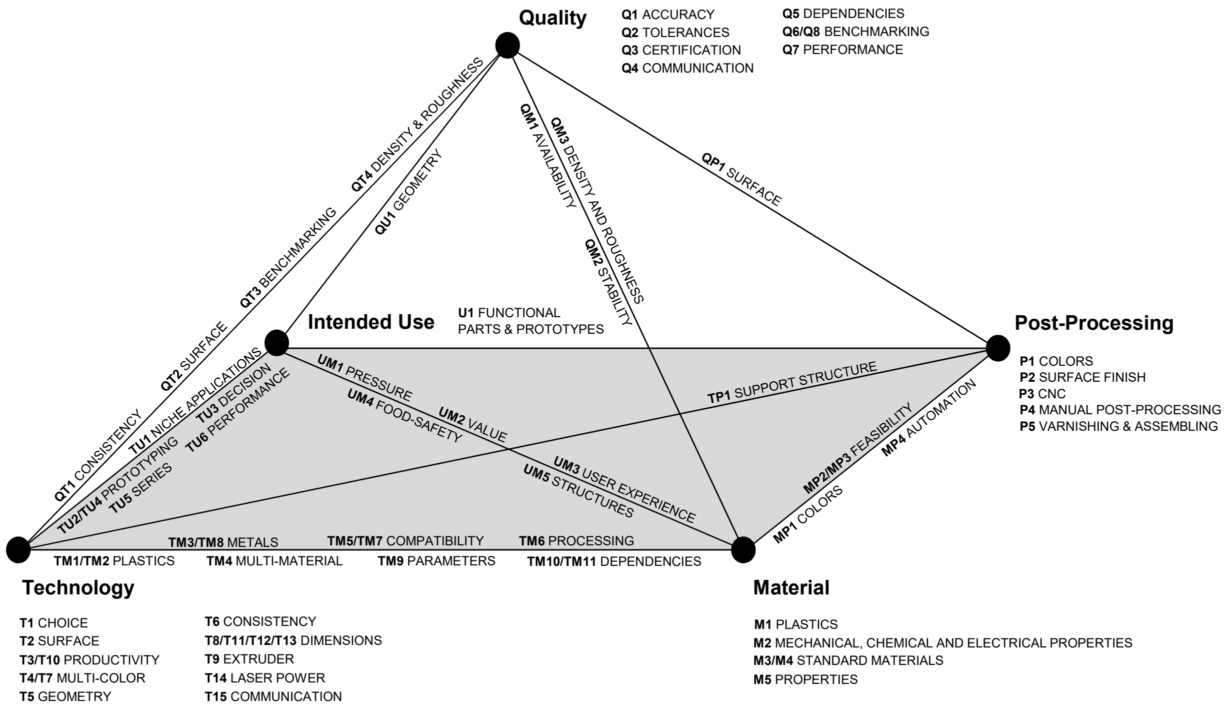

Figure 3: Requirements Categories and their Dependencies

strength of the product as one criterion which differs for different purposes (QU1). Manufacturer B concludes correspondingly concerning an achievable quality for functional parts: “[If] there are no welding seams, [...] the parts have a higher performance. This makes it more resilient than if it had a welding seam ”(Q7).

Requirement 7: To achieve qualitative comparability and consistency, manufacturers require *certification*. Alternatively, product benchmarking can be used.

Another main quality aspect is consistency for multiple product orders. Buyer A explains the difficulty of consistency when using different manufacturing technologies: “If the processes differ, the customer should not recognize this by the product and wonder why this product looks different from the other. It should be consistent‘ (QT1). To reach consistency and a specific accuracy, tolerances must be adhered to. Buyer A demands a guarantee from suppliers regarding tolerance compliance (Q2). Additionally, some experts, as well as their customers, require certification, e. g. according to ISO 9001, to obtain a quality guarantee (Q3). To ensure consistency and specified quality, manufacturer B produces special benchmark parts in an application center (Q6). The following statement emphasizes the importance of benchmark products: ’Comparability is very important here. That’s what customers do before they buy” (QT3).

Material

The category material is another important factor for exchanging additive manufacturing capacities according to the interviewees. The following four requirements show that material influences other categories significantly and has to be defined and specified.

Requirement 8: Due to various dependencies and attributes, *material* must be specified by buyers of additive manufacturing capacities.

By the interviewees, *material* is considered to be another important parameter for matching additive manufacturing technologies or machines with products. *Material* is strongly influenced by *technology*, *intended use*, *quality* and *post-processing* and correspondingly affects these categories. For this reason, it should be specified by the stakeholders and therefore considered separately. Mechanical, chemical, or electrical properties that are dependent on material include impact resistance, water resistance, temperature resistance, elasticity, stability, food safety, density and roughness (M2, M5, QM2, QM3, UM4). The material and particularly its properties, specify possible purposes of use (Q8). According to manufacturer B, parameter settings for each technology, such as machine temperatures or laser power, depend on the specific material within one group (e. g. metal or plastic) (TM7, TM9, T14). Most experts emphasize the relevance of quality factors in connection with materials (QM3, M2, UM5). Due to the dependencies mentioned above, we conclude that knowing material(s) in advance is more beneficial than deriving suitable materials from requirements.

Requirement 9: For exchanging production capacities, it is relevant to specify sales side available *materials*.

Besides other experts, buyer A highlights the importance of declaring available materials in the selling company: "The 3D-printing material is one of the main components and [...] also suppliers must satisfy this requirement' (QM1). According to some experts, some buyers only know which materials are used to manufacture their products instead of knowing the (appropriate) technologies (TM3, TM2). Consequently, they select producers according to their preferred or necessary materials. Manufacturer B states that powder-bed fusion technologies 'can process almost all types of metals that can be [...] pulverized" (TM8). For this reason, sellers do not always stock and use all metal powders, alloys, or other materials. In many cases, their material variety is limited to standard materials (M3, M4). For these reasons, it is necessary to declare available materials.

Requirement 10: If the *material* is unspecified, it should be chosen according to the desired properties.

Especially buyers of additive manufacturing capacities do not always know or specify materials for their products to be manufactured (M1). In this case, they have to choose the material according to the required characteristics. Buyer B highlighted that shock-resistant polyamides should be used for production to ensure stability (QM2). For this example, the materials, as well as their properties, are predetermined and provide flexibility for the exact material selection. Manufacturer B supports this statement, especially for density and roughness as desired properties: "[Desired product properties] [are] strongly dependent on the material and restrict the search a lot.' (QM3). Platform operator A adds the statement that '[...] filters [to] search for physical properties such as density, modulus of elasticity, bio-compatibility or corrosion resistance" should be used for choosing materials according to their properties (M5).

Requirement 11: The property *material* should be used to link *machines* and *sales offers* to *purchase inquiries*.

Platform operator A suggests an intense relationship between machines and materials ("processing"). Hence, we must account for them when matching, selling, and exchanging additive manufacturing capacities. The choice of additive manufacturing machines is largely determined by choice of one or more materials. The property material must, therefore, be related to the purchase order as well as devices. One or more materials can be selected for exactly one purchase request. In return, exactly one sales offer with one or more materials can be offered in the area of sales of additive production capacities, since not all materials to be processed for devices necessarily have to be offered by vendors. Again, one or more materials can be processed by one or more devices. This also results in the following requirement.

Technology

As described in Sect. 2, the additive manufacturing technologies differ greatly by the way they build the final model. To select and match the correct technology, it has to be specified and pre-filtered by different attributes, which are defined in the following six requirements.

Requirement 12: For exchanging production capacities, it is relevant to specify sales side available manufacturing *technologies* or *machines*.

The great benefit of a platform for exchanging production capacities is that not every manufacturer has to possess every machine type in-house. Therefore, suppliers must specify which machines and technologies are available in their company. Some technologies are so rarely used that it does not make sense for every supplier to offer them (PS2). For example, seller A offers only "Multijet Fusion, Binder Jetting, PolyJet and SL' (PS1), whereas seller B offers 'SLS, MJF, FDM, SL, 3DP/Binder Jetting" (PS2). Buyer A only uses SLS technology with the PA material (TM1). Therefore, seller A cannot meet this requirement of buyer A. Platform operator A states that not only the technology but the specific machine is an important factor to consider. On the one hand, it is much harder to give information about a specific technology because it depends on the printer used (T10). On the other hand, specific use-cases require specific machines for an optimal result (TU6).

Requirement 13: The choice of manufacturing *technologies* should be considered in combination with *material* choice.

In requirement 9 we defined, that sellers have to define the materials they have available. Additionally, they have to specify which of their machines process which material. Even though the choice of materials for a machine is relatively flexible and mostly depends on the parameter settings (TM9), not all materials can be processed with every manufacturing technology. Most buyers do not see the manufacturing technology as an important factor, as long as the right material is used, and the quality is up to specification (T1, T2). Overall, plastic materials that have to withstand high mechanical or thermal loads are easier to process with SLS (TM5, TM6). For metals, the energy of the laser decides which materials can be processed. Some metals such as titanium require a higher temperature to melt and, therefore, need a stronger laser (TM7). Platform operator A states that at the current state, they do not offer the customer the possibility to select the manufacturing technology, but only the material (TM10).

Requirement 14: The choice of manufacturing *technology* should be considered in combination with *build volume dimensions* and *product sizes*.

The dimensions of the build space vary strongly between different machines. The build dimensions strongly restrict the parts that can be manufactured on a certain machine (T12). While typical sizes of additively manufactured parts are between 30mm and 350mm, experts also mentioned part sizes from 5mm up to 800mm (T8). This has to be considered when designing a product, that should be manufactured with a certain process (T13). Depending on the part, the orientation of the part in the build space is important. Manufacturer A states that "[...] if the parts are rather flat and long, then it doesn't help if the printer is high" (T11). If this is not the case, platform operator A emphasizes that a model that does not fit into the build space can be made suitable by rotating the part (T15).

Furthermore, requirements 13 and 14 should not be considered separately. Filtering by dimensions and materials at the same time can often determine the manufacturing process or even the specific machine (T11).

Requirement 15: Additional technology-specific factors, such as *surface quality*, have to be considered when selecting the appropriate *technology*.

In addition to the above requirements, there are some differences in the technologies that do not have obvious implications for the final product.

For example, seller B states, that it is difficult to manufacture long and thin components with the SLS technology due to thermal distortion during the print process (T5). Besides these functional defects, there can be optical imperfections, like visible layer transitions. These can go as far as having a rougher surface due to a staircasing effect with the FDM technology (QT2, QT4).

Requirement 16: If products require *multiple materials* and *multiple colors*, this must be specified for *technology* selection.

There are different methods of achieving multi-colored or multi-material prints. While these features are impossible at the moment for powder-bed and liquid-material processes, material extrusion technologies have limited support for using different materials or colors in a single print. This is achieved by using multiple print heads but is mostly utilized to have water-soluble support structures (T9).

BJ technologies support multiple colors by mixing ink into the binder, comparable to 2D inkjet printing (T4). The process still has various downsides, such as a low color accuracy (T7).

The MJM/PJ technology offers the possibility of processing several colors and materials during a production process (TM4). However, the technology is only used in niche applications, such as combining a range of flexible and sturdy plastics in a product (TU1). Platform operator A confirms the request for multi-material on the market.

Multi-color products are not relevant for buyers A, B, and C. However, if this option is offered for a similar price, it would be an interesting option for the experts and, thus, according to buyer C, a unique selling point of the products.

It should be noted that the multi-color criterion can also be solved with appropriate post-processing such as painting and varnishing.

Requirement 17: Estimated *manufacturing times* should be available for the customer.

Especially for time-critical orders, the differences in the manufacturing speed of the technologies can have a large impact on the selection of the right technology. For example, powder-bed technologies are faster than most other technologies (T3). And even powder-bed machines from the same manufacturer have large printing speed differences, which depends on the number of lasers and the laser energy (T14). For FDM processes, the speed can be dependent on the printer size. A heavier print head has to be moved slower and results in a slower print speed (T10).

Intended Use

The category intended use especially plays an important role, if other categories are not specified.

Requirement 18: If the additive manufacturing *technology* is unspecified, the *intended use* should be utilized to determine the *technology*.

Experts argue that selecting an appropriate production technology leads to the product fulfilling the correct application purpose. Buyers often do not know or do not need to know which technology is used for their products. But, as mentioned in requirement 6, experts consider it necessary to be aware of the purpose of a product. Seller B confirms this statement: “Customers can decide which technology should be used, but mostly they are only interested in the product to work instead of the manufacturing technology. The product has to work, no matter if process A, B or C or material X, Y, or Z is chosen. The intended use is decisive” (TU3). Technologies define possible applications and vice versa. For this reason, the intended use leads to the appropriate technology. Seller C underlines: “Some [technologies] are simply better suited than others to certain requirements” (TU4). The technology “SLS [is primarily used] for mechanically resistant prototypes”, and “SL and PolyJet are typical prototype processes that both produce very sharp edges and high-quality surfaces” (TU2). Some technologies facilitate special niche applications, e. g. it is possible to select or combine soft or/and solid structures (TU1). Furthermore, technologies like SLM, are suitable for series production, according to manufacturer B (TU5).

Table 2: Summary of Technical Requirements

No.	Name	Explanation
Quality		
REQ 5	Quality Dependencies	The attribute *quality* has to be considered in the context of the characteristics *material* and *layer thickness* due to the large number of dependencies.
REQ 6	Intended Use	To define the required *quality*, details about the *intended use* have to be specified.
REQ 7	Certification	To achieve qualitative comparability and consistency, manufacturers require *certification*. Alternatively, product benchmarking can be used.
Material		
REQ 8	Material Dependencies	Due to various dependencies and attributes, *material* must be specified by buyers of additive manufacturing capacities.
REQ 9	Sales side Materials	For exchanging production capacities, it is relevant to specify sales side available *materials*.
REQ 10	Material Properties	If the *material* is unspecified, it should be chosen according to the desired properties.
REQ 11	Material as Link	The property *material* should be used to link *machines* to *sales offers* and *purchase enquiries*.
Technology		
REQ 12	Sales side Machines	For exchanging production capacities, it is relevant to specify sales side available manufacturing *technologies* or *machines*.
REQ 13	Material Compatibility	The choice of manufacturing *technology* should be considered in combination with *material* choice.
REQ 14	Size Compatibility	The choice of manufacturing *technology* should be considered in combination with *build volume dimensions* and *product sizes*.
REQ 15	Technol. Specifications	Additional technology-specific factors, such as *surface quality*, have to be considered when selecting the appropriate *technology*.
REQ 16	Multi-Material/-Color	If products require *multiple materials* and *multiple colors*, this must be specified for *technology* selection.
REQ 17	Manufacturing Times	Estimated manufacturing *times* should be available for the customer.
Intended Use		
REQ 18	Technology Choice	If the additive manufacturing *technology* is unspecified, the *intended use* should be utilized to determine the *technology*.
REQ 19	Material Choice	If the *material* and its properties are unspecified, the *intended use* should be utilized to determine the *material*.
Post-Processing		
REQ 20	Post-P. Specifications	*Post-processing* like coloring, surface treatment and assembly must be specified by buyers and sellers.
REQ 21	Material Dependencies	Available *post-processing* methods have to be specified in combination with the *material*.

Requirement 19: If the *material* and its properties are unspecified, the *intended use* should be utilized to determine the *material*.

It can be concluded from the experts' statements that the intended use leads to appropriate material properties, and these define the suitable material. Seller A illustrates one example: "As soon as functional parts have to withstand a certain pressure, only thermoplastics come into consideration". This expert extrapolates from intended use to material properties to material. Another example of concluding from an application scenario to materials states seller C whose customers develop cutlery for an airline. This application requires food-safe materials. In addition to this statement, seller A recommends "to choose between a functional part or a prototype" (intended use) because "customers usually don't know [the] field [of additive manufacturing] very well" and in reverse "if [...] customers are familiar with additive manufacturing, [...] it is better to do [the selection] in comparison to material classes. That would make it easier [...] to find the technology" (UM3).

Post-Processing

The value added does not occur at the point at which the additive manufacturing process is finished, but when the product is completely finalized. For this reason, post-processing options must be included in this study.

Requirement 20: *Post-processing* like coloring, surface treatment and assembly must be specified by buyers and sellers.

Most manufacturing processes require post-processing. This can range from removing metal dust (MP3) or support structures (TP1) from printed parts to polishing, coating, and painting surfaces (P2). To a large extend, these are manual tasks (P4), that manufacturers do automate as much as possible, such as removing metal dust from finished parts (MP3).
Not all manufacturers offer all post-processing methods, and seller A even says that "the primary differentiation is through post-processing" (P3). Buyers want information about whether a post-processing step is available, especially coloring is an interesting step (P1). Therefore, buyers should also specify which post-processing is needed.

Requirement 21: Available *post-processing* methods have to be specified in combination with the *material*.

Post-processing methods can differ depending on the material that was used. Some products are not easy to varnish because of the material (MP2) or the raw material's color. If the raw material is not perfectly white, the final color can be distorted (MP1). Seller C states that some metals require intensive mechanical post-processing, that they can not do internally (MP3).

We summarized the technical requirements in Tab. 2.

5 Conceptual Model

Based on the identified requirements, we can define a conceptual model that supports exchanging production capacities on an e-commerce marketplace. This section introduces such a model to ensure the structured and consistent storage of data and the efficient use of the database. The final objective is a matching of purchase inquiries and sales offers and thereby answers RQ2. This will provide the basis for the technical implementation in Sect. 6.

The relational database model represents an accepted method for database development and is a widely used basis of database systems currently available (Codd 1970). Therefore, it is selected for the present paper (Mertens et al. 2017; Vossen 2008). Relational databases rely on the relational theory as well as defined mathematical principles and mostly avoid object-oriented specifications (e. g. using the Unified Modeling Language (UML)), which is sufficient for most applications (Mertens et al. 2017; Vossen 2008). For the exemplary implementation, a relational database model proves to be suitable. The relational database model can be described as a structured collection of tables that are linked together. In order to create the model, only the structural element *relation* is required (Elmasri and Navathe 2015). A relation is a table with a fixed number of columns in which the attributes are represented. The header line contains the attributes. Any number of further rows, known as tuples, contains the concrete data values for the attributes. The name of the relation is given by the corresponding entity (Elmasri and Navathe 2015; Mertens et al. 2017).

Fig. 4 summarizes the resulting model for matching purchase inquiries and sales offers in a structured collection of relations with attributes.

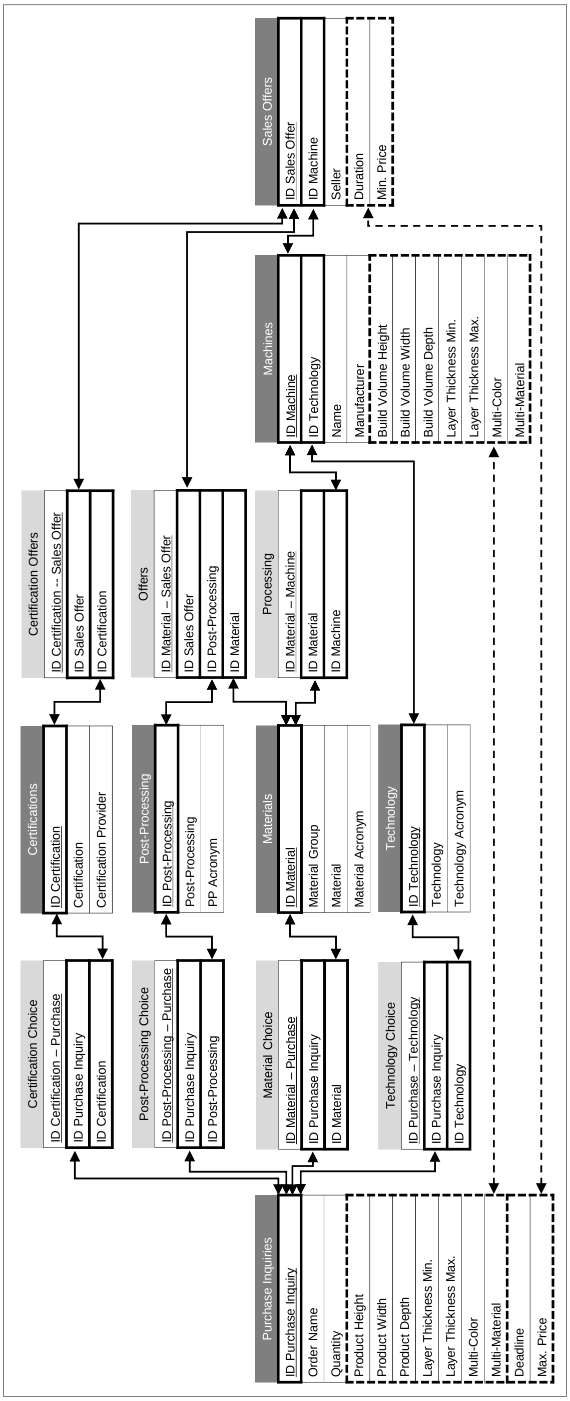

Figure 4: Conceptual Model for Matching Purchase Inquiries and Sales Offers for Production Capacity

Relations and attributes, as well as relationships, were derived from the requirements. To achieve a clear visualization, columns are displayed vertically in our model. Therefore, attributes are displayed in a fixed number of rows.

Relations in our model include *purchase inquiries, certifications, post-processing, materials, technology, machines,* and *sales offers* and are shown in dark grey in Fig. 4. Relations are connected via linking tables *certification choice, post-processing choice, material choice, technology choice, certification offers, offers,* and *processing*, which are illustrated in light grey.

Attributes with underlines or a surrounding rectangle have an identification function. These are referred to as key attributes. A primary key (underlined) uniquely identifies individual tuples of the attribute and can function as a foreign key (surrounded by a rectangle) by referring to another primary key that establishes the relationships between attributes. To avoid ambiguities, an "artificial" key such as a sequential number, in this paper *IDs*, is usually chosen, even if this creates an additional attribute.

Relationships are indicated with arrows. Dashed rectangles and arrows indicate further dependencies that are required for the matching.

In the following paragraphs, we discuss how the respective relations, attributes, and relationships were developed based on the requirements.

The relation *purchase inquiries* consists of twelve attributes. While the first two attributes *ID purchase inquiry* and *order name* are for identification purposes, the attribute *quantity* is needed according to requirement 3. Furthermore, the attributes *product dimensions* (requirement 14), *layer thickness* (requirement 5), *multi-material* and *multi-color* (requirement 16) are necessary. Finally, the attributes *deadline* and *max. price* (requirements 4 and 17) are needed to complete the description of *purchase inquiries*.

The primary key *ID purchase inquiry* shows a relationship to the linking tables *certification choice*, *post-processing choice*, *material choice* and *technology choice*. These resolve a many-to-many relation to *certifications*, *post-processing*, *materials* and *technology*. This results from requirements 7, 8, 11, 13 and 20 that require buyers to specify the desired certification, technology, material and post-processing.

The relation *certifications* describes available certifications as well as their providers. It is linked through *certification offers* to *sales offers*. This specifies the certifications that a manufacturer can offer.

The relations *post-processing*, *materials* and *technology* are all defined by attributes describing their name and acronym. *Material* additionally consists of the attribute *material group*, which indicates whether the material is associated with the group of plastics, metals, ceramics, waxes, or other groups. Therefore, we can fulfill requirements 1 and 2 by prioritizing plastics and metals in the first step.

According to requirement 11, the relation *materials* is connected to the relation *machines* by the linking table *processing*. As specified in requirement 13, the relations *technology* and *materials* are considered in combination and do both restrict the choice of *machines*.

The attributes framed by dashed rectangles *product dimensions*, *layer thickness*, *multi-color* and *multi-material* of the relation *purchase inquiries* and the attributes also framed by dashed rectangles *build volume*, *layer thickness*, *multi-color* and *multi-material* of the relation *machines* show a direct relationship to each other. This means we can match these attributes of *purchase inquiries* and *machines* directly. Furthermore, the named attributes fulfill requirement 14 and 16, because *machines* are assigned to a *technology*.

Based on requirement 9, sales side materials have to be specified, so that sellers can offer possible materials for their sales offer. Therefore, we connected the relation *sales offer* to the relation *materials* via the linking table *offers*.

According to requirement 20, we specify *post-processing* in an corresponding relation. We fulfill the dependencies between the relations *post-processing* and *materials* specified in requirement 21 by combining them in the linking table *offers* and therefore restrict *sales offers* based on both relations.

Sales offers have to specify *machines*, which are assigned to the relation *technologies*. These one-to-one relationships fulfill requirement 12.

The attribute *duration* defined in relation *sales offers* fulfills requirement 17. As specified in requirement 4, this can be matched directly with the attribute *deadline* in relation *purchase inquiries*. Furthermore, these relations allow a matching of *max. price* and *min. price*.

The intended use (requirement 6) is not included in the model since it influences other attributes such as layer height, material, and technology. How the intended use is still applicable in our model is further described in the buyer scenario in Sect. 6.2. Similarly, requirement 15 can not be mapped directly to the conceptual model, since the implications the manufacturing process has on the product quality are too complex to map in a simple model. Some implications are even subjective and, therefore, we included this requirement into the same decision process in Sect. 6.2.

6 Practical Implementation

To test not only the theoretical validity of the requirements and the conceptual model but also the practical applicability, we implemented a demonstrator and simulated typical scenarios for a potential buyer or seller of production capacity. The following sections describe the implementation of a prototype marketplace with an automated matching mechanism built upon the conceptual model from Sect. 5. Later, the implementation and thereby, the underlying model is evaluated.

6.1 Implementation

To implement the demonstrator, we utilized the LAMP stack (Lawton 2005) on the technological level and the model-view-controller (MVC) model (Tarasiewicz and Böhm 2014) to keep the data model and logic separate from each other.

We derived a relational database structure directly from the conceptual model. As described in Sect. 5, we created tables for *Purchase Inquiries*, *Sales Offers*, *Materials*, *Machines* and *Technology* as well as junction tables for *Technology Choice*, *Material Choice*, *Offers* and *Processing*. To ensure practical relevance, we filled the *Materials*, *Machines* and *Technology* tables with data sourced from data sheets of additive manufacturing machines and materials.

The matching of purchase inquiries with sales offers is conducted in a two-stage process. In the first step, for each purchase inquiry, the appropriate sales offers can be extracted with a single SQL statement. This is achieved by joining the tables on the primary and foreign keys as well as a less-or-equal relation between price, duration, and build volume. Then, we applied a heuristic, specifically designed for sharing production capacities to achieve a one-to-one matching to the sales offers. The algorithm maximizes the revenue on the platform based on stochastic optimization (Stein et al. 2019). Compared to other order book matching algorithms, as used in financial markets, this algorithm was specifically designed to match orders while accounting for future (uncertain) demand. Selling a slot of currently free capacity that could be needed in the future for the own demand could result in overbooking capacities and, therefore, additional cost for reallocating resources or penalty payments (Stein et al. 2019).

For the view component, we used plain HTML and CSS for this first demonstrator. While the user experience is not up to modern standards, it suffices for the evaluation of the matching logic. We created input masks to create new purchase inquiries, sales offers, machines, and materials. Additionally, we created views that display existing entries in these categories. Finally, we can start the matching and get a list of all purchase inquiries with the information if they could be matched and with which sales offer it was matched.

6.2 Evaluation

To evaluate the demonstrator, we used scenario-based evaluation. In the first step, we added potential sellers with a typical set of machines that were deducted from the interviews. Most sellers specialize in only a few specific machines and a few materials. We evaluated the implementation and, therefore, the model with two scenarios: one from a seller's perspective and one from a buyer's perspective.

The matching of products (purchase inquiries) and production machines (sales offers) can only be implemented if all attributes are defined, including the material and the technology, for which reason we have developed a decision process model. This model is subdivided into two parts.

Seller Scenario

In the following scenario, a fictitious company sells excess production capacities on the platform. According to their production planning for the week, the company has two days of production time left on one of their additive manufacturing

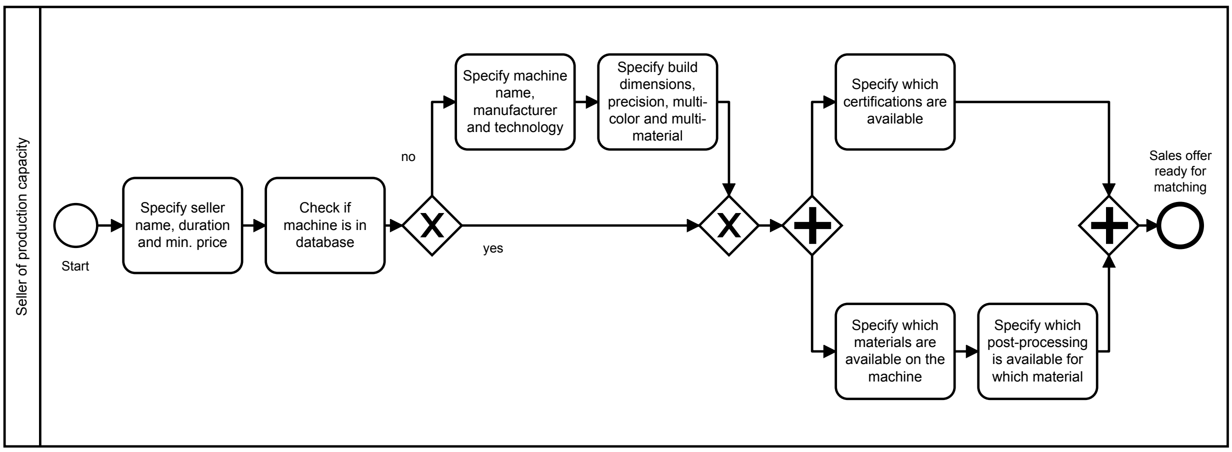

Figure 5: Process to Offer Capacities on the Marketplace

machines. The company can create sales offers for each free slot of production time. Alternatively, we implemented a rudimentary interface, that can fetch free production capacities from production planning systems.

The process described in the following paragraph is shown in Fig. 5. To create a new sales offer, the company has to specify the amount of time the machine is free and the minimum price they want for this capacity. We used an hourly price, even though we are well aware that this is a rather inaccurate measure, and the actual cost depends on other factors other than the time, such as the print parameters and material consumption of the part. The machine type can be chosen via a drop-down menu. If the machine is not yet in the database, a new machine can be added. Therefore, the manufacturer name, model name, and technology have to be specified first, then the build dimensions, precision, multi-color, and multi-material support have to be specified. After the machine is selected, the available materials for the machine can be chosen with check-boxes. Then, for each material, the available post-processing can be chosen. Additionally, the available certifications can be specified in this step.

The sales offer can then be saved and is ready for matching. The scenario and workflow showed that requirements 10, 18, and 19 could be satisfied by integrating the material and technology choice into a process independent of the model.

Buyer Scenario

On the buyer side, another company has a production bottleneck and wants to buy additional production capacities. The following described process is shown in Fig. 6. To buy capacities, the company has to create a new purchase inquiry and put in the required parameters for the print job, starting with the order name, quantity, deadline, and maximum price. After that, product-specific parameters regarding the product dimensions, multi-color, and multi-material have to be specified. These parameters could also be extracted from an uploaded `.stl` file. If the desired precision is known, it can be directly specified.

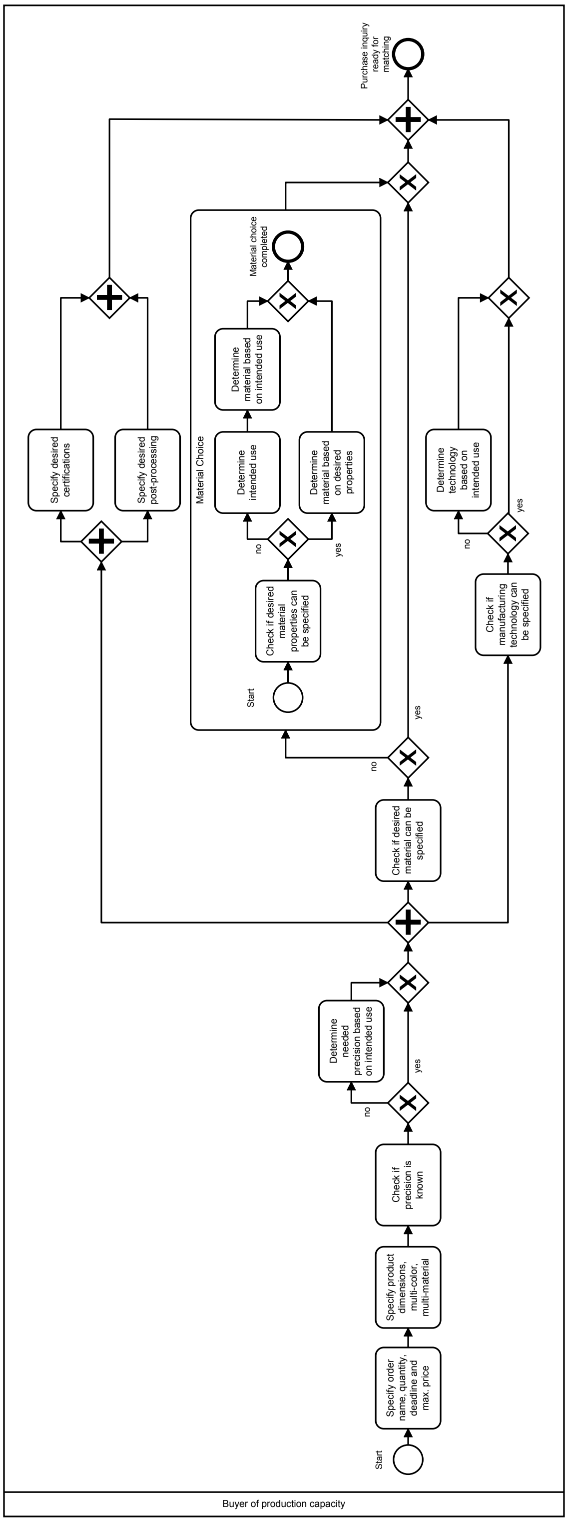

Figure 6: Process to issue purchase inquiry

If not, the platform offers recommended layer heights for different intended uses, like functional prototypes. With this information, a new purchase inquiry can be added to the table.

In the next step, required certification, post-processing, material, and production technology have to be selected. Unknown production technologies should be chosen according to the intended use. Additionally, multiple or all technologies can be chosen. If the material can not be specified immediately, it should be chosen according to the desired material properties.

In the case of unknown desired material properties, the material should be chosen according to the intended use. As for the technology choice, multiple or all materials can be chosen. After saving the choices, all information needed for the matching is available, and the process can be started.

Matching

After buyers and sellers have submitted their purchase inquiries and sales offers, these have to be matched with each other. This has to be done manually, but could at a later time be implemented as a regular batch process. The process first matches sales offers and purchase inquiries based on the conceptual model to check whether production is feasible at all. To achieve a one-to-one matching, we utilize stochastic optimization to maximize the overall revenue on the platform. If a purchase inquiry can not be matched, it is rejected by the platform, and the buyer is getting notified. The sellers get notifications for the purchase inquiries that got matched to their production capacities. Fig. 7 shows the platform screen with a matched order to the vendor and machine. Additionally, we implemented an interface for production planning systems to automatically schedule the production jobs accordingly.

7 Conclusion

The presented prototype marketplace allows companies to use the potentials of collaborative additive manufacturing. Manufacturers can significantly increase their competitiveness and reduce risks in interwoven supply networks and, therefore, accomplish their strategies and business goals. The marketplace addresses key challenges of manufacturers, such as reducing order risks caused by equipment failure or adaptability in case of changing market demands. By offering exceeding capacities on the platform to other companies, they can generate additional revenues. Therefore, we enable them to benefit from synergies, economies of scale, and economies of scope. The platform as an intermediary between the supply and demand side facilitates the efficient allocation of production capacities within the inter-organizational network.

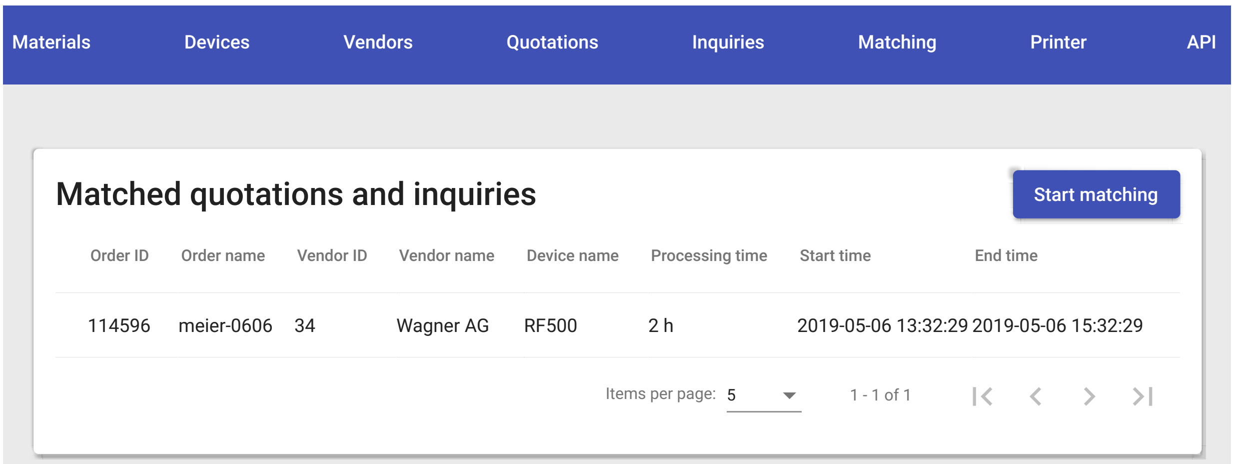

Figure 7: Matched Order to Vendor and Machine

In this paper, we provide the foundation to build a marketplace for trading additive manufacturing capacities. To accomplish this goal, we first set out to raise requirements for such a marketplace (RQ1). To answer this research question, we conducted qualitative interviews and compiled the overall 21 requirements. Since the core functionality of the marketplace is the correct matching of purchase inquiries and sales offers, we sought to provide a conceptual model of the data involved (RQ2). We used the requirements from RQ1 and developed a comprehensive conceptual model that shows how purchase inquiries and sales offers can be matched. Finally, we wanted to evaluate whether the model can fulfill the requirements in a practical implementation of a marketplace (RQ3). Therefore, we implemented a simple marketplace in PHP, HTML, and MySQL. We could map the conceptual model completely to a relational database model and implemented a web front-end to guide users through the purchase and sales processes.

We presented the implementation to our project partners and evaluated whether the marketplace fulfilled their requirements. Even though requirements 6 and 15 were not fully met by the conceptual model and, therefore, the marketplace itself, our evaluation showed that the decision processes are helpful to tackle this issue. Additionally, the evaluation partners could not provide other feasible solutions for this. Hence, further research is needed here.

Overall, we extended previous research by building a comprehensive model as well as implement and test it. Given that the current model includes an information model, it can be abstracted and extended to other industries and be transformed into a reference model for exchanging production capacities (Brocke 2007; Fettke and Loos 2007). Therefore, it has to be analyzed which production capacities can be converted into tradeable goods. Due to the novelty of research in this area and the lack of theoretical knowledge about opportunities and challenges, we lay the ground for further research and IS theory (Gregor 2006). Further, our prototype marketplace can serve as a basis for future research tackling concrete implementation in a real-world inter-organizational production network.

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Appendix

Table 3: Classification of Current Additive Manufacturing Technologies

Category & ISO process class	Technology	Ceramic	Plastic	Metal	Wax	Others
Liquid-material processes						
Vat (Photo) Polymerization	Beam Interference Solidification (BIS)		X			
	Continuous Liquid Interface Production (CLIP) Digital Light Synthesis (DLS)		X			
	Digital Light Processing (DLP)		X			
	Film Transfer Imaging (FTI)		X			
	Holographic Interference Solidification (HIS)		X			
	Liquid Thermal Polymerization (LTP)		X			
	Lithography Based Ceramic Manufacturing (LCM)	X				
	Low Force Stereolithography (LFS)		X			
	Stereolithografie (SLA)	X	X			
	Scan-LED-Technologie (SLT)		X			
Free-space processes						
Direct Energy Deposition	Electron Beam Welding (EBW)			X		
	Laser Metal Depostion (LMD) Laser Powder Deposition (LPD)			X		
	Wire Arc Additive Manufacturing (WAAM) Laser Engineered Net Shape (LENS)			X		
Material Extrusion	ARBURG Kunststoff-Freiformen (AKF)		X			
	Contour Crafting (CC)					X
	Fused Deposition Modeling (FDM) Fused Filament Fabrication (FFF) Fused Layer Modeling (FLM)		X			X
	Paste Extrusion Modeling (PEM)		X	X		X
	Continuous Filament Fabrication (CFF)		X			X
	Robocasting (RC)	X				
	Wax Depostion Modeling (WDM)				X	
Material Jetting	Ballistic Particle Manufacturing (BPM)		X			
	Gel Dispensing Printing (GDP)		X			
	Multi-Jet Modeling (MJM) PolyJet (PJ)		X		X	
	Drop on Demand (DOD)		X	X	X	X
	NanoParticle Jetting (NPJ)	X		X		
Sheet Lamination	Layer Laminate Manufacturing (LLM) Laminated Object Modeling (LOM)	X	X	X		X
	Selective Deposition Lamination (SDL)					X
	Solid Foil Polymerization (SFP)		X			
	Ultrasonic Additive Manufacturing (UAM)			X		
	3D Screen Printing	X		X		
Powder-bed processes						
Power Bed Fusion	Electron Beam Melting (EBM)			X		
	High Temperature Laser Sintering (HTLS)		X			
	(Selective) Laser Beam Melting ((S)LBM)			X		
	Multi Jet Fusion (MJF) High Speed Sintering (HSS)		X			
	Selective Heat Sintering (SHS)		X			
	Selective Laser Melting (SLM)			X		
	Selective Laser Sintering (SLS)	X	X	X		X
Binder Jetting	Binder Jetting (BJ) Three Dimensional Printing (3DP)	X	X	X		X

Table 4: Classification of Interview-Quotes

No.	Name	Interviewee	Quote
Quality			
Q1	Accuracy	Buyer A	In the end, the only important thing is that the quality, as well as the outer appearance is right. The sticking point is the accuracy.
Q2	Tolerances	Buyer A	We have to rely on the fact that the tolerances are kept. The supplier has to guarantee this to us.
Q3	Certification	Buyer A	For us, it is important that the supplier has a quality management system. He usually has to be certified according to ISO 9001, as our customers also require this.
Q4	Communication	Seller A	Much more important is the factor quality. We don't know how they produce, what parameters they use etc. Eventually there is a certain risk.
Q5	Dependencies	Seller B	Then the question arises whether it should be more about the price or the quality, e. g. layer thickness or material.
Q6	Benchmarking	Manufacturer B	We have an application center in which we have some devices with which we also manufacture ourselves, but we manufacture benchmark parts there.
Q7	Performance	Manufacturer B	There are no welding seams, so that the parts have a higher performance. This makes it more resilient than if it had a welded seam.
Q8	Dependencies	Platform Operator A	The difficulty is that it is unclear what certain products are intended to be used for, how durable they have to be, and whether they have to fulfil certain specifications, which in return depends on the technology, printer or material.
Quality – Postprocessing (QP)			
QP1	Surface	Seller A	The tolerance requirements are too high for a 3D printer. Another thing we currently discuss with a surface specialist is processing of the surface quality. Also in this point we are far from readiness for the marketing. So honestly, the answer to question 22 would be "none". Most of our competitors in Germany would have to answer this question the same way.
Quality – Material (QM)			
QM1	Availability	Buyer A	The 3D-printing material is one of the main components and there is no way around the fact that also suppliers must satisfy this requirement.
QM2	Stability	Buyer B	With regards to the material I highlighted that it should be shock-resistant polyamide. "In terms of quality you also value the stability of the product?" Yes
QM3	Density and Roughness	Manufacturer B	Density and roughness are determined more by the material than by the process: This is strongly dependent on the material and restricts the search a lot.
Quality – Intended Use (QU)			
QU1	Geometry	Buyer A	Otherwise the breaking strength is relevant. It depends on the shape, we have a lot with cylindrical shapes and in these cases the stability of the components are very important.
Quality – Technology (QT)			
QT1	Consistency	Buyer A	The various procedures must also be considered in terms of what the term "quality" means. Apart from the accuracy, the surface of the products is also important, as well as the optics. If the processes differ, the customer should not recognize this by the product and wonder why this product looks different from the other. It should be consistent.
QT2	Surface	Buyer B	Previously the conventional manufacturing technology in the past caused the problem of products looking injected. With the liquid material process, you often see the seam, with the powder-bed process the products look qualitatively better.

QT3	Benchmarking	Manufacturer B	Comparability is very important here. That's what customers do before they buy. Usually they want to have a certain number of tensile samples (round stands, which are built up on a platform) produced and then have them sent to them by the various suppliers. Afterwards they decide on a device. The main focus is on density, surface texture and such things.
QT4	Density and Roughness	Manufacturer B	In most cases, the requirements regarding density or roughness are so high that 80% of the processes can be excluded from the outset.
Technology (T)			
T1	Choice	Buyer B	Would it be an option for you to use another technology if the quality is the same as with the SLS technology. Yes, definitely. So far only this method has fulfilled our requirements. As soon as the quality and the price remain the same for another procedure, we will consider to apply this.
T2	Compatibility	Buyer C	The procedure is not relevant. It only depends on the right speed, material and quality.
T3	Productivity	Seller A	The powder-bed method is by far the most productive. The quality of the pieces out of this method is respectively good.
T4	Multi-Color	Seller B	Binder Jetting machines are able to mix colors.
T5	Geometry	Seller B	The differences between SLS and FDM are, for example, that with SLS long, thin components deform very strongly, whereby these objects are manufactured very flat with FDM.
T6	Consistency	Seller B	It is important that the product is produced on the same device with the same material or the same exposure time.
T7	Multi-Color	Seller C	The possibility of multi color printing has also evolved with ColorJetPriniting, but the color realness is not as expected. This is a relatively difficult subject. Colour mixibility etc.
T8	Dimensions	Manufacturer A	They differ mainly in the state of development and the size, it starts at 300 space and the largest is now 800. Quality differences in the product depends primarily on the setting, not directly on the model of the printer.
T9	Extruder	Manufacturer A	No, we have 1 and 2 models (extruder).
T10	Productivity	Manufacturer A	The large printers are of course slower due to the size than a small printer, because the head is much heavier.
T11	Dimensons	Manufacturer A	Mostly the build space. So if the parts are rather flat and long, then it doesn't help if the printer is high.
T12	Dimensions	Manufacturer B	Here you can separate by the sizes of the parts. This additionally differentiates the machines strongly and restricts the manufacturing of the products.
T13	Dimensions	Manufacturer B	On the one hand, we have three different build space sizes. These are xyz sizes, depending on the size and depth of the platform. This is a crucial issue for the designers of the companies.
T14	Laser Power	Manufacturer B	Then the second is speed. As already said we have between one and four lasers and then it depends on their strength of 400 watts or 700 watts per laser. Due to the higher setting of the laser, the powder can be melted faster. This has a positive effect on the speed.
T15	Communication	Platform Operator A	The printer operator specifies the size of the build space and as soon as the user has adjusted his models, the system checks whether they fit in or not. We have already adapted this scheme. In the beginning, all offers where the size did not fit were denied and not displayed. But we received a lot of customer enquiries that the customers would still like to have these displayed, because they know that they then have to adapt at a certain point so that the model fits again. This is very complex in this area.
Technology – Postprocessing (TP)			
TP1	Support Structure	Seller B	In addition, the FDM process produces a support structure that has to be washed out or removed at the end. SLS radiates this. This means that the postprocessing factor is definitely one of them.
Technology – Material (TM)			

TM1	Plastics	Buyer A	We use SLS and only plastic (PA) is used for our products.
TM2	Plastics	Buyer C	I don't know what the perfect technology is. You will probably be able to do a lot with a simple method like FDM. In that case some plastic processes will certainly be suitable.
TM3	Metals	Buyer C	The second is the process to manufacture metallic injection tools or tools for machines. An external company produces them for us, but I can't tell you what the technology is called.
TM4	Multi-Material	Seller A	The advantage of PolyJet is the choice of materials. I don't think we would choose PolyJet again. Apart from the material combination, the process has few advantages.
TM5	Compatibility	Seller A	Thermoplastics only work with a powder bed, because we only have this one.
TM6	Processing	Seller C	Certainly, also with regard to the materials themselves. Mechanical and thermal loads are considerably higher for materials that can be processed with SLS than with epoxy resins.
TM7	Compatibility	Manufacturer B	That's why they stayed in the SLM area, especially in the metal area. You can't melt every material with such high energy. That depends a lot on the material. With titanium, for example, you can work with higher energies and that depends on the parameters.
TM8	Metals	Manufacturer B	On the one hand there is a variety of materials that can be processed. You can process almost all types of metals that can be pulverized.
TM9	Parameters	Manufacturer B	On the other hand, the devices are relatively flexible in their settings so that any material can also be used in the course of the correct parameter settings. I can also develop my own parameters and work with other metals. Our system is an open system, so we can develop parameters ourselves.
TM10	Dependencies	Platform Operator A	At the moment the selection on the platform is limited to the materials, because it is difficult to give information about the technology, because it depends on the printer used. The next step would be to insert the printers, but at the moment it is purely material based.
TM11	Dependencies	Platform Operator A	We also sort by installation space. The materials are then displayed depending on the models, how large they are and whether it fits in.
Technology – Intended Use (TU)			
TU1	Niche Applications	Seller A	It is possible to select/combine soft or/and solid structures. These are relatively special applications, but this is also a certain niche.
TU2	Prototyping	Seller A	SL and PolyJet are typical prototype processes that both produce very sharp edges and high-qualitiy surfaces.
TU3	Decision	Seller B	Customers can decide which technology should be used, but mostly they are only interested in the product to work instead of the manufacturing technology. The product has to work, no matter if process A, B or C or material X, Y or Z is chosen. The intended use is decisive.
TU4	Prototyping	Seller C	Primarily I see SLS for mechanically resistant prototypes. You can certainly reproduce almost anything on many processes. Some are simply better suited than others to certain requirements.
TU5	Series	Manufacturer B	On the contrary, it focused on SLM, because at that time it moved from prototyping to series production and continued to develop in the direction of production.
TU6	Performance	Platform Operator A	Here it always depends very much on the afterwards component specifications. Here it must be clear what the component will be used for, what it has to withstand and here the information which printer is needed counts.
Intended Use (U)			
U1	Functional Parts and Prototypes	Seller A	In general, we seperate between functional parts and prototypes.
Intended Use –Materials (UM)			

UM1	Pressure	Seller A	As soon as functional parts have to withstand a certain pressure, only thermoplastics come into consideration.
UM2	Value	Seller A	For prototypes, we use a mixture of material features and price.
UM3	User Experience	Seller A	If your customers are familiar with additive manufacturing, I think it is better to do this in comparison to material classes. That would make it easier for me to find the technology. Customers usually don't know that field very well, therefore it's easier to choose between a functional part or a prototype.
UM4	Food-Safety	Seller C	We have a food license for polyamide. Our customers develop cutlery for an airline. This is rather the exception and the aim is to check how to stack these products properly and that they don't break when a guest steps on them.
UM5	Structures	Manufacturer B	Ultimately, the special features of the parts themselves are the bionic structure, which means that it is now possible to produce natural structures such as lattice structures that can't be produced using other processes. As far as metals are concerned, the focus is on weight reduction, which can also be achieved using bionic structures, but which are still highly stable. With the metal printer, relatively thin-walled parts can be produced with the metal printer.
Materials (M)			
M1	Plastics	Buyer C	They are very different. Besides polysterols there are various different plastics. I can't tell you which metals are used.
M2	Mechanical, Chemical and Electrical Properties	Seller B	It depends on how it's built. The obligatory questions are always strength values, water resistance, temperature resistance, elasticity, food safety and so on. Everything you can find in a data sheet. However, all this depends on the material, they are sub-features.
M3	Standard Materials	Seller C	Plastic models. We have PA12, epoxy resin and acrylates. Nothing else.
M4	Standard Materials	Manufacturer A	PLA, nylon, ABS, POM (?), HOLD (?), PET and polycarbonate. Mainly nylon.
M5	Properties	Platform Operator A	Otherwise, the filters can search for physical properties such as density, modulus of elasticity, biocompatibility or corrosion resistance. At the filter level in particular, we get a lot of feedback from customers, for example on how to use the things.
Material – Postprocessing (MP)			
MP1	Colors	Buyer B	The reason for this is "white". If you use black material, we have to check if the colour covers well at the end.
MP2	Feasibility	Seller A	Post-processing is required, but this is not so easy with plastics.
MP3	Feasibility	Seller C	There are very new processes and there are many processes that are more oriented towards the metal industry. This requires intensive mechanical postprocessing that we cannot do internal and therefore we have made a certain selection.
MP4	Automation	Manufacturer B	The next difference is automation. The question is how much does the operator really have to do himself to build a job? This has a lot to do with powder transport. The big problem with metal equipment is that the powder is like a kind of dust, extremely small and can go anywhere. The industry is thinking a lot about how automation can help prevent the customer from coming into contact with this dust. Especially for larger orders, which last several days, overflow tanks have to be emptied and sieved again and again - especially for smaller devices. And this is where the process is automated. The powder passes through the welding process and th excess powder must be screened and then returned to the machine.
Postprocessing (P)			
P1	Colors	Buyer A	With regards to the colour, it would also be interesting to dye the products in the desired corporate identity color.

P2	Surface Finish	Buyer B	That's when I actually meant that the products had to be polished, precoated and painted at the end.
P3	CNC	Seller A	Today, the primary differentiation is through the postprocessing. Here we are rather weakly positioned. Although we have our projects that should go in this direction, this is not a standard process for us. Examples include CNC post-processing. Here we have made parts several times with a partner, but unfortunately this is not yet stable.
P4	Manual Post-Processing	Seller C	There is a lot about manual postprocessing.
P5	Varnishing & Assembling	Platform Operator A	All steps after printing. Finishing, varnishing, assembling. These postprocessing steps can be further defined by the print provider so that the platform leaves the customer as much freedom as possible. Customers can then apply their individual steps in the process.
Time and Costs (TC)			
TC1	Customer Satisfaction	Buyer A	We have tested several suppliers and have now chosen one that produces very quickly, with which communication works well and with whose quality we are satisfied. These are the things that matter for us.
TC2	Delivery Time	Buyer C	For us only the delivery time of products is relevant. Of course, it depends on the priority of the order. Normally we need our products within two weeks.
TC3	Material Consumption	Seller A	The huge disadvantage is the expensiveness. Apart from high material costs the material consumption is also very high. This is not profitable.
TC4	Productivity	Manufacturer A	Mostly the factor costs differentiates technologies. Partially also speed and quality, but as already mentioned, costs to a large extent.
TC5	Communication & Filter	Platform Operator A	With us, you first choose a material, then a printer supplier and then the postprocessing that the company offers and then the price. The other possibility would be to choose the filter first, then the process, then the materials and then the suppliers and prices. Then you get a feeling for the price range. And the platform also has a price and delivery comparison. Exactly. We only refer to the processes. The next step would then be to include the devices. It will be a combination of process, material and printer. And then there is the problem that the model is decisive again.
Process Selection (PS)			
PS1	MJF,BJ,PJ,SL	Seller A	Multijet Fusion, Binder Jetting, PolyJet and SL i. e. Stereolithography.
PS2	SLS,MJF,FDM, SL,3DP,BJ	Seller B	SLS, MJF, FDM, SL, 3DP/Binder Jetting. Sheet lamination is not our field did not come to our mind. Of course, you think about which direction you chose in advance, but it is dangerous to commit yourself in an innovative and growing industry.
PS3	SLS,MJM,PJ,SL	Seller C	There are so many alternatives that you can't cover them. There are too many processes and the machines are expensive, you can't supply everything. It's about SLS, MJP, which we equated with MultiJet Fusion. Is it the same? I'd be careful. It's not powders, so it's not MultiJet Fusion. MJM you can take. We still have PolyJet. SL
PS4	FDM,SLS,DLP	Manufacturer A	Currently only FDM. It is the most widespread and most cost effective. But they are currently developing printers for SLS. Yes, but SLS and DLP should follow. DLP perhaps from a foreign manufacturer.
PS5	SLM	Manufacturer B	These are pure SLM procedures. In the case of competitor XX, others will be added because they are also active in the plastics sector.
PS6	SLS,CJP,SLM, MJM,SL,PJ,DLP	Platform Operator A	The filter includes Selective Laser Sintering, Colour Jet Printing, Indirect Metal Printing, Selective Laser Melting, Multijet Modeling, Division Molding, Direct Metal Casting, Wax Casting, Polyjet printing, Stereolitography, Digital light processing First of all, we want to restrict ourselves to the current procedures, since they are still very new and not widespread yet. We have a large offer, from which one can select which is suitable for the individual case. Therefore I would not limit myself to one particular procedure, but one has the possibility to choose something.