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Innovation pathways in additive manufacturing: Methods for tracing emerging and branching paths from rapid prototyping to alternative applications

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A R T I C L E I N F O

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A B S T R A C T

In recent years, the Forecasting Innovation Pathway approach (FIP) has shown to be a promising set of tools to capture potential developments in emerging fields through capturing indications of endogenous futures. However, the FIP approach is reliant on a clear demarcated area to study, a challenge for emerging technology fields where uncertainty and rhetoric abound. This paper presents an addition to the FIP toolbox that helps characterise and demarcate boundaries of emerging fields to allow for deeper analysis through other FIP methods. We illustrate this approach through an exercise for 3D printing technology (also known as Additive Manufacturing). We show that 3D printing can be represented by a dominant design: a tri-partite configuration of printer, material and digital design software. In the past decade we have seen significant branching from applications in rapid-prototyping to medical, fashion, aeronautics and supply chain management with a variety of elements coming together in tri-partite configurations. The paper adds to the current FTA literature an approach building on evolutionary theories of technical change to help with such situations – emerging, evolving and branching 'innovation pathways'. Moreover, we developed a methodology to construct these innovation paths.

1. Introduction

Characterising emerging technology fields is fraught with difficulties. Heterogeneous data, compounded by hype and promise, raises a challenge for future-oriented technology analysis (FTA): how best to approach, systematise and interrogate the data to filter out real evidence on emerging technology trajectories. This is a challenge for relatively clear emerging technologies, but what about those areas which are composed of technology families, perhaps developing at different rates but entangled together?

An interesting example of this is additive manufacturing (AM) or 3D Printing. 3D printing uses additive processes for the fabrication of objects in three-dimensions direct from a digital image. The earliest application was rapid-prototyping, around which a community of practice including a number of scientific journals, emerged. Throughout the 1990s and early 2000s, dedicated conferences, journals and user groups were established to promote the relatively discrete and incremental evolution of additive rapid prototyping. Today, AM is hailed as a revolution and is featured on the cover of publications such as The Economist ("Print me a Stradivarius", 2011), Wired (Anderson, 2012a) and the MIT Technology Review (LaMonica, 2013). AM is finding a place on factory floors, surgeries[1] and in space.[2] It is also equipping households as well as FabLabs and hacker spaces of the self-labelled community of "makers" (Bosqué, 2014),[3] in classrooms[4] and public

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[1] Dr. Bon Verweij (Utrecht Medical Centre) surgically implanted a whole 3D printed cranium into a patient in 2014: http://www.ibtimes.co.uk/3d-printed-skull-replacement-transplant-netherlands-patient-1441924 (accessed 12.16.2014).

[2] 3D printer on the International Space Station is used to print tools for in-orbit repair and maintenance: http://www.nasa.gov/mission_pages/station/research/news/3Dratchet_wrench/#.VOnb_PnF8tQ (accessed 12.23.2014).

[3] http://www.publiclibrariesnews.com/practitioners/3d-printers-and-maker-spaces-in-libraries (accessed 5.29.14).

[4] https://www.gov.uk/government/publications/3d-printers-in-schools-uses-in-the-curriculum (accessed 5.29.14).

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libraries. These examples indicate a visible shift in use of the technology from the original application of rapid-prototyping to other areas. What is not so evident is to what extent the different *uses* additive manufacturing are co-occurring with an evolution and diversification of the additive manufacturing technologies themselves. Is the evolution just a matter of the same technologies for new uses or is it more than this? Are these diversifications merely hope and promise, or can we see evidence of actual activity in these areas. Moreover, are the *producers* and *developers* of these technologies diversifying from the original world of engineers working in developing prototypes?

To translate into a conceptual and methodological question: are we able to produce an overview of all interconnecting branches of a (family of) emerging technology? And in pursuing this, doing justice to the co-evolutionary character and uncertainty involved, as well as being reflexive about the rhetorics of AM? Such an exercise would start from the notion of technological trajectories (Dosi, 1982), being paths of advancement of the techno-economic characteristics of innovations. For additive manufacturing, and for analysis of potentially breakthrough technologies in general, the emerging nature with many options and uncertainties means that determining a trajectory may not be possible. We offer an approach building on evolutionary theories of technical change to help with such situations – emerging, evolving and branching ‘innovation pathways’. Our research question is thus: how can we forecast innovation pathways based on an understanding of endogenous futures and taking into account multiple possible branches?

The paper adds to the current FTA literature a deepening of the conceptual understanding of innovation pathways as well as developing a methodology to construct the innovation paths. In doing so, we are the first to create an applicable approach that can inform Forecasting Innovation Pathways along with other FTA approaches based on endogenous futures (Ōhashi, 1995; Robinson, 2009). This is not merely an academic exercise: understanding and developing innovation pathways should be regarded as providing a meso-level overview of the development possibilities of an emerging technology that is relevant for and to which multiple stakeholders can relate. The paper presents a process that we think is broadly applicable to other emerging fields and can add to the modular toolbox of FIP (Robinson et al., 2013). We will explore the evolving ‘trajectory’ of developments of additive process technology for rapid prototyping and potential alternative branches of development from this field, by doing so we will showcase a method whilst providing insights into the field of AM.

2. Frameworks to explore trajectories and branching paths of development

This section provides a functional definition of AM technologies (proposing a dominant design we label the tri-partite schema), elaborates on the concept of technological trajectory with a view to the early stages of emergence, and develops a framework for characterising innovation pathways that differ from the rapid prototyping trajectory.

2.1. A tripartite schema as a dominant design of AM

AM is an interesting set of technologies to study because of its current emergence with related uncertainties, and because AM follows a “meta-design” (Disco et al., 1992) where the focus of study is on the conceptual models that steer the design process, rather than on the artefact itself. Although definitions and umbrella terms, as well as their use, vary, from their very beginning additive rapid prototyping systems have followed a three-part schema (Fig. 1), which describes and prescribes the functioning technological configurations (Rip and Kemp, 1998).

The ‘tripartite schema’ is composed of (i) computer-assisted design software, (ii) additive process technologies (or printers) and (iii) dedicated materials (Fig. 1). These three elements resonate with scientific literature where AM is usually classified along the lines of materials, additive process technologies and digital image file (Guo and Leu, 2013). All three are necessary for all AM systems to work, and for technologies to work as an AM system. This means that any characterisation of additive manufacturing must consider developments and interdependencies of the three elements in the tri-partite schema, and every concrete AM system fills out the three elements of the schema distinctly.

When we study how different forms of AM emerge in the near future the tri-partite schema forms the starting point as well as the backbone of how the innovation pathways can be characterised.

2.2. Forecasting Innovation Pathways

The Forecasting Innovation Pathways (FIP) approach has emerged in China, the U.S. and Europe as a foresight tool covering the area between trend analysis and speculation based foresight (Guo et al., 2012; Elwyn et al., 2012; Robinson et al., 2013; Zhang et al., 2014; Zhou et al., 2014a). Taking at its heart the notion of path dependency and path creation (Garud and Karnoe, 2001, 2003), FIP mobilises quantitative and qualitative approaches to make explicit endogenous futures, i.e. indicators of the future in the present. In the main, FIP begins through tech mining of publication, patent and business databases to capture key elements of the technology field under investigation and then couples this with serial expert engagement to flesh out the innovation pathways that are visible from this analysis.

Still, FIP needs a starting point, which presents problems. Previous examples of FIP have started with limited expert engagement to build a search query for tech mining. However, there are clear biases if only a limited number of experts are engaged with (also there is the issue of geographical coverage). If one removes expert engagement and relies on inductive analysis there is the danger of missing weak signals, alternative nomenclature, confusing persistent promises versus maturation of a technology domain. Also, the FIP publications (for example Guo et al., 2012, Zhou et al., 2014b, Robinson et al., 2013) do not give a clear definition of path or pathway, let alone dynamics of paths. This is a clear weakness, although they do refer to building blocks which do have a notion of path (Robinson and Propp, 2008).

Taking care of the issue of characterising the starting point we argue that, for complex and/or early-stage technology domains one should do a preliminary analysis of path characteristics. This allows for better tailoring of the FIP process, particularly important for technology domains with multiple innovation paths at different degrees of development. In the following we propose an approach to do this, building on theories of path dependency and technological trajectories. We then demonstrate this tool for the technology domain of 3D printing.

2.3. Stable technological trajectories versus emerging, evolving and branching paths

Directions of technological change have been described in the management and sociology of technology literature as “technological trajectories” (Dosi, 1982). Technological trajectories are paths of advancement of the techno-economic characteristics of artefacts and production processes, where a trajectory is typically invariant in terms of direction. The trajectories are advanced over significant periods of time through the activities of many different agents guided by a technological paradigm (Dosi and Nelson, 2013). Examples of technological trajectories include aircraft technologies which have followed two trajectories (military and civilian) particularly visible in aircraft engines (Bonaccorsi et al., 2005). Another well-known example is in the semiconductor industry where technical advances have been represented by the gradual improvement in the computation speed by reducing the cost per bit of information and the density of transistors on an electronic chip (Dosi, 1982).

To speak of trajectories in additive manufacturing is problematic, the field is at an early stage in its emergence so it is difficult to

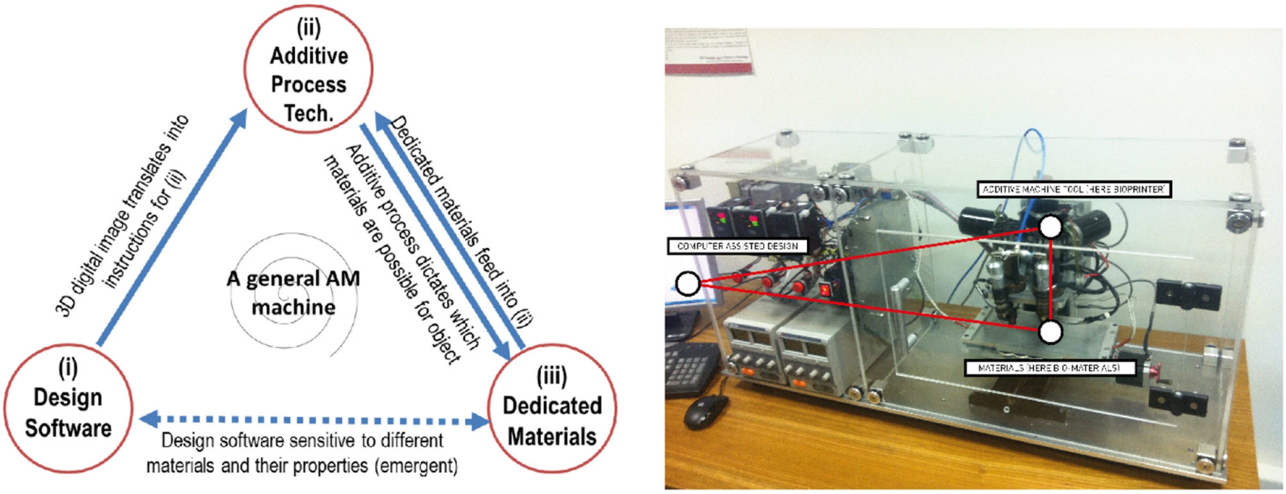

Fig. 1. The tripartite schema (left) that, when filled in, represents an additive manufacturing machine (right).

determine what will become a trajectory or not. Analysing emerging technologies in real-time in the early stages, where high uncertainty reigns and predictions are precarious, means that one cannot identify new trajectories of development *ex ante*. This is a challenge for analysts and foresight practitioners alike. However, one *can* observe differences in the thrust and patterns of technology development in a field of technology, and the momentum building up along this particular direction. These paths of technology emergence could be perceived as consisting of branching and forking paths, with some eventually become more predictable trajectories and some not. It is relatively easy in hindsight to see the multiple paths, shifts and setbacks linked with emerging trajectories, but how does one do this in real-time or indeed, with relation to foresight?

Though the challenge of identifying trajectories-in-emergence remains difficult, there is, by now, a large and growing literature on the dynamics of path emergence and stabilisation and we can draw upon this literature to provide a way of developing empirical markers for emerging and branching paths. Strands of literature that pay attention to regimes and trajectories (Nelson and Winter, 1982; Dosi, 1982; Van den Belt and Rip, 1987), that investigate pro-active consortia and organisational networks pushing particular paths over others (Schubert et al., 2013), that speak of technological interrelatedness and sunk investments (David, 1985) and that provide insight into branching and forking pathways of technology development in terms of innovation journeys (Van de Ven and Angle, 1989), critical junctures (Collier and Collier, 1991) and sociological path dependency (Mahoney, 2000). Related research has also included design thinking in path emergence, a number of authors have shown that cognitive frames structure design regimes and thus the continuation of paths (Thrane et al., 2010), whereas shifts in cognitive frames (Kaplan and Tripsas, 2008) or active opening up of design regimes (Agogué et al., 2012) can create new or multiple branching paths (Robinson and Propp, 2008).

2.4. Emerging and branching path framework and two hypotheses

Together, the above literatures shed light on the dynamics and key elements of path emergence, evolution and branching (in real-time). Whilst there is no clear agreed definition of path emergence (or indeed what a path is), one can imagine path emergence where the evolution is visible over time, with different socio-technical options being pursued and invested in, with branches, forks, setbacks and dead-ends. We see these dynamics in the examples of trajectories given earlier: the two aircraft trajectories merged as a fork from the early days of aviation, and the lithographic instrumentation used for the semiconductor industry shows indications of forking and dead-ends (Sydow et al., 2012).

To contribute to this, we will build a model of “path” at the level of a technology field. We take building blocks from path dependency and path creation literature (Garud and Karnøe, 2003; David, 1985; Sydow et al., 2012; Meyer and Schubert, 2007) and develop a model for paths in_emergence.[5] We propose that an *emerging and branching path model* can supplement the *technological paradigm and trajectory approach* for distinguishing and analysing early-stage innovation pathways in real-time. By focusing on emergent path dynamics, and through triangulating markers or indications of emergence, entanglement and emerging irreversibility (van Merkerk and Robinson, 2006), one can characterise emerging innovation pathways or potential trajectories-in-the-making.

Building on the literature described in the previous section on trajectories and path dynamics, we have identified seven key aspects that help us to empirically characterise (a) stable paths which perhaps represent the early stages of trajectories and (b) emerging and branching innovation pathways. We present them below in Table 1, providing the key literature building blocks in the text that follows.

The seven key aspects presented in Table 1 may be regarded as generalisable, and one can create general markers and indications of emergence. Since we argued in Section 2.1 that for additive manufacturing the tripartite schema plays a key role, we can treat the key aspects more specifically.

A stabilised path (or trajectory) is supported by a matrix of expectations which guides developments. These expectations collectively add up to a vision of the utility of the technology path and its direction (Van Lente, 1993). For branching (or new) paths, over time, a coherence in the driving *vision and expectations* (Key Aspect 1) about a promising new option builds up, reinforcing the new branch becoming convincing to others, with the consequence that there is increased attention and reference to a promising new direction (Borup et al., 2006). This ‘budding’ new option may shape research and development agendas to align with this option, rather than others (including the incumbent path if branching is occurring).

To decide whether there is a stabilised path in AM, we must see if there is a dominant design in terms of the way that the tripartite schema is filled in. Evidence of a branching is first made visible by a proof-of-principle of a configuration of the three (or more) functional parts of the schema. For this proof-of-principle to “get off the ground”, it must

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[5] We would like to emphasize that the majority of studies of path dynamics (as the interplay of path dependency and path creation) have been historical and not forward-looking, with the exception of Robinson and Propp (2008), Robinson (2009) and Agogué et al. (2012). This is a major bottleneck for the FIP approach which is by nature, focusing on how the present will flow into the future. It is this gap, which this paper contributes.

Table 1
Key aspects for characterising emerging branching paths alongside characteristics of stable or stabilising paths.

Key aspects of paths	Characteristics for stable of a stabilising path	Characteristics for an emerging/branching path
1. Visions of utility	Well-articulated vision of utility of the technology domain with little discourse on its relevance and value. Stabilised portfolio of business models.	New visions of application of the technology alternative cognitive framing. Visions and belief of the utility of the new path in terms of technological functions it can fulfil and societal value it can provide in the form of applications, including new business models and new industry scenarios.
2. Working technical configurations	A dominant design which is reproduced by the technological community.	Convincing justifications of new ways of following the dominant design (for additive manufacturing: the tripartite schema). Proof of principle of a new application context visible as a deviation in the way the tripartite schema is fulfilled (including the knowledge that is used or linked to this path).
3. Loci of knowledge exchange	Dedicated conferences and expos which become the recognised (and sometimes certified) locations for a community. Also recognised journals and other professional forums for exchange.	New spaces, venues and forums. New conferences and temporary events, including special sessions in mainstream events and special issues in mainstream journals.
4. Coordination and alignment	Dedicated industrial association(s), coordinating communities and platforms (producing roadmaps).	Explicit attempts at alignment around different foci than original trajectory. The initiation of forums by pro-active consortia to collectively articulate directions of development
5. Momentum and maturity of investments	Number of new entrants, mergers and acquisitions, IPOs, degree of investment, dedicated funding programmes.	Investments in the new path (momentum). Growth in activity and investment of resources in a particular vision/path.
6. Market infrastructures	Technical standards.	Questions and actions related to new industry structures and markets. New or evolving standards and regulations.
7. Societal embedding	Products in the market, identifiable community of users.	The beginnings of societal embedding and co-evolution. Emerging user groups, organised critical groups and controversies.

be convincing to others, that is to say, the *working technical configuration* (Key Aspect 2) should not only demonstrate the feasibility of the new application option, but also show that it is a potentially fruitful path to be involved in (Garud and Karnøe, 2003).

A branching path of AM may well require different or new knowledge. New *loci of knowledge exchange* (Key Aspect 3), i.e. new spaces, venues and forums will be needed to exchange and assess knowledge and techniques to fill in the tripartite schema for this new application context, and these are a marker of branching from the original path.

When a market is not yet in place, nor an industrial structure to support it, there is need for new forms of *coordination and alignment* and forums to support mutual adjustment and awareness in the stabilisation of an innovation pathway (Key Aspect 4). When institutionalised, such alignment forums may set the pace and direction of development and investments into complex breakthrough technology fields. Industry associations are an example of locations of alignment activity. Other examples include roadmapping forums and agenda-setting meetings and online community forums, often with a normative agenda.

To be able to gauge whether a 'budding' new option may evolve into a potential path, it is important to have an indication of what sort of activities and *investments* into the potential path are being made (Key Aspect 5). This provides insights into the degree of activity occurring in the potential path. Investments into a path with a particular motivating vision can be traced, knowledge production and invention can fuel the path, as well as other activities such as the appearance/frequency of knowledge exchange forums, policy programmes and the dedicated actions of organised critical groups (such as NGOs, patient associations etc.). These all provide an insight into path emergence. Examples include: publications as markers of knowledge production activity, patents as indicators of invention activity, press releases (including, details on product sales and mergers and acquisitions). Also, investments into facilities, departments, research centres etc. show the building up of momentum within a potential path. As such, these investment efforts become settled, and a reason to continue the path (David, 1985; Garud and Karnoe, 2001).

New business models, or the meso-level industry scenarios (Robinson and Boon, 2014), provide a marker of an industry taking shape and the *creation of market infrastructures* (Key Aspect 6). The emergence and persistence of new business models or business model disruptions are an indication of the growth and stabilisation of the path. In a similar vein, the preparation of support for new infrastructures relating to markets, e.g. in the form of dedicated technical standards committees, and market institutions distinguish the new path from an existing (or incumbent) one (Moors et al., 2018).

The final key aspect relates to the beginnings of *societal embedding* (Key Aspect 7) of additive manufacturing, especially specific incidences of uptake by users. Since AM technologies are used to produce objects, the potential users (and user settings) may be quite diverse. The type and breadth of use is an important aspect to determine how close a potential path is to becoming both a trajectory and a market. For societal embedding aspects include other forms of standards like quality assurance, regulation, but also social acceptance in general.

The seven key aspects may coincide or be present to a greater or lesser extent, however together they equip the analyst with markers and indicators of innovation pathway emergence so that a characterisation can be made (and justified). The aspects are also articulated differently for distinct combinations of the three elements of additive manufacturing as introduced in Section 2.1. Our starting point is that different articulations drive a co-evolutionary process in which there are moments in which key decisions are made and/or emerge that dictate a branch. Two hypotheses summarise this:

Hypothesis 1. The interplay of the foreseen or actual application and the filling in of the tripartite schema can motivate new paths branching from the original trajectory of rapid prototyping.

Hypothesis 2. In different application contexts the tripartite schema will require new knowledge, new industrial support structures and potentially additional elements to the schema.

The proposed framework and two hypotheses aim to improve the methodology of Forecasting Innovation Pathways in three ways. First, our approach now more explicitly links the past with the future in the sense that it includes analysis of path dependency but combines it with characterising and defining future paths. This allows to bring in expectations (important for handling uncertainty and new tech), but also for future-oriented work (the big weakness of path approaches are that they are historical not future-oriented). Second, the characterising and defining of future paths is done more in-depth by operationalising paths through the seven aspects presented above that intend to cover multiple dimensions of paths. Third, our approach extends the FIP framework to the field level, allowing a meso/macro application of the FIP (Robinson et al., 2013) which usually focuses on micro/meso.

In the following sections we shall mobilise this suite of seven key aspects to characterise (i) the more developed innovation pathway of

Table 2
Data sources and methods used to map ongoing socio-technical dynamics in AM.

Data source	Tag	mm/yy	Ctry	Method
Factiva (Dow Jones)	Database			Descriptive statistics
Google Trends (Google)	Database			Descriptive statistics
EPO Espacenet (European Patent Office)	Database			Descriptive statistics
Compendex (Elsevier)	Database			Descriptive statistics
Web of Science (Thomson Reuters)	Database			Descriptive statistics & scientometric analyses
Scopus (Elsevier)	Database			Scientometric analyses
Scientific literature	References			Content-analysis
Grey literature	References			Content-analysis
Web sites	References			Content-analysis
Open Bidouille Camp	Event	09/12	FR	Site visit
	Event	09/13	FR	Site visit
European Forum on AM	Event	06/13	FR	Site visit
Presentation of findings	Event	06/14	FR	Site visit
VR@P Conference	Event	10/13	PT	Site visit
Presentation of findings				
Sénat meeting with Mme Chantal Jouanno	Event	01/14	FR	Site visit
Presentation of findings				
Ateliers des Possibles – Les Tiers-Lieux de Fabrication	Event	05/14	FR	Site visit
Presentation of findings				
OuiShare Fest	Event	05/14	FR	Site visit
Paris Maker Faire	Event	06/14	FR	Site visit
Additive Manufacturing European Platform meeting	Event	06/14	BE	Site visit
AM and 3DP International Conference	Event	07/14	UK	Site visit
Joint ASTM F42 and ISO TC 261 meeting	Event	07/14	UK	Site visit
/TMP/LAB	Facility	10/12	FR	Site visit
FacLab	Facility	10/12	FR	Site visit
CDRSP, Instituto Politecnico de Leiria	Facility	10/13	PT	Site visit
IRCCyN, Ecole Centrale de Nantes	Facility	10/13	FR	Site visit
Utrecht Medical University, U. Utrecht, NL	Facility	06/14	NL	Site visit
EPSRC AM Centre, U. Nottingham	Facility	07/14	UK	Site visit
Does additive-bio-manufacturing mean business?[a]	Workshop	11/14	NL	Interactive workshops
3D Printing in Healthcare, RIVM, Utrecht	Workshop	01/15	NL	Interactive workshops

[a] Details of the workshop can be found here http://www.additive-bio-manufacturing.com/.

Rapid Prototyping and (ii) a number of branching paths that show a difference to Rapid Prototyping and have a degree of momentum. Before that we shall present the data sources and methods.

3. Data sources and methods

When measuring the key aspects introduced above we draw on a variety of methods and data sources (Table 2). We draw on structured databases, including patents and scientific articles, as one entrance point to analysing AM, particularly in the more mature rapid-prototyping area which has a reasonably long history and dedicated scientific journals. We look at other potential innovation pathways through descriptive statistics and scientometric analyses, where we use quantitative data to find markers of the diversification of the research problems that are being, or have been, explored in AM and the related knowledge base this requires. To dig deeper into, and to complement this, we employ content-analysis of AM-related scientific literature, grey literature and web sites. We triangulate this quantitative and qualitative data by visiting AM-related events and facilities. Also we have either organised or participated in interactive workshops on additive manufacturing. Methods 4 and 5 has been labelled 'insertion', and provides opportunities for formal and informal data collection as well as an opportunity for feedback on ongoing analysis. Both authors actively participated in events through presenting findings in AM conference sessions and through participation in discussions and breakout sessions. (See Table 3.)

The task then is to filter this data to observe the Key Aspects outlined in Table 1 for Rapid Prototyping and for other areas of 3D printing. This we do in Sections 4 and 5.

4. Exploring the starting point: Rapid Prototyping as root of many branches?

4.1. Characterising the emerging path of rapid prototyping through the seven Key Aspects

Though historical accounts of additive manufacturing occasionally go back to late 19th century topography and photo-sculpture (Prinz et al., 1997), "*the first significant work associated with modern photo-lithographic systems only emerged during the 1970s*" (Bártolo and Gibson, 2011). In the 1980s, advances in computing, computer-aided design, lasers, printing technology, programmable logic controllers (PLCs), and materials enabled the development of AM (I. Gibson et al., 2010). Pioneering inventors filed patents in the United States, Europe and Japan for 3D printing ensembles (Wohlers, 2013a). In the 1990s, new specialized supplier firms such as 3D Systems, Stratasys, EOS GmbH, D-MEC and CMET commercialized various AM patents. Incumbent firms such as Ciba-Geigy (now Huntsman), DSM (Somos) and JSR Corporation provided a limited range of materials for mainly plastic-based AM printers (Wohlers, 2013a). 3D Systems developed STL, a generic 3D file format suited for AM, which was made freely available (I. Gibson et al., 2010). STL quickly became a de facto standard among professional AM users (Jurrens, 1999). These developments highlight the importance of assembling computer-aided design, additive process technologies and materials into a "*configuration that works*" (Key Aspect 2), reinforcing the idea of the tri-partite schema (Fig. 1). Academic publications underline this, since AM is usually classified along the lines of materials and additive process technologies (Guo and Leu, 2013; Kruth, 1991; Kruth et al., 1998; Pham and Dimov, 2003; Pham and Gault, 1998).

Industrial designers were the first to use AM to produce concept models and functional prototypes. Compared to established methods, early AM machines significantly improved the speed and cost of product development cycles and came to be known as rapid prototyping

Table 3
Seven key aspects for the Rapid Prototyping innovation pathway.

Key Aspect 1 vision of utility	A core vision of use for speeding up new product development with expectations that bespoke single products may be a possible market.
Key Aspect 2 working technical configuration	Plastic additive printing technology combined with simple plastics and digital image form a core tripartite scheme that defines a 3D printer.
Key Aspect 3 loci of knowledge exchange	Dedicated journals (Journal of Rapid Prototyping), societies (GARPA) and annual conferences stabilise into a nexus for knowledge exchange (both science and industry).
Key Aspect 4 coordination and alignment	The rise of European and American networks conducting roadmaps, as well as dedicated consultancy reports (Wohlers) becoming a benchmark for foresight.
Key Aspect 5 momentum and maturity	Increasing machine sales, IPOs and Mergers and Acquisitions indicate a maturing industry.
Key Aspect 6 market infrastructures	STL as the standard digital file for 3D printing. Steady increase in standards setting (particularly after 2008).
Key Aspect 7 societal embedding	Rapid prototyping with 3D printers becomes common in the world of design and architecture.

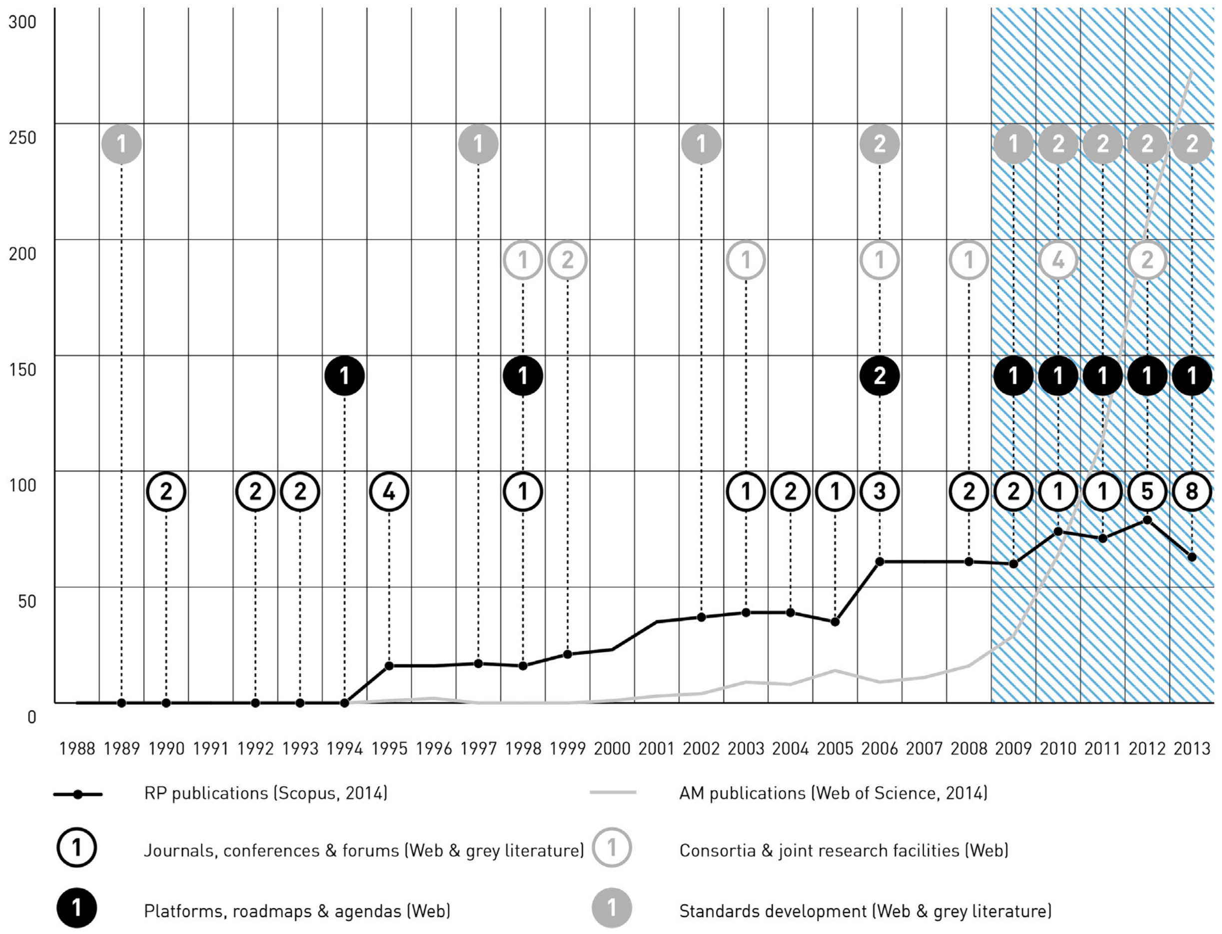

Fig. 2. Tracing Key Aspect 3 (knowledge exchange) and Key Aspect 4 (coordination and alignment activities) along a baseline of number of rapid prototyping scientific articles. Figures in the circles indicate the number of journals founded, platforms created, etc.

(RP) (Bernard and Fischer, 2002; Bernard and Taillandier, 1998). Rapid Prototyping became the prime vision of utility (Key Aspect 1) to improve new product development processes through rapid prototyping. Rapid Prototyping (RP) soon became the umbrella label for all developments in AM continuing to being the dominant term through the 1990s and early 2000s, were researchers fuelled the incremental development of rapid prototyping and rapid tooling. This consolidation is visible in the creation of dedicated conferences, academic journals and national RP associations (Key Aspect 3; see also: Fig. 2). Professional societies such as the International Academy of Production Engineers (CIRP), the Society of Manufacturing Engineers (SME) and the Verein der Deutschen Ingenieure (VDI) also helped to circulate RP-related knowledge. In 1998, members of various national RP associations created the Global Alliance of Rapid Prototyping Associations "*to encourage the sharing of information on additive manufacturing*" (GARPA, 2014) (Key Aspect 4; see also: Fig. 2). The annual publication of the Wohlers Report also played a role in monitoring and promoting the emergence of RP (Wohlers, 2013b). RP-related knowledge circulates through established channels such as the GARPA, Rapid Prototyping Journal and Virtual and Physical Prototyping. Over the period, generic policy instruments such as NSF grants (Weber et al., 2013) and SBIR funding (Wohlers, 2006, 2003, 2000, 1998) provided limited support for specialized supplier firms and researchers involved in AM. Regarding Key Aspect 4, coordinated efforts to define a common direction for RP-related research and development were rare. The European Network Offensive for Rapid Technologies as well as Department of

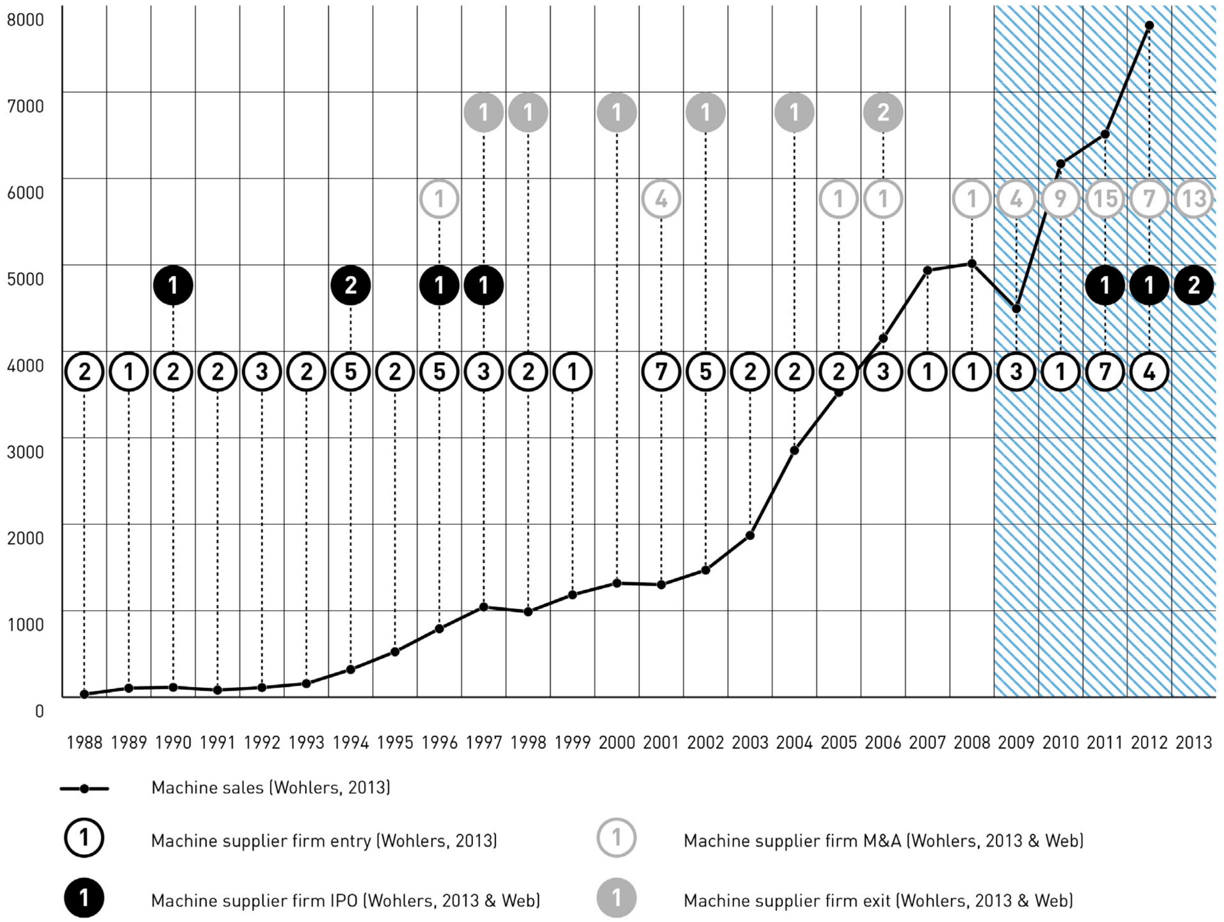

Fig. 3. Key Aspect 5 (momentum and maturation) represented by the growth in number of machine supplier firms overlaid on yearly machine sales. Figures in the circles indicate the number of firm entries, etc.

Energy and National Center for Manufacturing Science-sponsored road mapping exercises in the US are notable exceptions to the mainly unassisted development of RP.

In terms of Key Aspect 6 (standards), benchmark parts and material specifications were developed for specific user communities (Mahesh, 2004), efforts to define formal standards were "*quite limited*" (Jurrens, 1999; Malone, 2009). In other words, RP emerged in a context marked by limited policy support, few coordination efforts and the absence of formal standards.

Fig. 3 represents Key Aspect 5 in terms of machine supplier firm entries, IPOs, Mergers and Acquisitions and firm exits. There is consistent growth in sales since the early 90s with a dip following the global financial crisis of 2008. What is interesting here is there are two phases visible. The first phase sees a burst in supplier firms including IPOs. This period is followed by a period of firm exits, merges and acquisitions and some further firm entries. However, if one looks at the period after the financial crisis of 2008, there is a spike in both machine entries, mergers and acquisitions and what seems like a second wave of IPOs.

Despite the explosive growth, by the mid-2000s plastic-based AM reached a state of technological and economic maturity (Campbell et al., 2012). This coincided with the growing availability of metal-based AM process technologies and the emergence of a new vision of utility, namely manufacturing (visible in the data presented in Section 4.2). Following a series of patent infringement lawsuits, acquisitions and failures (Fig. 4), the RP industry has consolidated around a small number of specialized supplier firms and service providers catering to the well-defined niche requirements of a specific set of professional users. Since most patents have expired or will expire soon (Wohlers, 2013b), this status quo may crumble, particularly visible with the proliferation of open-source variants of additive process technologies initially used for RP (see the shaded area of Fig. 4).

Below we summarise this section for each key aspect.

4.2. Can we see indications of branching in the forms of knowledge being produced?

As 3D printing for Rapid Prototyping stabilised in the early 2000s, researchers and professional users involved in RP began to explore new uses of 3D printers beyond RP. To capture preliminary evidence of this diversification, we chose to explore the codified scientific knowledge as published in loci of knowledge exchange (Key Aspect 3): peer-reviewed journals. Our first data set is comprised of 824 articles published in the Rapid Prototyping Journal and Virtual and Physical Prototyping between 1995 and 2013. This dataset was chosen since both journals are central to the field of rapid prototyping with both journals being endorsed by the Global Alliance of Rapid Prototyping Associations (GARPA). Furthermore, both are referenced by Scopus, a database that provides structured bibliographic data in the form of RIS file formats, which is compatible with state of the art visualization tools. We chose to visualize the co-occurrences of author keywords associated with these articles in order to identify the diversification of prominent research and development in the field of rapid prototyping research. We used the CorTexT Manager to build co-word and co-citation networks with the structured data re-arranged in these databases.

On the lower right hand corner of the co-occurrence network shown in Fig. 5, we can see the core of rapid prototyping research centred on issues linked to software and resin-based additive process technologies

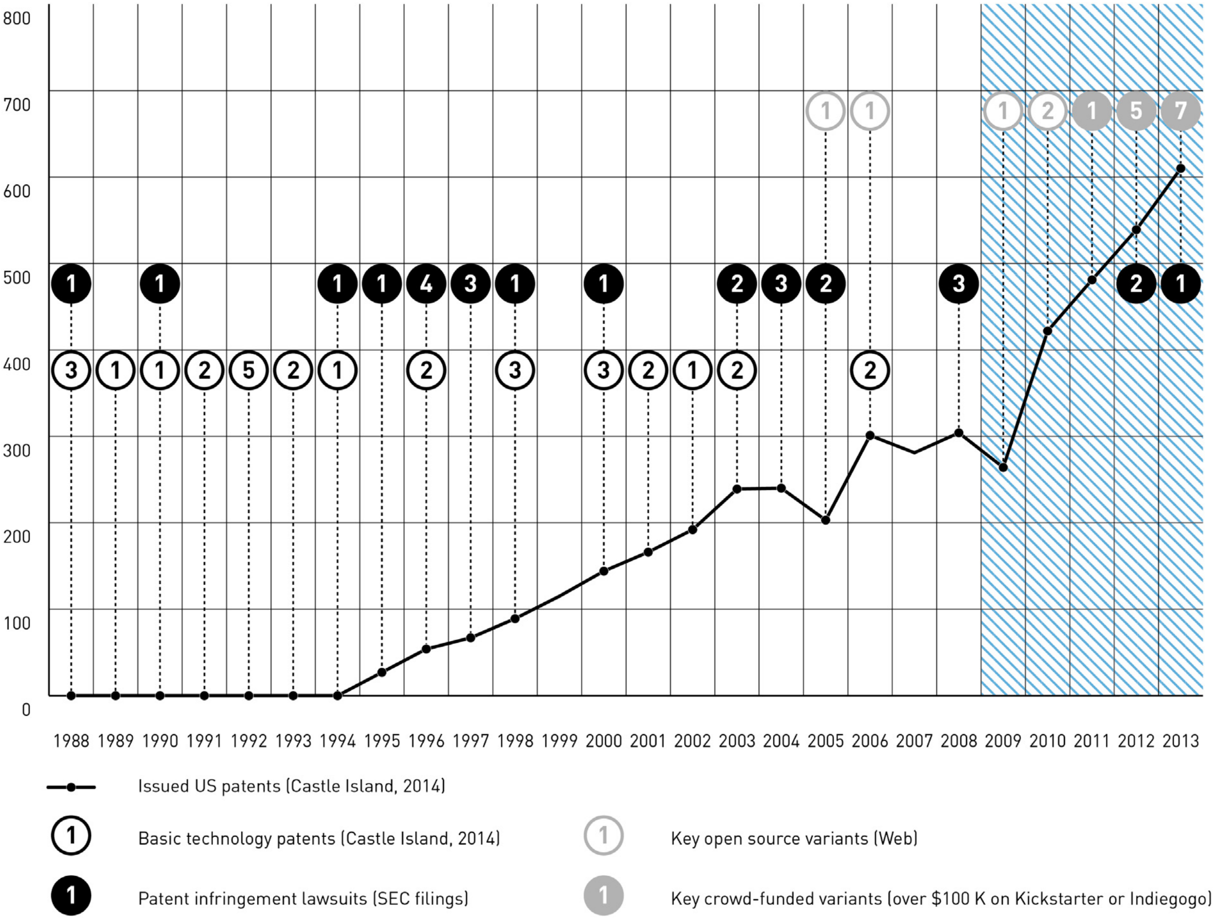

Fig. 4. Key patents overlaid on issued US patents for AM. Figures in the circles indicate the number of patent infringements, etc.

for applications in product development. Clustered around the upper left-hand corner we observe the diversification of research problems related to metal-based additive process technologies for applications in product manufacturing. On the upper right-hand corner of the network we find a third cluster of problems related to the use of additive process technologies for applications in medical research.

Ubiquitous in Fig. 5 is "manufacturing", visible as Rapid Manufacturing (top left), Additive Manufacturing (centre) and Computer-Aided Manufacturing in the bottom right. Against the background that the journals have "prototyping" at the heart of their journal goals (including in the title of the two journals) and manufacturing being present in multiple ways in the scientific articles in these journals might be indicative of an increasing interest in manufacturing. The method reveals that this new function (manufacturing rather than prototyping) is part of the knowledge landscape in these two journals. How it is present and whether this is a new path, requires further investigation.

Two areas of research have significantly grown over the time period covered. Research on additive process technologies and materials for manufacturing (of metals and ceramics) and tissue engineering (of bones and tissues) are two new problem areas distinct from RP. They are branching paths that differ in their motivating visions, degrees of activity and investment, degrees of technology development and coordination, qualification processes and the hurdles and issues they raise. This branching of paths from RP is echoed in our co-citation analysis (not shown in a figure) of the top 50 AM-related journals and proceedings and the top 50 AM-related cited journals and proceedings (both indexed by the Web of Science). Our heterogeneous co-citation network displays similar diversification, with new journals and proceedings distinctly clustered in the life sciences and in materials science and applied physics.

4.3. *Can we see stabilising or emerging paths?*

What is clear in our scientometric analysis is that previously unrelated and distinct areas of research have appeared within the RP research community and in knowledge production 'at large'. In knowledge production, growing interest in AM coincides with a diversification of the problems to be solved and a subsequent diversification in the knowledge base required to solve these new problems. These form new research-dependent paths that differ significantly from RP.

So in the world of knowledge production, and potentially technology development, there are new research areas being explored. From our other analysis in Section 4.1 we see that there are a number of envisioned application areas very different from applications to rapid prototyping (the initial application area for additive manufacturing).

Combining Sections 4.1 and 4.2 we can argue:

- There is stabilisation occurring in AM technology for the application to Rapid Prototyping.
- There may indeed be potential branching paths, visible in the diversification of research activities visible in the analysis of the Key Aspects (notably Figs. 2–4) and the scientometric analysis (Fig. 5).
- The developments of Rapid Prototyping yielded four potential branching paths: the scientometrics analysis combined with the analysis in Section 4.1 suggest (1) 3D printing for manufacturing (not prototyping), (2) advanced functional material printing and (3) 3D printing of bio materials. The data on open source printers, and visits of conferences and events (see Table 2) hint at a fourth potential path which we label as (4) Open source and open access 3D printing.

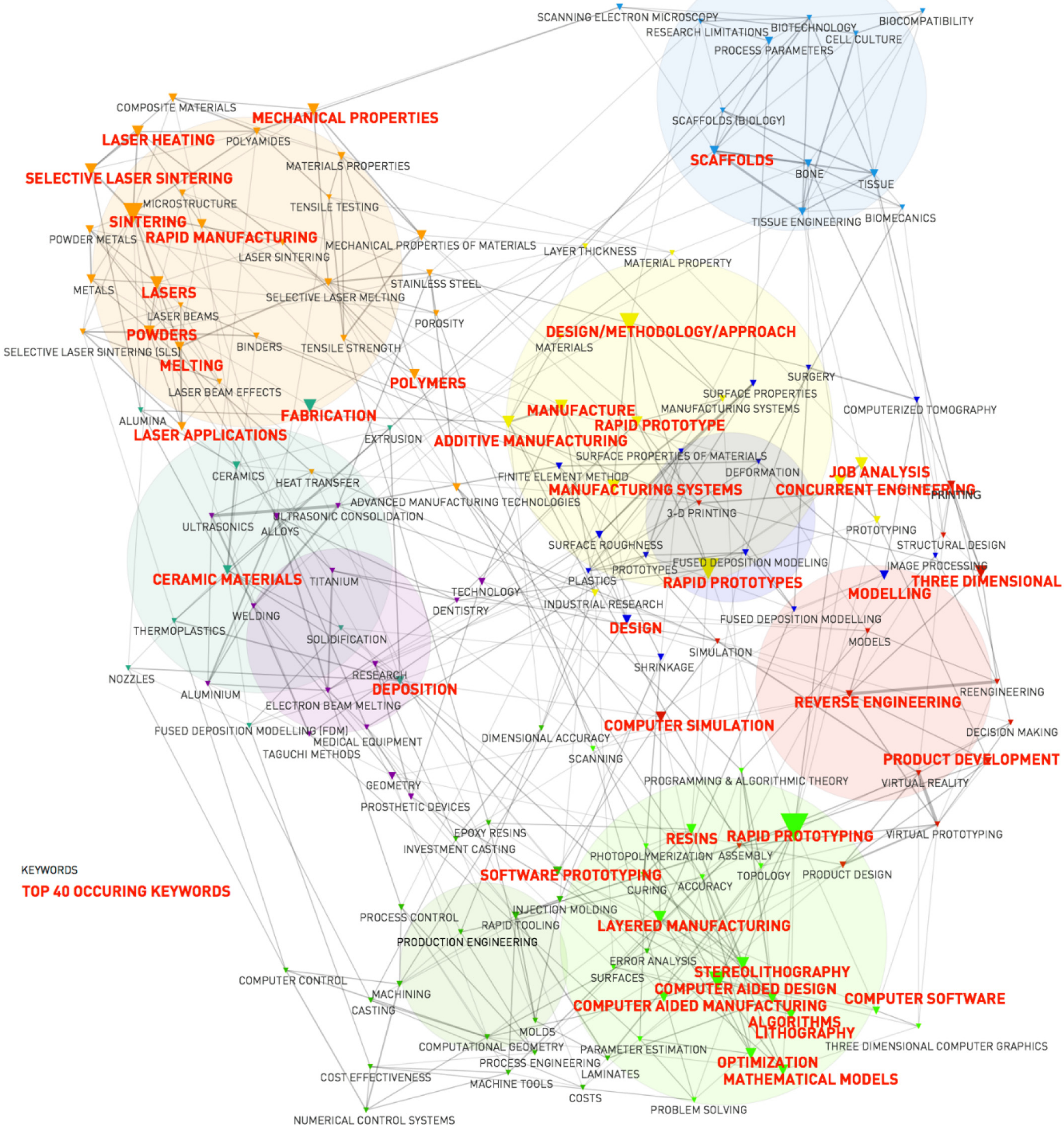

Fig. 5. Co-word analysis of top 150 author keywords (In bold and red we chose to highlight the top 40 keywords accounting for 20% of all keyword occurrences. Concerning the choice of parameters, the network is based on a Chi 2 proximity measure between top 150 keywords with a proximity threshold of 0.2. The network was filtered to include only top 5 neighboring nodes. Communities were detected using the Louvain community detection algorithm. The size of communities is proportional to the number of records attributed to community member nodes.) published in the Rapid Prototyping Journals and Virtual and Physical Prototyping between 1995 and 2013. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Section 5 digs deeper into the potential branching paths mobilising the framework described in Table 1.

5. Exploring potential branching innovation pathways

5.1. Rapid manufacturing: design freedom and tool-free distributed production

Rapid manufacturing can be traced to the late 1990s among professional users and researchers involved in RP (Hopkinson and Dickens, 2001; Rudgley, 2001). Rapid manufacturing (RM) is defined as "*the use of a computer aided design (CAD)-based automated additive manufacturing process to construct parts that are used directly as finished products or components*" (Hopkinson et al., 2006). The main envisioned advantages of RM are greater design freedom and the absence of tooling (Reeves, 2008; Reeves et al., 2011). First, AM machines are able to produce complex designs other manufacturing methods cannot achieve. Second, the removal of tooling means changes to designs can be made without significant effect on cost. Furthermore, the absence of tooling means RM reduces the time-to-market for low-volume production that would otherwise not be economically viable (Key Aspect 1). Put together, this enables the production of both high and low value-added components and products. For these reasons, RM has already been adopted in several industries. In the medical industry, firms such as Align Technologies use RM to produce patient-specific dental aligners (Hopkinson and Dickens, 2001). Similarly, Phonak and Siemens Hearing Instruments market patient-specific hearing aids produced with AM machines (Masters et al., 2006). In both cases, 3D scanners are used to determine the custom-fit of medical devices. The resulting CAD file is sent to an AM machine. This method "*has greatly reduced the uncertainties in producing a custom-fitting item*" and yields "*a greater degree of consistency in the product*" (Reeves et al., 2011). In the aerospace industry, metal-based AM is used to produce complex high-performance parts (Nathan, 2011) with mechanical and internal functionality (i.e. cooling channels, internal honeycomb structures etc.). Thus, AM can be used to make geometrically complex lightweight structures. This is critical for the aerospace industry's "*buy to fly ratios*". Therefore, firms such as Boeing are applying AM to produce ducts and similar parts for F-18 fighter jets (Khajavi et al., 2014), whilst competitors such as EADS and GE are using AM to make fuel injectors and titanium satellite parts (Freedman, 2011). Closer to consumer markets, jewellers and fashion designers are using RM to make intricate jewellery and apparel (Brooke, 2014; Campbell et al., 2012). So, proofs of principle seem to pop up in different sectors, indicating proven filling of the tripartite schema (Key Aspect 2).

Beyond design freedom and the absence of tooling, RM promises to disrupt logistics and supply chains by enabling distributed production (Huang et al., 2012) (Key Aspect 1). RM is expected to reduce the cost of packaging; transport and warehousing, and improve the general responsiveness of supply chains, particularly for aircraft maintenance and repair (Holmström et al., 2010). Aircraft maintenance and repair requires costly inventories of infrequently demanded parts. To circumvent the need for such inventories, military and civilian aircraft operators are experimenting with RM for on-site production of spare and legacy parts. For instance, the US military has set up a mobile parts hospital at sites in Kuwait and Iraq to print replacement parts for damaged combat vehicles. Broken parts are replaced within hours instead of waiting days or weeks for replacements (Reeves et al., 2011). Online platforms such as Ponoko, JuJups, Shapeways and Sculpteo are developing innovative business models based on distributed production with AM. These web sites offer the possibility to buy and sell customized consumer products shipped through the mail. In addition to these web-based ventures, brick-and-mortar service providers are catering to the growing consumer demand for customized products made with plastic-based AM machines.

Multi-disciplinary research is increasingly supporting the production and circulation of RM-related knowledge. The creation of dedicated conferences and journals are indications of this, as is the involvement of academic researchers in collaboration and coordination activities with professional users and specialized supplier firms (Key Aspect 3). This is particularly striking in the United States, Europe and Asia. From 2006 onwards a wide range of conferences have taken place. Examples include the European Rapid Manufacturing Platform (EU RM Platform) that was established by a community of industrial and academic stakeholders to define "*research and development priorities, timeframes and action plans on a number of strategically important issues related to RM*" ("What is the RM Platform?", 2006) with the support of the European Commission.

Coordination and alignment activities took the form of the creation of platforms and facilities (Key Aspect 4). National policy initiatives are supporting the creation of dedicated research facilities and consortia such as the Direct Manufacturing Research Center ("Direct Manufacturing Research Center", 2013), the Fraunhofer AM Alliance ("Fraunhofer Additive Manufacturing Alliance", 2014), the EPSRC Center for Innovative Manufacturing in AM ("EPSRC Centre for Innovative Manufacturing in Additive Manufacturing", 2014), the National Netshape and Additive Manufacturing Center ("MTC - About us", 2014), the National Additive Manufacturing Innovation Institute ("High Value Manufacturing Catapult", 2014) and the China 3D Printing Technology Industry Alliance ("2013 World 3D Printing Technology Industry Conference", 2013). Further indications of this are provided in roadmaps and agendas. The 2009 Roadmap for AM is an example of this (Bourell et al., 2009), as are the three EU RM Platform strategic research agendas published in 2006, 2010 and 2013.

Industry dynamics revolved around a few large companies that have acquired a range of smaller ones over the years. 3D Systems alone bought around 30 firms including solid ink R&D teams of Xerox over the period of 2009–2014. Other bigger players that took over companies included Stratasys and Materialise. The same period also saw at least 6 companies making their IPO, 4 IP infringement cases, and 1 failing company (Soligen) (Key Aspect 5). Rapid manufacturing aims to produce finished products and components. This raises issues of technical interoperability, quality and safety of AM file formats, machines, materials and end-use manufactured parts (O'Sullivan and Brévignon-Dodin, 2012). For RM to stabilise, standards must be in place to guarantee it does not pose a risk for customers and manufacturers (Key Aspect 6). The negotiation of such guarantees started in the late 2000s, when national standardization efforts were launched in the United States, France and Germany. In the United States, the ASTM F42 technical committee on AM held its first meeting in 2009 to develop AM standards (Stucker, 2009). The committee is composed of members from national standard bodies (i.e. NIST), professional societies (i.e. SME), multinational corporations (i.e. BMW, Siemens, Stryker and Honeywell), small and medium-sized firms, research universities and US federal agencies and institutes (i.e. NASA, the Naval Warfare Center, the Air Force Research Laboratory) (Malone, 2009). In France and Germany similar technical committees were launched to establish standards. These standardization efforts are receiving dedicated policy support in Europe and the United States. Standards are high on the European Union's political agenda. In September 2012, the European Parliament voted the standardization package, a set of regulatory measures designed to increase the competitiveness of European SMEs by getting them involved in standardization efforts. The European standardization package also recognises the importance of forums and consortia in the development of standards. Similar dedicated policy support is visible in the United States, where the National Institute of Standards and Technology is funding AM standard development.

Branching from RP, RM is currently explored for the tool-free low-volume production of complex end-use components and products. Innovative RM business models are visible in medical, aerospace and customized consumer product industries. Dedicated research infrastructures, agendas, roadmaps and standardization efforts indicate significant levels of investment in this path, which indicates cautious societal embedding (Key Aspect 7). However, developing compromise-based standards from scratch is a particularly difficult and slow task. Thus, AM standards are a major hurdle for the development of RM. Next to the difficulty of collectively qualifying design, machines and materials for AM, intellectual property has also become a controversial issue among RM stakeholders. Coupled with a reverse engineering scanner, AM can be used to reproduce copyright protected parts. Legal debates on why and how to regulate this have only recently become salient in RM (Burns and Howison, 2001; Mendis, 2013; Weinberg, 2013). They originated in a second path branching from RP in the mid-2000s, namely grassroots innovation.

5.2. Grassroots innovation: empowerment, entrepreneurship and education

In 2005, Adrian Bowyer, then a lecturer at the University of Bath, launched the Rep Rap project to build a self-replicating open-source 3D printer ("Rep Rap Wiki", 2014). By 2013, over 400 variants of the Rep Rap existed (Gilloz, 2014). Much like open-source code, Rep Rap variants have proliferated through the efforts of a worldwide community of high-tech tinkerers often referred to as the "*maker movement*" (Anderson, 2012b; Bosqué, 2014; Doctorow, 2010; Morozov, 2014; Rotman, 2013; Söderberg, 2013; Söderberg and Daoud, 2012; Tochetti, 2012). Policy makers in the United States, the United Kingdom, France, Spain, Russia and China are paying close attention to these developments. Indeed, boosting open-source 3D printing in FabLabs, hackerspaces, schools and libraries could not only spur a new wave of entrepreneurship but also promote education among young generations ("3D Printers and Maker Spaces in Libraries", n.d., "3D printers in schools", 2013, "America Makes Supports MakerBot in its Mission to Put a Desktop 3D Printer in Every School in America", 2013). Thus, public funds are supporting citizen-led initiatives as well as public educational facilities so they may equip themselves with the tools of an expected "*third industrial revolution*" (Stinchcomb, 2013).

In the mid-2000s, researchers developed open-source 3D printers such as the Rep Rap (U. Bath) and Fab@Home (Cornell) by drawing on expired or expiring IP (particularly generic FDM patents). What motivated these developments is described in emancipatory terms (Söderberg et al., 2013). According to Adrian Bowyer, the diffusion of open-source rapid prototyping machines "*will allow revolutionary ownership, by the proletariat, of the means of production*" (Bowyer, 2011). Similarly, the Fab@Home project was launched "*to promote SFF technology by placing it in the hands of hobbyists, inventors and artists*" (Malone and Lipson, 2007). Tech guru Chris Anderson claims the diffusion of open-source 3D printing will enable a radical democratization of entrepreneurship. According to Anderson, "*just as the Web democratized innovation in bits, a new class of 'rapid prototyping' technologies, from 3D printers to laser cutters, is democratizing innovation in atoms*" (Anderson, 2012b). Anderson believes that the practices of peer-production, open-source technology, crowdsourcing and user-generated content are spilling from open-source software over to the real world (Anderson, 2010). These practices offer "*a billon little entrepreneurial opportunities that can be discovered and exploited by smart, creative people*", a phenomenon that will supposedly bring to an end "*the days of companies like* '*General Electric*', and '*General Mills*' and '*General Motors*'" (Anderson, 2012b) (Key Aspect 1).

In open-source 3D printing and the grassroots innovation it enables, a number of network forums have been created over the past few years where self-labelled makers converge to collaborate and imagine themselves as members of a new and distinct community (Key Aspects 3 and 4). Sara Tochetti has documented the emergence of this community in publications such as Make magazine and events such as Maker Fairs (Tochetti, 2012). Following Turner and Tochetti, we argue it is in these spaces of collaboration, spaces that provide access to open-source technology and the skills required to operate it, that grassroots innovation is taking place. Today, open-source 3D printers are becoming a part of the international standard toolset found in commercial Tech Shops and non-commercial FabLabs and hacker spaces. Online forums such as Instructables, Thingiverse and Bldr3r provide spaces to exchange knowledge and designs. Cheap and relatively easy to tinker with, open-source 3D printing could not be possible without these physical and virtual spaces where makers converge to build, hack and discuss their projects.

Driven by a Do-It-Yourself ethos, makers are "*more than mere consumers of technology*" (Dougherty, 2005). They are an emerging community of lead-users shaping a path branching from RP through distributed practices of bricolage and entrepreneurship (Garud and Karnøe, 2003). They are doing this in dedicated spaces of exchange and collaboration. Anthropologist Levi-Strauss coined the term bricolage to connote resourcefulness and improvisation on the part of involved actors (Garud and Karnøe, 2003). This characterises academic open-source 3D printer projects like the Rep Rap, Fab@Home or the open-source metal 3D printer developed at Michigan Technological University (Thryft, 2014). It also characterises the social embedding and more specifically the political use citizens have of open-source AM technology in non-commercial spaces of collaboration such as FabLabs and hacker spaces (Key Aspect 7). For instance, the MIT's Grassroots Invention Group and Center for Bits and Atoms initially developed FabLabs as these communities in the developing world by giving them access to open-source digital fabrication tools (Mikhak et al., 2002). Similar dynamics of collaborative resourcefulness and improvisation can also be found in the proliferation of crowd-funded open-source 3D printing variants on websites such as Indiegogo and Kickstarter.

The myriad of start-ups established over the past three years to sell 3D printers, materials and components to the maker community is another indicator of this trend. Interestingly, it appears markets are emerging for these actors and spaces, as visible in the investments of incumbent firms like Leroy Merlin, Snecma and Renault (Barbaux, 2014). Universities are also jumping on the bandwagon, setting up in-house FabLabs to stimulate innovative thinking among employees and students (Dunn, 2005; "Fabulous fabrications", 2005; Tlhage, 2014). Moreover, there have been a number of acquisitions, notably 9 by the company 3D Systems. A large part is played by crowdfunding schemes organised through Kickstarter (30 firms) and Indiegogo (6 firms) (Key Aspect 5).

Public libraries, primary schools and secondary schools are catching up on the DIY trend. In the United States and the United Kingdom, public funding is going into open-source 3D printers for schools and libraries to address deficiencies in science, technology, engineering and math education ("3D printers in schools", 2013; Lipson and Kurman, 2010) (Key Aspect 7). What is more, the French, Russian and Chinese government are supporting the creation of FabLabs and hacker spaces to stimulate grassroots innovation. In the United States, a Bill has been introduced twice in Congress to establish a FabLab network across the nation (Foster, 2010; Titsch, 2013).

Though open-source 3D printing has only recently emerged through bottom-up initiatives, it is already raising a number of issues. First, though most of open-source machines commercialized by entrepreneurs are based on expired AM patents (particularly US 5121329), some open-source variants have led to patent litigation with dominant specialized supplier firms active in RP and RM (i.e. 3D Systems vs. Formlabs in 2012 and Stratasys vs. Afinia – Microboards Technology in 2013). Also, exchange of open-source 3D printing CAD files has generated debate on the protection of intellectual property (Burns and Howison, 2001; Mendis, 2013; Weinberg, 2013). Foreshadowed by Marshall Burns in the early 2000s, AM could lead to a widespread "*napsterization*" (Burns and Howison, 2001) of reality as any object could be reverse engineered and reproduced with a hacked Kinect 3D scanner coupled to an open-source AM machine. This has already led to litigation (Doctorow, 2013; Hurst, 2013). However, some companies such as Authentise and Fabulonia are anticipating and these IP issues by providing electronic watermarks or secure and time-limited software for 3D printing designs that protect designer copyrights. Parallel to these IP issues, the development of unregulated 3D printed gun designs has sparked controversy and regulatory action by national and local governments (Beckhusen, 2012; Steadman, 2013) (Key Aspect 7).

RM and open-source 3D printing also intersect when it comes to standards (Key Aspect 6). By lowering the cost of engaging in a production run, open-source 3D printing brings both opportunities and perils. For instance, "*it is likely to encourage the production of substandard goods*", what the Institute for the Future has labelled "*crapjects*" and "*physical spam*" (Townsend et al., 2011). Though this has not yet translated into significant efforts within the maker movement to guarantee part quality and safety, initiatives like Watertight Mesh Certification indicate that this may become a growing area of activity and investment in the future (Vesanto, 2013). The WMC is an initiative to guarantee the integrity and quality of 3D models for 3D printing ("Watertight Mesh Certification", 2014).

Initially driven by the bottom-up initiatives of the maker community, open-source 3D printing is beginning a shift towards the mainstream. The fact that technology enthusiasts are buying open-source 3D printers as home appliances is symptomatic of this trend. Competition in this nascent industry of consumer-grade 3D printers is mainly based on price and not on innovation (Key Aspect 2). Such developments may lead to tensions within the maker community. Much like personal computing branched into proprietary and open-source technology, grassroots innovation is fuelled by entrepreneurial and political dynamics that may both align and clash as this path evolves (Key Aspect 7). Along with issues related to IP, safety and quality, these clashes are problems the path of grassroots innovation may encounter in the coming years.

5.3. *Functional materials: structural optimization and embedded electronics*

Rapid prototyping and rapid manufacturing are maturing. This coincides with a wider availability of materials for AM machines. The entry of new (i.e. DWS and SLA Materials) and incumbent (i.e. CRP Technology, Rhodia and Arkema) feedstock developers and materials providers is an indication of this trend (Wohlers, 2013a). Until recently, the vision of utility of RP and RM has been to fit into existing industrial manufacturing processes of new product design (RP) or the manufacture of uni-material parts (RM) which can be combined with other parts to create components or products. This is common to traditional manufacturing approaches, where parts are produced separately and later assembled to create a component or finished product. Beyond these uni-material approaches, current AM-related research is exploring ways to print beyond uni-material parts, to whole devices or parts which have unique properties due to changing the material properties within a single printed part (Key Aspect 1). For example, the potential to dynamically mix, grade and vary ratios of various materials leading to continuous gradients and structurally optimized designs is a problem addressed in research (Hascoet et al., 2013; Miyamoto et al., 1999; Oxman et al., 2011; Yakovlev et al., 2005). The problem has been labelled as functionally graded materials and is a driving vision for materials scientists and designers (Key Aspect 1). In nature, most materials are varied or graded, such as the cross section of a palm-tree trunk (L.J. Gibson et al., 2010) or bone (Ortiz and Boyce, 2008). Only recently have there been demonstrations of man-made functionally graded materials and these have been produced additively. For instance, Neri Oxman of the Massachusetts Institute of Technology created a mixing nozzle to mix different colours of polymer to demonstrate the potential of producing parts in a functionally graded way (Oxman, 2011).

Concerning Key Aspect 2, we see the tri-partite scheme being followed but with developments and expansions regarding the materials, the types of additive printing as well as the type of digital image that is necessary (many more variables). Early demonstrations of functional parts produced additively can be found in projects led by researchers and specialized supplier firms ("3D Printing is Merged with Printed Electronics", 2012, "Microtec-d News", 2014, "Optomec Showcases 3D Printers for Metal and Electronic Applications at RAPID", 2013; Lopes et al., 2012). This is particularly interesting when one sees how the semiconductor industry is evolving from integrated circuits to systems/networks-on-a-chip. The European FP7-funded project Diginova has this convergence of 3D electronics with AM at its heart, with the aim of creating a road map to guide their convergence in order to solve both market demands and societal challenges (Potstada et al., 2016). In light of these developments, the creation of functional AM parts appears to be an important development both for and beyond RM.

Early research on multi-functional AM materials is receiving dedicated policy support. For instance, the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing was established with public funding to "*go […] toward the challenges of investigating next generation, multi-material active AM processes, materials and design systems*" ("Additive Manufacturing and 3D Printing Research Group", 2014). Continuing indications of growing loci of knowledge exchange (Key Aspect 3) are becoming visible. The EPSRC has also recently funded the creation of an EPSRC Centre for Doctoral Training in Additive Manufacturing with 40 academic supervisors from the University of Nottingham, Loughborough University, Newcastle University and Liverpool University ("CDT in Additive Manufacturing and 3D Printing", 2014). At the European level, research funding for research on AM materials is combined with the idea of scaling down to nano. In its Horizon 2020 funding programme, the European Commission mentions additive manufacturing as part of its "*Leadership in enabling and industrial technologies: Nanotechnologies, Advanced Materials, Biotechnology and Advanced Manufacturing and Processing*" Work Programme 2014–2015 ("Horizon 2020 Work Programme 2014–2015", 2013). There are also indications of coordination with consortia like the Fraunhofer Institute ("Fraunhofer Additive Manufacturing Alliance", 2014) or the EU-funded RAPOLAC project ("Rapid Production of Large Aerospace Components", 2010) involved in process development and demonstration projects to advance the development of AM materials (Key Aspect 4).

Whilst there is anecdotal evidence on Key Aspect 4, there is no convincing evidence of Key Aspects 5, 6 or 7. Many issues and challenges must still be addressed and the state-of-the art in functional materials remains at the level of research. For instance, CAD software has traditionally assigned material properties to pre-shaped building components and industrial fabrication processes are not geared to factor in variation of material properties within solids. Thus, there is a need for adapted design tools and technical standards for graded materials. Other hurdles have been identified, such as the limitations of the STL file format (which is unable to handle functionally graded and multi-material parts) and challenges in the materials sciences (such as bonding dissimilar materials). Beyond these future directions for research, there are problems related to the automation of different manufacturing processes and materials in the same construction cycle. The prospect of using graphene in AM machines ("First Demonstration of Inkjet-Printed Graphene Electronics", 2011) and the longer-term visions of "*programmable matter*" (Lipson, 2012) indicate that this branching path from RM is still its early stages.

Functional materials and embedded electronics can indeed be described as a budding and branching innovation pathway. There is momentum building up, but not enough evidence to show whether it will stabilise or not.

5.4. *Biofabrication: patient-specific implants, scaffolds, living constructs and food*

Clinical researchers and practitioners have been interested in AM since its early days as a rapid prototyping technology. They used RP to make surgical guides, medical instruments and external implants (i.e. prosthetic sockets and exoskeletons ("3D printed Exoskeleton arms change the life of a little girl", 2012; Faustini et al., 2008; Rogers et al., 2001)). In the mid-2000s, medical researchers and professionals began to investigate AM for new applications (Key Aspect 1), namely to produce internal implants (i.e. acetabular cups, cranial plates and artificial jawbones (Mitsuishi et al., 2013; Zax, 2012)). This is the outcome of research by engineers and life scientists to make biocompatible medical instruments and implants, a trend sometimes referred to as biomanufacturing (Bartolo et al., 2012; Mitsuishi et al., 2013). The recent convergence of AM and tissue engineering is an extension of this trend (Bártolo et al., 2009). Tissue engineering is a multi-disciplinary field focusing on "*the development of biological substitutes that restore, maintain or improve tissue function or a whole organ*" (Langer and Vacanti, 1993). Though the production of biocompatible implants and living tissues with AM are still in their early stages, they feature in shared visions manifested in academic publications and some commercial products.

Clinical AM initially emerged within the path of rapid prototyping from interactions between surgeons and researchers using medical images, additive process technologies, biocompatible materials and CAD software to produce patient-specific prosthetics (Bibb et al., 2010; Dalgarno et al., 2006; Giannatsis and Dedoussis, 2009). The tripartite scheme is followed again, however the use of biomaterials creates a different type of knowledge than the other branches as it includes highly-specialized practices like printing with stem cells (Key Aspect 2). Essential to bioprinting is the addition to the tripartite schema of medical imaging, for example imaging of someone damaged skull as an input into the digital design of a part to be printed. Though no dominant design has yet emerged, ink-jet printing of bio-inks to assemble stem cells into a given form (much like a glue-gun) is receiving increasing attention. This technology was demonstrated in the mid-2000s (Boland et al., 2006, 2006; Jakab et al., 2010) but challenges still remain. Research efforts now focus on technical bottlenecks such as continuous flow (avoiding clogs in the bioprinter's nozzle head) and maintaining the correct temperature to keep cells alive (Devillard et al., 2013).

Much like in functional materials, engineers, researchers and medical professionals are investigating new applications for AM. In the field of tissue engineering, researchers are exploring AM to assemble biocompatible 3D scaffolds seeded with stem cells to assist bone repair (Seyednejad et al., 2012a). The promise of producing tissues and artificial organs is a rapidly growing area of research, visible in RP, RM and tissue engineering conferences and publications (Almeida et al., 2007; Almeida and Bártolo, 2012; Seyednejad et al., 2012b). This requires a variety of skills, knowledge and technologies (i.e. bioreactors) that have previously been absent from AM research. Dedicated conferences have appeared to support these efforts, most notably the newly-founded and yearly International Conference on Biofabrication (Key Aspect 3) and the related Biofabrication Society (Key Aspect 4). Launched in 2009, the journal Biofabrication has also become a central peer-reviewed space of exchange to present demonstrations of AM in regenerative medicine (Key Aspect 3).

Established in 2007, Organovo is a start-up focusing on the production of artificial tissues to produce phantom organs for drug testing ("About Organovo", 2014). Established in 2011, TeVido is a start-up investigating 3D bioprinting of living cells to build custom implants and grafts for breast cancer (Jeffery, 2013). Founded in 2011, Modern Meadow is a start-up using AM to create artificial meat and leather that does not require the killing of animals ("About Modern Meadow", 2014). Next to these science-based entrepreneurial ventures, surgeons are evaluating the relevance of bioprinted skin for burn victims and the cosmetics industry (Gerstle et al., 2014). A number of medical firms have received FDA and CE clearances for medical instruments and internal implants produced with AM. For instance, in 2007, Adler Ortho and Lima Corporate were granted CE certification for acetabular cups manufactured with additive process technologies (Wohlers, 2013b). Similarly, Exatech was granted FDA clearance for a metal acetabular cup implant in 2010 (Wohlers, 2013b) and Oxford Performance Materials received the first FDA clearance for medical instruments and implants produced with AM machines and biocompatible PEKK polymer in 2013 (Molitch-Hou, 2013). These firm foundations and regulatory approvals show a building up of momentum in the area (Key Aspect 5) but far from maturity.

Despite these many promising demonstrations, biomedical applications of AM have "*not taken off quite as much as might have been expected… probably due to the fact that [they are] driven bottom-upwards from the clinicians*" making "*it difficult to establish a cost model*" (Campbell et al., 2012). What is more, implants require lengthy and individual certification processes before they can be used in clinical settings. This is a major hurdle that is beginning to be addressed in the United States. In a blog post published in August 2013, the American FDA explains: "*3D printing is fast becoming the focus in our practice of regulatory science – that is, the science of developing new tools, standards and approaches to assess the safety, effectiveness, quality and performance of FDA-regulated products*" (Steven and James, 2013). Two laboratories in the FDA's Office of Science and Engineering Laboratories are investigating how AM may affect the manufacturing of medical devices and implants in the future. The Functional Performance and Device Laboratory is developing and adapting computer-modeling methods to help determine the effect of design changes on the safety and performance of medical devices based on different patient populations. Biofabrication enables the FDA to "*tweak the design in ways large and small, and too see precisely how those tweaks will change both fit and functionality*" (Steven and James, 2013). The Laboratory for Solid Mechanics is investigating how different additive process technologies can affect the strength and durability of materials used is medical devices. This will be used to "*develop standards and set parameters for scale, materials and other critical aspects that contribute to product safety and innovation*" (Steven and James, 2013) (Key Aspect 6).

Though biomanufacturing of medical devices, implants and living constructs is still nascent, there are clear signs of this path branching path from RP and RM. Medical firms, researchers and professional users are participating in this shift. Knowledge aggregation is occurring in dedicated conferences, journals and research facilities such as the Wake Institute for Regenerative Medecine ("Insitute of Regenerative Medecine - Our story", 2014), Drexel University's Biofabrication Lab ("Biofabrication Laboratory", 2014), the Brazilian Research Institute in Biofabrication ("Biofabris INCT", 2014), Manchester University's Biofabrication Centre ("Bio-engineering research theme", 2014) and the Utrecht Biofabrication Facility ("Utrecht Biofabrication Facility", 2014) (Key Aspect 3). There is also anticipation of how to integrate biomanufacturing of implants and living constructs into clinical practices. Particularly visible is a group at Loughborough University, led by Robert Bibb, which emphasizes that the success of biofabrication for clinical applications will rely on the co-evolution of technology and clinical practices (Bibb et al., 2010) (Key Aspect 7).

6. Discussion

6.1. Exploring and contrasting potential branching paths

Fig. 6 shows a schematic of the branching paths evidenced in Sections 4 and 5. Whilst this diagram may capture the evolving interest and promise of AM overtime, in relation to the vision of use, it is only through the lens of the seven Key Aspects that we can qualify and characterise these pathways to understand the degree of development and the nature of those developments.

Table 4 below provides a summary of the seven key aspects for each of the pathways.

Our evidence shows a *stable* rapid prototyping pathway for 3D printing. We also see a *stabilising* of Rapid/Additive Manufacturing and the Open Source/Grassroots 3D Printing path that branched quite early on and shows stabilisation as well. These paths show momentum building up, specialized supplier firms and development communities which produce and share knowledge, provide the elements of the tri-

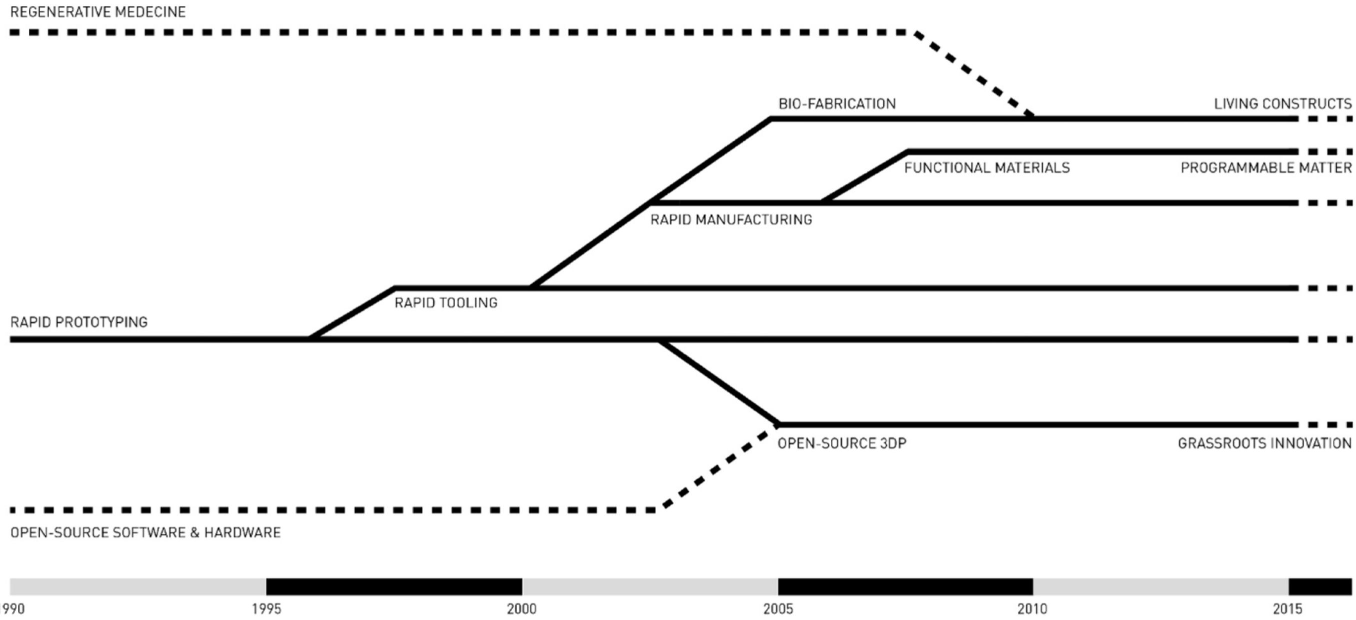

Fig. 6. A schematic of the various innovation pathways visible in 3D printing activities and rhetoric.

partite schema and are maturing into quite different markets. For these stabilising paths the vision of utility is quite different: additive manufacturing promises applications in light-weighting aircraft and automobiles along with potentially distributed manufacture whereas Grassroots 3D printing promises access to manufacturing to a wide range of stakeholders, often via Fablabs but also through maker communities.

3D printing for biomedical applications seems to have two subpaths, one maturing around 3D-printed prosthetics and implants using dead biocompatible materials and a second involving printing with stem cells. Prosthetics with dead material is maturing with standards being set, FDA approvals and a large number of companies. Bioprinting of tissues shows a lower level of maturity, though loci for knowledge exchange are stabilising and some first basic products are on the market. Both medical 3D printing paths could be argued as distinct branching paths, with bioprinting being a young promising path (a budding path). The potential pathway of functional material printing has yet to provide evidence of momentum building up. Without momentum and stable loci for knowledge exchange one cannot argue that there is a path. It is a path-in-potentia with a coherent promise and matrix of expectations but with little momentum (Agogué et al. 2012).

6.2. Limitations and areas for future research

We have described the tool and how we have mobilised it for a particular case domain (Additive Manufacturing) and at a particular time (2015). One limitation is that the data is prior to 2015, a further study of Additive Manufacturing today, applying the same method, could be useful to see how the branching paths have further solidified, vanished or evolved. Another limitation is the translation of the output of this analysis into a decision-making process: what will this data be used for? Our interest lies in using this path analysis and forward looking projections to inform scenarios of how various possibilities will unfold, similar to the Co-evolutionary Scenario Approach described in Robinson (2009). This is for future work and reporting on how such path analysis can inform and structure scenario-based foresight will be a useful contribution. Another area of future work would be to test this approach on other domains.

7. Conclusion

Characterising emerging paths and exploring budding and branching is key for better targeting Forecasting Innovation Pathways (FIP) approaches. We have shown how innovation pathways can be forecasted based on an understanding of endogenous futures and taking into account multiple possible branches. Using this approach has helped in characterising a complex field, being aware of the path dynamics at the heart of FIP and helping positioning all the data. One can now specifically target the various tools and processes of FIP to different elements of the Additive Manufacturing family of paths with a better understanding of the field and its dynamics and a better understanding of the endogenous futures, for example a FIP dedicated to biofabrication can be developed using targeted datasets around the specific ways the tri-partite schema is used, drawing data from the specific loci of knowledge exchange and the identification of relevant experts to inform the analysis. Such targeting is crucial to produce high-quality future-oriented intelligence.

We use the case of additive manufacturing as an illustration on how to characterise the different developments and potential markets through (1) characterising the innovation pathways based around specific motive forces related to applications and visions of use and (2) the different technologies that have been developed to fit the tri-partite configuration, often bespoke developments dedicated to particular innovation pathways. Going back to our hypotheses, our findings show that the interplay of the foreseen or actual application and the filling in of the tripartite schema can indeed motivate new paths branching from the original trajectory of rapid prototyping. Moreover, there are indeed different innovation pathways, which could be argued as different industries, requiring different filling in of the tripartite schema and as such new knowledge, new industrial support structures, etc. Our study also shows that some areas are more mature than others, some are more prospective. We can see that some of the prospective paths have momentum being built (and thus a perfect target for refined FIP analysis), others are more vision-based with little momentum and perhaps suitable for more prospective foresight not based on endogenous futures.

Endogenous futures are a key element of for FIP. In contrast to foresight which envisions alternative working worlds in the future as a means of learning and exploring choices, FIP is based on a broadened notion of trend analysis. Endogenous futures are those visions of utility and the matrix of expectations that drive emerging fields forward,

Table 4
Seven Key Aspects for the various potential innovation pathways.

	Rapid prototyping	Additive manufacturing	Grassroots 3D printing	Functional materials and printed devices	Biofabrication (dead material)	Biofabrication (live material)
Key Aspect 1 vision of utility	A core vision of use for speeding up new product development with expectations that bespoke single products may be a possible market.	Vision of design freedom and tool-free low-volume manufacturing; short time-to-market for low-volume production	Vision of democratization of the design and production process	Whole device printing plus novel functionalities through graded and mixed material parts.	Tailored prosthetics with biocompatible materials external and internal to the body improving existing products.	Printed skin, tissue constructs and organs to fill a large gap in the market.
Key Aspect 2 working technical configuration	Plastic additive printing technology combined with simple plastics and digital image form a core tripartite scheme that defines a 3D printer.	Proofs of principle seem to pop up in different sectors	Shift towards the mainstream: printers, materials and designs become available for single households	Follows tripartite schema but material and design file elements at very early stages	Follows the tripartite scheme similar to Rapid Pro and Additive Manufacturing with the addition of biocompatible material development and the addition of medical imaging	Requires novel approaches to all three elements of the tri-partite schema, especially the material aspect (printing stem cells) and the design file (living and squashy constructs)
Key Aspect 3 loci of knowledge exchange	Dedicated journals (Journal of Rapid Prototyping), societies (GARPA) and annual conferences stabilise into a stabilised nexus for knowledge exchange (both science and industry).	Creation of dedicated conferences and journals; initiation of for a such as the EU RM Platform	A number of network forums have been created; physical ones like FabLabs as well as virtual online communities like Thingiverse	Limited loci though government investment in building such loci is visible	Us elf existing forums for Rapid Prototyping and additive Manufacturing (particularly around material development).	Dedicated journal and international conference (2009 and onwards) provides platform for exchange.
Key Aspect 4 coordination and alignment	The rise of European and American networks conducting roadmaps, as well as dedicated consultancy reports (Wohlers) becoming a benchmark for foresight.	The creation of platforms and facilities as well as roadmapping exercises in the US, Europe, China, etc.	Through the online forums and physical makerspaces	Anecdotal evidence, though little specific/ dedicated activities	Little evidence of coordination and alignment.	Little evidence of coordination and alignment
Key Aspect 5 momentum and maturity	Increasing machine sales, IPOs and Mergers and Acquisitions indicate a maturing industry.	Big companies (like 3D Systems) acquire a large number of smaller companies; range of IP infringement cases; a few companies making their IPO	Myriad of start-ups established; incumbent firms invest and acquire; universities create in-house labs; crowdfunding schemes to support small companies	No convincing evidence	Broad range of prosthetics have been demonstrated and used (3D printed skull parts have been implanted in people). Companies emerging around this (Materialise BV as example)	Organovo as key player offering basic sheets of printed liver cells with a target market of research and for drug/cosmetic screening. Other supplier firms emerging (particularly around stem cell "inks")
Key Aspect 6 market infrastructures	STL as the standard digital file for 3D printing. Fig. 2 shows a steady increase in standards setting (particularly after 2008).	Standardization efforts across Europe (France, Germany) and the US	AM and open-source 3D printing also intersect when it comes to standards	No convincing evidence	Various 3D printed implants have received FDA approval.	Little evidence of technical standards, though there is some inheritance from the tissue engineering world regarding use and regulation of stem cells.
Key Aspect 7 societal embedding	Rapid prototyping with 3D printers becomes common in the world of design and architecture.	Applications in the fields of medicine, aerospace and customized consumer product industries creates societal awareness and acceptance	There is embedding in non-commercial spaces of collaboration (partly political use); there are issues about IP and sustainability	No convincing evidence	DIY prosthetics emerging for external body use. Evidence of printed skulls and bone parts that have been implanted.	Demonstrations only for screening of drugs and cosmetics, no visible commercial application for medical use.
Path diagnosis	Stable path	Stabilising path	Branching, stabilising path	Budding (promising) path	Branching path	Budding (promising path)

influence strategy making and guide path emergence. Our approach allows the analyst to get to grips with a complex field. The list of Key Aspects (Table 1) provides a heuristic in which one can categorise, structure and analyse qualitative and quantitative data to be able to assess the *degree of emergence* and the *nature of emergence* of a new technology field.

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