The emergence of the Digital Fabrication industry: Domains, applications, and key technology challenges

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Abstract

Novelties created by newly emerging sciences and technologies also capture a substantial amount of promises around their transformative character. Promises and resulting expectations concerning performance and applications but also regarding the impact of new technology on society arise. Key features of emerging industries are high uncertainty, different stakeholder groups that are involved in different phases of development and a strong need for management through these phases. In the context of this innovation ecology, interaction between science and industry is an important aspect to consider. This is usually easier conceptualized as put into practice. Decisions about which technological areas to focus on and to invest in have to be made before marketable technologies or products emerge. Prioritizing a key application field relevant to a disruptive technological domain thus poses significant challenges. In this paper, we first describe how consensus on the most pressing and high potential domains and applications in digital

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fabrication was reached in a consortium-based approach. What is more, we can show at hand of stakeholder survey results what the future expectations are regarding the maturity of the respective applications. In a next step, we bring key technology challenges (KTCs) into the picture and argue for varying pressures to overcome them along the industry emergence process. This allows both practitioners and researchers to see how the challenges of an emerging field can be addressed with context-driven strategic intelligence.
Keywords: digital fabrication, industry emergence, technology promises & expectations, evolution, Diginova consortium, key technology challenges

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1. Introduction

Digital fabrication (DF) can generally be defined as a new kind of industry that uses computer-controlled tools and processes to transform digital designs directly into useful physical products. This includes technologies that make use of digital material deposition methods to create two dimensional products in form of digital printing technologies (2D DF) and additive manufacturing technologies (3D DF). Complementary technologies may be used to supplement these digital technologies in order to deliver full production systems. The development of well-matched combinations of advanced new material deposition tools and materials is emerging as a key success factor for DF. When matched with fully developed production systems, this enables a huge paradigm shift in the manufacturing industry. DF has huge potential to bring a new generation of products to the market that will allow to deliver new applications beyond customer expectations [1]. In its current state, DF is already experiencing hype in the industry [2, 3, 4], the media

[5, 6, 7], and the maker community [8, 9, 10].

While there is considerable hype about the potential of this disruption wave, the key challenge faced by managers today is to identify future opportunities enabled by DF. Indeed, basic science is a great source of new opportunities and ideas but translating science into marketable products fulfilling latent customer demand can often take decades ([11]). In emerging technologies, markets are not yet clearly defined, can shift rapidly or might not even be existent (e.g. [12]). Thus, it is hard to actually forecast future demand of a technology when actual market applications are in the realm of technological promises and associated expectations but are not yet realizable[12]. Accordingly, decision-makers have to act strategically and have to make assessments of future possibility spaces where others (e.g. science, the government, competitors, customers) will move and what is actually technologically feasible and most promising to invest in.

Indeed, new technologies, such es e.g. biotechnology, nanotechnology or DF emerge under substantial uncertainty but are associated with substantial technological promises resulting in high expectations [13, 14]. These promises are put forward to stimulate societal awareness, attract governmental support, and nurture interest within the industry [15].Investing in R&D and failing to commercialize the developed technology can lead to critical losses [16]. Losses can be financial, opportunity costs incurred regarding other investments foregone but also reputational losses. Techno-scientific promises that are in circulation also imply a massive societal impact encompassing transformation of traditional business models, regulatory arrangements and societal structures including productionconsumption-relationships

[17].Considering technological innovation as a process which comprises both technological change and social change, technology and society can be regarded as being mutually shaped [13]. So there is a co-evolution [18] [19]. Parandian [13] stresses that the selection mechanisms of science and technology in this co-evolution are influenced at an early stage and subject to promises and expectations.

Emerging technologies and associated innovation policies are facing a constantly changing and unstable environment [12]. As Yasunaga et al. [20], who provide a showcase of a roadmapping initiative by the Ministry of Economy, Trade and Industry of Japan, point out: Research on governmental activities regarding technology roadmapping and its impact is underrepresented. So while the techno-scientific promises related to DF are being articulated and discussed, initiatives on the part of actors to organize anticipatory coordination has received less attention.

In this paper, we will address this gap by using a consortium-based approach towards advancing DF as a showcase. In Europe, the first explicit attempt to pursue anticipatory coordination for DF is facilitated by the EU funded Diginova project[1]. The findings of the project will result in the first European DF roadmap describing new business as well as technology drivers, aligned with a map of the most attractive and innovative product categories for applications of new materials and processes, derived from a well-founded business perspective. With a highly diversified consortium of actors joining forces to set up a European research agenda and to promote alignment

[1]The Diginova project is funded by the European Commission (grant agreement no. 290559) and was initiated in March 2012 (lasting for 24 months).

creation through networking activities, this may herald a new phase in the development and embedding of DF in Europe[2].

The paper at hand provides three contributions:

1. We describe DF as an emerging industry and provide a consortium-based approach to define the future of DF in Europe as a showcase.
2. We address an assessment and resulting typology of the most promising four domains in DF and twenty applications with their respective key technology challenges (KTCs) for this emerging industry.
3. We address the pressure to overcome these KTCs by considering the evolution from technology promise to market realization

We describe both the process and results of the Diginova consortium-based analysis and relate our empirics to established industry emergence theory such as e.g. the extensive roadmapping framework by Phaal et al. [21]. We analyze qualitative and quantitative project data to shed light on the relationship between a domains emergence stage and pressure to overcome technological barriers. Our empirical findings suggest that the emergence of DF is a process with multiple domain evolutions with autonomous commercialization phases and technology barrier priorities. What is more, key technology challenges prevail in all stages of the industry emergence process but our data gives us reason to believe that the pressure to ovecome KTCs is higher at growth than at embryonic stage - the phase in which technology

[2]The Diginova consortium brings together 20 partners consisting of some of the leading European research institutes, large companies and SMEs active in the domain of DF. See for details http://www.diginova-eu.org

promises are exposed to highest pressure of market expectations.

2. Conceptual Background

Emerging technologies capture a lot of uncertainty. Underlying our theoretical consideration in this chapter is our notion that technological change in the form of new industry establishment such as e.g. the DF industry is like a journey (see e.g. [22, 23]) which still has an undefined destination. Addressing emerging technologies, innovation policies and assessments have to testify themselves against a constantly changing and unstable environment [12]. It thus sounds quite reasonable to reduce this high degree of uncertainty, even though there might also be adverse effects to this in terms of limiting options due to too stringent routines[12] . Diuse and open-ended envisaged benets and challanges make actors uncertain about directions to take and thus create reluctance to invest in concrete developments which hinders industry emergence [24]. We postulate that, most predominantly at an early stage , discussing the future of a new technology within its relevant context among stakeholders is fruitful to collaboratively anticipate trajectories of emergence and to subsequently develop strategic intelligence [13, 22] for actors in the nascent field. Emerging industries such as biotech or nanotechnology [25, 14] do not evolve from scratch but follow an evolutionary, non-linear path and their origins can be traced back to an interlude of already existing technology fields. This is not only the case regarding meaning but also regarding the underlying base technologies. We have mapped DF as a co-joint space of the established fields of material sciences, software development and printing processes as depicted in Fig. 1 Entering this intersection of established fields bares substantial uncertainty, as the existence of the industry in itself may even be questionable [25, 26].

[INSERT FIGURE 1 ABOUT HERE]

Actors exposed to these uncertainties are in need of strategic intelligence to support better decision making [13]. As a result, over decades various technology forecasting methods arrised to meet this need [1, 27, 28].Technology roadmapping (TRM) consitutes one of these methods and is widely acknowledged and applied throughout various organizations and numerous industries (for a detailed overview refer to Carvalho et al. [29]). Yasunaga et al. [20] pronounce that research on TRM is predominantly focused around single actors, which calls for more elaboration on how TRM initiated by governmental entities functions in practice and what results can be derived from a more consortium-based approach . We follow this call and argue that collaborative anticipation events, like government-driven TRM, are a valuable approach to coordinate and align actors from diverse fields to blend knowledge silos for a holistic perspective on an emerging industry's markets, applications, and technologies. In other terms, bridging uncertainties by firstly defining a common language and understanding (e.g. [14]). This is in line with [30], who state that foresight can be a systematic innovation policy instrument in terms of networking, vision building and resulting priority setting.

Considering the example of DF, we can expect that prioritizing key application domains relevant to a disruptive emerging technological field poses significant challenges. In particular because the scope is generally broad and stakeholders with different backgrounds (both organizational and individual) associate diverse promises and expectations with the new technology. Due to this diversity of rationals by stakeholders, it is common practice in technology forecasting to draw on a multitude of expert assessments, like in the nominal group technique. Others, like the Delphi method, even extend this approach by incorporated feedback loops[31]. In the same vein a consortium-based TRM can provide a comprehensive forecast via rich contextualisation. What is more, the roadmap of an diversified consortium selected by the government has the opportunity to actively shape the emergence of an industry as it typically porvides outcomes for a broader audience, and not just for one organization. [25, p.34] states that "During field emergence, several mechanisms might influence the convergence of meaning. One mechanism is that a legitimate actor starts to promote specific views of the organizational field. These actors can, for example, be the government, large corporations, or influential non-profits." In consortium-based TRM all these parties are simultaneously involved in industry emergence assessment.

2.1. Domains and key technology changes

As stated previously, emerging industries can be traced back to the intersection of established technologies and markets. It is important to stress, that these intersections are not symmetric, nor do they take place simultaneously because each eld has its own forces that shape the trajectories of its past, present, and future development [18]. These intersections result in new applications that exhibit idiosyncratic characteristics, like commercialization stage or specific technological obstacles. Hence, there is no one emergent field called DF that is coherent and clear-cut regarding its terminology and conceptual boundaries. The diversified applications can be grouped in domains as anchor points in the landscape of an emerging industry. Furthermore, domains also posses a meaning-giving mission to umbrella terms, like in the case of DF. Due to non-linearity and co-evolutionary patterns in technology emergence as outlined above (see also [21, 13, 22, 30]), these domains are not static but subject to continues reconfiguration and evolutionary in their manifestation. Constant adjustments due to external selection processes are shaping a domain and its applications. Key technology challenges (KTCs) are one example for a dominant selection factor. Thus, both strategic management and policy measures require estimates of future technology development, most promising domains, and KTCs associated with this development. Fig. 2 is inspired by Geels 'multiple levels as a nested hierarchy illustration' [32, 33]. It conceptualizes the evolutionary structuration of applications to form domains that give meaning to the umbrella term DF. Due to non-linearity and co-evolutionary patterns in technology emergence as outlined above [21, 13, 22, 30], we thus formulate our first proposition as follows:

Proposition 1: The emergence of the DF industry is characterized by developments being pursued in different sub-domains. Each sub-domain will entail distinct priorities to overcome technological obstacles and will differ in commercialization readiness.

[INSERT FIG. 2 ABOUT HERE]

2.2. Promises and expectations

Coming back to our journey parabola, emerging industries create a multitude of promises and expectations about the potential destination. According to [15, p. 286], promises and expectations are also important for actor groups beyond scientists and engineers. They play a central role in mobilizing resources both at the macro level, for example in national policy through regulation and research patronage, and at the meso-level of sectors and innovation networks, and at the micro-level within engineering and research groups and in the work of the single scientist or engineer. Taking into account promises, expectations and the co-evolutionary pat- tern of industry emergence we connect to [24]. Parandian et al. Their approach starts with signalling of an opportunity, consensus and consequential promise-requirement cycles. The overall promise that leads to expectation is an umbrella promise that needs, regarding its domains, some successful realizations and manifes- tations in order to remain credible. This is in line with pressures on nanotechnology for which [22] identies for technology enactors. Among these pressures are the responsibility to innovate and to produce solutions with benets to society by contributing to the economy. Moreover efficiency needs to kick in to contain growing costs of science and technology development. All this is restricted and enabled by KTCs that emerging industries and subsequently their domains face. Drawing on the industry emergence framework of Phaal et al. [21] we postulate that the outlined pressures to overcome KTCs vary among emergence phases. Following our picture of the journey, once we have made great promises about our destination the closer we get to the real target location, the less there is room for unrealistic reveries and imperfections. Promises have to be fulfilled before new once can be claimed. KTCs thus have to be resolved or markets will e.g. switch to a technology substitute to satisfy their needs. Same holds for research patronage by governmental agencies. As a result, we claim that there is a higher pressure at the later phases of industry emergence, driven by market expectations about materialization of promised benefits. Our second proposition is thus as follows:

Proposition 2: We expect that there is a growing pressure to operate more efficiently at the later stage of industry emergence, driven by the cost of science and technology development as well as market expectations about materialization of promised benefits.

3. Technological Background

The term DF is used as an umbrella acronym, to refer to a field of innovative opportunities of various technologies and their applications together generating the potential for what some observers signify as "the next industrial revolution [5, 6]. The key novelty relates to the use of computer controlled tools and processes to transform digital designs directly into physical products. This includes technologies that make use of digital material deposition methods to create two-, or three dimensional products - i.e. both modern digital printing technologies (2D DF) and additive manufacturing technologies (3D DF). In e.g. inkjet printing, both 2D and 3D DF are employing similar technologies. In fact, many 3D DF techniques use 2D processes, such as printing and lithography, to additively combine materials layer-by-layer, thereby extending into the third dimension. In these cases, individual layers of the finished 3D device or model can be described as finite 2D cross-sections. However, since the intention with a 3D DF process is to produce a three dimensional part with a pre-determined geometry and functionality, achieving desirable material properties in the part is crucial [3].

[3]Material properties depend on the molecular bonding, and therefore the determining point in a 3D additive/DF process will be how the bonding of the material in the final part is achieved. On the other hand, 2D DF technology processes are determined by the

The broad promise of DF has become particularly interesting because the underlying technologies enable disruptive functionalities to various products across different markets and value chains. The resulting opportunities for use in different sectors are broad, but one important focus is the shift from conventional mass manufacturing to potentially cleaner, on demand, and thus way more flexible manufacturing processes. However, the developments in the variety of application fields under the umbrella of DF are linked to other technological and social dynamics, which implies complex challenges regarding the types of materials to be used, manufacturing techniques and further acceptance issues by society (Fig.1). There are lots of open issues which actually co-evolve with the evolution and application of new technology.

[INSERT FIG. 3 ABOUT HERE]

Following the notion of Fig.1 and Fig.2, we briefly discuss the set of technologies that are covered under the umbrella acronym DF. Fig. 3 provides a brief overview of technology variants of 2D and 3D DF. With the exception of electrophotographic processes, 2D DF technology is based on jetting deposition techniques. Ink-jetting is the most promising 2D DF technology mainly due to its low cost and low waste characteristics. Although Inkjet technology is already well established its possibilities as a manufacturing principle goes far beyond printing ink on paper. Ink jet technology could now also be used to print highly functional materials on flexible substrates to create electronic devices such as sensors, organic light emitting diods and solar cells. [4].

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technique for deposition of material in a digitally controlled manner, but limited to a more two-dimensional (quasi-planar) functionality [34]

[4]Event though considered as quasi-planar and therefore 2D, in most cases printed

This development would create a shift from present silicon and lithography based manufacturing in the electronics industry to potentially more flexible and cost effective manufacturing processes like printed electronics [35]. One effect would be that printer manufacturers and the printing industry gain new grounds in the electronics industry, which result in a change in industry structure [24].

The principles for additive manufacturing technology offer a wide range of possibilities for development of new processes as well as applications. Currently, the commercially available additive manufacturing systems can be described as belonging to one of seven different process categories as described in Fig. 2[5]. While the developments on different technologies and applications of additive manufacturing have been progressing for the past two decades in protected spaces of university labs and research institute, the actual industrial impact of additive manufacturing technology has mostly been limited to various, but specific, niche applications such as: prototyping, tool inserts manufacturing, production of dental implants and hearing aids, orthopedic implants, and some non-critical components for example in aerospace industry.

It is however envisioned that in the longer run additive manufacturing techniques will become complementary to conventional production techniques like injection molding, stamping and milling [2]. In the future this joint

electronics devices are multi-material and multi-layer systems [34]

[5]In January 2012 the ASTM International Committee F42 on Additive Manufacturing Technologies approved a list of AM process category names and definitions. http://www.astm.org/COMMITTEE/F42.htm

capability is expected to enable and stimulate the development of new materials and products. This will require production and assembly techniques that are able to apply small units of numerous different materials in defined positions. The combination of multiple material capabilities with standard components and sub-assemblies will enable unconventional design concepts and products with disruptive functionalities [34]. In line with ongoing advances in social networking and online communities, additive manufacturing is likely to provide a powerful tool to individuals to express their own creativity and imagination to the development of their highly customized physical goods rather than buying mass manufactured products [1]. Empowering individuals to take part in product development is a fashionable phenomenon that drives the democratization process of technology and product development [8]. Additive manufacturing is thus becoming increasingly accessible to general public [36]. This phenomenon is facilitated by an emergence of new online virtual communities and network forums and enables product development to become more entrepreneurial and interactive[6].

This brief description shows that the narrative of the techno-scientific promise linked to DF portrays an accelerated movement towards the materialization of digital information. This move is enabled by advances in and new combinations being formed across different areas such as (novel) materials, processing tools, printed intelligence and software as previoulsy outlined in Fig.1. The techno-scientific promises that are in circulation also imply a massive societal impact encompassing transformation of traditional business

[6]See for instance the emergence of companies like Shapeways (shapeways.com), Materialise(materialise.com) and Ponoko (ponoko.com)

models, regulatory arrangements and societal structures including productionconsumption relationships [1]. While the techno-scientific promises related to DF are being articulated and discussed, initiatives on the part of actors to organize anticipatory coordination has received less attention. In Europe the first explicit attempt to pursue anticipatory coordination for DF is facilitated by the EU funded Diginova project, which we will outline in the subsequent section.

4. Method and Approach

Our research is of a qualitative and descriptive nature and follows a consortium-based approach that is further elaborated on in form of a showcase in the next chapter. The Diginova consortium consists of 20 partners representing some of the leading European research institutes, large companies and SMEs that are active in the domain of DF [7].With a highly diversified portfolio of actors joining forces to set up a European research agenda and to promote alignment creation through networking activities, this initiative may foster a new phase in the development and embedding of DF in Europe. In 2013, the project team distributed two stakeholder online surveys. This was part of the consortium's attempt to reach relevant stakeholder and expert communities. The overall approach is twofold and best captured by the following two themes that will be further explicated in the subsequent section:

1. Process of identifying and ranking the top opportunities for DF and

[7]for more details consult http://www.diginova-eu.org/

their estimated time to market

2. Process of articulating key technology challenges

With respect to 1., the paper at hand refers to the most recent online-questionnaire that was distributed to participants of the four major DF-related conferences held in Europe and the United States at which the Diginova project also organized dedicated interactive stakeholder workshops[8] The workshops helped gaining deeper insights and to select the 20 most promising applications out of a previously developed long list. The approach is described more in detail in the subsequent section. Among other innovation related questions, the online survey participants were explicitly asked to assess the years to market of each of the 20 identified key applications in the emerging field of DF. Respondents could choose from a Likert scale answering scheme, ranging from "in the next 5 years to "next 20 years or "never" . Since specific application expertise varies among stakeholders an abstention from assessment was possible. Hence, sample size varies from 80 to 96 among responses. To control for potential science versus business biases we conducted a mean-comparison analysis by contrasting answers from respondents with a science and those with a business affiliation using Welch-Satterthwaite t-testing.

[8]Smart Lighting Community (Smart Lighting 2013, May 14-15, Frankfurt, Germany), Printed Electronics Community (LOPE-C 2013, June 11-13 , Munich, Germany), Flexible Organic Electronics Community (ISFOE 2013, July 8-11, Thessaloniki, Greece) and 4) Society for Imaging Science & Technology (Digital fabrication 2013, September 29 - October 3, Seattle, USA)

With respect to 2., the project team distributed two stakeholder online surveys in 2013. In the first survey that was conducted the participants of the survey were provided the opportunity to validate the dimensions that were developed by the project consortium related to the 2D/3D process types and the current and future applications of the technology as well as the application specific barriers to technology adoption. In addition, more than ten interviews were conducted to generate information of the causal factors related to the technological barriers for each of the four main application domains identified in theme 1. Interviewees were selected based on differences in their position in the value chain and included experts from equipment suppliers and material suppliers to system integrators and end users. In a final expert workshop the barriers to 2D and 3D DF technology adoption and the detailed analysis of the key contributing or causal factors and causes leading to these barriers formed the basis for deliberation to select a list of key technology challenges [34]. The consortium partners were then requested to score the urgency attached to address each KTC in each of the four identified application domains.

5. DIGINOVA Consortium - An anticipatory coordination mechanism showcase

This paper elucidates the findings generated by the consortium of DF R&D centers and innovation actors participating in the EU funded Diginova project. Fig. 4 schematically shows the approach that has been followed in the project in terms of two themes. On the one hand the process to further articulate the potential applications of DF and respective expectations about when applications will be ready to enter the market; and on the other hand to articulate key technological challenges (KTC) and the urgency attached to address them, particularly in the European context. In each separate theme the activities and resulting outcomes are shown in sequential order. We must note however that in the course of the project there was frequent information exchange between the activities of the twin themes. In the following sections we describe the process followed in each separate theme.

[INSERT FIG. 4 ABOUT HERE]

5.1. Process of identifying and ranking the top opportunities for DF and their estimated time to market (Theme 1)

The first step in theme 1 had a crucial function: to scope the context in such a way that the findings would be relevant to the development of the EU manufacturing economy. This required the project consortium to first agree on a definition to use for DF. In doing so, the consortium partners, through intensive interactions, broadly defined DF as a new kind of industry that uses computer controlled tools and processes to transform digital designs directly into useful physical products. [3]. A key outcomes of the interaction process relates to the emergence of a consensus that 2D digital printing and 3D additive manufacturing form the two constituents of a set of technologies falling under the umbrella term 'DF'. In addition, contextual factors for the development of the future EU manufacturing economy were discussed in depth. After lengthy discussions the following contextual factors were considered important to keep in mind when brainstorming to generate a long list of application opportunities:

1. changes in distribution channels

2. trends of EU industrial policy
3. state of the art engineering capability in Europe
4. potential impact of DF on different industry structure
5. tandem developments in materials and printing processes
6. opportunities related to the availability of big data

Considering the above, the consortium came-up with a 'long list' of 78 opportunities during a brainstorming session. The opportunities were then grouped into four main application domains consisting of

1. Digital Printing (26 opportunities)
2. Additive Manufacturing (15 opportunities)
3. Printed Electronics (19 opportunities)
4. Human Applications (18 opportunities).

Due to the length of the initial long list and the resulting complexity it was agreed that all opportunities should be assessed on four key guiding evaluation criteria including

1. the potential for development or use of new materials
2. the extent to which an opportunity will benefit from advantages resulting from DF
3. durability or life expectancy of a specific opportunity and
4. the estimated size of future revenues resulting from the pursuit of a specific opportunity

This allowed a structured and results driven selection process. Technology experts from the consortium debated intensively in a workshop to select the most promising 20 applications out of the previously developed long list. The organizational diversity of the consortium (consisting of four large companies, seven SMEs, and nine research institutes) facilitated a holistic perspective on each domain.

1. Digital Printing (graphical applications)
   (a) Digitization of Traditional Printing Industry
   (b) Decoration of Products & Surfaces
   (c) Packaging
   (d) Textile Printing
   (e) Display Graphics
2. Additive Manufacturing
   (a) Durable goods
   (b) Integrated Electronics
   (c) Sensing
   (d) Power Generation & Transmission
   (e) Energy Storage
3. Printed Electronics
   (a) OLED Lighting & Displays
   (b) Smart Windows
   (c) Printed Sensors
   (d) Thin Heating Elements
   (e) Smart Textiles (2D)
4. Human applications
   (a) Medical Microfactories
   (b) Personalized Diagnostics & Drug Delivery
   (c) Tissue Engineering Scaffolds
   (d) Treatment Planning Tools ("OrganonaChip")
   (e) Digitally fabricated 3D garments

In the course of the brainstorming sessions, various contextual factors like business drivers and KTCs were identified, discussed, and considered for the final application decisions. How these KTCs were determined is outline in the following

5.2. Process of identifying and ranking the top opportunities for DF and their estimated time to market (Theme 2)

Theme 2: Process of articulating key technology challenges

Similar to the first theme, a list of the state of the art and near-to-market technologies was articulated during expert workshops. This was done on the basis of the emergence of a consensus that 2D digital printing and 3D additive manufacturing form the two constituents of a set of technologies falling under the umbrella term DF. The applied methodology in theme 2 originates from a successful implementation in a previous study of key technology challenges and research opportunities in the Additive Manufacturing area by the Technology Strategy Board Additive Manufacturing Special Interest Group [4]. Essentially, this methodology implies that the business drivers intrinsic to the applications of technology should be established first, on the basis of the current state of technology usage. This provides a basis for identification of barriers to technology adoption, through which the key technology challenges can then be articulated.

As an initial step a series of large two dimensional matrices were developed describing technology classes relevant for both 2D digital printing and 3D additive manufacturing to capture relevant dimensions. Ink or substrate material configurations and specific processes were then associated with each technology class. The technology variants and their actual commercial or developmental implementations were listed as subordinate to process class and material type. Effectively, these matrices expressed current and future technology applications relative to industry sector, discrete applications against the business drivers inherent to the technology, and discrete applications against business and technology barriers [37].

The information on the core technologies and the subordinate materials and processes and an extensive list of barriers for both 2D digital printing and 3D additive manufacturing were the result deliberations among Diginova consortium members through an online survey (for the internal consortium members) and in a series of workshops. Although the results reflect the views of a limited number of experts, its validity was justified by the high level of expertise of the individuals involved from prominent digital printing and additive manufacturing technology companies and leading academics active in the field. One striking result from the interviews was that depending on the stakeholders position within the value chain, the perception of barriers and key technology challenges was very different. The difference in perception implied that key technology challenges identified by one party were sometimes viewed as barriers by another party not involved in the same development field and thereby missing the necessary insight to clearly identify the key technology challenges.

The responses to interview questions were grouped in technology relevant and market relevant aspects and tasks [34]. Based on the above collected information separate tables were developed for 2D and 3D DF describing the identified technological barriers, its contributing or causal factors and possible approaches that the consortium experts considered adequate to tackle these barriers [34]. For 2D DF, six barriers were identified which included relative process economics, inter-system capability, reliability, process architecture, jet head and compatibility with other systems. For 3D additive manufacturing e.g., eight barriers were identified which included relative process economics, productivity, reliability, machine concept, ownership, finance and personnel design and acceptance issues.

6. Findings & Discussion

DF as an emerging technology is characterized by the specific conditions of co-evolutionary patterns that were discussed in the theoretical part of the paper at hand. The result of the FP7 project Diginova gives us an approximation of the most promising applications in this technology field and their respective time to market. In this context, it is intriguing to take a closer look at the technology expectations the survey respondents associate with DF. Regarding the conceptual foundation of this paper, we first stressed the potential of consortium-based TRM, second we outlined the relationship between domains, applications and respective KTCS in emerging industries, and lastly we stressed the role of promises and expectations for the pressure to overcome KTCs. That there is quite some variation in how DF as an umbrella term is perceived becomes evident when asking where to position DF in Gartner's life cycle perspective. Our results show that to the majority of respondents see DF as a promising technology in a nascent stage (56%) and 37% of stakeholders perceive the emerging industry positioned on the "peak of inflated expectations. Interestingly, responses cover the entire spectrum till maturity. So if DF actually was close to the peak of a 'hype of inflated expectation', what are more realistic expectation regarding its time to maturity? The results make a strong call for a more differentiated view according to the identified core dimensions of the DF domain. Moreover, there is a need for a roadmap to overcome the 'trough of disilusionment following a 'peak of inflated expectations.

In order to differentiate the expert-identified domains of DF more in depth, Table 1 represents the survey-determined average expert opinion on time to market per domain and per application. The relevant question being asked was "When (if at all) will the following (product) domains appear for the first time in the market - based on DF technology?"

[INSERT TABLE 1 ABOUT HERE]

Our survey results suggest that the emergence of DF is a process with multiple evolutions with autonomous commercialization and technology barrier priorities in its relevant applications. Furthermore, we can say that applications from one domain do not necessarily need to exhibit same years to market patterns and can have individual market challenges. We have further analyzed the mean responses per category[9] to consider whether expectations of market readiness differ between the overall mean response and sub groups. The groups are science (operationalized as a combination of university respondents and respondents from the applied sciences) and corporate (operationalized as a joint measure of larg, medium-sized and small enterprises). We have thus controlled for differing expectations by organiza-

[9]1 to 4 on an ordinal scare with 1= in the next 5 years and 20= in the next 20 years; "not reaching market readiness at all" is treated separately; for more detailed results please consider Exhibit 1 in the Appendix

tional type. Quite surprisingly, these are none-existent. We find no evidence at the 10% significance level that the mean responses vary across organizational types except for Packaging and Textile Printing in the domain of Digital Printing and Medical Micofactories in Human Applications. In the latter subdomain, university/ scientists are significantly more optimistic that the corporate representatives.

Next to applications, their domains and time to market, the expert consortium elaborated and defined priorities to overcome KTCs that influence the development of each application domain in the DF industry. Combined with the time-to-market estimation of stakeholder assessment, this allows us to map expert-informed patterns of emergence in DF. The illustration in Fig. 5 Fig. is adapted from the industry emergence framework developed by Phaal et al. [21].

[INSERT FIGURE 5 ABOUT HERE]

In Fig. 5, we match data on years-to-market on the X-axis in a reversed order to the frameworks industry emergence phases, so that we can reflect maturity. This means that for example application domains that are assessed to reach market commercialization within the next 20 years will be positioned in the precursor stage, whereas those considered to reach a substantial market entry within the next 5 years will be located in the growth stage. The Y-axis represents the time priority and the need to overcome the KTCs of each application domain. A high score on this axis relates to a high importance of prompt solutions to respective KTCs. Table 1 and the more in depth version in Exhibit 1 in the Appendix, which also reflects sample sizes and the "will never reach maturity" response, serve as an input for the time to market proxies. The proxy should be regarded as a rough indicator, as it provides a weighted average of the categorical responses represented in Table 1 multiplied with the respective year category. Mapping domains (and their applications) time to market with priority/need to overcome corresponding KTCs enables us to make empirically grounded statements about the relationship between these two factors of emergence. Fig. 5 illustrates this relationship on two levels: A domain level and a application level.

Our results indicate that all four identified domains differ substantially in their market-readiness as well as on our KTC measure. We can observe that two domains, additive manufacturing and human applications, are positioned in the embryonic phase. The domain printed electronics can be found in the nurture phase, and digital printing is placed on the transition from nurture to growth phase. Considering the urgency to overcome KTCs, the two embryonic domains demonstrate a relatively low need. Please keep in mind that this value does not reflect the sole number of KTCs but focuses on the assessed urgency to overcome these challenges. The two domains approaching market commercialization do score high on this factor. From these observations we can argue that pressures to overcome KTCs do increase in the later stages of industry emergence at hand of the DF example. Our illustration also contains data points on a second level, namely applications. As previously described, the four domains stand for various applications. In each domain the individual applications do exhibit an own pattern of time to market (see Exhibit in in the Appendix for detailed figures). This is striking, as one would assume that applications on a sub-domain level are even more in line with the commercialization stage of their domain. The highest deviation of this relationship can be found in the domains 'printed electronics' and 'human applications'. Whereas KTCs prevail in all stages of the industry emergence process, our data gives us an indication that industries do face highest pressure to overcome their KTCs at the later phases of new industry emergence. This is in line with Selin [38] finding on a shift towards immediate and achievable goals with increasing maturity.

7. Conclusion

DF is an industry emerging from the intersection of three established technology fields and markets, namely material sciences, software development, and printing processes. These intersections are not symmetric, nor do they take place simultaneously because each field has its own drivers and barriers that shape the trajectories of their past, present, and future development. Different intersections lead to different commercialisation stage and technological obstacles for a respective DF application.

In this paper we argue that industry emergence of DF is characterized by the developments being pursued in different domains. These domains are subject to continuous reconfiguration and evolutionary in their manifestation. Our data supports the argument that industry emergence is a non-linear process and considering the umbrella technology development alone is highly insufficient.

Within DF we can observe a diversity of positioning for application subdomains. Interestingly, our data also exhibits a high diversity on years-to-market among applications in the same domain. This hints to the assumption that industry convergence patterns do not only influence an emerging industrys domains but also its potential applications.

Applications associated with the precursor and embryonic stages of industry emergence are considered to be science-driven since no dominant design is in place. The explorative nature of theses stages allows for various paths of developments and therefore multiple promises are articulated. Although scientific and technological endeavours are at the core of these phases, the urgency to overcome respective KTCs is not pressuring since we still operate here in an explorative phase. In the case of DF this can be observed with the two domains human applications and additive manufacturing. Both are positioned in the embryonic phase but they exhibit relative low priorities to overcome KTCs. On the other hand, once a domain works its way through the transition phases to the nurture and growth phase of industrial emergence it demonstrations relative high urgencies to overcome technological obstacles. This can be explained on the one hand with the promises and resulting expectations of an emerging technology. The market has expectations that the technology needs to fulfil in a timely manner since expectations were raised in the explorative phases. At this stage, its crucial for an domain to overcome its KTCs is a timely manner to prove its value proposition. If this does not happen, the market might turn to a substitute. In the case of DF the application domains Digital Printing and Printed Electronics unveil these conditions. Both are expected to reach commercialization in a relative short period of time and respective both priorities to overcome KTCs are the highest in our sample.

Our findings have several practical implications for various groups. The paper at hand distils major findings of the FP7 Diginova project in regards to domains, applications, and key technology challenges of DF. In doing so, this will serve as a resource for decision makers in firms or public agencies to assist strategy articulation and further future-oriented assessment activities. Policy makers can assess the value of coordinated anticipatory events like the EU funded Diginova project and build on its learnings to develop continues technology programmes that support the industry emergence of DF. We contribute to established industry emergence literature with our empirical finding that necessity to overcome KTCs is not on its peak in the early (technology dominated) phases, but instead it reaches it highest point in the later stages where articulated technology promises are exposed to highest pressure of market expectations.

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Appendix A. Figure Captions

Figure 1: Digital fabrication as a co-joint space of established fields.

Figure 2: Increasing structuration of applications to form domains that give meaning to the umbrella term of digital fabrication. Adapted from [32, 33].

Figure 3: Overview of technology variants of 2D and 3D digital fabrication.

Figure 4: Schematic approach followed in the Diginova project; two themes.

Figure 5: Anticipated time to market commercialization and need to overcome KTCs.

Appendix B. Table Captions

Table 1: Mean comparison of application time to market commercialization by organizational type.

Exhibit 1: Mean comparison of application time to market commercialization by organizational type (full table).

Appendix C. Biographical Endnotes

Appendix C.1. Michael Potstada

Michael is a PhD candidate in high-technology management at the University of Mannheim and associated with the Graduate School of Economics and Social Sciences (GESS). What is more, he is a project manager at InnovationLab GmbH, an innovation company founded by industry representatives, such as BASF, Roche, Merck, SAP, the University of Heidelberg and the University of Mannheim. He is participating in a FP7 consortium and currently works on technology roadmapping for the European Commission.

Appendix C.2. Alireza Parandian

Alireza Parandian is the business development manager at InnovationFab and currently a work package leader in different EU funded projects including Diginova. He received his PhD degree from Delft University of Technology and his thesis was part of Technology Assessment program of the Dutch Nanoned R&D consortium. The focus of his research is on methodology development contributing to future oriented technology and innovation studies, in particular the approach of constructive technology assessment.

Appendix C.3. Jan Zybura

Jan Zybura is a researcher in the fields of entrepreneurship, family business and corporate entrepreneurship at the Mannheim Institute of SME Research (ifm). He is lecturer for Entrepreneurship (Chair of Small and Medium Sized Companies and Entrepreneurship) and Management PhD fellow at the Graduate School of Economics and Social Sciences (GESS) at the University of Mannheim, Germany.

Figure 1
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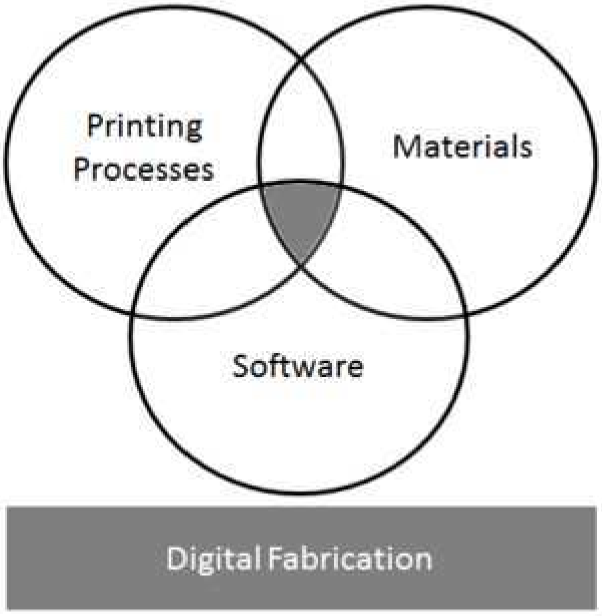

Figure 2
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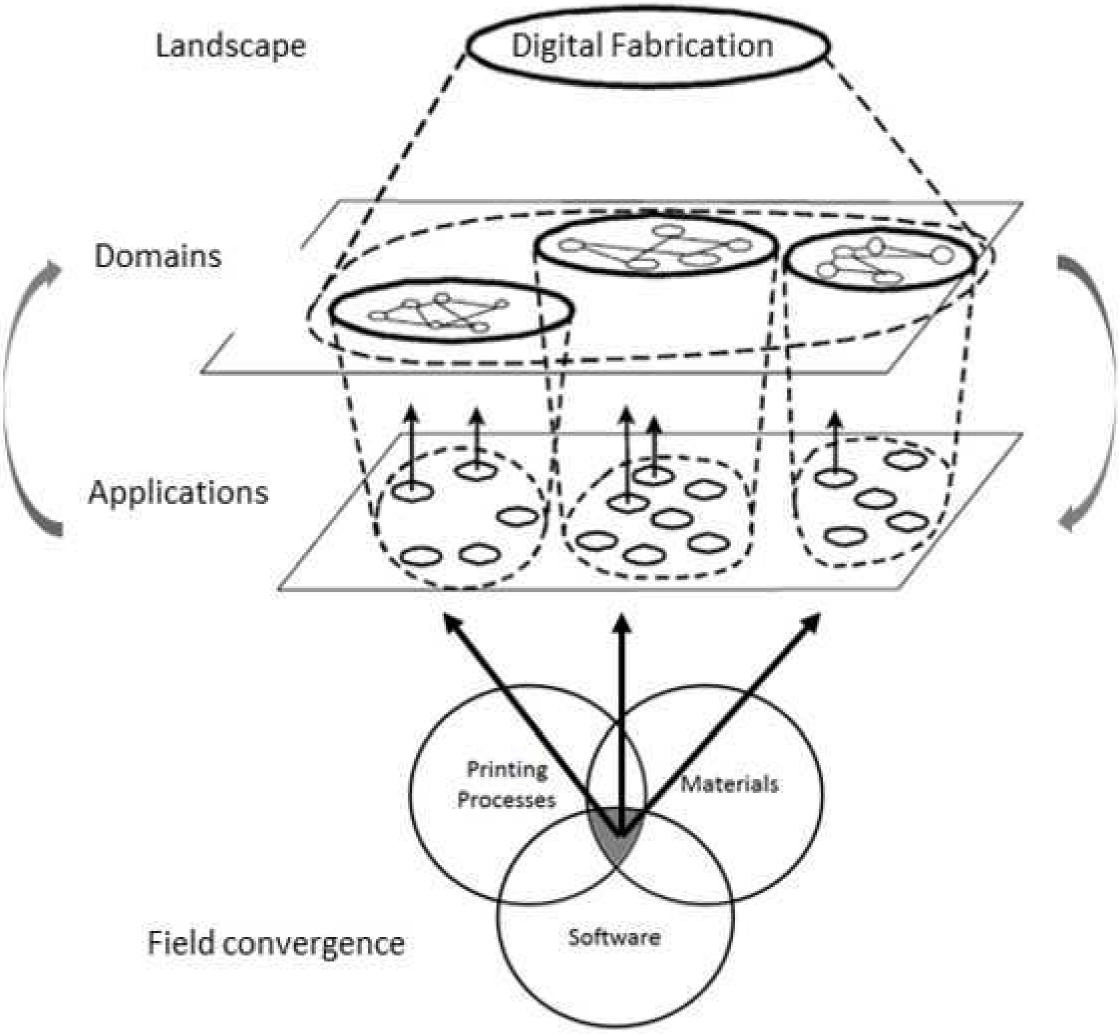

Figure 3
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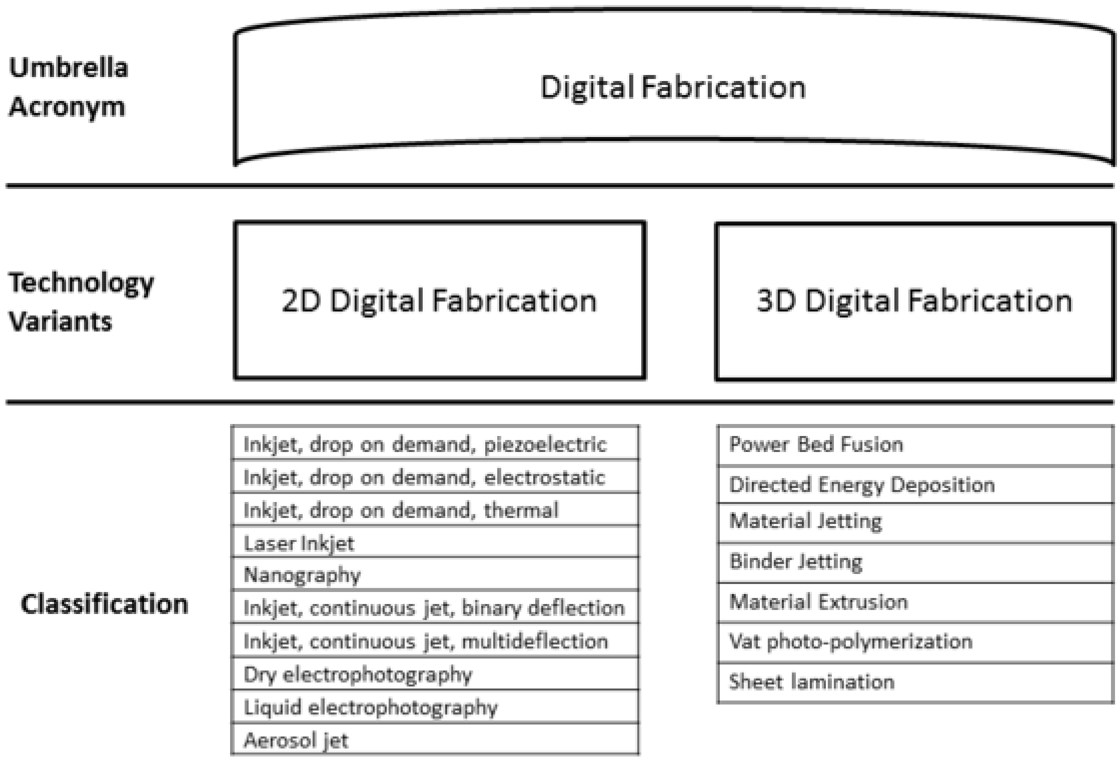

Figure 4
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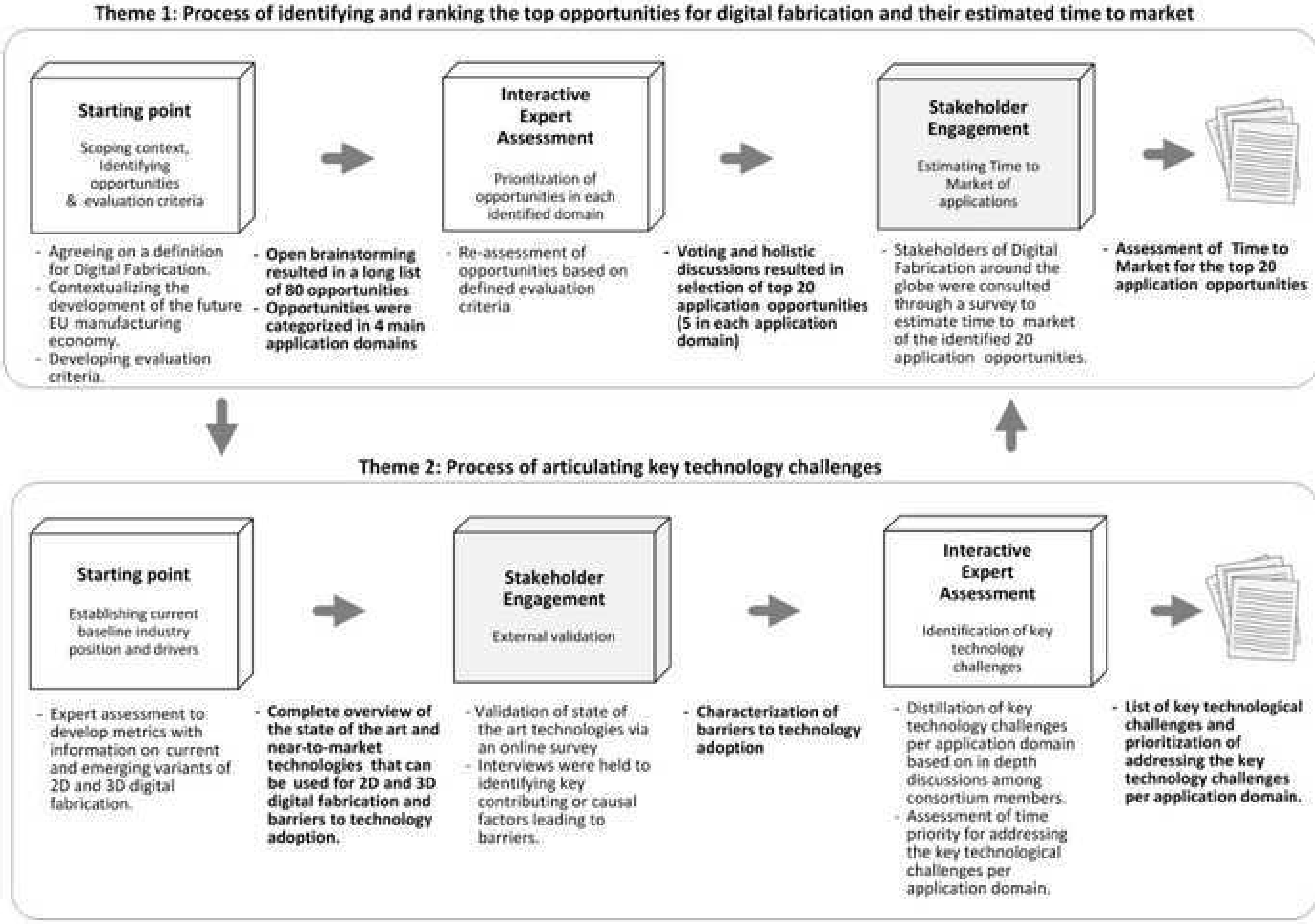

Figure 5
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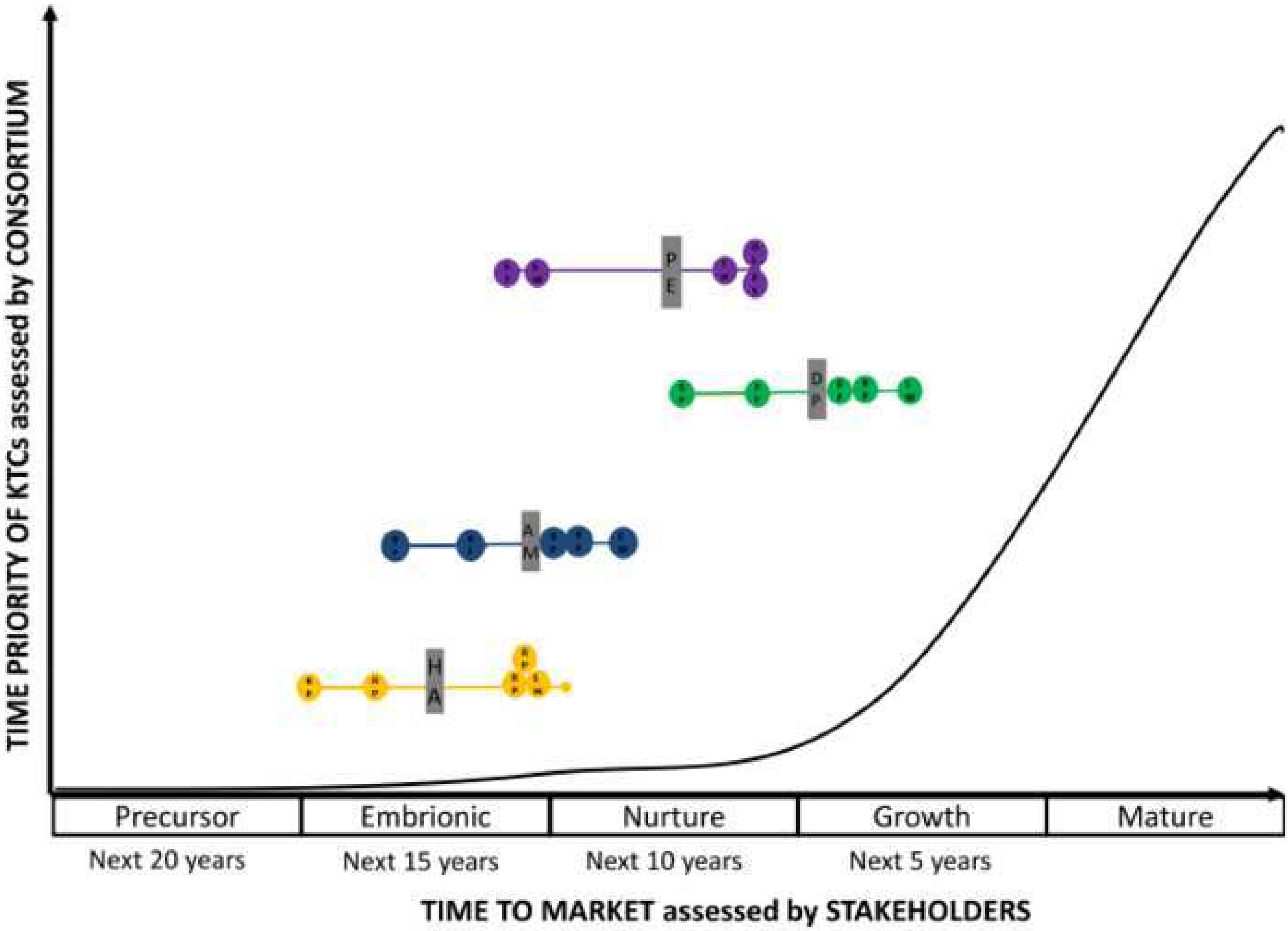

Table 1
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		1	2	3	4	Mean Comparison		
		Mean	Univ	Corp	Sci.	1-2	3-2	3-4
1 Digital Printing/ Graphical Applications		**1.29**	**1.34**	**1.27**	**1.29**	**-0.05**	**-0.07**	**-0.01**
1	Digitization of Traditional Printing Industry	1.33	1.67	1.31	1.38	-0.33	0.36	-0.06
2	Decoration of Products & Surfaces	1.21	1.25	1.25	1.17	-0.04	0.00	0.08
3	Packaging	1.29	1.09	1.30	1.17	**-0.71***	**0.21***	0.13
4	Textile Printing	1.24	1.08	1.25	1.23	**0.16***	**0.17***	0.01
5	Display Graphics	1.36	1.62	1.26	1.50	-0.25	-0.35	-0.24
2 Additive Manufacturing		**2.11**	**2.25**	**2.09**	**2.16**	**-0.14**	**-0.16**	**-0.07**
1	Durable Goods	2.10	2.18	2.10	2.18	-0.08	-0.09	-0.08
2	Integrated Electronics	1.87	2.15	1.82	1.97	-0.28	-0.33	-0.15
3	Sensing	1.63	1.58	1.65	1.63	0.05	0.07	0.03
4	Power Generation & Transmission	2.67	2.85	2.59	2.77	-0.17	-0.25	-0.17
5	Energystorage	2.29	2.50	2.29	2.28	-0.21	-0.21	0.02
3 Printed Electronics		1.74	1.76	1.74	1.71	-0.02	-0.02	0.03
1	OLED Lighting & Displays	1.52	1.77	1.53	1.50	-0.25	-0.24	0.03
2	Smart Windows	1.99	1.91	1.94	1.97	0.08	0.03	-0.02
3	Printed Sensors	1.51	1.54	1.54	1.48	-0.03	0.01	0.06
4	Thin Heating Elements	1.60	1.42	1.62	1.52	0.18	0.20	0.10
5	Smart Textiles (2D)	2.07	2.15	2.07	2.06	-0.09	-0.08	0.01
4 Human Applications		2.50	2.21	2.57	2.39	0.29	0.36	0.18
1	Medical Microfactories	2.35	1.75	2.58	2.00	0.60**	0.83***	0.58***
2	Personalized Diagnostics & Drug Delivery	2.32	2.23	2.35	2.33	0.09	0.12	0.01
3	Tissue Engineering Scaffolds	2.56	2.25	2.59	2.55	0.31	0.34	0.04
4	Treatment Planning	2.96	2.83	2.98	2.81	0.13	0.15	0.16
5	Digitally Fabricated 3D Garments	2.32	2.00	2.35	2.25	0.32	0.35	0.10

Note: ***1%, **5%, *10% sign. level, two-sided, WelchSatterthwaite t-testing

Exhibit1(Appendix)

	1	2	3	4	Mean Comparison			Years to market (proxy)			
	Mean	Univ	Corp	Sci.	1-2	3-2	3-4	Overall Mean	Univ	Corp	Science
1 Digital Printing/ Graphical Applications	**1.29**	**1.34**	**1.27**	**1.29**	**-0.05**	**-0.07**	**-0.01**	**6.4**	**6.7**	**6.4**	**6.4**
1 **Digitization of Traditional Printing Industry**	1.33	1.67	1.31	1.38	-0.33	0.36	-0.06	6.7	8.3	6.6	6.9
SE	0.08	0.31	0.10	0.14	0.32	0.32	0.17				
n	96	12	58	32							
n never feasible	3	1	2	1							
2 **Decoration of Products & Surfaces**	1.21	1.25	1.25	1.17	-0.04	0.00	0.08	**6.1**	**6.3**	**6.3**	**5.8**
SE	0.05	0.18	0.06	0.08	0.19	0.19	0.11				
n	90	12	56	30							
n never feasible	3	1	2	1							
3 **Packaging**	1.29	1.09	1.30	1.17	**-0.71***	**0.21***	0.13	**6.5**	**5.5**	**6.5**	**5.8**
SE	0.05	0.09	0.07	0.07	**0.11**	**0.12**	**0.10**				
n	92	11	57	30							
n never feasible	4	1	3	1							
4 **Textile Printing**	1.24	1.08	1.25	1.23	**0.16***	**0.17***	0.01	**6.2**	**5.4**	**6.2**	**6.2**
SE	0.05	0.08	0.06	0.08	0.09	0.10	0.10				
n	92	13	57	30							
n never feasible	3	0	3	0							
5 **Display Graphics**	1.36	1.62	1.26	1.50	-0.25	-0.35	-0.24	**6.8**	**8.1**	**6.3**	**7.5**
SE	0.06	0.27	0.06	0.13	0.27	0.27	0.15				
n	94	13	57	32							
n never feasible	3	0	2	1							
2 Additive Manufacturing	**2.11**	**2.25**	**2.09**	**2.16**	**-0.14**	**-0.16**	**-0.07**	**10.6**	**11.3**	**10.5**	**10.8**
1 **Durable Goods**	2.10	2.18	2.10	2.18	-0.08	-0.09	-0.08	10.5	10.9	10.5	10.9
SE	0.09	0.30	0.11	0.18	0.31	0.32	0.21				
n	86	11	52	28							
n never feasible	7	2	3	4							
2 **Integrated Electronics**	1.87	2.15	1.82	1.97	-0.28	-0.33	-0.15	**9.4**	**10.8**	**9.1**	**9.9**
SE	0.08	0.27	0.10	0.17	0.29	0.29	0.20				
n	95	13	56	34							
n never feasible	3	0	3	0							
3 **Sensing**	1.63	1.58	1.65	1.63	0.05	0.07	0.03	**8.2**	**7.9**	**8.3**	**8.1**
SE	0.07	0.23	0.09	0.13	0.24	0.24	0.16				
n	92	12	55	32							
n never feasible	3	1	2	1							
4 **Power Generation & Transmission**	2.67	2.85	2.59	2.77	-0.17	-0.25	-0.17	**13.4**	**14.2**	**13.0**	**13.8**
SE	0.10	0.27	0.13	0.18	0.29	0.30	0.23				
n	83.00	13	49	30							
n never feasible	7	0	5	1							
5 **Energystorage**	2.29	2.50	2.29	2.28	-0.21	-0.21	0.02	**11.4**	**12.5**	**11.5**	**11.4**
SE	0.10	0.23	0.13	0.16	0.25	0.27	0.21				
n	84	12	51	29							
n never feasible	9	1	5	3							
3 Printed Electronics	1.74	1.76	1.74	1.71	-0.02	-0.02	0.03	**8.7**	**8.8**	**8.7**	**8.5**
1 **OLED Lighting & Displays**	1.52	1.77	1.53	1.50	-0.25	-0.24	0.03	7.6	8.8	7.6	7.5
SE	0.08	0.32	0.10	0.15	0.33	0.34	0.18				
n	90	13	53	32							
n never feasible	5.00	0.00	4.00	1.00							
2 **Smart Windows**	1.99	1.91	1.94	1.97	0.08	0.03	-0.02	**9.9**	**9.5**	**9.7**	**9.8**
SE	0.09	0.28	0.11	0.16	0.30	0.31	0.19				
n	87	11	52	30							
n never feasible	4	1	2	2							
3 **Printed Sensors**	1.51	1.54	1.54	1.48	-0.03	0.01	0.06	**7.6**	**7.7**	**7.7**	**7.4**
SE	0.07	0.27	0.09	0.12	0.28	0.28	0.16				
n	96	13	57	33							
n never feasible	4	1	2	2							
4 **Thin Heating Elements**	1.60	1.42	1.62	1.52	0.18	0.20	0.10	**8.0**	**7.1**	**8.1**	**7.6**
SE	0.08	0.15	0.11	0.11	0.17	0.19	0.16				
n	89	12	55	29							
n never feasible	4	1	2	2							
5 **Smart Textiles (2D)**	2.07	2.15	2.07	2.06	-0.09	-0.08	0.01	**10.3**	**10.8**	**10.4**	**10.3**
SE	0.09	0.22	0.12	0.15	0.24	0.25	0.19				
n	91	13	55	31							
n never feasible	3	0	2	1							
4 Human Applications	2.50	2.21	2.57	2.39	0.29	0.36	0.18	**12.5**	**11.1**	**12.8**	**11.9**
1 **Medical Microfactories**	2.35	1.75	2.58	2.00	0.60**	0.83***	0.58***	11.7	8.8	12.9	10.0
SE	0.10	0.25	0.13	0.15	0.27	0.28	0.20				
n	89	12	52	31							
n never feasible	6	1	4	2							
2 **Personalized Diagnostics & Drug Delivery**	2.32	2.23	2.35	2.33	0.09	0.12	0.01	**11.6**	**11.2**	**11.7**	**11.7**
SE	0.10	0.28	0.13	0.18	0.30	0.31	0.23				
n	90	13	52	33							
n never feasible	4	1	3	1							
3 **Tissue Engineering Scaffolds**	2.56	2.25	2.59	2.55	0.31	0.34	0.04	**12.8**	**11.3**	**12.9**	**12.8**
SE	0.12	0.35	0.15	0.23	0.37	0.38	0.27				
n	85	12	51	29							
n never feasible	6	1	3	3							
4 **Treatment Planning**	2.96	2.83	2.98	2.81	0.13	0.15	0.16	**14.8**	**14.2**	**14.9**	**14.1**
SE	0.11	0.30	0.13	0.23	0.32	0.33	0.26				
n	80	12	48	27							
n never feasible	8	1	5	3							
5 **Digitally Fabricated 3D Garments**	2.32	2.00	2.35	2.25	0.32	0.35	0.10	**11.6**	**10.0**	**11.8**	**11.3**

Note: ***1%, **5%, *10% sign. level, two-sided, WelchSatterthwaite t-testing

Michael Potstada

Michael is a PhD candidate in high-technology management at the University of Mannheim and associated with the Graduate School of Economics and Social Sciences (GESS). What is more, he is a project manager at InnovationLab GmbH, an innovation company founded by industry representatives, such as BASF, Roche, Merck, SAP, the University of Heidelberg and the University of Mannheim. He is participating in a FP7 consortium and currently works on technology roadmapping for the European Commission.

Jan Zybura

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Alireza Parandian

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