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Exploring innovation ecosystems across science, technology, and business: A case of 3D printing in China

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ABSTRACT

The concept of the innovation ecosystem is receiving increasing attention worldwide. Governments and industrialists are keen to foster innovation ecosystems to systematically cultivate favourable environments and encourage local innovators to create knowledge and capture business value. In particular, innovation ecosystems require specific attention when faced with fast-developing emerging industries that closely link science, technology, and business. This study, therefore, develops a framework to investigate the innovation capacities of a multi-layered innovation ecosystem that involves science, technology, and business sub-ecosystems, when considering two core attributes of the innovation ecosystem: the integrated value chain and the interactive network. Furthermore, this framework analyses the interplays across science, technology, and business layers; on that basis, a four-quadrant diagram can be plotted to denote innovation pathways. China's 3D printing ecosystem was selected as a case study. This study found that China's 3D printing ecosystem performs well in science and technology, and may have new development pathways that originate from basic research and technology rather than from duplicating technologies and low-cost production. This study contributes to the literature on innovation ecosystems and has implications for industrialists, researchers, and policymakers.

1. Introduction

In recent years, the concept of the innovation ecosystem has received increasing attention. It is considered as an indispensable component for enhancing the innovation capabilities of individual corporations, industries, regions, and nations (Jackson, 2011). Governments and industrialists are particularly interested in creating innovation ecosystems that connect multiple innovation actors (e.g. universities, research institutes, business firms, etc.) to cultivate favourable environments for innovators to pursue value synergistically (Frenkel and Maital, 2014; Iansiti and Levien, 2004). In addition, these organisations are expected to generate value in concert and co-evolve in sustainable ways (Adner and Kapoor, 2010). However, some argue that the innovation ecosystem is not yet a clearly defined concept and is often used with an over-emphasis on market forces (Oh et al., 2016).

In general, an innovation ecosystem comprises two distinct ecosystems — the knowledge ecosystem and the business ecosystem (Oh et al., 2016). The former is driven by research and development, the latter by the market economies. Knowledge creation in the knowledge community and value capturing in the business economy should both be emphasised when examining innovation ecosystems (Clarysse et al., 2014). In addition, within the knowledge ecosystem, there are also two separate yet connected components – the creation of scientific knowledge for public goods, and the production of technological knowledge that is intellectually-protected and somehow private. These business, technology, and science layers form an innovation ecosystem, and they have idiosyncrasies – understanding their specifics may help to better assess the innovation capacities of innovation ecosystems in a holistic view; however, the relevant research remains sparse.

On top of this, these science, technology, and business communities are separate but inter-connected, especially when considering the science and technology-based new industries – the current surge in emerging technologies and industries makes innovation ecosystems even more appealing, as emerging technologies may create important 'windows of opportunity' for traditional technology-

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follower countries to catch up in innovation and possibly surge ahead of current technology leaders (Rifkin, 2011; Zhou et al., 2015a, 2015b).[1] In general, these emerging technologies often start from the scientific research phase, and then move to technological development phase – these phases may take place, though not necessarily in a consecutive way, before knowledge can be converted into commercial value through business activities. Therefore, the connections and interplays between these science, technology, and business layers are dynamic and need further inquiry, which may lead to better understanding of the growth pathways of a specific innovation ecosystem.

This paper, therefore, proposes a framework for analysing innovation ecosystems across science, technology, and business layers — especially in emerging economies — to assess the innovation capacities of multi-dimensional innovation ecosystems, and to explore the development pathways of innovation ecosystems. This study attempts to address the following questions: (1) What is the profile of a holistic innovation ecosystem in terms of integrated value chain? (2) What is the profile of a holistic innovation ecosystem in terms of interactive network? (3) What are the inter-connected dynamics across layers, and what development pathways can be identified? To answer those questions, we chose China's 3D printing industry as a case study to test our method.

The rest of this paper is organised as follows. Section 2 reviews the existing literature on innovation ecosystems. Section 3 elaborates on the proposed analytical framework and the methodology involved. Section 4 presents the case study and applies the framework to China's 3D printing industry. Section 5 further discusses the findings from the case study. Section 6 draws conclusions and provides policy implications.

2. Theoretical background

2.1. Innovation ecosystem concept: science, technology, and business

Existing ecosystem concepts have used the term ‘business ecosystem’ to denote widely connected networks of organisations where key firms may evolve and gain competitive advantage through interactions with other players (Moore, 1993). This emphasises that business or commercial economic actors that are driven by market forces play key roles in establishing value networks (Oh et al., 2016).[2] Later research extended this concept to include ‘innovation ecosystems’, which aim to enable technological development and innovation (Iansiti and Levien, 2004; Jackson, 2011). The emphasis on technological innovation adds complexity to the concept. Novel technological innovations, or knowledge, are generated through complicated, dynamic ecosystems that include not only firms but also government agencies, industrial players, universities, research institutes, and so on (Frenkel and Maital, 2014).

2.1.1. Business versus knowledge ecosystems

[3]These two components (business ecosystems and knowledge ecosystems) are distinct and largely separate in extant ecosystem communities. The gap between these two economies could be attributable to the underlying drivers behind the term ‘innovation ecosystem’. First, business ecosystems mainly aim to create value for companies and customers while knowledge ecosystems aim to generate new knowledge. Thus, knowledge ecosystems are generally centred on universities or research institutes while large companies are the leaders of business ecosystems (Clarysse et al., 2014). Second, business ecosystems are commonly viewed as market driven (mainly in supply chain or value chain management studies) and therefore focused on experiential learning and information exchange across value chains in pursuit of cost reduction and quality improvement (Barclay et al., 2014). Though such pursuits require innovation, they generally do not involve the kinds of radical or disruptive innovations knowledge ecosystems usually consider when seeking to use new technology to create new user benefits (Oh et al., 2016).

We argue, therefore, that the two ecosystems need to be examined in an integrated way. Specifically, the interactions or dynamics between knowledge and business ecosystems become highly significant and require further inquiry. For example, basic knowledge and knowledge networks can contribute to or evolve into the business ecosystem through knowledge spillovers (Oh et al., 2016) from knowledge creators (e.g. universities, research institutes, national laboratories) to business players (e.g. firms, distributors, customers). Meanwhile, the business ecosystem can provide value propositions to knowledge creators through the feedbacks of demand. Some recent literature, though still limited, has attempted to explore the gaps between knowledge and business ecosystems. For example, Clarysse et al. (2014) found significant differences between the two ecosystems in terms of organisation and dynamics. Specifically, the anchor organisations in knowledge ecosystems do not directly compete with each other. By contrast, firms in the business ecosystem strive to become vital players that fill niches by providing key products, services, and commercial infrastructure. This suggests that the expected evolution from knowledge to business ecosystems might not be quasi-automatic. However, such research still fails to address the interplays between knowledge and business ecosystems, which could help to better understand the evolution process.

2.1.2. Science versus technology knowledge ecosystems

The knowledge creation aspect of technological innovation involves scientific knowledge discovery (e.g. R & D) and technical feasibility experiments (Suarez, 2004).[4] These processes must take place before knowledge can be converted into commercial value through business activities. According to Phaal et al. (2010), the knowledge-generation phases associated with the emergence of science and technology industries can be understood as science and technology phases (either nonlinear or consecutive), where the early scientific phase is the initial proof-of-concept, which is then translated into technology prototypes and applications through transitional processes. These two components (science and technology) are disparate and have idiosyncrasies in their knowledge characteristics. For example, scientific knowledge tends to be public oriented and is produced by universities or research institutes. Meanwhile, technological knowledge can come from any innovative organisation with R & D capabilities, and, through patenting and

[1] The term ‘catch-up’ means that developing countries tend to develop technology competences to reduce the innovation gap and keep pace with traditional technology leaders, or even go beyond them.

[2] The concept of the innovation ecosystem derives from ecology, a field centred on biological ecosystems which consist of a system of organisms and the relationships among them (Iansiti and Levien, 2004). Existing innovation ecosystem literature involves a variety of perspectives, including: (1) corporate ecosystems concerned with value integration across industrial value and supply chains; (2) national and regional ecosystems that focus on public interest and knowledge spillovers to promote business growth, which is related to prior research on national innovation systems and triple helixes; (3) university-based ecosystems and incubated high-tech SME ecosystems that are more interested in converting science and technology into entrepreneurial activities, which can be traced to ‘technopolis’ studies; and (4) other ecosystems, including city-based (geographical economies) and digital innovation ecosystems (digital technologist) (Oh et al., 2016).

[3] Xu (2007) subsumed the ecosystem concept into their TIM (total innovation management) theory, which takes a broad view of organisational innovation ‘by anyone at any time in all processes, among different functions and around the world’ (p. 13). Their work, like that of Carayannis and Campbell (2009), urges us to look beyond the technological aspects of innovation ecosystems to see the importance of non-technological elements (strategy, cultures, organisations, and institutions) in building up the competency of innovation ecosystems.

[4] F. F. Suarez, ‘Battles for technological dominance: An integrative framework’, Res. Pol. 33 (2004) 271–286. The business parts follow up with three processes, such as creating the market, decisive battles, and post-dominance.

copyrights, it tends to be somewhat private (Oh et al., 2016). In general, the creation of scientific knowledge produces public goods and substantial knowledge externalities to technological knowledge producers (e.g. corporate labs, high-tech spinoffs, etc.), who are concerned with intellectual property ownership (e.g. through patenting) for 'appropriability' regimes (Hughes, 2012). Traditional triple-helix, or 'technopolis', literature has shown this to be the case, arguing that firms in these systems can benefit from physical proximity to universities or research institutes (Saxenian, 2006). Few studies, however, have recognised the discrepancies between scientific and technological communities within the knowledge ecosystem, and even fewer have explored the links and interplays between public science spillovers and private technology intellectual benefits (Phelps et al., 2012). As one of the few attempts, Shibata et al. (2010) explored the gaps between scientific knowledge discoveries and technological development for emerging industries, establishing a solid theoretical basis to further explore the heterogeneities of science and technology layers within the knowledge ecosystem.

Policymakers in general are keen to create vibrant and productive science and technology (S & T) knowledge hubs, anticipating that such value-adding discoveries will be converted into the business economy. Emerging economies in particular hope to promote local S & T knowledge creation to enhance the indigenous innovation capacity of certain industries, ultimately aiming to catch up in the global innovation race. For example, China has launched a series of programmes to cultivate local knowledge production in science (e.g. the 973 programme) and applied technologies (e.g. the 863 programme), aiming to develop indigenous technology platforms and ecosystems (OECD, 2008). This creates a need for further explorations of S & T knowledge and business ecosystems as well as the connections between them. Few studies, however, have investigated this. In addition, regarding emerging innovation ecosystems, developments in science, technology, and business are usually not synchronous, sometimes starting in one segment and evolving to others. Development pathways can differ between innovation follower countries and global leaders. Therefore, the present research aims to further explore S-T-B connections in emerging economies and fill the abovementioned gaps in the research.

2.2. Key attributes of innovation ecosystems: integrated value chains and interactive networks

Given the concerns over missing links between science-technology-business (S-T-B) ecosystems, the existing literature has also explored the essential attributes that could enable an 'innovation ecosystem' to provide more tangible and practical benefits and value to corporations, sectors, regions, and nations. Successful ecosystems allow firms to create value that no single firm could have created alone. The benefits of these systems have been studied from many theoretical perspectives, such as open innovation, platform leadership, keystone strategies, value networks, and hyperlinked organisations. Aside from firm-level managerial benefits, these studies also highlight the key concerns of an innovation ecosystem: the interactions and coordination between anchor and niche players, as well as the integration of value complementariness across the value chain (Adner, 2006; Battistella et al., 2013; Oh et al., 2016). Following this line of reasoning, the present study views innovation ecosystems as S-T-B ecosystems with two core attributes: integrated value chains and interactive networks.

First, the innovation ecosystem concept emphasises the integration of value complementariness across the value chain, which could enrich the ecosystem as a whole. Traditional research views the ecosystem as a system of loosely interconnected participants dependent on each other for mutual benefits; each participant is specialised within a specific activity across the value chain while the collective efforts generate value. Across the value chain, there are differentiated roles, or 'niche' players, that can correspond to links in industry value chains (Frenken et al., 1999; Raven, 2005). This suggests that if there is an absence of specific 'niches' or weak links in the value chain, the ecosystem's collective value generation could be dampened. Adner and Kapoor (2010) followed the flow of inputs and outputs in the innovation ecosystem to distinguish between upstream components and downstream complements, and examine their different effects on a firm's performance. Adding to this, Schot and Geels (2007, 2008) emphasised niches in the evolution of technological and socio-technical regimes, highlighting the interplays between science, technology, market users in business, and regulatory environments. Echoing this, we believe the integration of value complementariness requires further attention, not only in the business ecosystem but also in the science ecosystem, which is public-knowledge oriented, and in the technology domain, which is more intellectually protected. The interplay across these layers requires further attention as well.

Second, innovation ecosystem literature emphasises inter-organisational collaborative networks among innovation actors; business and S & T knowledge ecosystems emphasise collaboration and interplay. The actors in the ecosystem (e.g. firms, governments, science parks, universities) form a community in which they cooperate and compete. Business ecosystem literature views complex inter-firm relationships (tangible or intangible) as essential for value generation (Battistella, 2014). Here, the players in the ecosystem jointly generate value and social capital for long-term, sustainable growth and have shared fates. By collaborating in a value network, organisations exploit their interdependencies and have a competitive advantage over isolated organisations (Iansiti and Levien, 2004; Binz et al., 2014). Existing research on business ecosystems has explored collaboration and competition for value creation as well as key impact factors such as information exchange and knowledge sharing through networks (Pierce, 2009). Specifically, business ecosystems emphasise the emergence of anchor players to ensure that each member of the ecosystem remains in good health (Iansiti and Levien, 2004). Knowledge ecosystems also emphasise the importance of the interplays between key knowledge actors, recursive actions, and the institutional embeddedness of co-evolving networks; together, this supports the generation, diffusion, and utilisation of new technologies (Bergek et al., 2008). Some have also explored specific knowledge ecosystems (e.g. university entrepreneurial ecosystems), arguing that the richness and diversity of actors can enhance the vibrancy of the ecosystem (Fetters et al., 2010, p. 181). However, few studies have explored the roles of anchor players within S & T ecosystems and their effects on commercial actors in business ecosystems through knowledge spillovers/transfers, as well as the interplays between them (Powell and Giannella, 2010; Clarysse et al., 2014). This research attempts to address this gap.

2.3. Modelling of innovation ecosystems

Existing modelling of innovation ecosystems studies have been restricted to a mostly qualitative and metaphorical levels (Kastelle and Steen, 2010), such as the value network of intangibles (Allee, 2002), agent-based modelling (Marín and Siotis, 2007), business ecosystem analysis and modelling (BEAM) (Tian et al., 2008), and Methodology of Business Ecosystem Network Analysis (MOBENA) (Battistella, 2014). Attempts to quantitatively model innovation ecosystems, although limited, have discussed as follows.

One the one hand for business ecosystem, Basole and Rouse (2008) has tentatively used the web data-based approach to investigate business ecosystem dynamics from the perspective of network analysis. Based on this, they have developed a series of visual network-based methods that help to identify the business deals, alliances, and the funding relationships between key firms and organisations within the ecosystem, as we as the public opinion and discourse on the development trend (Basole, 2014; Basole et al., 2015; Basole et al., 2016a, 2016b). Adding to this, Rubens et al. (2011) has also used web data and social network analysis to study the investment networks and their value-added supply chain, specifically in China's e-commerce ecosystem.

On the other hand, literature-based methods (e.g. bibliometrics, patent analysis) have also been used—albeit in limited ways—to explore the knowledge components of innovation ecosystems (e.g. Binz et al., 2014). Firstly, bibliometrics can help to better address the scientific innovation positions, and also help us to identify the leading experts for in-depth innovation analysis. For example, some has analysed academic publications to reveal the key innovators and their innovation performance (Dagnino et al., 2015). In addition, some integrate bibliometrics and social network analysis to describe the collaborate network of entities and organisations in the knowledge network, and the knowledge flow among key players (Al Hasan et al., 2006). Secondly, patent analysis can be used to examine technological activities. For example, some have used patent analysis to understand technology portfolios and innovation capabilities of key innovators (Tseng et al., 2011; Park and Leydesdorff, 2013; Kong et al., 2017). In addition, others have combined patent analysis and network methods to understand the technological knowledge flow (Ju and Sohn, 2015) and the collaboration between knowledge network players (Bekkers and Martinelli, 2012a, 2012b; Zhou et al., 2015c).

As summarized above, there is limited research that has used the web data to analyse business ecosystems, and bibliometric/patent analysis for examining science and technological knowledge ecosystems. Even fewer literature has explicated the linkage between business ecosystems and knowledge ones, as well as the interplays between science and technology layers. As one of the few attempts, Kajikawa et al. (2006) and following research has established a solid framework that uses patent/papers citation networks and topological clustering methods, to extract the gap between science and technology layers through assessing the similarity of cross-layer knowledge clusters (Kajikawa et al., 2006; Shibata et al., 2010; Nakamura et al., 2015; Wang et al., 2015). Adding to this, Clarysse et al. (2014) integrates the patent and firm-level survey data to explore the chasms between knowledge and business ecosystems, and Ittipanuvat et al. (2014) investigates Literature Based Discovery (LBD) approach to reveal linkages between technology and social issue to elucidate plausible contribution of science and technology for solving social issues. However, there is hardly research that consider the integrated synergies across science, technology, and business ecosystem. This study, therefore, proposes a framework that integrates literature-based data and qualitative interview data to better analyse the S-T-B ecosystem and the interlinks between the layers.

3. Framework and methodology

This study proposes a science-technology-business (S-T-B) ecosystem framework to examine an emerging innovation ecosystem and explore its growth pathways, especially in the context of a developing country. Based on this framework, we use China's 3D printing industry as a case study to diagnose the nascent-stage innovation ecosystem and identify its typical innovation paths.[5]

3.1. S-T-B ecosystem framework and data

This study conceptualises the innovation ecosystem as a complex, interconnected system consisting of three complementary and synergistic sub-ecosystems: science, technology, and business ecosystems. In this study, the science ecosystem refers to a system that generates scientific knowledge from basic research, and the technology ecosystem produces industrial knowledge that advances technological development. Lastly, the business ecosystem develops products and services and realises value propositions.

This framework examines those three S-T-B sub-ecosystems as well as the interplays between them (Fig. 1). Multi-dimensional data, including quantitative literature-based data and qualitative interviews, are used to analyse each sub-ecosystem. The quantitative data can help to enrich the validity and reliability of the research, and can be complemented by traditional qualitative enquires for information richness.

3.1.1. Science ecosystem

The science ecosystem, which focuses on basic research and generates scientific knowledge, can be analysed using bibliometrics. This method can help researchers identify 'hidden patterns' in the knowledge-creation process (Daim et al., 2006; Li et al., 2015). It has contributed to science and technology studies for decades (Van Raan, 2005). Most bibliometric studies examine the nascent stage of emerging technologies and industries, such as the scientific research stage (Kostoff, 1999; Kostoff et al., 2008). Databases such as the Science Citation Index and the Ei Compendex database are used for bibliometric analysis (Kostoff et al., 2001).

In this study, we searched for specific keywords related to 3D printing among the papers listed in the Web of Science (SCI-EXPANDED) database as indicators of the seeds of scientific knowledge.[6] The most recent search was performed on September 30, 2016, and 27207 relevant articles were selected from the database. Based on this, we scanned for articles written by Chinese authors (including co-authors), and 3685 published articles were identified.

3.1.2. Technology ecosystem

The technology ecosystem, which focuses on applied technology and generates industrial knowledge, can be examined using patent analysis. Patent information contains useful, detailed technical information and is a useful indicator of the technological strategies adopted by individual enterprises in response to market conditions (Suzuki, 2011). Assuming that knowledge reflects competitiveness, patent counts can be used to explicate core technologies and portfolio strategies (Tseng et al., 2011; Ju and Sohn, 2015). Furthermore, patent networks can be used to analyse knowledge creation and flow within industries and across national borders (Bekkers and Martinelli, 2012a, 2012b). Patent databases such as the Derwent World Patents Index (DWPI), Derwent Patents Citation Index (DPCI), and US Patent and Trademark Office (USPTO) are often used for patent analysis.

In this study, we retrieved worldwide patent data from the DWPI and DPCI databases through the Thomson Innovation (TI) search engine as indicators of the seeds of industrial knowledge.[7] The most recent search was performed on September 30, 2016. In total, 9737 patent applications were retrieved from the database. Then, we extracted patent data for China, and 3217 patents were selected.

3.1.3. Business ecosystem

Extending Moore (1998)'s definition, the business ecosystem can be defined as an economic community that selectively collaborates on

[5] Following Eisenhardt (1989), this research selected a purposive case study to elaborate and validate the applicability of the proposed framework. This study purposively selected China's 3D printing industry as the case. Following Huberman and Miles (1994), our case-selection criteria considered the significance of the case, its representativeness, its theoretical relevance, and data accessibility. The 3D printing industry is a rapidly growing emerging industry with an annual CAGR of over 30%, and it is expected to have global revenues of over $10 billion in 2018. In addition, 3D printing is especially emphasised by the Chinese government, which believes the creation of an ecosystem will become an opportunity for innovation leapfrogging. It is included in the latest national strategy, 'Made in China 2025'.

[6] As the query for searching published papers, this research used the following term: '(3D printing) OR (three-dimensional printing) OR (3-dimensional printing) OR manufact*) OR (rapid* prototyp* manufact*) OR (Layered Manufact* Technology) OR (Solid free-form Fabrication) OR (Stereo Lithography Apparatus) OR (Laminated Object Manufact*) OR (Selective Laser Sinter*) OR (Fused Deposition Model*) OR (Laser Engineered Net Shap*) OR (Patternless Casting Manufact*) OR (Direct Metal Laser-Sinter*) OR (Direct Laser Fabrication) OR (direct metal deposition) OR (Laser clad* forming technology) OR (Electron Beam Selective Melt*) OR (Digital bricklay*) OR (3D mosaic) OR (ballistic particle manufact*)'.

[7] This research used the same query mentioned above to search for worldwide patent data in 3D printing.

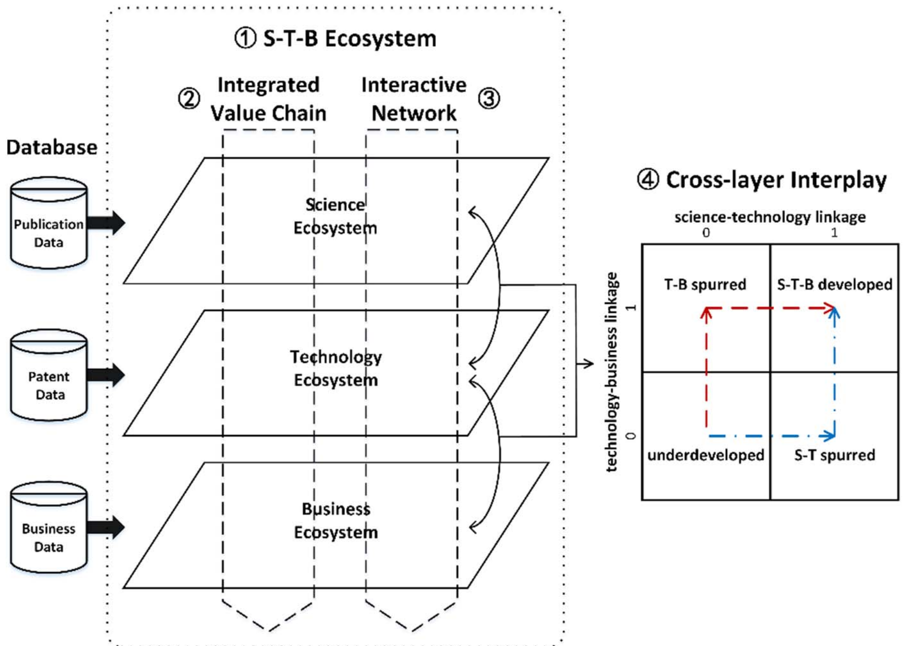


Fig. 1. Analytical framework of S-T-B ecosystem.

products and services based on central technologies. In this ecosystem, the relationships between key players are more complex than in a traditional value chain (Kandiah and Gossain, 1998a, 1998b). This is because the interactions can form a network around a specific technology and create commercial value that sustains the ecosystem (Santos and Eisenhardt, 2005). Thus, a business ecosystem can contain outsourcing partners, technology providers, and complementary product makers (Iansiti and Levien, 2004). A business ecosystem can be analysed by extracting information from interviews and desktop research, with a focus on collaboration between key organisations on specific products and services.

In this study, we examined business value-creation activities based on expert interviews and secondary resources—including industrial reports, news, official websites, and annual reports—as indicators of the seeds of industrialisation. Specifically, to gain a deeper understanding of the business ecosystem, we conducted in-depth interviews with 28 leading experts in 3D printing from both universities and firms in China. Based on these interviews, we selected 40 critical Chinese firms with different roles in the value chain of the 3D printing industry, representing key components in the business ecosystem.

In the following sections, we will analyse two aspects of the S-T-B ecosystem: integration and interaction. These are considered the two most important characteristics of an innovation ecosystem. We will also use interplay analysis to understand the dynamics between the three layers of S-T-B.

3.2. Analysis of integrated value chains in the S-T-B ecosystem

The success of an innovation ecosystem often depends on the efforts of complementary innovators operating within the system (Adner and Kapoor, 2010). The balanced development of complementary value functions in the value chain is vitally important. Therefore, we first diagnose the innovation ecosystem according to its integrated value chain.

To begin, we need to define the boundaries of the ecosystem and identify the value functions along the value chain. For this study, we focused on China's 3D printing innovation ecosystem at the sectoral level and divided the value chain into four segments: materials, design, equipment manufacturing, and services. Then, we further identified 19 main value functions within those four segments.[8] Then, we analysed the status of value-function integration in each of the sub-ecosystems (② in Fig. 1).

(1) Analysis of the science ecosystem

We analysed the scientific knowledge creation in each value function. We used the number of publications within a value function to measure its scientific outcome. Various methods can be used to categorise publications into different value functions. These include co-word analysis (Kostoff, 1993), term clumping (Porter and Zhang, 2012), text clustering (Hotho et al., 2003), citation analysis (Kajikawa et al., 2007), and text categorisation (Joachims, 1998).

In this research, to categorise publications, we used SVM—a supervised machine learning algorithm for text categorisation. Using training sets determined by experts, text categorisation performs better because of its higher accuracy compared to other methods. Among all of the supervised machine learning algorithms, SVM circumvents the problem of dimensionality (Chaves et al., 2009) that may arise during the process of text categorisation and has high-speed training. Based on previous studies of SVM-based classification (e.g. Kong et al., 2017), as well as our own classification experiments, we first divided all publications into four segments and then further classified the publications of each segment into specific value functions through SVM.[9] Using

[8] See Fig. 3 for the detailed 19 value functions.

[9] We designed the two-step method to build the sample sets. In the first step, we divided the publications related to 3D printing into four segments (material, design, equipment manufacturing, and services). The most relevant and representative publications (approximately 200 for each segment) were selected from 3685 publications, according to the respective keywords of the four segments. These four initial corpuses were treated as candidates for the sample sets. Then, we convened a group of four experts from the field of 3D printing to conduct a workshop. These experts focused on judging whether the publication in each corpus belonged to this segment. After the experts verified these publications, we finally obtained the sample sets for the four segments. The number of specific sample sets is listed in Annex. Before classification, we randomly divided each sample set into two parts: train set (60%) and test set (40%). In the second step, we further categorised the publications of each segment into more detailed value functions. We used an approach similar to that of the previous step to select the train/test sets—that is, preliminary retrieval using keywords and workshops to further verify the train sets.

VSM, we extracted important words as features from title and abstract data of each document by term frequency–inverse document frequency (TF–IDF) to build document-term matrix. To avoid overfitting, SVMs in spark MLlib were trained with L2 regularisation, and the parameter of the regularisation term was 1.0. After classifying the publications into 19 categories using SVM, we asked two experts to evaluate the validity of the results. The experts randomly extracted some of the literature and double-checked whether the article was related to the topic of its current category.[10] Finally, the experts approved the classification and affirmed that it had a high degree of accuracy.

(2) Analysis of the technology ecosystem

We analysed the technical knowledge creation in each value function by using the number of patents to indicate the technological outcome of a value function. The text categorisation method applied to the science ecosystem was also used for the technology ecosystem.

(3) Analysis of the business ecosystem

We analysed the business-value capture in each value function. The business output of a value function can be measured by indicators such as product-type variety, sales, and the number of firms.

For this study, we selected the 40 most important firms and identified their business scopes according to value functions. A firm can count multiple times in different value functions. Then, we used the number of firms in a value function to demonstrate the strength of the value function in the business ecosystem.

3.3. Analysis of interactive networks in the S-T-B ecosystem

According to the S-T-B ecosystem framework, we analysed the interactive network of each sub-ecosystem using social network analysis (③ in Fig. 1). Following Binz et al. (2014), we defined local players as those that are indigenous within a nation's boundaries. This research focuses on the analysis of native universities, research institutes and firms, because they are key actors as knowledge creators and value capturers in innovation ecosystem. Other organisations, such as the local offices of multinational companies or international subsidiaries, were not considered local players since they are headquartered outside the country and are considered global players.

(1) Analysis of the science ecosystem

Inter-organisational interaction in the science ecosystem is a unit of analysis. Social network analysis methods—including collaboration networks (Choe et al., 2013; Guan and Chen, 2012) and citation networks (Bekkers and Martinelli, 2012a, 2012b; MacGarvie, 2005)—can be used to analyse a scientific knowledge network. In particular, collaboration networks can be used to examine knowledge exchange between actors and identify key players and their knowledge positions (Bekkers and Martinelli, 2012a, 2012b).

In this research, we used TDA software to analyse collaboration networks based on a matrix using the affiliations of the authors of each article to establish links between organisations. Linkages and networks were visualised using UCINET software. To measure network structure, we examined density, average distance, degree centrality, and betweenness centrality to identify and describe key actors in the network.

(2) Analysis of the technology ecosystem

To analyse inter-organisational interactions in the technology ecosystem, we used collaboration network analysis based on co-patenting relationships to indicate cooperative innovations. To identify the key actors in the technology collaboration network, we used degree centrality and betweenness centrality to identify the key actors in the co-patenting network and their knowledge positions.

(3) Analysis of the business ecosystem

We analysed inter-organisational interactions in the business ecosystem. In this ecosystem, social network analysis can be conducted based on R & D collaboration relationships (Gulati et al., 2000; Rindfleisch and Moorman, 2001), trading relationships (Achrol and Kotler, 2012; Snehota and Hakansson, 1995a, 1995b), mergers and acquisition (Fors, 2007; Oberg and Grundström, 2009), and talent exchange (Fang et al., 2015), among others.

In this research, an interaction network within the business ecosystem was based on the relationship arising through joint product development between actors. Collaboration networks are created by a matrix containing ‘1’ (firms with collaborative relationships) and ‘0’ (companies with no collaborative relationships). Using this approach, we identified key actors by measuring significant indicators (degree centrality, betweenness centrality, and density) to explore the innovation patterns of actors.

3.4. Interplay between layers

To conduct a cross-layer interplay analysis of the S-T-B ecosystem, two types of linkages were identified between layers: science-technology linkages and technology-business linkages.[11] From an integrated value chain analysis perspective, a science-technology linkage exists when a value function is prominent in both the science and technology ecosystems; a technology-business linkage exists when a value function is prominent in both the technology and business ecosystems. Regarding interactive network analysis, a science-technology linkage exists when an organisation's scientific knowledge has been converted into a technological concept in the technology ecosystem and vice versa. A technology-business linkage exists when an organisation in the technology ecosystem works with an organisation in the business ecosystem to commercialise a technology as a product.

These two types of linkages should produce a four-quadrant diagram that visualises cross-layer interplays; these include underdeveloped, S-T-spurred, T-B-spurred, and S-T-B developed quadrants (see ④ in Fig. 1). Segments in the underdeveloped quadrant are isolated in the science, technology, or business ecosystems, and there is no linkage between layers. In the S-T-spurred quadrant, these segments have well-established scientific and technological research but have not been commercialised. In the T-B linked quadrant, these segments are more market oriented and have developed relevant industrial knowledge but lack the necessary basic research. In the S-T-B developed quadrant, the segments are linked on all three levels and have achieved a balanced operational state.

An innovation ecosystem usually cannot directly grow from the underdeveloped quadrant to become S-T-B developed; it often proliferates either via the S-T-spurred path or the T-B-spurred path. In developing countries, the typical innovation mode, called secondary innovation, typically starts with equipment and technology imports from developed countries to enable technology catch-up through reverse engineering and imitation, which can be regarded as a business-spurred path that will transition into an innovation mode (Lee and Lim, 1999; Wu et al., 2009; Xu et al.,

[10] We randomly select 50 samples for 3D printing experts to double-check the accuracy of the categorization respectively for publications and patents.

[11] The direct linkage between science and business is not specified here. From our observations, such linkages are only found in some natural-science-based industries (e.g. bio-industries). As for manufacturing industries, externalities are minimal to the business ecosystem by knowledge itself alone, and technology plays a critical intermediate role in linking the science and business ecosystems. The evidence suggests very few direct science-business linkages. Therefore, we only focus on science-technology linkages and technology-business linkages in our analytical framework.

2015). Innovation modes in emerging industries can have unique features different from traditional industries. The four-quadrant diagram of cross-layer interplay allows us to explore the innovation paths of emerging industries in developing countries.

4. Case study: China's 3D printing ecosystem

4.1. Overview: 3D printing industry in China

3D printing is an emerging technology that was first commercialised in the late 1980s. It is a process that involves creating three-dimensional solid objects based on digital schematics. A 3D-printed object is created using additive processes and putting down successive layers of materials until the entire object is created. Each layer can be seen as a thinly sliced horizontal cross-section of the final product. 3D printing has a wide spectrum of applications in various sectors, including aerospace, industrial machinery, motor vehicles, architectural designs, national defence, medicine, consumer products, and academic research.

Various technology breakthroughs have occurred in 3D printing over the past decade. However, 3D printing is still in its embryonic stage with few industry leaders (e.g. 3D Systems, Stratasys, EOS), and there are no dominant designs or evident technological paradigms. In this case, technology-follower countries still have opportunities to catch up with technology leaders.

China, for instance, began researching 3D printing in the early 1990s. It is now ranked third in the world in terms of the total number of industrial 3D printing systems, accounting for 9.2% of total global installations (Caffrey, 2015). In addition, Chinese researchers and innovators are ranked second and first in terms of total publications and patent applications, with 32% and 39% of the global total, respectively (Fig. 2). Some Chinese organisations have distinguished performance in certain niche domains,[12] though some still argue that R & D is weak in China. Hence, this study applied the S-T-B ecosystem framework to examine China's 3D printing innovation ecosystem and explore its catch-up modes in this emerging industry.

4.2. Analysis of the integrated value chain in China's 3D printing ecosystem

The 3D printing value chain consists of four major segments: materials, design, equipment manufacturing, and services. Fig. 3 collates the 19 main value functions of these segments (value functions in the same dashed box indicate alternative technology paths or fields). Processes in the equipment manufacturing segment are vitally important. Among them, vat photopolymerisation, powder bed fusion, directed energy deposition, and material extrusion are the current mainstream processes; the last three are regarded as having the highest growth potential. Material is also a key segment, with metals and polymers as the two major categories while smart and biological materials are at the frontier of development. There is a wide range of manufacturing processes for producing 3D printing materials, and the dominant technological paths are not yet formed. Fig. 4 shows the statistics for publications, patents, and firms for each value function.

4.2.1. The science ecosystem's integrated value chain

Among the 3685 publications available as of September 2016 (see Section 3.1), the segments for materials, design, equipment manufacturing, and services account for 29.5%, 22.7%, 32.2%, and 15.5%, respectively. In Fig. 4, we can see that China's 3D printing research community has developed considerable competence in the mainstream manufacturing processes of powder bed fusion and directed energy deposition. Echoing this, China also developed a robust capacity in metallic and polymer materials as well as industrial and consumer applications that can support the development of the abovementioned manufacturing processes. We can argue, therefore, that in the science domain, China has developed integrated scientific knowledge bases for metal-based and polymer-based 3D printing.

In addition, biomedical-based 3D printing is a promising yet embryonic field. China has become a first mover in terms of producing quality literature on biomaterials, supported by the abovementioned established manufacturing processes.

4.2.2. The technology ecosystem's integrated value chain

Among the 3217 patents by 2016 (see Section 3.1), the segments for materials, design, equipment manufacturing, and services account for 24.9%, 20.0%, 53.6%, and 1.5%, respectively. The equipment manufacturing accounting for over half of the total patents, while services segment are negligible. This suggests that China should invest more effort in the service segment to strengthen and integrate the value chain in the technology ecosystem.

Regarding manufacturing process technologies, we can observe China's efforts in diversifying technology trajectories, among which powder bed fusion and material extrusion account for over 22% of total patent applications in 3D printing fields. It is important to note that powder bed fusion is a high-end process while material extrusion is a relatively low-end one. Powder bed fusion, including SLS and EBM, is a common technology used for large metal printings, and it is considered the most advanced 3D printing technology. On the other hand, FDM, a major technology in material extrusion, is widely applied in relatively cheap 3D printing machines for printing polymer or other non-metallic materials. In the materials segment, China's advancements shed light on various materials, among which polymer and metal are the two most outstanding, supported by the abovementioned processes.

4.2.3. The business ecosystem's integrated value chain

In our sample of 40 leading 3D printing firms, from 2000 to 2016 there were 121 entries for value functions: 22.3% in materials, 11.6% in design, 43.8% in equipment manufacturing, and 22.3% in application.

Polymer materials (9.9%) and composite materials (6.6%) have drawn the most attention among materials in the business ecosystem. This includes their related technologies and services: vat photopolymerisation, material extrusion, 3D scanning software, and commercial applications, which are significant at 9.9%, 8.2%, 9.1%, and 13.3%, respectively. This suggests that there is an integration of the value chain for non-metallic trajectories.

Regarding metallic 3D printings, powder bed fusion and directed energy deposition are the mainstream technology trajectories in China, accounting for almost 20% of the total number of businesses. However, the performance of metallic materials in the business ecosystem is not as good due to shortcomings in the equipment manufacturing segment.

For emerging materials, there are no entries among the top 40 business entities in the industry, suggesting they are a missing piece in China's 3D printing industry whose value functions have not been exploited. It is also noteworthy that the design and implementation of key components remains weak, which could dampen the business ecosystem's integration capability.

4.2.4. Cross-layer analysis

Fig. 5 summarizes the innovation outcome of the value segments throughout the integrated value chain (Sections 4.2.1 to 4.2.3). From Fig. 5, we can argue that equipment manufacturing is the best-performing value segment out of the four throughout the integrated value chain, by counting the numbers of papers/patents/businesses. In addition, the equipment manufacturing segment appears to have strong capacity in its technology layer, followed by its business layer, while the science capacity is the weakest. This may illustrate that China's 3D

[12] For example, Professor Bingheng is leading Shaanxi Hengtong (a spinoff from Xi'an Jiaotong University) to develop the cutting-edge SLA (stereo lithography appearance) that has been used to produce the metal components of machinery and high-value equipment products. In addition, Professor Wang from Zhonghang Tiandi Laser Technologies (a spinoff from Beihang University) has led the team in manufacturing the world's largest single-piece component for aerospace use.

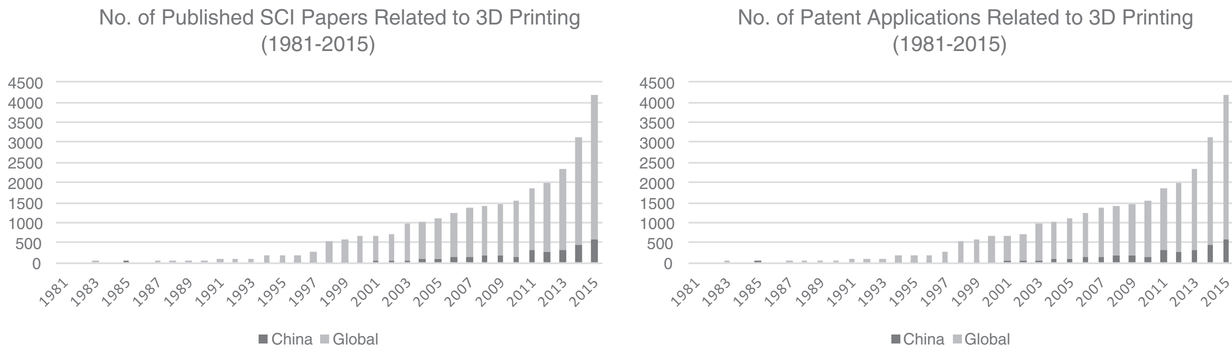


Fig. 2. Number of publications and patent applications related to 3D printing (1981–2015).

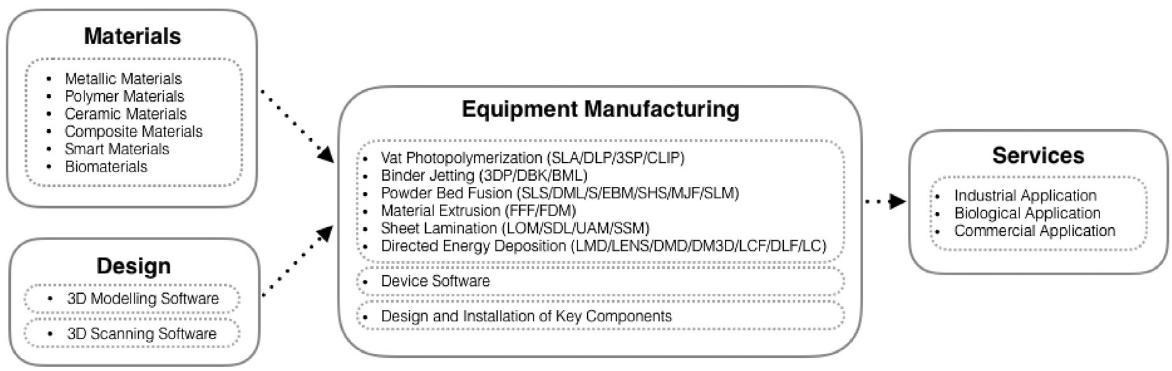


Fig. 3. Integrated value chain of 3D printing industry.
Sources: the authors, adapted from expert interviews and Wohlers Report 2015.

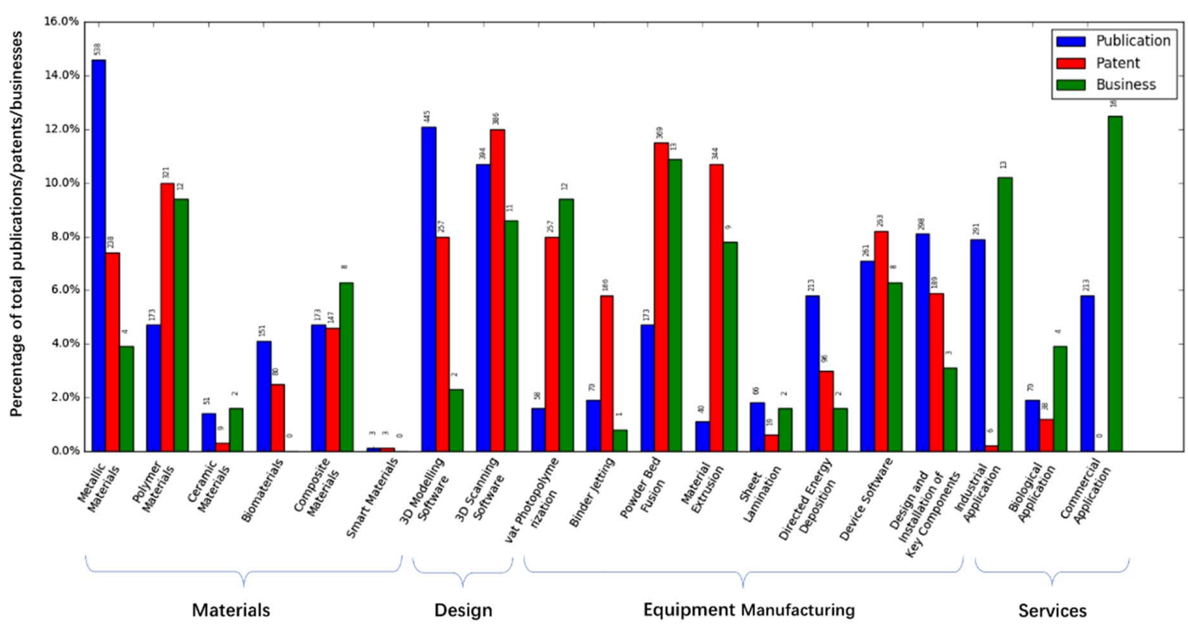


Fig. 4. Innovation outcome in each value function (by counting publications/patents/businesses).

printing generally gives the emphasis to equipment manufacturing in the technology domain, while partly neglects the original research competence in science domain – this may call for more policy support and investment in basic research on manufacturing segments.

On top of this, Fig. 5 shows that materials and design are the moderately performed value segments in the value chain. Both segments follow the same pattern: strongest science, followed by technology, and weakest business. This may indicate that China's 3D printing has good scientific and technological basis for materials and design; however, more effective commercialisation activities are called for to better convert the knowledge into real business.

Last but not least, Fig. 5 demonstrate that the service segment is the least-performing value segment. More importantly, the service segment has a missing link between science and business – its technology capacity is almost negligible compared to business output as well as the moderate science basis.

As noted in Section 3, we used four-quadrant analysis to grasp the cross-layer interplay between science, technology, and business layers in the 3D printing industry (Fig. 6).

In the underdeveloped quadrant, we identified weak functions, such

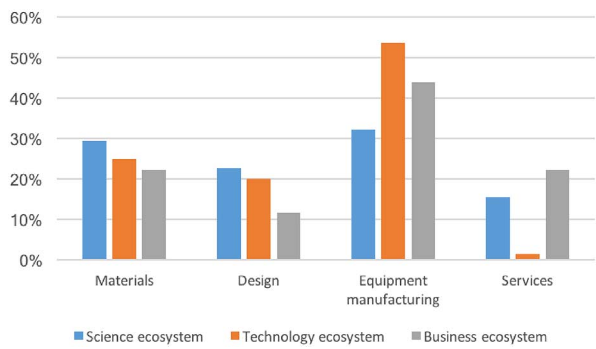


Fig. 5. Innovation outcome in each value segment (by counting publications/patents/businesses).

value functions is at the technology and business levels. This is more closely linked to the market and is usually driven by profit or market potential. Therefore, these are often not the most advanced or technology-intensive value functions. The market-driven mode is regarded as a typical innovation mode for developing countries. In the case study, we only observed two value functions—vat photopolymerisation and material extrusion—which are both embedded in manufacturing technologies.

In the S-T-spurred quadrant, the value functions show strength at both the science and technology levels but have few business outcomes. These are more likely to have a solid knowledge base, but the business value might not be realised in the near term. In China's 3D printing industry, many of the value functions fall into this category, especially materials, where metallic, composite, and biomaterials are all regarded as science and technology oriented, indicating a lack of material commercialisation.

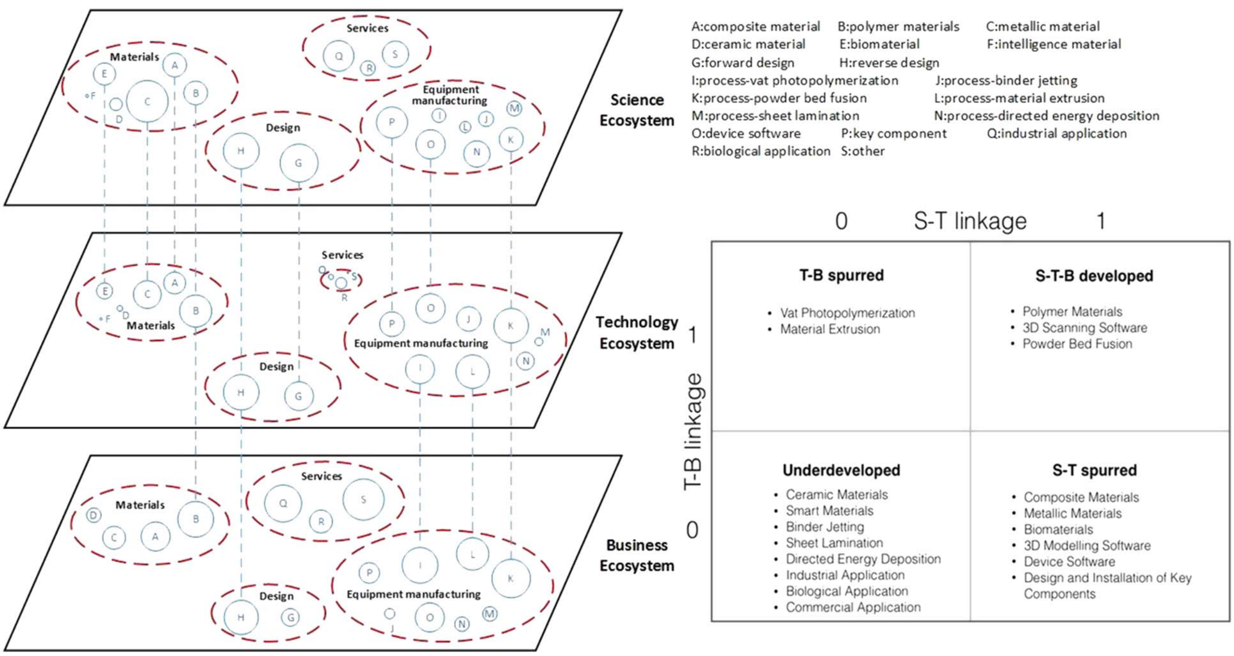
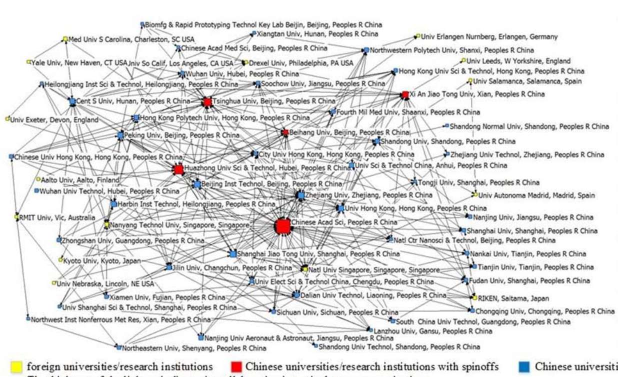


Fig. 6. Cross-layer analysis of integrated value chain of 3D printing in China.



	Type	Degree (centrality)	Betweenness (centrality)	Network Centralization	Network Density
Network				10.33%	0.3427
Chinese Acad Sci, Peoples R China	University	185	90		
Zhejiang Univ, Zhejiang, Peoples R China	University	44	32.5		
Huazhong Univ Sci & Technol, Hubei, Peoples R China	University	73	29		
Tsinghua Univ, Beijing, Peoples R China	University	87	13		
Shanghai Jiao Tong Univ, Shanghai, Peoples R China	University	44	12		
Harbin Inst Technol, Heilongjiang, Peoples R China	University	14	9		
Xi An Jiao Tong Univ, Xian, Peoples R China	University	37	6		
Beijing Inst Technol, Beijing, Peoples R China	University	34	6		
Peking Univ, Beijing, Peoples R China	University	43	5.5		

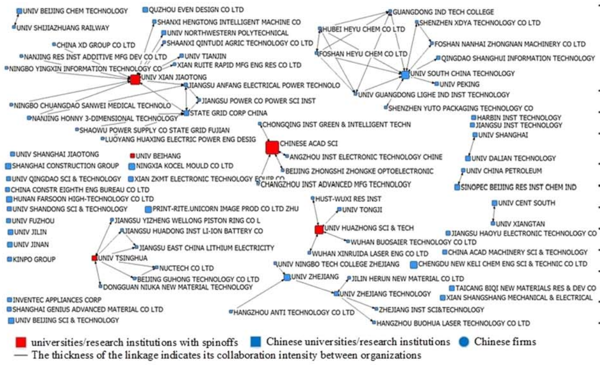
Fig. 7. Publication-based collaboration network of China's 3D printing organisations.

as ceramic and intelligent materials, binder jetting, sheet lamination, and directed energy deposition technologies. In particular, value functions in the service segment all fall into this quadrant, which is mainly due to the weakness of the technology ecosystem. The missing aspect of technology suggests inconsistency in the value-creation process, which could limit the quality of innovation.

In the T-B-spurred quadrant, the concentration of activities in the

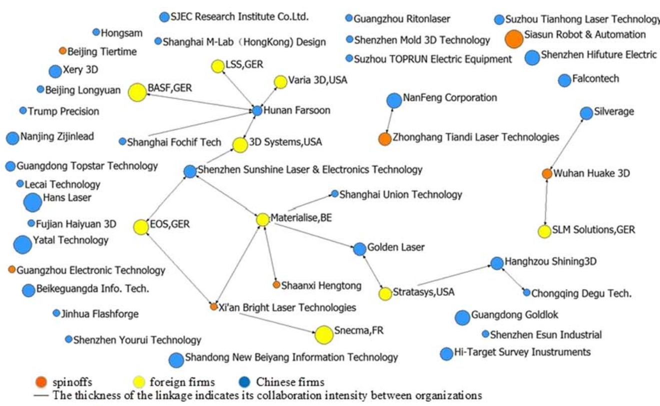
In the S-T-B-developed quadrant, the value functions are strong in all three ecosystems, indicating the healthy development of an innovation ecosystem. The three S-T-B-developed value functions are polymer materials, 3D scanning, and power bed fusion.

Overall, based on the integrated value chain analysis, a promising innovation path for China's 3D printing industry emerges since more



	Type	Degree (centrality)	Betweenness (centrality)	Network Centralization	Network Density
Network				13.16%	0.0179
UNIV XIAN JIAOTONG	University	12	90		
UNIV SOUTH CHINA TECHNOLOGY	University	9	29		
UNIV TSINGHUA	University	6	13		
STATE GRID CORP CHINA	Company	6	32.5		
CHINESE ACAD SCI	University	4	6		
UNIV HUAZHONG SCI & TECH	University	4	6		
UNIV ZHEJIANG TECHNOLOGY	University	4	12		
JIANGSU ANFANG ELECTRICAL POWER TECHNOLO	Company	4	5.5		
UNIV ZHEJIANG	University	3	9		

Fig. 8. Co-patenting network of China's 3D printing organisations.



	Type	Degree (centrality)	Betweenness (centrality)	Network Centralization	Network Density
Network				8.69%	0.0161
Materialise, Belgium	Company	5	167		
Shenzhen Sunshine, China	Company	3	133.5		
3D Systems, USA	Company	2	115		
Hunan Farsoon, China	Company	5	90		
Golden Laser, China	Company	2	81		
Stratasys, USA	Company	2	58		
Xi'an Bright Laser Technologies, China	Company	3	38.5		
Hanghzou Shining3D, China	Company	2	31		
Shaanxi Hengtong, China	Company	2	16		
EOS, Germany	Company	2	14		

Fig. 9. Interactive network in business ecosystem of China's 3D printing industry.

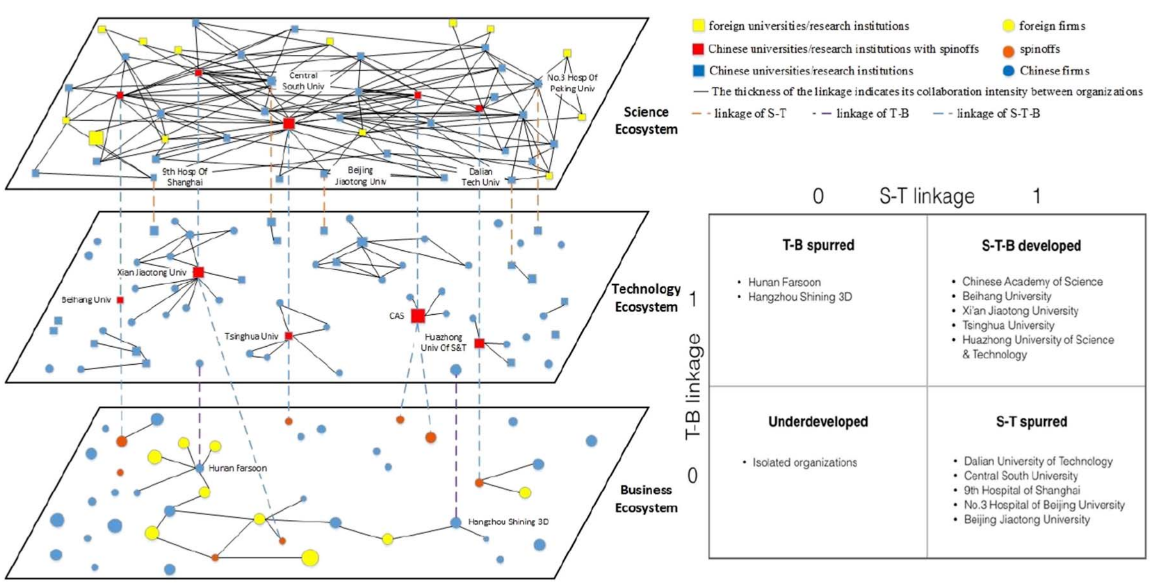


Fig. 10. Cross-layer analysis of collaborative network of 3D printing in China.

value functions fall into the S-T-spurred path than the T-B-spurred path. This indicates a new catch-up mode for developing countries in terms of emerging industries. Unlike the traditional secondary innovation mode—where China is a follower that innovates via imitation and reverse engineering—in the 3D printing industry, China is investing in the scientific frontiers and state-of-the-art technologies. It has even gained leading positions in niche areas such as metallic materials and power bed fusion.

4.3. Analysis of interactive networks in China's 3D printing ecosystem

4.3.1. The science ecosystem's interactive network

Regarding the science ecosystem's interactive network, this study selected the top 40 Chinese organisations with the highest number publications, as well as their 16 key collaborators in network for science corporations. The network has a density (matrix average) of 0.3427, implying the existence of a large number of dyads (Fig. 7). Its centralisation is 10.33%, indicating that some dominators exist in the science ecosystem. Looking at individual organisations, there are

Table 1
Summary of the three-layer analysis of China's 3D printing ecosystem.

Factor		Science ecosystem	Technology ecosystem	Business ecosystem
Ecosystem objectives		Scientific knowledge	Industrial knowledge	Business value
Integrated value chain	Best-performing segment	Materials, equipment manufacturing	Materials, equipment manufacturing	Equipment manufacturing, services
	Completeness of value chain	Good	Lack of complement in service segment	Lack of complement in material segment
Interactive network	Density	High	Medium	Low
	Anchor players	Universities and research institutes	Universities and research institutes	Firms

several platforms, led by the Chinese Academy of Science (CAS), Zhejiang University (ZJU), Huazhong University of Science and Technology (HUST), Tsinghua University (TSU), and Shanghai Jiao Tong University (SJTU). Among these anchor players, CAS, which has the most SCI publications in 3D printing (458 papers), holds the central position in the science ecosystem and acts as a knowledge hub with a centrality degree of 185, which is significantly higher than the others. CAS also has the most resources in the network with a betweenness centrality of 515, exerting a large influence on the transfer of knowledge. While the others have relatively less significant centralities, the existence of multiple small platforms indicates that a collaborative ecosystem exists. Thus, we can conclude that the science ecosystem has a healthy outlook. It is also worth noting that all organisations in the network are universities and research institutions.

4.3.2. The technology ecosystem's interactive network

Regarding the technology ecosystem's interactive network, we selected the top 40 organisations with the highest patent applications, as well as 83 key collaborators. As shown in Fig. 8, network centralisation is 13.16%, and the network density of the top 40 domestic players is 0.0179. Compared to the publication collaboration network, the density of the patent collaboration network is much sparser, indicating less cooperation in the technology ecosystem. This could be because publications usually serve the public interest while patents are intellectually protected for private interests.

The key actors in technology ecosystems are usually firms who have core technology competitiveness. However, in the technology ecosystem of China's 3D printing industry, universities and research institutions still hold a dominant position.

Moreover, six cliques can be identified in the patent collaboration network. The gatekeepers—with high betweenness centrality and degree centrality—control core resources and provide R & D cooperation platforms. We found that all gatekeepers in the cliques are universities or research institutions, and the node of firms is situated around them. Further, each clique focuses on different technology trajectories led by their gatekeepers. Specifically, Xi'an Jiaotong University specialises in vat photopolymerisation using polymer materials as well as powder bed fusion using metallic materials. South China University of Technology focuses on software development, including 3D modelling software, 3D scanning software, and device software. Huazhong University of Science and Technology specialises in powder bed fusion using composite and metallic materials, and it also has expertise in 3D scanning software development. Tsinghua University focuses on the development and application of biological materials for 3D printing as well as powder bed fusion. Zhejiang University develops its research in the biological domain. The Chinese Academy of Science has multiple technology pathways within the value function of materials, including metallic, ceramic, and biological materials, as well as equipment manufacturing for sheet lamination and device software development. This phenomenon points to the uncertainty of the dominant technology paths in this emerging industry. China has invested in several parallel technology paths.

4.3.3. The business ecosystem's interactive network

Regarding the business ecosystem's interactive network, we selected the top 40 organisations with major business contributions, as well as eight foreign firms that collaborate with them in product development. Fig. 9 shows a scattered network with a density of only 0.0161 and a centralisation of 8.69%, indicating a less collaborative ecosystem.

Further, when ranking organisations by betweenness centrality, Materialise, Shenzhen Sunshine Laser & Electronics Technology, 3D Systems, and Hunan Farsoon are the top organisations, of which two are foreign entities. In particular, Materialise, a Belgian firm, has the highest centrality. Since we find hardly any direct collaboration between Chinese firms, we argue that there is still no domestic keystone firm in China's business ecosystem.

Regarding university spinoffs, they have strong technological foundations but tend to be isolated in the network, with limited collaboration with other organisations, indicating limited interactions.

4.3.4. Cross-layer analysis

After linking cross-layer players according to the methodology described in Section 3.4,[13] we used four-quadrant analysis to identify organisational interactions across layers. As shown in Fig. 10, we put the anchor players with cross-layer linkages into four quadrants.

In the T-B-spurred quadrant, both anchor players are companies (Hunan Farsoon and Hangzhou Shining 3D) who mainly collaborate with foreign entities. Innovation in these firms begins with the introduction of overseas equipment and technology, and is realised through reverse engineering and imitation. This innovation path can be regarded as secondary innovation, which is prominent in catch-up countries (Wu et al., 2009; Xu et al., 2015).

In the S-T-spurred quadrant, five universities and research institutes are identified as anchor players (Dalian University of Technology, Ninth Hospital of Shanghai, etc.). These organisations are active in scientific and industrial knowledge creation and conversion. They are embedded in R & D collaboration networks and conduct indigenous innovation.

In the S-T-B-developed quadrant, five universities and research institutes with spinoffs exist as anchor players. This means that Chinese universities and research institutes play a very important role in the innovation ecosystem of 3D printing. This has a twofold implication. First, the central position of universities can provide well-developed fundamentals for technology development. Second, since fewer collaborations are identified between universities and business entities (aside from spinoffs), there could be limitations on business development and technology commercialisation. Nevertheless, the emergence of primary innovation in an emerging industry provides a window for accelerating China's process of catching up with foreign pioneers.

Overall, the analysis of interactive networks highlights a promising innovation pathway for Chinese players in the 3D printing industry: there are more players with indigenous innovation who fall into the S-T-spurred path than players with exogenous innovation who fall into the T-B-spurred path. Moreover, there are some anchor players with established linkages between science, technology, and business.

[13] The link between S and T was measured by the number of quotes between patents and research papers. Players with links of three or more were identified. The link between T and B was measured by firms' business or ownership relationships with universities. Universities with business corporations with three or more firms or ownership of firms in the business ecosystem were linked.

5. Discussion

Summarized from Section 4, Table 1 shows the innovation outcome of China's 3D printing ecosystem across science, technology and business.

From the integrated value chain perspective, we find that China has expertise in various value functions, with multiple technology trajectories in each layer. In the science ecosystem, China shows very good performance in terms of the number of publications and has established a complete value chain in scientific research. In the technology ecosystem, China also performs well in terms of patent applications, but the integrated value chain is not as complete regarding technological development, especially in the service segment. In the business ecosystem, China's value capture is relatively weak in the business domain, and the value chain is incomplete, especially in the materials segment. Generally speaking, China has a better international position in the 3D printing industry than in most traditional industries, indicating its catch-up in this emerging industry.

Regarding interactive networks, in the science ecosystem, local universities and research institutes are the anchor players in a dense network that provides a strong base of scientific knowledge for China's 3D printing industry. Surprisingly, they are also the anchor players in the technology ecosystem. This contrasts with the phenomenon in developed countries where the anchor players are firms in the technology ecosystem that are more oriented toward private interests (Li et al., 2016). In the business domain, 3D printing firms, as anchor players, operate within a very loose network, and keystone firms have not yet emerged. In addition, domestic Chinese firms are mostly isolated from each other, though there are cliques through connections with established overseas firms that hold more central positions in the network. Overall, China's universities and research institutes seem to be leading scientific and industrial knowledge creation for the advancement of China's 3D printing innovation. Meanwhile, Chinese university spinoffs constitute a major force engaged in the technology commercialisation of local leading-edge basic research.

Regarding the interplay between layers, there are more linkages between the science and technology ecosystems than between the technology and business ecosystems. Given that the S-T-spurred path has a greater number of value functions than the T-B-spurred path, the catch-up pathways for 3D printing in China have apparently shifted from the traditional imitative innovation mode to an S & T-based innovation mode. The aggregated outcome of this study shows a promising pathway for China's 3D printing industry. This outcome is clearly different from the previous follower modes of industrial development in developing countries, which often begins with technology import and imitation (Luo et al., 2011; Wu et al., 2009; Kim, 1997). This indicates that China's 3D printing industry could have a new development pathway (from S-T spurred to S-T-B developed) that is driven more by knowledge than by merely relying on duplicating technologies and low-cost production. This coincides with some recent studies of emerging economies (Zhou et al., 2015a).

However, better connections are still needed between each sub-ecosystem, especially between the technology and business ecosystems. On the one hand, China has acquired knowledge competencies in some high-value-added technology trajectories (e.g. powder bed fusion and metallic materials). However, the development of these technology trajectories and their business-value capture rely heavily on universities and their spinoffs. Since their research findings have low commercialisation efficiency, outcomes in the business domain seem weak. On the other hand, T-B-spurred entities such as Hunan Farsoon have good business potential but lack collaboration with native universities and research institutes. As for emerging industries with undetermined dominant designs, it is important for firms to leverage local research resources for open innovation (Mortara and Minshall, 2011).

6. Conclusion and implications

This study contributes to existing theories as follows below.

First, this study proposed a framework for an S-T-B ecosystem that examines innovation ecosystems in terms of innovation processes and provides an in-depth understanding of synergy and symbiosis in such systems. We conceptualised an innovation ecosystem as a complex, dynamic system that includes science, technology, and business sub-ecosystems. We analysed it in terms of the integration and interaction of the S-T-B ecosystem, which helps to provide a landscape of innovation ecosystems and comprehensively evaluate their outcome. Moreover, this framework bridges the knowledge and business economies, and specifically examines the interplay between science and technology layers within the knowledge economy. It helps assess whether scientific and technological knowledge have been transferred to business values and whether business values are supported by local technology development and basic research. This is especially important for understanding emerging industries since there is high uncertainty about cutting-edge technology trajectories, and there is more interplay between science, technology, and business than in mature industries.

Second, this paper identified new pathways for developing countries to catch up in emerging innovation ecosystems. Based on the analysis of value chain integration and inter-organisation collaboration in the S-T-B ecosystem, we used a four-quadrant diagram to identify S-T-spurred paths and B-T-spurred paths. We found that in an emerging industry such as 3D printing, late movers like China perform well in science and technology. This might require a more knowledge-driven innovation mode as opposed to merely relying on duplicating technologies and low-cost production, which is valuable for improving our understanding of innovation pathways in emerging economies.

Third, this study used integrated data and data mining methods to analyse innovation ecosystems. The framework used multi-dimensional data to analyse each sub-ecosystem in the S-T-B ecosystem individually—namely, bibliometrics for science, patent analysis for technology, web-data and in-depth interviews for business, and expert discussion for the interplays between ecosystems. Machine learning was applied to improve analysis efficiency for data processing. These data and methods provided support for describing the landscape and conducting an in-depth analysis of innovation ecosystems.

This research has the following policy and managerial implications for emerging economies. (1) China and other developing economies should continue to invest in science and technology knowledge creation, especially in emerging industries. This is because the disadvantage of being a late mover is not significant in an embryonic innovation ecosystem, and local investment in knowledge creation can finally translate into business value, contrary to conventional arguments that it is not efficient for latecomers to invest in science (Forbes, 2006). (2) Governments should pay more attention to the interplay between science, technology, and business; take measures to improve the effectiveness of translating science and technology into business value; and support demand-pull value capture through support for local R & D. Governments can conduct application demonstration projects, provide public service platforms, and enhance interactions between industries, universities, and research institutes. (3) Universities and research institutes need to improve the conversion of scientific and technological achievements to business value via technology transfer or licensing to firms. Technology agencies should play positive roles in the process of university-industry technology transfer so that S-T-spurred knowledge can achieve practical value and realise commercialisation. (Al Hasan et al., 2006) Firms should emphasise their roles in creating industrial knowledge, including patents, and improve open-innovation mechanisms. Since technology breakthroughs emerge so frequently that only cutting-edge scientific actors can provide guidance for trajectories, firms should seek support from local universities and research institutes and forge closer links with the science ecosystem, especially when working on state-of-the-art emerging technologies.

This research has some limitations. First, bibliometrics and patent analysis methods can cause data bias (e.g. geographic and institutional bias), especially when using a single indicator. Therefore, future research might consider using integrated indicators. Second, although bibliometrics and patent data can provide quantitative outcomes and may help identify aggregated phenomena that qualitative inquiry cannot detect or might overlook, in some cases, literature-based data can only explain explicit knowledge bases and might have difficulty deciphering other tacit capabilities, especially for countries trying to catch up. For example, some Chinese firms have limited patents, but they can learn very quickly by adopting various measures and can achieve market success by leveraging other competitive advantages. Therefore, in future studies, literature-based analysis needs to be better integrated with qualitative inquiries, such as expert interviews.

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Appendix A. Supplementary data

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