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Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030

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ABSTRACT

Additive manufacturing (colloquially: 3D printing) is a highly discussed topic. Previous research has argued that this technology not only has profound effects on manufacturing businesses but also on society, which demands new corporate strategies and policies alike. Thus, the development of reliable future scenarios is key for strategic planning and decision making as well as for future research. Dedicated academic studies in this field remain scarce. We present the results of an extensive Delphi survey on the future of additive manufacturing with a focus on its economic and societal implications in 2030. Via an initial round of extensive qualitative interviews and a Delphi-based analysis of 3510 quantitative estimations and 1172 qualitative comments from 65 experts, we were able to develop and validate 18 projections that were then clustered into a scenario for the most probable future. The scenario is built on the six Delphi projections with the highest consensus on the likelihood of occurrence. We complement this most probable scenario with a discussion on controversial, extreme scenarios. Based on these findings we derive implications for industry, policy, and future research.

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1. Introduction

Additive manufacturing, colloquially known as 3D printing, has progressively gained importance not only in various fields of business, but also in the daily life of consumers (Rayna and Striukova, 2016). The technology is capable of joining various materials and creating objects from 3D data, usually layer upon layer in contrast to traditional subtractive manufacturing technologies (ASTM International, 2012). Additive manufacturing has been called a disruptive technology (Petrick and Simpson, 2013) that will fundamentally influence many processes in production (Mellor et al., 2014), supply chain design (Bogers et al., 2016), logistics (The Economist, 2012), product life-cycle planning (The Economist, 2013), and also consumer behavior (Berman, 2012). The Royal Academy of Engineering (2013) declared that "Additive manufacturing is not only a disruptive technology that has the potential to replace many conventional manufacturing processes, but is also an enabling technology allowing new business models, new products and new supply chains to flourish."

Two characteristics of the technology facilitate this disruptive potential: First, it enables direct production of physical objects from digital design data, which also provides new opportunities for freedom of design. Additionally, customized products can be manufactured without the high surpluses conventionally connected with one-of-a-kind manufacturing. Hence, current products or production processes can be substituted by additive manufacturing (Gibson et al., 2010), which is making established companies anxious about new competitors (Gausemeier et al., 2011). Second, on the consumer side, additive manufacturing allows private and industrial users to design and produce their own goods (Rayna and Striukova, 2016), enhancing Toffler's (1981) idea of the rise of the 'prosumer' (Birtchnell and Urry, 2013), which is further enhancing the competitive threat proposed by additive manufacturing to established firms.

Despite the great opportunities for this technology, uncertainties and speculations about its future developments remain. Changes in the localization of production, development of consumer demand, and the emergence of new competitors are just a few of the factors that may lead to turbulence in many industries. Despite the vast potential of additive manufacturing and the hype about this technology, there are no scientific studies available developing scenarios about the future of additive manufacturing from an economic and policy perspective, including predictions regarding the economic impact of this technology (Baumers et al., 2016). Our objective is to close this gap, addressing one core research question: How will additive manufacturing influence the business ecosystem of firms, consumers, and society by 2030?

Using a novel Delphi approach, we investigate how the technology will influence the business ecosystem of firms, consumers, and society by 2030. Our results support both firm planning processes and the research and analysis of this technology in academia. Overall, our research makes three main contributions. First, we identify relevant projections

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regarding the future of additive manufacturing and validate these projections using a broad expert survey to assess the probability of their occurrence along with their impact/relevance for firms and society. In so doing, we deliver a basis to substantiate academic discussions and support firm decision-making on the technology's future development and economic implications that go beyond current speculations surrounding the “3D-Printing hype”.

Second, our empirical results allow us to build a scenario for the most probable future of additive manufacturing, helping long-term strategic planning. The scenarios support managers when drafting new strategies and challenging those already in place. Researchers can use the scenarios as a starting point for further study of the technology's development.

Finally, we are among the first to verify the applicability of a novel form of Delphi methodology in a technology management context. This so-called “Real-Time Delphi” (Gordon and Pease, 2006) aims at overcoming some of the earlier limitations of the Delphi approach.

Our paper proceeds as follows: In Section 2, we present our literature review on forecasting and scenario development. Section 3 presents the research question and methodology. This also includes a brief overview of implications of additive manufacturing in the areas of policy, economy, society, and technology (Section 3.3). Section 4 presents the results of our main study. We discuss our findings and identify theoretical as well as managerial implications in Section 5. Finally, we outline limitations and give directions towards future research within Section 6.

2. Literature review

2.1. Forecasting and scenario development for emerging technologies

The future is uncertain and most often unpredictable. Technological developments are part of that uncertainty and dictate the speed and pace our societies change. Thus, there is an increasing need for all concerned parties to manage this change and uncertainty (Branson et al., 2002). Therefore, institutions strive to predict future developments and their economic and policy implications. For many of the technologies currently emerging, such developments do not only impact single firms, but create change in an entire business ecosystem, including the public (Koh and Wong, 2005) and private sector (Karaca and Öner, 2015). Within such forecasting projects, technological developments are usually studied from a specific perspective, respectively with a specific objective in mind.

But forecasting technological progress and developments inherent to emerging technologies almost always pursue a common goal: the generation of possible future scenarios, depicting trends and factors of influence (Gausemeier et al., 1998). These scenarios of the future allow us to follow and understand different directions of possible development (Daim et al., 2006), especially recognizing the uncertain nature of some trajectories. Examples for emerging technologies where scenario construction on implications within socio-technical or socio-cultural systems have been applied include nanotechnology (Karaca and Öner, 2015) or the energy sector (Kajikawa et al., 2008). Time horizons considered for such “pictures of the future” range from 8–10 years to >20 years (von der Gracht and Darkow, 2010). The two main stages of scenario planning are (i) the development of possible scenarios for future outcomes and situations, and (ii) strategic planning based on these projections (Bishop et al., 2007).

Forecasting studies, however, are complex and, of course, not always accurate at depicting the future. They can only try to anticipate future developments as best as possible (Saritas and Oner, 2004). The core idea of forecasting as a long-range planning tool (Courtney et al., 1997) is to guide decision makers towards certain directions within political, economic, socio-cultural and technological developments and support them in times of high uncertainty (Powell, 1992). At the same time, forecasting methods should facilitate a discussion among decision makers and topical experts to better understand the trajectories and possible futures that result from the technology being studied.

Since the early 1960s, several technology forecasting methods have been developed. They are commonly classified into exploratory, normative, and combined methods (Cho and Daim, 2013). Exploratory methods are meant to illustrate the “inevitable future” and project the present state of a technology into the future, assuming a certain progress rate. Methods of this category include trend extrapolation, s-curves, and bibliometric analyses. Normative methods are used to assess the path to reach certain future needs and goals, not only determining the steps to get there, but also assessing the probability of events, and thus work backwards from future to present (Roberts, 1969). This category consists of methods like multi-criteria decision models, morphological analyses, and backcasting. A third category, normative/explorative forecasting, is a mix of these two general categories and includes methods such as the Delphi method, nominal group techniques, and trend impact analyses (TFAMW Group, 2004). Given the motivation of our study to both project the current state of additive manufacturing technologies into the future and to assess the probability of corresponding effects on industry and society, we selected the Delphi method as a suitable approach for our purpose.

2.2. The Delphi method

The Delphi method is an interactive multi-stage forecasting method relying on experts to identify technical developments and trends. Its objective is to structure complex group opinions (Rauch, 1979) and to develop consensus on future developments among a set of experts participating on the panel (Linstone and Turoff, 2002). The method was developed by the RAND Corporation to generate scenarios for long-range strategic planning in the 1950–1960s (Gordon and Helmer-Hirschberg, 1964) and became a widely accepted approach (Kameoka et al., 2004).

Delphi, as a forecasting technique, is described as “reductionist inductive consensual” (Saritas and Oner, 2004) as it lays particular focus on separate events and tries to reduce the discussed issues to select a best or optimal outcome (Mitroff and Linstone, 1996). The original job of the method was to seek reliable consensus about dedicated propositions among a group of experts (Dalkey, 1969). Later, the obligatory need and search for consensus has been dissolved. The Delphi method is now regarded as a research technique facilitating the development of reliable group opinions using expert panels (Landeta, 2006). A core benefit of this method is to provide domain experts a place to discuss within a structured setting and to communicate with each other.

The central element of a Delphi study is the evaluation of projections by experts, i.e. statements about the possible future. These projections must be short, unequivocal, and concise in order to make sense of the content and to avoid ambiguity about what the questioner has in mind (Linstone and Turoff, 2002). Furthermore, the current state of development must be known to the chosen expert panel (Georghiou, 1996). The survey itself is considered “a judgmental forecasting procedure” (von der Gracht and Darkow, 2010). Delphi surveys are generally conducted anonymously, in written form, and in a multi-stage process.

Saritas and Oner (2004) recommend a “systems approach” to the Delphi methodology and scenario planning. This means to take multiple perspectives, not only following the Delphi questionnaire and its propositions, but also to use additional tools to keep the “big picture” in mind. One source of insights in this regard can be qualitative comments provided by the experts when validating a proposition, and discussions among the experts on these comments. In a similar vein, Linstone (1981) proposed the “Multiple Perspective Concept” which stresses the importance of having different viewpoints to address complex problems. This enables unique insights that suffice to deal with complex systemic problems more than a single-person view. Linstone (1981), in particular, suggests three interconnected perspectives: technical, organizational and societal, as well as the personal and individual perspective. Additionally, Mitroff and Linstone (1996) recommend to complement the Delphi questionnaire with direct interviews.

Despite its opportunities and popularity, the Delphi method has been subject to criticism. The method was thought to lack justification for judgments that differed significantly from the mean (Hill and Fowles, 1975). Furthermore, the conventional Delphi method often consumed much time and failed to produce insights into results (Gnatzy et al., 2011), leading to low response rates and high drop-out rates in spite of extensive moderator effort (Keller and von der Gracht, 2014). The "Real-Time Delphi" introduced by Gordon and Pease (2006) tries to eliminate most of these drawbacks. Its main idea is to make the judgement process more interactive, engaging, collaborative, and faster at the same time. An internet-based Real-Time Delphi tool developed by Gnatzy et al. (2011) goes another step further. Here, experts receive instant feedback after evaluating a proposition and learn how their peers judged a particular item. This enables them to adjust their initial estimate immediately. Hence, they need less time overall to contribute to an entire study, which results in lower drop-out rates. Moreover, experts can re-access the study at any point to check for new arguments from other participants until the study is closed. The judgement process is therefore more efficient, but also more collaborative and consensus-driven – supporting a fundamental feature of the Delphi method.

In order to tackle the problem of lack of justification, participants are invited to share arguments for or against a projection. By assigning a random number to each expert, their entries and procedures are kept anonymous, but other participants can follow to see the flow of arguments from one particular expert. The immediate feedback and change of estimates correspond to the several rounds of surveys in a conventional Delphi (Gnatzy et al., 2011). Furthermore, direct feedback in combination with statistical and qualitative arguments can improve the accuracy of the results (Best, 1974). Recent research shows that such an internet-based Real-Time Delphi works as effectively as conventional Delphi surveys with regard to the quality of validating the propositions (Markmann et al., 2013), but in addition provides much more qualitative insights into the development of these validations. These features of the internet-based Real-Time Delphi motived us to adopt this method for our study.

3. Research methodology

3.1. Scenario development for the future of additive manufacturing

Our paper strives to develop scenarios for future outcomes in the context of additive manufacturing (Bishop et al., 2007) to enable strategic planning and to prepare for future developments. As outlined in the introduction, our research is guided by one core question: How will additive manufacturing influence the business ecosystem of firms, consumers, and society by 2030? As the additive manufacturing ecosystem is characterized by diverse stakeholder groups, we followed common practice to draw on expert assessments (Landeta, 2006). Our scenario development builds on a two-round Delphi survey with 65 participants from industry and research. As we will outline in the following, we carefully selected experts to represent the ecosystem around additive manufacturing broadly.

As typical for the Delphi approach, we used a set of projections to prompt future developments within our survey. We applied the PEST framework (including political, economic, socio-cultural, and technological aspects) to structure the development of the projections (Wilson and Gilligan, 2012). After several rounds of expert interviews, desk research, and expert workshops, we derived 18 projections in total. The Delphi study's participants assessed each of the 18 projections regarding (i) their estimated probability of occurrence, (ii) the estimated firm impact, and (iii) the estimated societal impact. In addition, they were asked to provide comprehensive written arguments explaining the evaluations. Based on these quantitative and qualitative assessments, we developed a most probable scenario. Furthermore, we discuss some controversial projections within our implications section to extend the scenario results.

3.2. Application of the Real-Time Delphi

Given its advantages, we decided to adopt the Real-Time Delphi approach described in Section 2.2. When conducting a Delphi study, methodological strictness is important to ensure validity and reliability of results (Hasson and Keeney, 2011). This starts with the creation of the projections. To deliver this, we followed a four-step procedure recommended by von der Gracht and Darkow (2010) (Fig. 1). We will provide an overview of these steps in the following and discuss their findings and results in the subsequent sections.

3.2.1. Step 1: formulation of Delphi projections

First, we developed a set of projections on the future of additive manufacturing, following the procedure outlined in Fig. 2. In order to address the call of including multiple perspectives (Mitroff and Linstone, 1996), we followed the broadly applied PEST analysis framework, which is well established in the forecasting literature (Wilson and Gilligan, 2012), to structure this activity (results will be reported in Section 3.3). We conducted 14 expert interviews (see Appendix, Table 3) with a duration of 45–60 min each.

We also co-organized three expert workshops reaching >90 industry participants, allowing reflection on the interview results and adding further input on relevant developments of additive manufacturing. We used additional sources from a literature review to triangulate our results (Gausemeier et al., 1998). Following this approach, we were able to identify an initial set of 92 projections. We were especially careful with the formulation of the projections as their overall quality and comprehensibility impacts the quality of the outcome immensely (Mićić, 2007). After consulting academic experts in the field of Real-Time Delphi, we reduced the number of projections dramatically (following the

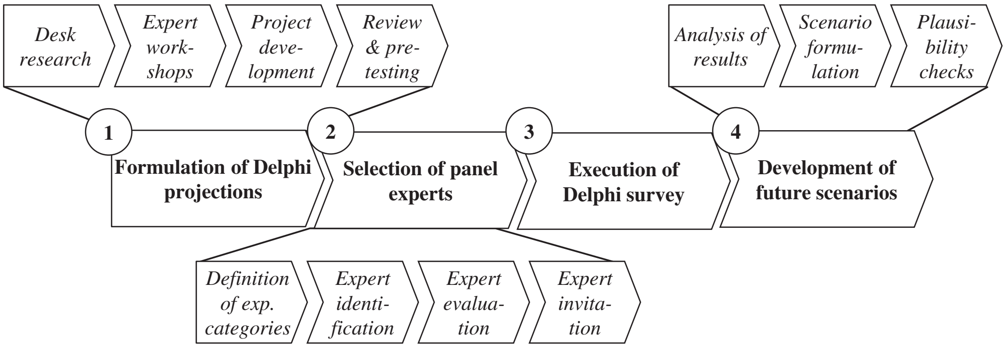

Fig. 1. Delphi process steps (based on von der Gracht and Darkow, 2010).

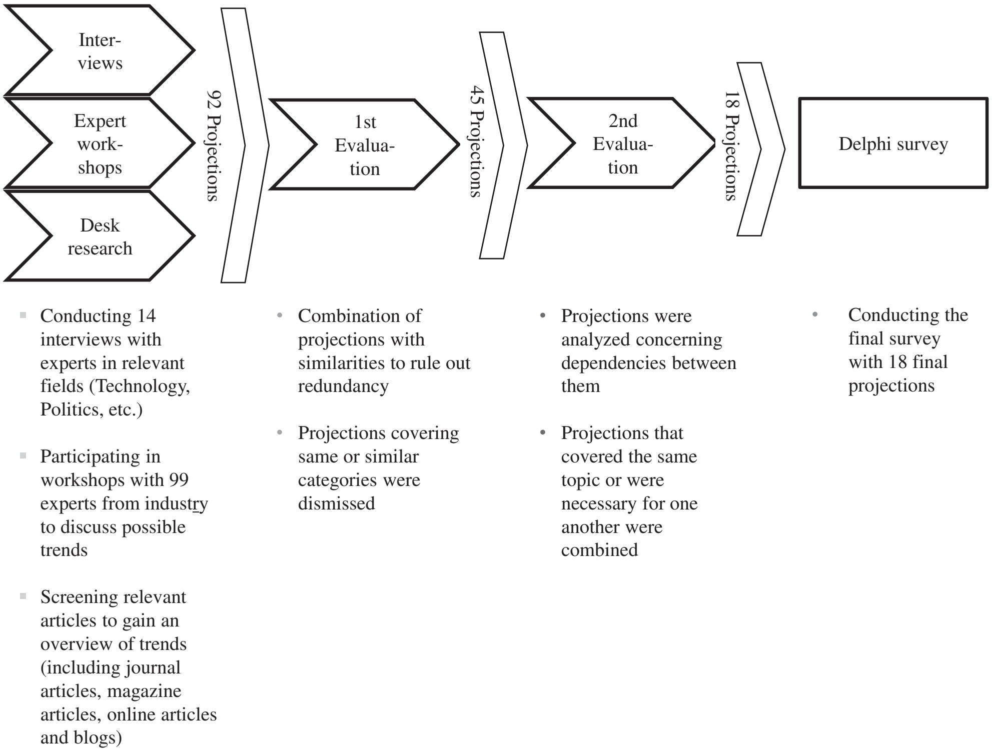

Fig. 2. Formulation of Delphi projections.

procedure outlined in Fig. 2) to gain valid results without causing research fatigue.

This procedure resulted in a final set of 18 projections for our Delphi survey. To ensure methodological rigor and to achieve specificity in formulation, these projections were checked for ambiguity and precise wording by six senior researchers familiar with additive manufacturing (Salancik et al., 1971). Afterwards, all final projections were pre-tested with external (industry) experts in order to ensure content reliability as well as face validity. Finally, the projections were implemented in the internet-based Real-Time Delphi tool developed by Gnatzy et al. (2011).

3.2.2. Step 2: recruitment of panel participants

Next, we composed the main panel of experts by identifying, evaluating, selecting, and finally recruiting relevant actors in the field (Gordon and Pease, 2006). There is no general rule for the optimal panel size in a Delphi survey. Panel sizes depend on the research scope, desired panel heterogeneity, and the availability of experts in the area under investigation (Loo, 2002). There are Delphi studies featuring 15–35 participants (Gordon and Helmer-Hirschberg, 1964) but also others with 40–60 participants (e.g., Schmidt et al., 2001). Our target panel size was oriented towards the latter, as additive manufacturing is a topic with broad scope, a heterogeneous structure of stakeholders, and numerous available experts. Also, heterogeneous panels have been shown to deliver more accurate estimates as "more diverse viewpoints reduce certain polarization of preferences and responses" (Yaniv, 2011).

Thus, we included not only different stakeholders (from industry and academia), but also from a broad spectrum of nationalities. We identified potential experts by database research, a networking approach, and search in professional social networks (such as LinkedIn). Selection criteria were technical specialization in the related field, publications in the domain, profession, and expressed interest in the topic of additive manufacturing. The experts needed to be both capable of delivering suitable statements about future developments and to be interested in the results of our study. Otherwise, experts may have lacked motivation to reconsider their own evaluations by reflecting on the responses of their peers. We then evaluated the experts according to their field of study, corporate function, and their company's stake in the technology's domain. Researchers from academia were chosen based on previous publications in the field. This approach led to a list of 85 additive manufacturing experts who were invited to participate in the Real-Time Delphi survey. 20 of them, however, aborted after < 25% progress had been made and were excluded from the analysis. Thus, our final panel consisted of 65 experts (41 experts from industry and 24 from academia). To our knowledge, our panel has been the most educated and comprehensive group of experts utilized for an academic study on the future of additive manufacturing.

3.2.3. Step 3: execution of Delphi survey

For our Delphi survey, we used the Real-Time Delphi software tool described before. To reduce information overflow, a clear "one-question-one-screen" format has been recommended (Gnatzy et al., 2011). We therefore only presented one projection per page and asked the experts to evaluate it according to their estimated probability of occurrence, its firm impact, and its societal impact for the year 2030. The probability of occurrence was measured in percentages, firm and societal impact were measured on a 5-point Likert scale (ranging from 1 = 'very low' to 5 = 'very high' impact). After each response on a projection by an expert, intermediate results (mean, standard deviation, and interquartile range) were automatically displayed to the expert, who was then asked to revise his or her answer immediately if deemed appropriate.

In addition, we invited the experts to comment on their estimates in an open textbox. The amount of qualitative data gathered was large. We were able to collect 1172 arguments in total, showing that participants thoroughly evaluated their responses and confirming the commitment and expert status of our participant panel. These arguments were later aggregated using content analysis.

After collecting a sufficient number of responses, results were analyzed by calculating mean, standard deviation, outliers, and interquartile range measures. The interquartile range measure specifically shows whether consensus among participants was reached for a projection by calculating the dispersion from the median. It measures the difference between the upper and lower quartiles, and thus represents the middle 50% of observations (Sekaran and Bougie, 2013). We then decided to start a second Delphi round, now including only those projections that did not reach consensus in Round 1. Panelists were given feedback on Round 1 results and asked only to reevaluate their estimation of probability of occurrence, as it seemed unlikely that experts would change their opinion regarding the impact of a projection. Participants were asked in particular to consider the arguments provided by the other panelists in Round 1. The motivation of Round 2 was to increase the consensus among expert evaluations by reconsidering previous answers, and to reach higher data validity (von der Gracht and Darkow, 2010).

3.2.4. Step 4: scenario development

Finally, as suggested by Saritas and Oner (2004), we analyzed the Delphi results to derive scenarios regarding the probability of occurrence and impact of additive manufacturing in 2030. Following von der Gracht and Darkow (2010), this step included further desk research and cluster analysis. We developed a most probable scenario according to the aggregated means of our experts' quantitative assessments, while also using their qualitative arguments for further illustration and verification. The scenario will be presented in detail in the Results section.

3.3. Propositions on the economics and technological development of additive manufacturing

A Delphi study is only as insightful as the quality of the underlying projections. Hence, we took great care that our projections remained sufficiently diverse and covered a broad spectrum of developments and influencing factors in the additive manufacturing field. As mentioned before, we used the PEST framework to reach this objective.

In particular, we considered political and legal factors such as intellectual property discussions and policy making, economic aspects like implications for established business models or entry of new competitors, socio-cultural aspects such as changing consumer behavior and product demand, and technological factors like new production methods, inherent supply-chain changes, or localization issues (Fig. 3).

3.3.1. Policy aspects

Within *policy aspects*, the impact of additive manufacturing on intellectual property rights is clearly a key area (Kurfess and Cass, 2014). Many experts discuss how intellectual property policy might have to change in the future (Hornick and Roland, 2013), when products can be easily replicated based on digital representations in the cloud, following the (challenging) distribution model of digital goods like music, films, and books. Defending conventional intellectual property as we know it may become very difficult (Miller, 2014). Instead, novel forms of intellectual property such as Creative Commons licenses, sharing licenses, or the concept of open source applied to hardware could become promising alternatives (Kurfess and Cass, 2014). Also, questions of liability and ethical measures in an age of additive manufacturing are frequently discussed (Pierrakakis et al., 2014), as illustrated by the drastic case of 3D-printed firearms and public repositories which allow a public download of the corresponding print files.

3.3.2. Economic aspects

Regarding *economic aspects*, additive manufacturing is supposed to challenge established business models and market structures (Weller et al., 2015). An additive manufacturing-induced shift of the origins of competitive advantage is a frequently discussed topic, proposing a shift from manufacturing and supply chain capabilities to design capabilities, and access to customer and designer networks (Cohen et al., 2014). One example is the change in product development where conventional success factors such as managing time-to-market or ramp-up may diminish when all products are individually produced on demand (Gausemeier et al., 2011). In turn, additive manufacturing has the capability of enabling new forms of business models as well as changing existing ones (Mahindru and Mahendru, 2013). Still, there are open questions like handling quality assessment and warranty conditions for 3D printed products (Dillow, 2013).

3.3.3. Socio-cultural aspects

A main aspect of the *socio-cultural implications* of additive manufacturing is a potential shift in consumer behavior and demand. Pioneering consumers are already using design databases to purchase or download freely accessible product designs (Subramani, 2004) for additive manufacturing printing purposes (Birtchnell and Urry, 2013). With additive manufacturing, consumers are able not only to customize existing products (by modifying their design files with an easy-to-use toolkit), but also to create and co-design their very own offerings. Consumers could even have their own printers at home (or have them accessible in very close proximity) (Berman, 2012), which could change purchasing behavior even more drastically (Birtchnell and Urry, 2013). On a larger scale, this could help developing countries to produce their own goods, adapted to local needs (Gebler et al., 2014). Further in the future, printed human organs might become possible via additive manufacturing, bringing even more opportunities, but also challenges (Easton, 2009).

3.3.4. Technological aspects

The *technological drivers* enabled by additive manufacturing are understood relatively well. In general, four types of technological drivers have been identified: the potential for precise replications of existing products (Gibson et al., 2010), the potential for performance increase by improving product function and reducing weight (Gausemeier et al., 2011), the potential for customizing products for specific applications or individual customer needs (Kurfess and Cass, 2014), and the potential for functional integration, reducing the need for assembly (Weller et al., 2015). Building on these characteristics, an often discussed development is the sharing of additive manufacturing resources between companies or via production hubs to enhance asset utilization, which is enabled by the universal character of additive manufacturing technologies and the lack of switching costs (Conner et al., 2014). At the same time, additive manufacturing enables the shift from globally spread (centralized, large-scale) production to more local production models (Birtchnell and Urry, 2013).

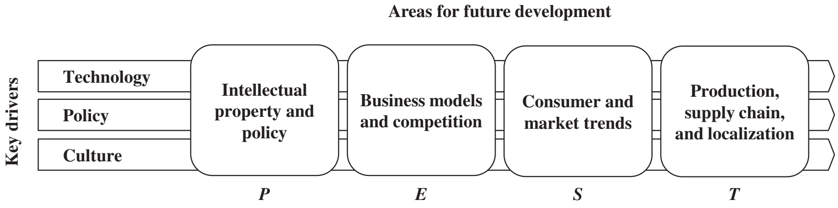

Fig. 3. Research framework based on PEST structure (building on Wilson and Gilligan, 2012).

3.3.5. Final projections

Based on this analysis, and following the procedure described in the Methodology section above, we derived 18 projections on the future of additive manufacturing. Table 1 lists our final set of projections.

4. Results

4.1. Descriptive statistics of the Delphi survey

Table 2 shows the final results of our Delphi study, indicating the interquartile range, mean, and standard deviation for the estimated probability of occurrence as well as the mean for estimated firm and societal impact for each projection. Specifically, consensus development through Delphi Rounds 1 and 2 is depicted here. In line with previous studies, an interquartile range of 2.0 or less indicates that consensus was reached for a defined projection (von der Gracht and Darkow, 2010). The participants were able to reach consensus in 4 out of 18 projections after Round 1 (22.2%) and 6 out of 18 after Round 2 (33.3%).

In Round 1, consensus was reached for Projection 14 (what kind of products will be produced), Projection 15 (3D bioprinting of organs), Projection 16 (demand for new forms of intellectual property), and Projection 17 (regulatory policies for file-sharing platforms distributing product designs). After Round 2, additional consensus could be achieved on Projection 6 that additive manufacturing will reduce emissions and for Projection 7 on the shift of sources of competitive advantage from manufacturing and supply chain capabilities towards design capabilities and access to consumer networks.

The fact that only 6 out of 18 projections fulfill the interquartile range criterion shows that the topic of additive manufacturing is still the subject of rather controversial discussion, especially when including the perspectives of different stakeholders. However, a final consensus rate of 30% is not a rare occurrence in Delphi studies (Keller and von der Gracht, 2014). Furthermore, in our particular case we are dealing with a technology that encompasses several sub-categories, making it even harder to consent to one outcome alone. For each technology, there is a different spectrum of possibilities and potential. This impression is further solidified when splitting the sample into experts from academia and industry. Academic experts tend to agree more on research-related topics such as the question of how competitive advantage will be maintained in the future (Projection 7), or whether end-consumers will own private 3D printers (Projection 13), while industry experts tend to agree on topics like the location of production (Projection 3) and the kind of products that will be produced by additive manufacturing (Projection 14).

Analyzing the change in standard deviation of all projections evaluated in Rounds 1 and 2 revealed an overall decrease in standard deviation. This reflects the fundamental rationale for the Real-Time Delphi method. Reconsidering their own results after having seen the responses and comments of fellow participants led to a stronger convergence among the estimations. The strongest change can be found with Projection 2 (resource sharing). Here, standard deviation decreased by 7.57%.

Results on average estimates for probability of occurrence and firm impact are plotted in Fig. 4 for all 18 projections. Aside from consensus or dissent, the plot reveals some interesting findings. Most projections

Table 1
Delphi projections for 2030.

No.	Projections for 2030
	Production, supply chain, and localization
1	In 2030, >50% of the overall industrial additive manufacturing capacity will be in-house production capacity (i.e., printers not in the possession of an additive manufacturing service bureau or additive manufacturing specialist).
2	In 2030, a significant amount of small and medium enterprises will share industry-specific additive manufacturing production resources to achieve higher machine utilization, learning effects, quality assessments, etc.
3	In 2030, across all industries local production near customers enabled by additive manufacturing will increase significantly whereas globally spread production chains will decrease, resulting in a de-globalization of supply chains.
4	In 2030, distribution of final products will move significantly (>25%) to selling digital files for direct manufacturing instead of selling the physical product (similar effect to the MP3 format on music distribution).
5	In 2030, manufacturing of spare parts will be divided into two systems: less critical parts will be produced locally via additive manufacturing, whereas critical parts will be made at specialist hubs with specific qualification/quality control skills, primarily using conventional manufacturing techniques.
6	In 2030, the carbon footprint of manufacturing and transportation will be reduced substantially by additive manufacturing.
	Business models and competition
7	By 2030, additive manufacturing will have shifted the sources of competitive advantage from manufacturing and supply chain capabilities towards access to customer and designer networks.
8	In 2030, firms' business models will not be immensely influenced by additive manufacturing, as it is just another production technology requiring novel knowledge and skills.
9	In 2030, conventional measures of “time to market”, “product life cycle” and “ramp-up” will have diminished as digital products will be in a continuous beta stage and be subjected to frequent design iterations and constant modifications.
10[a]	In 2030, Germany will be among the Top5 global players in developing industrial additive manufacturing technology and machinery due to existing machine producers, research institutions, and a large number of end users.
	Consumer and market trends
11	In 2030, the market share of additive manufacturing-produced articles (products, components) versus conventionally produced articles will be significant (>10%) across all industries.
12	In 2030, a significant number of consumers will utilize online databases (repositories) to purchase product designs or to access open-source designs freely for additive manufacturing printing purposes.
13	In 2030, the majority of private consumers in industrial countries will have additive manufacturing printers at home.
14	In 2030, a significant amount of additive manufacturing-produced products will consist of multi-materials and/or contain embedded electronics, enabling a broad range of applications.
15	In 2030, additive manufacturing-printed human organs will be a viable and largely utilized substitute for donor organs.
	Intellectual property and policy
16	In 2030, the difficulty of defending conventional intellectual property for digital products will lead to a significantly larger use of novel forms of intellectual property like Creative Commons, or open source.
17	In 2030, an important regulatory measure will be the regulation of additive manufacturing file sharing platforms.
18	In 2030, questions of liability due to unclear intellectual property rights and the inability to monitor and prosecute intellectual property infringements will have led to a much lower utilization of additive manufacturing as technically possible.

[a] Projection 10 was not included in our further analysis, as it served a special purpose for the organization funding our research. As our sample contained a larger number of German experts, we expect its evaluation to be biased.

Table 2
Descriptive statistics for the Delphi projections.

Projection	Round 1			Round 2			Mean change	SD change	Firm impact	Societal impact
	IQR	Mean	SD	IQR	Mean	SD				
Production, supply chain, and localization										
1. Localization of production	3.60	48.17	22.26	3.50	47.86	20.67	−0.64	−7.13	3.54	3.11
2. Resource sharing	3.00	51.80	23.79	2.60	50.57	21.99	−2.38	−7.57	3.43	3.00
3. Deglobalization of production	3.00	54.28	20.63	3.00	54.28	19.89	0.00	−3.59	3.68	3.52
4. Distribution of end-products	4.00	40.64	24.01	3.00	39.23	23.01	−3.46	−4.17	3.33	3.38
5. Spare parts	2.50	62.62	21.84	2.50	63.46	21.39	1.35	−2.05	3.63	2.97
6. Emissions	3.00	43.15	22.15	2.00*	42.54	20.72	−1.43	−6.44	2.83	3.18
Business models and competition										
7. Competitive advantage	3.50	50.09	20.14	2.00*	49.63	18.99	−0.92	−5.68	3.32	3.26
8. Business models	4.00	45.85	23.67	4.00	46.77	22.49	2.01	−5.01	3.18	2.83
9. Product development	3.00	55.23	22.11	3.00	55.85	21.42	1.11	−3.11	3.66	3.38
10. Market power	3.00	68.08	19.80	3.00	67.77	19.08	−0.45	−3.66	3.68	3.29
Consumer and market trends										
11. Market share	4.00	51.94	25.77	3.50	51.25	23.84	−1.33	−7.50	3.51	3.15
12. Purchasing channels	4.00	60.65	25.26	4.00	60.42	24.67	−0.38	−2.33	3.40	3.77
13. Ownership	3.50	32.22	21.39	2.75	31.48	20.89	−2.27	−2.33	2.72	3.23
14. Product attributes	2.00*	58.58	19.80						3.65	3.45
15. Bioprinting	2.00*	27.68	20.45						3.00	3.97
Intellectual property (IP) and policy										
16.IP forms	2.00*	59.25	14.79						3.82	3.57
17. File sharing	2.00*	55.62	21.13						3.52	3.18
18. Infringement	2.50	37.35	18.53	2.50	37.58	17.64	0.62	−4.82	3.00	2.83

Notes: * indicates projections where final consensus was reached (i.e. interquartile range (IQR) of minimum 2.0). *SD = standard deviation. N* = 65.

are considered to have a firm impact equal to or higher than 3.0. This indicates that the projections developed beforehand seem to be relevant for the purpose of our study. Still, for seven projections, the estimated probability of occurrence is <50%. Most projections where consensus could be reached have an expected probability of occurrence above 50% (4 out of 6), which is in line with other Delphi studies (e.g., Ogden et al., 2005). Naturally, dissent is higher for developments where the future is even more vague compared to other projections (e.g., Projections 8, 11, and 12).

One of the main goals of our research was to develop relevant scenarios for the future of additive manufacturing in 2030. Fig. 4 illustrates the scenario cluster we derived from our analysis for this paper. The following sections will introduce the scenario in larger detail.

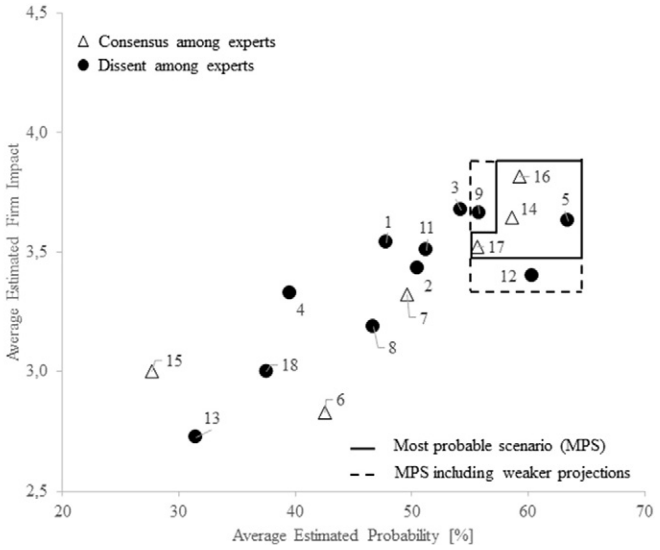

Fig. 4. Scenario I (most probable scenario): The most probable future of additive manufacturing in 2030 (numbers indicate the projections according to Table 1).

4.2. A most probable future for additive manufacturing in 2030

The scenario cluster for the most probable future contains those projections evaluated by the expert panel with the highest probability of occurrence in 2030 and a sufficient amount of certainty between the expert evaluations. For a narrow version of the most probable scenario we took those projections (5, 14, 16, and 17) showing both a high degree of certainty among experts' evaluations (three projections with interquartile range larger than 2.0, and one with 2.5) and having a sufficient probability of occurrence (larger than 55%). If looking at a broader scenario, Projections 9 and 12 can also be included, which show a relatively high estimated probability of occurrence, but their estimations are fraught with uncertainty (interquartile range of 3.0 and 4.0, respectively). The most probable scenario for 2030 consists of a production-centric and a more supply chain centric theme.

The first theme predicts changes in the production system regarding spare parts, efficiency measurements, and new material attributes such as multi-material production and embedded electronics. In detail, spare parts manufacturing will be divided into two systems: less critical parts will be produced locally via additive manufacturing, whereas critical parts will be made at specialist hubs with specific qualification/quality control skills, primarily using conventional manufacturing techniques. The experts believe that "*making spare parts using additive manufacturing will simplify logistics, and also is a need for companies with time-critical service contracts*" (industry expert). According to researchers, all spare parts may be produced with additive manufacturing: "*I think spare parts for critical components will also be made using additive manufacturing*", as the technology will continue to improve, so that "*in 2030, the quality will be on the level of analogue technologies*" (research expert).

Moreover, when spare part distribution moves towards on-site production via additive manufacturing, opportunities for operational efficiency arrive: "*Right now, a high degree of warehousing of 'slow moving' spare parts is a big concern and companies are working hard to solve this issue*" (industry expert). "*[There will be a] reduction of spare parts stocks*" (industry expert). This should allow for large gains in efficiency, as distribution costs for spare parts (often shipped as a single piece of airfreight) can be reduced dramatically.

Furthermore, a significant amount of additive manufacturing-printed products will consist of multi-materials and/or contain embedded electronics, enabling a much broader range of applications as "*hybrid products combining additive manufacturing & conventional manufacturing will become common*" (industry expert). The experts see this development as the logical consequence: "*This [multi-material products] is an inevitable development of additive manufacturing*" (research expert). They argue that multi-material products and embedded electronics is "*what additive manufacturing is capable of and meant for!*" (research expert), realizing the technological drivers identified in the PEST analysis above to a large extend (especially the ability to further reduce assembly operations and automate manufacturing).

However, some experts believe that this development will not be realized as quickly as projected: "*It will take another ten years before single-material additive manufacturing products can be made, development of multi-material additive manufacturing will take another ten*" (industry expert). Still, the ability to manufacture products with advanced attributes (multi-material, embedded electronics) via additive manufacturing will impact the possible scope of applications, which also implies a larger impact for the other projections. Experts predict that "*if this technology is shown to work well, its impact on how we manufacture things would be even greater than [with current] 'standard' additive manufacturing*" (industry expert) and that there is high commercial value and "*opportunity for [firms] with smart manufacturing skills*" (industry expert).

With less estimated impact, experts predict that conventional measures of success in product development, such as "time to market", "product-life-cycle management" or "ramp-up speed", will diminish, also demanding a fresh view on the design-manufacturing interface (and the broad body of academic literature in this area). Digital products are in continuous beta and are subjected to frequent design iterations and constant modifications in 2030, hence conventional accounts of a manufacturing ramp-up do not have relevance any longer. Both industry and research experts believe that this projection may happen in a less radical way, as this will be "*not valid for components that need certification of their manufacturing route (like many B2B products)*" (research expert), but rather for consumer products: "*This [development of conventional measures] depends on the industry. For many critical components, a validation period and staged introduction is required*" (industry expert). However, given the strong opportunities and perceived likelihood of this development, we believe that this is a field where policy makers and regulators have to adapt regulation to a new technological reality.

A strong focus on customization and individualization is an additional sign that firms will become affected by this projection: "*Physical products will become increasingly like software based services. They are continuously differentiated and improved*" (research expert). However, "*those measures [time-to-market, ramp-up etc.] will still apply but the way in which they are considered will have changed*" (research expert). Overall, the breadth and depth of comments on this projection indicate that this is a particularly interesting domain, challenging current thinking in innovation management. When products remain in a continuous "beta" state with frequent modifications, as is common for web services today, a new understanding of the product development process is required, challenging current "stage gate" thinking. At this point, it will be interesting to see how, for example, agile development approaches will not just be enabled, but also demanded by additive manufacturing.

The second set of developments in this scenario refers to the design of supply chains in 2030, which will be affected in three ways: the importance of intellectual property will diminish, infringement will become a major threat, and distribution channels will undergo severe changes. It will become immensely difficult to defend conventional intellectual property rights for digital products. Experts believe that there will be a significantly larger use of novel forms of intellectual property like Creative Commons or open source (hardware) licenses, as these are "*necessary and an enabler for the digital manufacturing community*" (industry expert). Also, complementary measures for protecting intellectual property will become necessary: "*I feel that intellectual property protection will be less critical compared with the ability to being quickest to market*" (research expert). The "*control of usage information will be important for digital products. The combination of design and use will become the basis for defending intellectual property*" (research expert). "*This will move in the same direction as copyright for music and films etc. New models need to be developed*" (industry expert). When "*the importance of digital rights will decrease as it gets more difficult to defend, other factors for market success get more predominant (customer access etc.)*" (industry expert).

From a company perspective, this demands the ability to develop new strategies. This could become a major challenge, as "*Intellectual property is a critical control point for a lot of companies. Creative commons and open source software/hardware initiatives are very new and companies need to figure out how to work in this framework*" (industry expert). "*The importance of digital rights will decrease as [they become] more difficult to defend and other factors for market success [will become] more predominant (customer access etc.)*" (industry expert). Therefore, "*changing business models will be needed to capture the development costs*" (industry expert). So, from the experts' perspective, it is firms and their ability to innovate their business models systematically that help companies to cope with intellectual property challenges in the age of additive manufacturing, and not regulatory measures.

However, these challenges will not lead to a significantly slower progress and advancement of additive manufacturing: "*I don't see how intellectual property issues will slow down the growth of additive manufacturing. If additive manufacturing enables a better product, higher value, or lower cost, then companies will use it, regardless of liability and unclear intellectual property rights*" (industry expert). We did not include blockchain technology in our propositions as a novel measure for digital rights management of digital products. This will probably become a foresight study of its own, but a few mentions of this technology in the qualitative comments of some experts indicate that blockchain technologies could become a potentially strong tool for managing the intellectual rights connected to a digital product.

At the same time, regulatory measures for additive manufacturing file-sharing platforms will become important. Governments are expected to engage in regulating such platforms, even though the experts think that "*controlling infringement by outlawing it won't be effective (see the music industry)*" (industry expert) and "*effective protection against intellectual property infringement is almost impossible to realize. At least for the consumer market this is a good thing*" (research expert). Still, if businesses are supposed to use additive manufacturing technology, there is a need for some sort of protection as "*regulation will be critical but is likely to be not effective*" (industry expert). Firms will have to look for other forms of success and ways to establish competitive advantage, like a new emphasis on branding, after sales support, but also support of user co-design of custom products or the ability to build and nurture a community of design-savvy users around one's products.

Another interesting development is consumers utilizing online databases (repositories) to purchase product designs or to freely access open-source designs for additive manufacturing printing purposes, thus changing the way things are sold: from e-commerce to file-commerce. Still, some experts believe that "*only a small community of enthusiasts will do this. Not everyone will be interested and creative enough for this [but] for children and tinkerers the share will be high (70%)*" (industry expert). For these customers, new business models will arise to serve their needs: "*Most [of the other] people are not creative by nature and do not want individual products! There would be too much choice*" (research expert). "*This [using online databases for their own production] is already happening, and with broad access to either consumer 3D printers or 3D-P[rinting] services, the number [of users] will be significant*" (industry expert). "*Printing on demand will become more and more important, for some products consumers will not even be aware that the product is produced on demand.*" (industry expert).

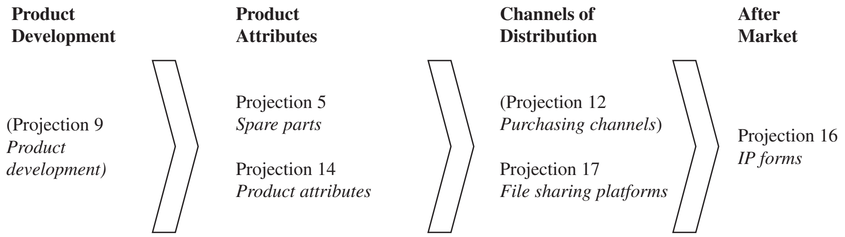

Fig. 5. Most probable scenario for additive manufacturing in 2030.

In our preliminary interviews, an expert predicted that "*new generations of children will be taught to think differently from the start and learn during their education to think 'generatively', meaning thinking in terms of design for manufacturing and not, as it is today, manufacture for design.*" Overall, these predictions ask for a paradigm shift in consumer research and marketing, but also for the implementation of new business models, like a kind of streaming-service for product files (similar to music streaming as a solution to the digital dilemma in the music industry).

In conclusion, the most probable scenario for 2030 affects all elements of the value chain (Fig. 5). Connecting the projections of this scenario, we obtain a new picture of a future in 2030 where additive manufacturing is dramatically changing the way that products are developed, distributed, and acquired. Product development changes from traditional stage-gate models (Cooper et al., 2004) to iterative, agile processes where conventional measures such as time-to-market or time-to-ramp-up have partly become obsolete (Projection 9). The scope of products printable via additive manufacturing will be much larger, as multi-material additive manufacturing production and embedded electronics will be possible to a large extent (Projection 14). Spare part production will take place on-site (Projection 5), totally changing the role of suppliers in production chains.

Furthermore, private consumers will utilize file-sharing platforms (Projection 17) and digital purchasing channels (Projection 12) to obtain product files and later produce them autonomously on their own or a local, shared additive manufacturing machine (again a development facilitated largely by multi-material printers). This digitization of physical products challenges the current intellectual property system due to difficulties in protecting traditional forms of intellectual property (Projection 16), leading to the deployment of new intellectual property regimes or the development of new business models like file sharing or product streaming.

Supplementing the scenario for the most probable future, also Projection 3 should be considered when looking at the impact for firms interested in additive manufacturing. It proposes that additive manufacturing will enable decentralization of production to localities near customers. The inherent benefits (fast availability, short shipping times) of this capability will hence move manufacturing back from globally spread production to local facilities. The projection shows a rather high rate for probability of occurrence (54.28%) and also reaches consensus amongst experts from industry: "*Manufacturing dislocation will become [a] necessary [development]*" (industry expert), in particular as "*individualism and design requirements put pressure on production close-to-market*" (industry expert). Also, "*this is happening already for consumer products, [as illustrated by] the FabLab movement or by what 3DHubs is doing.*" (industry expert).

Moreover, comments regarding firm impact indicate the high significance of this projection for companies: "*Large companies need to catch up to this trend. Manufacturing in factories is efficient for mass produced products that have low variety. [But] for a lot of companies, the market is shifting, and companies need to redesign manufacturing to become more flexible, data driven, and able to achieve cost-effective production across a large range of volumes (from 1 to 1000s of products/SKU)*" (industry expert). In this regard, current developments in the sports good industry may also become pioneering examples for other industries. Companies like Adidas or Under Armour are currently investing heavily in relocating manufacturing from Far East to Western markets, enabled by highly automated digital manufacturing technologies (Adidas' Speedfactory or Under Armour's Lighthouse project).

4.3. Projections with low probability of occurrence

Following common standards, our scenario has been based on the projections that were estimated to be highly most to become reality by 2030. But it is also worth looking at the projections with small probabilities of occurrence, as they may indicate popular myths or high uncertainties (as all projections were derived by the same rigorous, multi-stage process described at the beginning of this paper). Three projections (13, 15, 18) with the lowest probabilities of occurrence shall be discussed briefly.

Projection 13 (probability of 32%) states that consumers will use their own 3D printers at home, a frequently mentioned prediction in the general discussion of additive manufacturing. An interquartile range of 2.75 indicates that evaluations about ownership of home printers were relatively unanimous. The experts in our sample did not think that home printers would be purchased and owned by private consumers: "*When [digital] printers first came out, almost everyone had one. But now, most people are printing at offices where you have a state of the art printer. No need to have one at home too. I see a similar evolution for 3D printers. You [also] can access a 3D printer at local community places, e.g., libraries*" (industry expert). This evaluation also contradicts several streams in academic literature attributing highly disruptive business model changes to home fabrication (D'Aveni, 2015; Rayna and Striukova, 2016). This indicates a need for further validation on this future path.

In Projection 15 (probability: 27.68%) we stated that bioprinting of human organs would become an established technology in 2030. Again, experts' opinions are unanimous (interquartile range: 2.0). While experts agree that bioprinting of organs is very likely to be possible one day, evaluation of the qualitative comments revealed that they did not see this technology being realized before 2040. Printing simpler organs, like tissue or tooth implants, however should be possible in 2030: "*3D bioprinting is in a research state, tissue printing will happen within 10 years, human organs will need breakthroughs which take more than 10 years*" (industry expert).

Projection 18 (probability: 37.35%) proposed that challenges of intellectual property infringement will slow down the penetration of additive manufacturing technology (interquartile range: 2.5). The majority of our experts do not see such a development; on the contrary, their low evaluation of the probability makes a case for additive manufacturing diffusion. Despite challenges for intellectual property, additive manufacturing will move forward (as also indicated by Projections 16 and 17): "*The music industry tried to sue the heck out of illegal music sharers, but all [what] that really did was to irritate a lot of people. I don't think this will be any different for additive manufacturing content online*" (industry expert).

5. Implication for research, practice, and policy

The objective of this paper was to close the research gap of forecasting the uncertain future of additive manufacturing to differentiate between hype and expected realities. To the best of our knowledge, we conducted the first Delphi-based forecasting study to examine the future of additive manufacturing in 2030. Through initial qualitative interviews, industry workshops, and an expert panel of 65 participants evaluating 18 future projections in an innovative Delphi study setup, we developed a future scenario for how additive manufacturing will change industry and business models in 2030. We complement the existing literature that has focused predominantly on the technological developments of additive manufacturing. Only few studies have explicitly targeted the economic or societal implications of additive manufacturing, and none has, to our knowledge, dealt with possible scenarios for the future.

Our Delphi results confirm that additive manufacturing is a school of technologies still in the making. For only 6 out of 18 projections, consensus could be achieved. We summarized the implications of these projections in a most probable scenario. But despite the differing opinions on single topics, most experts deemed the projections highly important, evaluating the vast majority of them with a firm impact of 3.0 or higher on a 5-point Likert-scale (average: 3.38). Similarly, the societal impact of additive manufacturing is regarded highly (average: 3.28).

These results indicate that scholars and managers alike should continuously engage in monitoring and forecasting the additive manufacturing domain. Companies should engage in an experimental mode of learning before making large investments to create learning opportunities and validation for their particular company and industry. Researchers can further utilize our results for the future study of additive manufacturing. Future research should focus more on those projections where our data currently indicates a broad spread of opinions and thus high uncertainty. While often the focus of attention is on the most probable projections, we believe that also those with high controversy are of large importance.

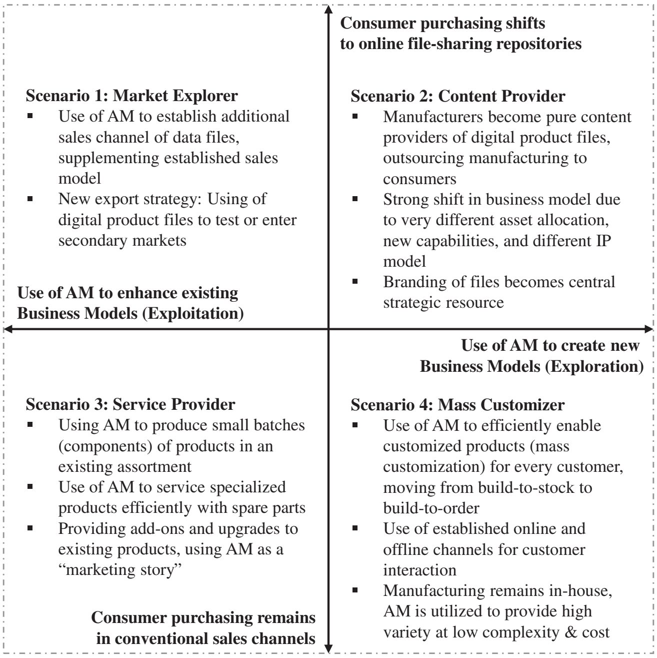

Fig. 6. Four controversial extreme scenarios how additive manufacturing affects consumer purchasing models.

Following the example of Markmann et al. (2013), our research supports future analysis by applying the Delphi data to structure developments in form of extreme scenarios. For this purpose, we exemplarily constructed four extreme scenarios by selecting the two projections which showed the lowest level of consensus among the experts (both have an interquartile range of 4.0): the impact of additive manufacturing on firm's business models (Projection 8) and on consumer distribution channels (Projection 12). We built two development continuums, spanning between the trajectories expressed by these two projections. Fig. 6 illustrates the scenario axes and resulting scenarios. The qualitative expert comments helped us characterize the resulting scenarios in more detail.

The horizontal axis derives from Projection 8: For those experts who agree on it, additive manufacturing can be regarded as just another production technology requiring novel knowledge and skills, but mainly improving the operational excellence of a company. While some operations may change drastically, the operating model of the company will remain the same. For those rejecting this projection, however, established business models will be disrupted by additive manufacturing, demanding incumbents to make radical changes. These two extremes resemble the established debate on exploitation versus exploration in the innovation management literature (March, 1991).

The vertical axis builds on Projection 12, which covers one of the most frequently debated implications of additive manufacturing (Rayna and Striukova, 2016; West and Kuk, 2016). The experts believing in this projection foresee a strong change in consumer behavior: Instead of acquiring physical products, consumers will utilize online databases to download product designs for self-printing, either purchasing the file (similar to downloading a music file in an online music store) or using a sharing model with open-source designs. Experts rejecting this projection, however, expect that also in 2030, products produced via additive manufacturing will be purchased as physical objects via established online or offline channels.

Combining these two axes, we derive four possible scenarios (Fig. 6). The extreme Scenario 1 combines the exploitation model with a new distribution model. Here, a company uses the efficiency of selling online files instead of exporting products to test new foreign markets, but also to cover niches of demand in established regions. Once a market is established, however, the products will be sold via a conventional business model (moving to Scenario 3). Scenario 2 combines the two extreme positions of an exploration strategy with a distribution model via online file-sharing. In this model, the business model of the company shifts fundamentally. A former manufacturer becomes a pure "designer" (providing the digital print files only). The core job of the company here is to guarantee the "3D printability" of the files. For its revenue model, it has to utilize new forms of intellectual property protection to allow for value capture.

Scenario 3 is the most conservative setup where additive manufacturing is mainly used to support an established business. The case of spare parts, as discussed before, can be placed here. Another option is to utilize additive manufacturing for the manufacture of niche products which are not economically feasible with conventional manufacturing models. Finally, Scenario 4 builds on the idea of mass customization, i.e. providing an individual product for every consumer, but with mass production efficiency. The business model of the company, hence, shifts drastically. Instead of forecasting product demand and producing it on stock, all operational activities are purely reactive, staring with the individual demand of each single customer.

For managers, our results offer both a validated starting point in a field characterized by rather uncertain conditions and an inspiration for future developments. We recommend that managers should, first of all, discuss all 18 individual projections before the background of their respective markets and industries, also engaging in an exercise of deriving extreme cases, as demonstrated above. This will support them either to formulate new business strategies or to validate existing ones. In the first case, managers can use the scenarios for decision support and development of new strategies, like illustrated in the development of the four extreme scenarios. The latter case implies that the data can be used to test existing strategies already implemented. The experts from industry revealed that currently many companies have developed an "additive manufacturing strategy." Matching its implementation progress with the projections from the Delphi study can provide strategic guidance on required adaptations and market realities.

For policy makers, our results indicate a continuous need for future study and observation. While the technology development of additive manufacturing has moved into a stage of continuous improvement and refinement, the regulatory and policy framework for additive manufacturing is still in its infancy. Those projections with highly rated societal impact should be looked at in more detail (like Projection 3 on deglobalization of production (societal impact of 3.52), Projection 12 (purchasing channels, 3.77), Projection 15 (bioprinting of organs, 3.97), and Projection 16 (intellectual property forms, 3.57)). This indicates a necessity to look into possible forms of intellectual property protection, preparing for ethical issues in the realm of additive manufacturing-enabled innovation in healthcare, and adopting infrastructures when supply chains become more local again.

Finally, our research also has implications from a methodological perspective. We contribute to the development of forecasting methods by presenting a rigorous and structured application of a novel variation of the Delphi method. With the Real-Time Delphi tool introduced by Gnatzy et al. (2011), we applied a more efficient variation of an online-based Delphi survey. The approach circumvents the necessity of sequential rounds, common in conventional Delphi studies, as it provides real-time feedback after each evaluation of an expert. It further features various graphical tools to make participation easier and even 'fun' for experts (consensus portal, graphical real-time feedback). Our study validates the advantages of this approach and may serve as a template for further applications of the Real-Time Delphi.

6. Limitations and opportunities for future research

Our research is not without its limitations. We were not able to analyze discontinuities (Grossmann, 2007) and surprising future occurrences in our scenario study (Cornish, 2003). Due to the fact that the scatterplot of our results (Fig. 4) resembles the slope of a regression line, projections with high firm impact were also evaluated with higher probability and vice versa. Biases such as the confirmation bias could be a cause for this phenomenon (Plous, 2007) as the participating experts are more likely to evaluate projections falling into this category with a higher degree of probability. It is also possible that experts are more likely to rate the projections that are currently of greater importance to them as more probable to become true. Hence, a further analysis of these so-called wildcard scenarios with the help of other datasets could reveal more insights.

Our scenarios are basically grounded on qualitative data, although they are supported by quantitative assessments. Including more statistical data aside from the Delphi estimations could improve the accuracy of our prognosis. For example, cost implications or growth rates could be included. Moreover, our panel was skewed towards industry experts and lacked a larger representation of experts from Asian countries. As countries like China, Japan, and India were frequently mentioned as important players in additive manufacturing by the experts of our Delphi panel, future research should address these geographies with more detail.

Future research should also try to better differentiate between the various types of additive manufacturing technologies. However, our objective was to provide a comprehensive picture of the general trends common to all additive manufacturing technologies that enable direct manufacturing from digital product files without conventional set-up costs, hence breaking with most of the established rules and models in (operations) management and product development (Weller et al., 2015). Despite its limitations, we hope that our research will inspire further study of this fascinating field that surely will affect the lives of us all – and probably even before 2030.

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Appendix

Table 3
Interviews conducted to develop the propositions.

Expert	Affiliation [industry, country]	Competency
#1	Design and art, South Africa	Head of design and art company using additive manufacturing
#2	Consultancy, Netherlands	Founder of additive manufacturing consultancy
#3	Foresight consultancy, Germany	Futurologist; co-founder and consultant in a foresight consultancy
#4	Additive manufacturing services, France	CEO and co-founder of an additive manufacturing cloud engine service
#5	Consultancy, Netherlands	Consultant in additive manufacturing projects
#6	Attorney, Germany	German and European patent and trademark attorney specializing in additive manufacturing
#7	Attorney, Germany	Head of law firm specializing in IT and media law
#8	Attorney, Germany	Attorney in IT law
#9	Research and education, Germany	Professor of production engineering and author of additive manufacturing literature
#10	Politics, Germany	Politician; member of the Bundestag
#11	Additive manufacturing services, Germany	Author on and founder of additive manufacturing company
#12	Additive manufacturing services, Belgium	Business development manager in additive manufacturing firm
#13	Additive manufacturing printing and scanning services, Germany	Head and co-founder of additive manufacturing firm
#14	Research and education, Germany	Researcher in the field of laser technology and additive manufacturing

Table 4
Propositions and selected expert commentary used for scenario development.

No. of proposition	**Projection 2030 and associated qualitative arguments** [number of entries]			
3	*In 2030, local production near customers enabled by additive manufacturing will increase significantly across all industries, whereas global production chains will decrease, resulting in a de-globalization of supply chains.*			
Total number of arguments: 92	High probability arguments: 24	Low probability arguments: 28	Firm impact arguments: 21	Societal impact arguments: 19
Top low probability	This depends highly on the product: for mass-produced products globalization still makes sense, for customized parts and spare parts etc. this might happen. [9 entries] Additive manufacturing will not make up for all produced parts, products are built with mass-produced parts and Additive manufacturing parts so that the total supply chain will remain global. [4 entries] Costs for local production with additive manufacturing are too high and transportation is very cheap. [4 entries]			
Top high probability	This is already happening (FabLab movement, 3DHubs) and will steadily increase due to the need for customized and sustainable production. [9 entries] Only mass production will be global, long shipping times would contradict the very use of fast additive manufacturing production and availability. [5 entries] Elimination of tools for production eliminates the restrictions of centralized production. Deglobalization of assembly and globalization of materials is integral to digitalization. [2 entries]			
Conclusion	**In 2030, mass-produced parts and materials will remain globally produced but customized production, and instances where sustainable production is demanded, will occur locally.**			
5	*In 2030, manufacturing of spare parts will be divided into two systems: less critical parts will be produced locally via additive manufacturing, whereas critical parts will be made at specialist hubs with specific qualification/quality control skills, primarily using conventional manufacturing techniques.*			
Total number of arguments: 68	High probability arguments: 18	Low probability arguments: 23	Firm impact arguments: 17	Societal impact arguments: 10
Top low probability	Additive manufacturing quality will be on the level of analogue technologies so that there will be no difference between critical and non-critical components. All spare parts will be produced with additive manufacturing. [6 entries] Even for less critical parts there will be issues with quality assurance and liability so that none will be produced locally. [6 entries] I see it exactly the other way around, standard parts will be conventionally produced on a large scale, whereas specialized parts will be additive manufacturing manufactured. [2 entries]			
Top high probability	There will be a trend towards local production of spare parts with additive manufacturing due to time- and money-saving options (on-demand availability, logistics). [9 entries]			
Conclusion	**In 2030, all (critical as well as non-critical) spare parts will be produced with additive manufacturing.**			
9	*In 2030, conventional measures of "time to market", "product life cycle" and "ramp-up" will have diminished as digital products are in continuous beta stage and are subjected to frequent design iterations and constant modifications.*			
Total number of arguments: 63	High probability arguments: 18	Low probability arguments: 17	Firm impact arguments: 16	Societal impact arguments: 12
Top low probability	This is very industry specific. In a lot of industries (and for a lot of consumers) there will still be regular demand for standard, final products. [4 entries] Not valid for products and components that need quality control, validation or certification of their manufacturing route (B2B, healthcare etc.). [4 entries] Consumers will not accept "bad" products, the initial product has to fulfill all customer requirements and expectations with full functionality. [2 entries]			
Top high probability	Physical products will increasingly become like software-based services or apps. This development is especially likely in industries where design and style play an important role. [9 entries] This will be true for small-series, less-critical parts, and consumer goods. [2 entries] Those measure will still apply but the way in which they are considered will have changed. [1 entry]			
Conclusion	**In 2030, design and manufacturing of consumer products and less-critical industrial products will not be subject of conventional performance measures any longer as they will be modified in frequent iterations.**			

12	*In 2030, a significant number of consumers will utilize online databases (repositories) to purchase product designs or to freely access open-source designs for additive manufacturing printing purposes.*			
Total number of arguments: 60	High probability arguments: 18	Low probability arguments: 13	Firm impact arguments: 14	Societal impact arguments: 15
Top low probability	It will only be a small community of enthusiasts, children and tinkerers, not all consumers will be interested and creative enough. [9 entries] The quality of materials will not be good enough for this to create sufficient enough end-products. [2 entries]			
Top high probability	This is already emerging and people already do this. With broad access to either consumer 3D printers or additive manufacturing services, the number will increase even more. [7 entries] We will teach our children to think digital, future customers will want freedom of design and use channels such as this. [4 entries] If there are affordable commercial job shops people will try out additive manufacturing technologies and use open-access databases. [2 entries]			
Conclusion	**In 2030, enthusiasts, tinkerers, and new consumer generations will utilize additive manufacturing and use online databases to purchase designs due to broad availability of printers in job shops etc.**			
14	*In 2030, a significant amount of additive manufacturing-produced products will consist of multi-materials and/ or contain embedded electronics, enabling a broad range of applications.*			
Total number of arguments: 62	High probability arguments: 17	Low probability arguments: 14	Firm impact arguments: 18	Societal impact arguments: 13
Top low probability	It is still a long way to go, single-material products will take another 10 years, multi-material products will take another 10, they are too immature right now. [9 entries] Multi-component additive manufacturing parts face competition from other technologies. [1 entry]			
Top high probability	This is what additive manufacturing is capable of and meant for and an inevitable development. [8 entries]			
Conclusion	**In 2030, there will be multi-material products as industries and users pursue these strongly.**			
16	*In 2030, the difficulty of defending conventional intellectual property for digital products will lead to a significantly larger use of novel forms of intellectual property like Creative Commons, open source*			
Total number of arguments: 42	High probability arguments: 16	Low probability arguments: 9	Firm impact arguments: 8	Societal impact arguments:9
Top low probability	There will be certain intellectual property management methods established for additive manufacturing as the current intellectual property system is too strong. [3 entries] Firms have to protect their intellectual property even more strongly with the advent of additive manufacturing. Open source is not a sustainable model as designers/firms do not earn revenue from this. [3 entries]			
Top high probability	The adoption of additive manufacturing requires non-conventional intellectual property. It is a necessary enabler for the digital manufacturing community and will move in the same direction as the music and film industry. [7 entries] The importance of digital rights will decrease as they get more difficult to defend. Other factors for market success will become predominant (customer access, being quickest on the market). [2 entries]			
Conclusion	**In 2030, other forms of intellectual property will be necessary in order for additive manufacturing to be adopted in industries.**			
17	*In 2030, an important regulatory measure will be the regulation of additive manufacturing file-sharing platforms.*			
Total number of arguments: 45	High probability arguments: 12	Low probability arguments: 17	Firm impact arguments: 8	Societal impact arguments: 8
Top low probability	Effective protection against intellectual property infringement will not be possible anymore. For the consumer market, this is a good thing. Firms need to look for other success factors. [8 entries] Technology know-how and product improvement will be the response to infringement. [4 entries]			
Top high probability	If businesses should grow around additive manufacturing, there needs to be some sort of protection for design platforms. [3 entries] Government is likely to try to regulate this. If current law is not clear, policy making needs to intervene to balance intellectual property protection and technology accessibility. Otherwise, applications like distributed manufacturing of spare parts will not be possible. [2 entries]			
Conclusion	**In 2030, governments will try to regulate file sharing platforms, but will not be effective in doing so. Firms will have to look for new sources of competitive advantage.**			

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