Initiation and evolution of systemic innovations

Patterns and interactions in the emergence of additive manufacturing technologies

Luomaranta, Toni; Martinsuo, Miia; Ortt, Roland

DOI
10.1111/caim.12600

Publication date
2024

Document Version
Final published version

Published in
Creativity and Innovation Management

Citation (APA)
Luomaranta, T., Martinsuo, M., & Ortt, R. (2024). Initiation and evolution of systemic innovations: Patterns and interactions in the emergence of additive manufacturing technologies. *Creativity and Innovation Management*. https://doi.org/10.1111/caim.12600

Received: 13 February 2023 | Revised: 21 December 2023 | Accepted: 22 December 2023
DOI: 10.1111/caim.12600

ARTICLE

WILEY

Initiation and evolution of systemic innovations: Patterns and interactions in the emergence of additive manufacturing technologies

Toni Luomaranta[1] | **Miia Martinsuo**[2,3] | **Roland Ortt**[4,5]

[1]Institute for Managing Sustainability, Vienna University of Economics and Business, Vienna, Austria

[2]Faculty of Technology, University of Turku, Turku, Finland

[3]Department of Industrial Engineering and Management, Tampere University, Tampere, Finland

[4]Department of Technology, Policy & Management, Delft University of Technology, Delft, The Netherlands

[5]Bold Cities, Erasmus University Rotterdam, Rotterdam, The Netherlands

Correspondence
Miia Martinsuo, Faculty of Technology, University of Turku, Turku, Finland.
Email: miia.martinsuo@utu.fi

Abstract

Technological innovations are becoming increasingly systemic in the complex and interconnected world. The initiation and evolution of systemic innovations take time and include numerous challenges, and the mechanisms through which systemic innovations emerge in the interaction between different technologies represent a research gap. This paper explores the emergence of ceramic additive manufacturing as an example of a systemic manufacturing technology innovation. We implemented an event history analysis of four ceramic-material additive manufacturing technologies. We traced the initiation and evolution paths of each of the four technologies over time and showed a pattern of activities within and across the technologies. The study contributes by revealing that systemic innovations emerge as a result of parallel and sequential development paths of within-technology system components as well as the interaction between multiple technologies. The timing of the coalescing development paths of the system components and technologies appears crucial but serendipitous instead of coordinated. The findings open new pathways for speeding up the emergence of systemic innovations and forthcoming research to support the evolution of additive manufacturing.

KEYWORDS
additive manufacturing, event history analysis, systemic innovation, technology evolution

1 | INTRODUCTION

Organizations invest in radically new, innovative manufacturing technologies to outperform their competitors. Before radically new technologies can be implemented, they need to be developed through processes that match the degree of technology novelty (Chaoji & Martinsuo, 2019). Organizations developing novel technological innovations need to be involved with multiple interrelated innovations concerning technologies, products, services and processes that together form a complete system. These kinds of systemic innovations require coordination between different organizations (Chesbrough & Teece, 2002). The initiation of systemic innovations has been portrayed as an inter-organizational endeavour, requiring the creation of new business ecosystems and innovative business models (Takey & Carvalho, 2016), but the emergence of a systemic innovation requires also attention to the pattern of evolving system components and interplay of technologies. More research on the initiation and evolution of technologies has been called for already more than a decade ago (Arthur, 2009).

This study concerns the initiation and evolution of novel, systemic manufacturing technology innovations and specifically the patterns and interactions between system components (i.e. raw material, manufacturing technology, process, application, product, service, etc.) within and across multiple technologies. While research tends to focus on different types of innovations and their emergence separately (Arthur, 2009; Coccia & Watts, 2020), systemic innovations assume an interrelationship of system components and even multiple technologies during the initiation and evolution of different technological innovations. A major challenge with systemic innovations deals with the slow pace and even failures in technology emergence and diffusion (Agarwal & Bayus, 2002; Ortt, 2010; Schnaars, 1989). The interrelationship between the system components implies that some form of coordination is required to achieve compatibility (Takey & Carvalho, 2016) and readiness of all technologies for the entire systemic innovation at the right time. There is a need to understand the interplay of multiple technologies better in connection with technology initiation and evolution (Schneider & Kokshagina, 2021) and this represents a research gap (Arthur, 2009; Coccia & Watts, 2020).

To address the research need, this study analyses the initiation and early evolution of systemic innovations. This study intends to reveal patterns in the emergence of systemic innovations, especially concerning the interaction between system components and technologies, the timing of key events, and actors' involvement. The main research question is: *How do systemic innovations emerge, through the interaction of system components and multiple technologies?* To delimit the scope of the empirical study, we focus on selected technologies of ceramic additive manufacturing (AM), where AM generally represents a topical and attractive technological innovation in manufacturing and encompasses multiple families of related technologies (ASTM, 2012). Ceramic AM has been considered as a particularly lucrative manufacturing technological opportunity, for example, in medical implants (Chen et al., 2019; Suominen et al., 2019) and signal processing (Chen et al., 2019; Lakhdar et al., 2021). Each ceramic AM technology has its own evolution path, but there are possible interconnections within a specific technology (among its system components) and across a technology family. We pay attention to the initiation and evolution of different system components and the possible interactions between technologies.

We complement the inter-organizational view to initiating systemic innovations by revealing the within-technology and inter-technology development paths which potentially explain the slowness in the emergence of systemic innovations and could be improved to speed up commercialization. We also add to current product-centric technology commercialization knowledge by reporting patterns in the parallel and sequential development of within-technology system components required for the emergence of a complete systemic innovation. While the system components are normally developed in separate organizations in parallel and in sequence, organizations need to allow the development paths of system components to coalesce at the right time through coordinated efforts of basic and applied research, which requires inter-organizational optimization of timing and system component development. Furthermore, systemic innovations are shown to emerge through serendipitous knowledge transfer between parallel technology evolution paths. Where inter-technology competition often leads organizations to avoid cooperation during initial technology diffusion, we show that the emergence of systemic innovations may be improved through more coordinated inter-technology knowledge transfers between the parallel technology development paths. Examples from ceramic AM reveal the usefulness of learning between neighbouring technologies, as the system components may emerge for one technology but become useful for a commercial application in another technology.

In the second section, the literature on systemic innovations, technology initiation and evolution, and AM technologies as examples of systemic innovations are reviewed to summarize current-state knowledge. The third section introduces the research method of a document-based historical event analysis in an embedded multiple case study concerning ceramic AM technologies. The development paths of four AM cases are introduced and a cross-case analysis of within-technology patterns and inter-technology interactions is presented in Section 4. The fifth section will answer the research question on how systemic innovations emerge, benefiting both from within-technology interaction between system components and inter-technology interaction. The last section will conclude the paper's insights and propose future research avenues.

2 | LITERATURE REVIEW

2.1 | Systemic innovations

Some innovations require that development takes place throughout a broader system instead of merely a product for the realization of value benefits: they can touch upon technologies, processes, products and services, customers and markets, supply chains and business logics together (Chesbrough & Teece, 2002). While manufacturing innovations tend to be viewed dominantly as technologies from a certain focal firm's perspective focusing on customers in specific markets (Chaoji & Martinsuo, 2019), their adoption is affected by various complementary innovations in raw materials, products, software and services, all of which require new processes and business logics (Martinsuo & Luomaranta, 2018; Mellor et al., 2014). The emergence of systemic innovations needs to be covered holistically, due to their complexity and requirement of complementary, simultaneous innovations (Luomaranta & Martinsuo, 2022; Pedota & Piscitello, 2022).

From the perspective of technologies and technology development, systemic innovations cannot be developed autonomously and alone by a certain organization, and the realization of the benefits from some innovations requires complementary innovations (Chesbrough & Teece, 2002; Takey & Carvalho, 2016). Such innovations require collaboration across organizational boundaries to seek and benefit from crucial synergies and coordinate the creation of multiple innovations (Chesbrough & Teece, 2002), and this inter-organizational collaboration has been covered in many domains. Previous research on systemic innovations has covered technologies and related business ecosystems, for example, in electric vehicles (von Pechmann et al., 2015), intelligent technologies and materials (Martinsuo, 2021), construction-related systems (Alin et al., 2013; Lavikka et al., 2021; Lindgren, 2016; Lindgren & Emmitt, 2017) and energy-related systems (Andersen & Drejer, 2008; Kang & Hwang, 2016; Mlecnik, 2013). The dominant case-based approach emphasizes that systemic innovations always take place in their specific context, and both the type of innovation and the context need to be understood while studying the initiation and evolution of systemic innovations.

The initiation, that is, the early phase of systemic innovation emergence, concerns all possible phases covering research, technology and process development, and identifying products, services and applications that could be developed for possible commercialization. Takey and Carvalho (2016) conducted a literature review on the front end of systemic innovations and emphasized that general practices of autonomous innovations need to be combined with such practices that enable the inter-organizational ecosystem to join forces and function effectively. This implies ecosystem mapping and related positioning of organizations in the ecosystem map; defining mechanisms for coordination, collaboration and adaptation in the ecosystem; and designing new business models, ventures and strategic positions for the ecosystem and its actors (Takey & Carvalho, 2016).

Managers searching for radical manufacturing technology innovations may engage in either a closed partner search among their known suppliers or an open search to identify completely new technology suppliers of manufacturing technology (Chaoji & Martinsuo, 2022). Empirical research concerning intelligent materials suggested that an insufficient market pull, insufficient industry readiness, pervasiveness of the systemic solution and significant financial investments might act as barriers to moving the systemic innovations toward implementation (Martinsuo, 2021). While both Martinsuo (2021) and von Pechmann et al. (2015) suggest various managerial mechanisms for scaling up systemic innovation, they both dominantly take a single firm's viewpoint to a business network, not covering the early development paths of technology system components required for the systemic innovations nor the inter-technology interplay over time.

Systemic innovations in a certain industry, or more broadly in society, have been researched to some extent from the diffusion perspective, but more research has been called for to focus on the emergence of systemic innovations (Arthur, 2009; Coccia & Watts, 2020). Diffusion-centric systemic innovation research deals with disruptive solutions that could transform the way in which a certain industry sector operates and modern solutions for the construction industry have been introduced as examples of such systemic innovations (Lindgren, 2016; Lindgren & Emmitt, 2017). The inter-organizational and knowledge-sharing aspects are emphasized (Gattringer et al., 2021; Lindgren, 2016), and multiple parallel and sequential projects are needed for the innovations to evolve and spread across organizations over time (Lindgren & Emmitt, 2017). Key issues either driving or restraining the evolution and application of systemic innovations relate to key actors (often clients), political forces and regulations, and competitors' actions that might stimulate such projects and promote learning of the novel technologies in the industry (Lindgren & Emmitt, 2017). The importance of political and funding instruments for diffusing systemic innovations has been acknowledged also in the renewable energy sector (Kang & Hwang, 2016). The diffusion might be challenged if local clusters of development are not properly connected with each other in the broader societal context (Kang & Hwang, 2016).

The above consideration already indicates that systemic innovations cannot be treated in isolation, but their emergence requires understanding connections both between the system components concerning a focal technology (including raw material, manufacturing technology, application demand, software and services) and between technologies (each potentially with their unique supply chains). Understanding such influences requires elaborate forms of technology assessment (Gartner et al., 2015). Systemic innovations tend to imply a transition of systems (Midgley & Lindhult, 2017): where multiple innovations occur in parallel or in sequence, they together drive change in certain systems, to achieve a novel, more desirable pattern of production and consumption (Bergman et al., 2008; Whitmarsh & Nyqvist, 2008).

2.2 | Initiation and evolution of technological innovations

Several scholars (Day & Schoemaker, 2004; Gattringer et al., 2021; Gillier & Piat, 2011) have studied how technological innovations are initiated and evolve. The emergence of technological innovations is covered both in general innovation research and technology diffusion research. The innovation management field mostly considers the development processes of innovations as projects. Innovation projects are described as chains of activities and decisions that reduce uncertainty, add value and yield a new product (Crawford, 1991; Urban & Hauser, 1993; Wind, 1982), or as teams that commit to develop adaptive solutions to complex problems and, thereby, create value (Schwaber & Sutherland, 2020). It is commonly understood that different types of innovation projects are needed, depending on the innovation task and context (Artto et al., 2008; Fernandez et al., 2018; Ortt & Van der Duin, 2008). Technology diffusion research perceives the diffusion process of innovation as a gradual process of adoption of a particular innovation by members of a population (Meade & Islam, 2006; Rogers, 1962; Valente & Rogers, 1995). The combination of these scientific fields implies that developing innovations can be mastered as a special kind of project that, if managed properly, will lead to a successful large-scale diffusion process.

The characteristics of systemic innovations described in the previous chapter have important consequences for the pattern of initiation and evolution. Firstly, the emergence of systemic innovations cannot take place as isolated projects within a single organization. As a systemic innovation is made up of different complementary technologies, products and services, it requires a new supply chain and the involvement of multiple organizations (Chesbrough & Teece, 2002). The different organizations engage in both their own and joint innovation projects to create the different elements of systemic innovation. Hence, after the invention of the technological principle of systemic innovations, an entirely different process can be observed than a single innovation project. The process of evolving technology is described in the Minnesota studies (Schroeder et al., 1986; Van de Ven et al., 2008) and has been documented by other scholars tracking historical processes (Ortt, 2010; Ortt & Schoormans, 2004). After the invention, multiple companies are often active: multiple projects are started, aborted and combined, after which all activities are stopped for some years and then revived again. This phase between invention and first introduction is shown to last about 10 years on average for a large set of technological innovations (Ortt, 2010) and that is considerably longer than a singular innovation project typically lasts.

A second consequence deals with systemic innovation appearing through a more chaotic early diffusion than the smooth diffusion curves of single technologies, and such chaotic patterns result from a range of causes. For example, Rosenberg (1982) showed how the development of technology proceeds while its diffusion has already started. Such a combined development and diffusion process may hamper smooth diffusion because customers will wait for the technology development to stabilize in order to prevent the risk of investing in a technology that is outdated soon after its implementation. This phenomenon that customers wait to adopt when technology develops fast is referred to as 'leapfrogging' and is documented on the level of nations (Brezis et al., 1991), companies (Yap & Rasiah, 2017), and individual customers (Schilling, 2003). In the case of systemic innovations, innovations need to occur in many different complementary technologies, each with its own development and diffusion process.

Also, the combination of within-technology competition (different versions of the new technology compete) and between-technology competition (the new technology competes with the old one) may represent another cause for an erratic initial innovation diffusion. The combination of within and between-technology competition is documented for mobile phones (Funk, 2001; Koski & Kretschmer, 2005) and Formula 1 race cars (Jenkins & Floyd, 2001), for example. Both types of competition are highly likely for systemic innovations. Within-technology competition occurs when all organizations develop different system components for the same technologies, the innovation projects in different organizations are not coordinated, and each organization attempts to align the entire system around its own system component. Between-technology competition is likely to be fierce when multiple technologies are developed for the same application simultaneously and the systemic innovation affects and even endangers existing business ecosystems.

Another cause of a somewhat erratic initial diffusion process is the fact that parts of the innovation will most often start diffusing when the system is not yet complete (Ortt & Kamp, 2022). For systemic innovations, such a process is highly likely. Organizations developing a system component may try to commercialize that component even before the systemic innovation to which their component belongs is ready. In that situation, fragmented commercialization efforts in several market niches can be witnessed, shaping a chaotic start of the diffusion process. Furthermore, systemic innovations are interdependent with their environment and advances happen because of historical events (Sahal, 1981), such as political changes and natural disasters.

Such erratic patterns in the emergence of technological innovations are covered in previous research in limited ways and only for selected technologies. The erratic phases are seen separated by more stable periods of progress in studies of innovation cycles (Schumpeter, 1939; Tushman & Rosenkopf, 1992; Utterback & Abernathy, 1975), as part of technological evolution (Sahal, 1981), and technological paradigms (Dosi, 1982). Some empirical evidence concerns specific novel technologies used for radical manufacturing innovations (Chaoji & Martinsuo, 2019). A three-phase pattern has been proposed for the full timeline of emerging systemic technological innovations (Ortt, 2010; Ortt & Schoormans, 2004): (1) The development phase: between invention and initial introduction; (2) The adaptation phase: between initial introduction and the start of industrial production and large-scale diffusion; and (3) The stabilization phase: after the start of industrial production and large-scale diffusion.

As indicated above, systemic innovations are composed of different types of technological innovations representing different system components (Arthur, 2009; Murmann & Frenken, 2006), all of which need to emerge timely for the systemic innovation to be complete. Competition between alternative technologies as one way of interaction between technologies is well understood, whereas other types of interaction between related technological innovations in their initiation and evolution are much less described (Arthur, 2009; Coccia & Watts, 2020; Schneider & Kokshagina, 2021). The system components can be created as part of the same or different technology innovation processes, but the required interplay of different system components within the same technology and between technologies may hinder or slow down the emergence of systemic innovations. To conclude, with the interest of speeding up the emergence of systemic innovations, there is a need to understand the initiation and evolution of related technologies and the different ways in which these technologies interact over time, and this is the gap we focus on, specifically in the domain of AM.

2.3 | Initiation and evolution of additive manufacturing as a systemic innovation

We examine a specific technology from the technology families of AM as a topical example regarded as a systemic innovation (Martinsuo & Luomaranta, 2018). AM refers to a group of manufacturing technologies that build up parts by adding layer after layer rather than moulding or casting materials, or cutting, sawing and sanding material to create such parts (ASTM, 2012). Due to the variety of materials used for AM (i.e. plastics, metals, ceramics) and techniques to build up parts, AM encompasses families of related technologies (ASTM, 2012). AM ceramics refers to AM technologies that apply ceramic materials (Chen et al., 2019; Lakhdar et al., 2021), and depending on the technique, these ceramic AM technologies can be divided into finer subgroups (Chen et al., 2019). From the manufacturing capabilities perspective, AM is expected to enable completely new complex product geometries, reduced time-to-market and new supply chain configurations for manufacturing (Luomaranta & Martinsuo, 2022; Pedota & Piscitello, 2022), and it is used both in rapid prototyping for concept and product testing, rapid tooling and manufacturing unique end-products (Mellor et al., 2014).

The existing literature describes the systemic innovation traits of AM stemming from its requirements for complementary innovations in applications, products, services, materials, manufacturing supply chains and service processes, and more broadly in society, as its overall success requires sparking innovations broadly in the entire system (Luomaranta & Martinsuo, 2020, 2022; Pedota & Piscitello, 2022), and we refer to these as system components. The systemic innovation nature is visible in the technology development phase of AM, where the need for supply chain involvement has been acknowledged (Luomaranta & Martinsuo, 2020, 2022; Mellor et al., 2014). For example, companies providing feedstock do not necessarily need a direct contractual relationship with the producer of the AM machine, but they still need to adapt the format, the amount and the material properties to the characteristics of the AM machine (Sobota et al., 2021). Hence, these companies need to adapt their development and production to each other. The systemic innovation at the societal level is visible for example in the case of AM with polymers, where the formerly large-scale and centrally organized production processes using injection moulding could be replaced with a more small-scale, locally organized process of AM (Ortt, 2016). That may have consequences on job requirements and on the design of entire supply chains and hence considerable societal consequences in the long run (Ortt, 2017; Sischarenco & Luomaranta, 2023). As an example of systemic innovations, AM thus carries both large managerial and societal relevance (Sobota et al., 2021).

Despite acknowledging the systemic nature of AM, current AM innovation literature includes a research gap concerning the consideration of the systemic nature of AM technology development. The complexity of the system concerning ceramic AM and the slowness of bringing AM-related innovations to the market highlight the challenge of managing interrelations between multiple technologies and multiple involved organizations in the value chain. Contrasting with the traditional linear view of technology evolution, systemic technology-based innovations, like ceramic AM, require a different pattern of initiation and evolution. Currently, the parallel and sequential emergence of the system components for AM technologies is weakly understood. There is a need for research to uncover the patterns and interactions of system components and multiple technologies to discover possibilities for speeding up the development and advancing the diffusion of AM.

3 | RESEARCH METHOD

3.1 | Research design

The analysis of initiation and evolution of systemic innovation requires a methodology that captures the dynamics of technology innovation. In this type of research, traditional methods do not capture all the desired outcomes by themselves (Suurs & Hekkert, 2009). Therefore, we employ historical event analysis, adopted from the Minnesota innovation studies (Poole et al., 2000; Van de Ven & Garud, 1993; Van de Ven & Poole, 1990). Historical event analysis is often applied to technological innovation and innovation systems studies (Bessagnet et al., 2021; Negro et al., 2008; Suurs & Hekkert, 2009) when investigating the innovation and development trajectories and processes of new technologies.

The historical event analysis offers a methodological basis for systematically collecting and treating qualitative historical data. The unit of observation is the event, which means 'what central subjects do, or what happens to them' (Poole et al., 2000, p. 40). Each event contains information on the what, the who, the when and the where. This information is then classified into relevant analytical categories, in this study into a chronological order, which also creates sequences of interrelated events that can link multiple dimensions and multiple actors (Van de Ven & Poole, 1990). It is considered as an appropriate method to study the co-evolution of multi-dimensional processes and the sequence of events (Bessagnet et al., 2021; Poole et al., 2000; Sewell, 1996), and therefore suitable to analyse the initiation and evolution of systemic innovations.

To understand the technology development process, researchers' aim is to understand the logic of a sequence of events that form episodes, meaning that the events are interlinked by the goals and actions of the entities (Poole et al., 2000). The basis of event history analysis is to form a narrative of developments (Suurs & Hekkert, 2009; Van de Ven et al., 2008). The narrative plot is thus constructed through the events by actions and routines of organizations, groups and individuals, and also by regulations, institutions, patents and new scientific knowledge all the way to market activities of companies (Poole et al., 2000). But not only that plot is constructed by the previous, it can have other meaningful aspects such as the interlinkage points—events—such as conferences, research projects and new technologies emerging outside (Suurs & Hekkert, 2009).

3.2 | Context and cases

To construct the narratives for historical analysis, we focus on four focal AM technologies to form an embedded four case analysis. We concentrate on ceramic AM as the type of manufacturing (i.e. holistic case) to ensure sufficiently similar contexts of the four technologies involving systemic innovations (i.e. embedded cases). We originally mapped the alternative technology families and technologies of ceramic AM (see the additional material) and purposely chose to focus only on one technology family and two different types of materials.

The mapping concentrated on AM in a worldwide context, with a focus on documents available in the English language.

Currently, there are seven different technology families for AM of ceramics, and each technology family has a number of different techniques (Chen et al., 2019; Lakhdar et al., 2021). For this study, we focus on material extrusion and four different techniques as cases in this technology family: fused deposit modelling (fused filament) of ceramics, pellet-based fused deposit modelling, direct-ink writing (robocasting) and freeze-form extrusion fabrication. The material extrusion technology family is the most well-known AM technology type, it has a sufficient historical background, and the technologies represent complex systems in themselves.

Ceramic AM technology innovation includes the following system components: ceramic AM technology (mechanics, software and post-processing), ceramic AM materials (already existing ceramic materials combined with the binder material that enables AM) and ceramic AM applications (Lakhdar et al., 2021). The inter-organizational networks involved include multiple different organizations providing ceramic AM machines, materials, designs, services and research. Thus, ceramic AM represents a good example of systemic innovations.

3.3 | Data collection

For each of the four technology cases, a scientific literature and documentation search was conducted. Scientific literature was accessed through academic library services, and the articles were available either publicly or behind the paywall. The language of the sought material was English and covered AM innovations worldwide. The first search strategy dealt with reviewing all the technology-specific scientific articles of existing ceramic AM literature reviews (including Chen et al., 2019; Deckers et al., 2014; Lakhdar et al., 2021; Travitzky et al., 2014; Zocca et al., 2015). Next, a snowballing strategy was used based on the identified publications. Through snowballing, also the related patents covering relevant technologies were identified and sought, and each found patent was reviewed to identify and search for other related patents. Patent databases are publicly available. The focus was only on the core technology-related patents. Lastly, an internet search was conducted to collect documentation and news articles concerning any relevant research projects, use of the technology in industry and company activities concerning the technology. The main dataset used for the analysis consists of 96 scientific publications, nine primary patents with their follow-up, and secondary data including 109 documents on research projects, pieces of news and company articles.

3.4 | Data analysis

For the purposes of the empirical study, we divided the main research question into three sub-questions: (1) How are systemic innovations initiated? (2) How do systemic innovations evolve? and (3) What are the interrelationships between the four AM technologies during the emergence of systemic innovation? We applied a historical analysis in which we carefully tracked events per technology to track the emergence of system components within each technology, build up four patterns and detect interrelationships between the technologies over time.

For each technology in the material extrusion family, a timeline reflecting the pattern of innovation emergence was first constructed, including three phases commonly covered in introducing innovations: the development phase (between invention and initial introduction), the adaptation phase (between initial introduction and the start of industrial production and large-scale diffusion) and the stabilization phase (after the start of industrial production and large-scale diffusion) (Ortt, 2010). We took an exploratory and inductive approach in developing such timelines to prevent a priori conclusions.

Second, over the timelines, we mapped any key events that were deemed relevant for the emergence of the systemic innovation for each technology separately and developed four case narratives and a graphical illustration of the events. Each event was coded for the dataset in terms of the key questions indicated in Table 1. We thus adapted the logic of event history analyses such as those of Poole et al., 2000; Suurs & Hekkert, 2009; Van de Ven & Garud, 1993; Van de Ven & Poole, 1990). These results are introduced at the beginning of Section 4. We will report case-specific narratives and related timelines first separately to reveal the different development paths and identify the events central to the emergence of each ceramic AM technology.

Third, the coding and visualization of the events for the four technologies over time were then used as a foundation for analysing the specific episodes central to the emerging and evolving system. We paid attention to the key inventions, involvement of key actors, introduction and the start of large-scale use and diffusion, interrelationships between system components, their timing and how they evolved over time. The patterns of within-technology emergence and interplay of system components are summarized based on this analysis phase, and we use the code abbreviations from Table 1 in the results in square brackets. Consequently, the systemic elements regarding the emergence of AM at the level of a single technology will be reported.

Fourth, the analysis continued with exploring the linkages between the four ceramic AM technologies and identifying further linkages to other AM technologies. We investigated the connections between the timelines of separate technologies, both in terms of technology sharing, material sharing, technology-related learning, similar technology roots, involvement of the same actors and overlap of innovation timing as part of a broader technological innovation system. The interactions between technologies reveal a cross-technology pattern of systemic elements, reported at the end of the results.

TABLE 1 Coding approach and structures.

Code	Explanation
Within-case analysis: mapping of key events and developing the case narrative	
What was the event?	Patent: patent filing, expiry or abandonment; basic research: focusing only on technology development; applied research: using technology to produce a component or object in general, that is, proof-of-concept for application; company: either establishment of company or launching of ceramic AM in some form; prior technologies used in ceramic AM innovation
When was the event?	Timing of scientific publications, patents, company histories
Where did the event take place?	The affiliations of scientific publications, company histories
Who was involved in the event?	The affiliations of scientific publications, acknowledgements, company histories
What were the connections between subsequent events either for the same or one of the other technologies?	Citations, cross-citations, mentions, acknowledgements, companies' historic
Analysis of within-technology patterns: identifying the emergence and interplay of system component innovations	
B: Birth	Prior innovation initiation; ceramic AM innovation initiation
C: Within-technology combination	Combining pre-existing technologies in a novel way
I1: Within-technology integration	Integrating system components developed for and within the same technology
D: Within-technology research and development	Basic research; applied research; commercialization (relevant technology or ceramic AM technology)
Analysis of cross-technology interactions: identifying the systemic elements concerning cross-technology interrelations	
K: Knowledge transfer	Transferring or using knowledge from the parallel technology development path
I2: Cross-technology integration	Integrating system components from other technologies

Abbreviation: AM, additive manufacturing.

4 | FINDINGS

4.1 | Initiation and evolution of AM ceramic technologies

4.1.1 | Case 1. Solid material extrusion (filament-based)

The technology of ceramic injection moulding started to develop already in the 1930s, but in the early 1980s, it became a cost-effective manufacturing solution. AM technology utilizing material extrusion was first invented in 1989 and registered under the name of fused deposition modelling (FDM). The term FDM is now trademarked by Stratasys Inc., a company co-founded in 1989 by S.S. Crump, the inventor of material extrusion. Currently, the names fused filament fabrication and solid freeform fabrication are also used. However, it is not widely known that one earlier patent from 1985 from a Finnish inventor V.K. Valavaara in Canada exists and that was later assigned to Stratasys Inc. So, the innovation of material extrusion using polymer filaments was initiated in the 1980s combining technology from polymer injection moulding (the old technology) and computer numerically controlled (CNC) mechanics with suitable software to steer the process of adding material in layers (the new technology) [B, C, I]. As FDM technology started to diffuse in the 1990s, the invention to combine ceramic-infused polymer feedstock with FDM technology was done in 1995 by S. Danforth at Rutgers University [B, C], followed by a patent in 1996. The majority of the first research was conducted by Danforth's research team at Rutgers University, and it was funded by AlliedSignal (known as Honeywell today), DARPA and the U.S. Navy.

Basically, every FDM (or fused filament fabrication [FFF]) AM machine can produce ceramic parts. However, the process requires embedding ceramic material into polymer filament, which demands basic research [D]. The part produced with material extrusion technology needs to be debinded where the binder polymer is removed, and the ceramic part is sintered causing shrinking and requiring further research [D]. After the developed technology matured into usable solutions, two distinct phases of applied research streams [D] followed to discover where to use this new technology, one focused on using this technology to produce components for signal processing and the other one for producing biomedical lattices for medical use.

The expiry of FDM patents speeded up the diffusion of the technology from 2014 onwards, which then skyrocketed the market for FDM AM machines [I1, D]. Influential FDM ceramic patents expired in 2016. The explored data shows that commercial producers of ceramic filaments started to emerge after that [D]. Also, the first European research projects [D] (with funding both for single companies and industry–university consortia) took place in this timeframe, focusing on ceramics applications in general and more in-depth medical applications and accelerated commercialization. Figure 1 summarizes the events for filament-based solid material extrusion technology emergence in a timeline.

The case of filament-based solid material extrusion illustrates a pattern of how this new AM technology emerged by combining parts and modules of the previous injection moulding technology with new

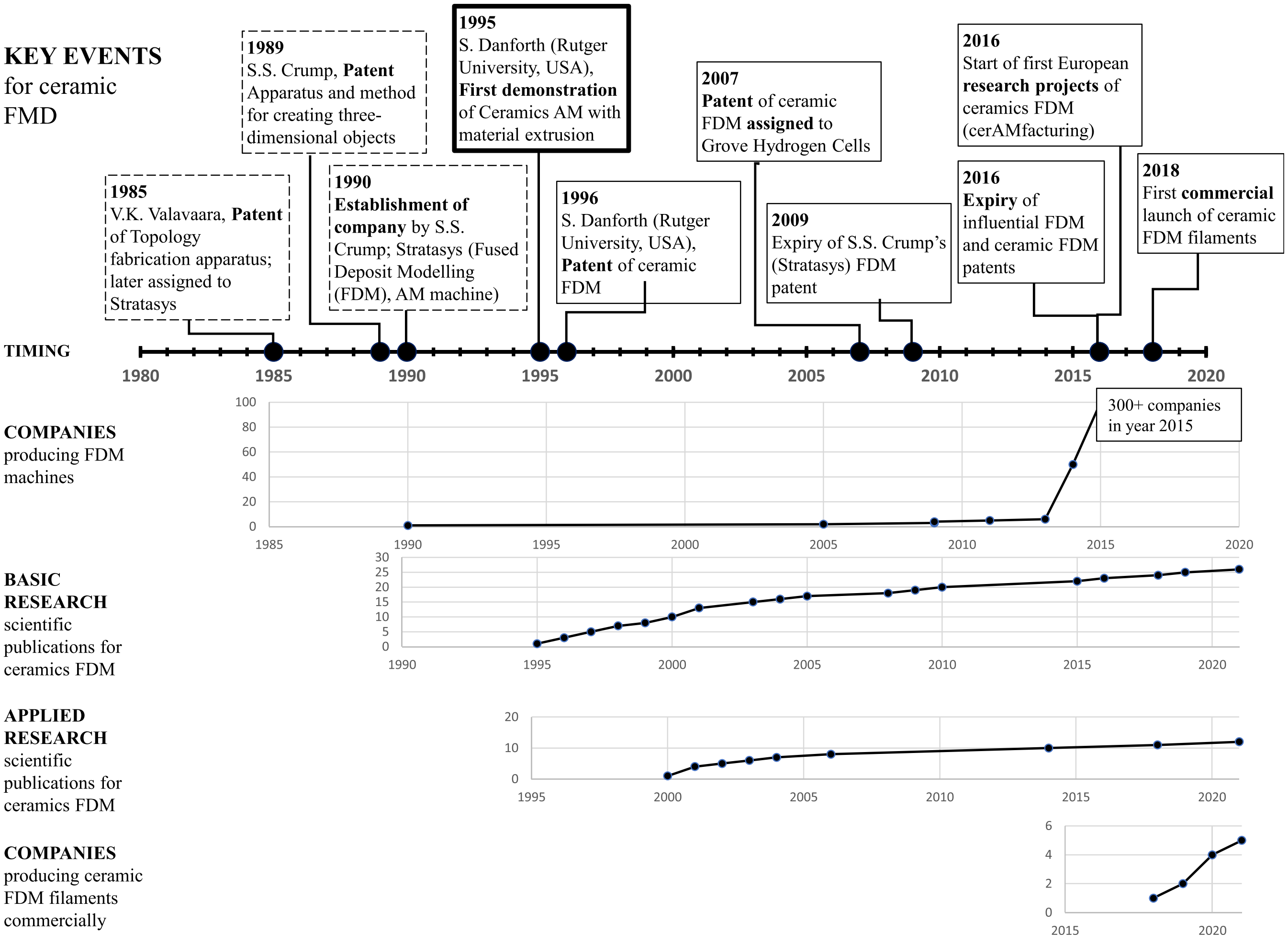


FIGURE 1 Timeline of key events for filament-based solid material extrusion. *Note*: Events preceding the focus on ceramic additive manufacturing (AM) are marked with dashed line rectangles; the key initiating event is indicated with a thicker solid line. [Colour figure can be viewed at wileyonlinelibrary.com]

insights [C, I1]. The case also shows how basic research on the ceramic AM technology started in 1995 [D], about 5 years after the first polymer FDM company emerged and about 10 years after the first patent was filed. Substantial applied research started to grow from 2000 onwards [D]. At first sight, the timelines of basic and applied research seem to illustrate how applied research follows more basic research. At a second glance, the timeline illustrates how research in companies and universities take turns and in combination develop the technology.

This case finally shows a pattern of how companies emerged initially that sold both AM production technology and filaments [D, C]. Later, universities took the turn to combine ceramics and after companies emerged that specialized in selling ceramic filaments. The filament is a complementary good, required as part of the system component of systemic innovation. There is a gap in data between the invention and before commercialization of filament. Based on publicly available data we cannot see the applications where ceramic AM was used during the period of patent duration.

4.1.2 | Case 2. Solid material extrusion (pellet-based)

After the invention of filament-based material extrusion, A. Bellini together with L. Shor and S. Güceri invented a new extrusion nozzle that allowed to use ceramic infused pellets as feedstock for material extrusion (in 2005) [B, C]. The analysis of the citations shows that the original FDM process as well as ceramic FDM, conducted by Danford's research group, was greatly used for this innovation [K, I2] and the applied research with the earlier technology was well applicable for this invention [I1, D].

Additional development and learning from the earlier technology led later to the commercialization of this new technology by two different companies [K, D]. Originally the companies started developing more generic pellet-based AM machines and added the necessary functionalities of ceramic pellets later, as shown in Figure 2. The logic for commercially developing this type of machine was to find a market segment from cost and material point of view as stated by the other

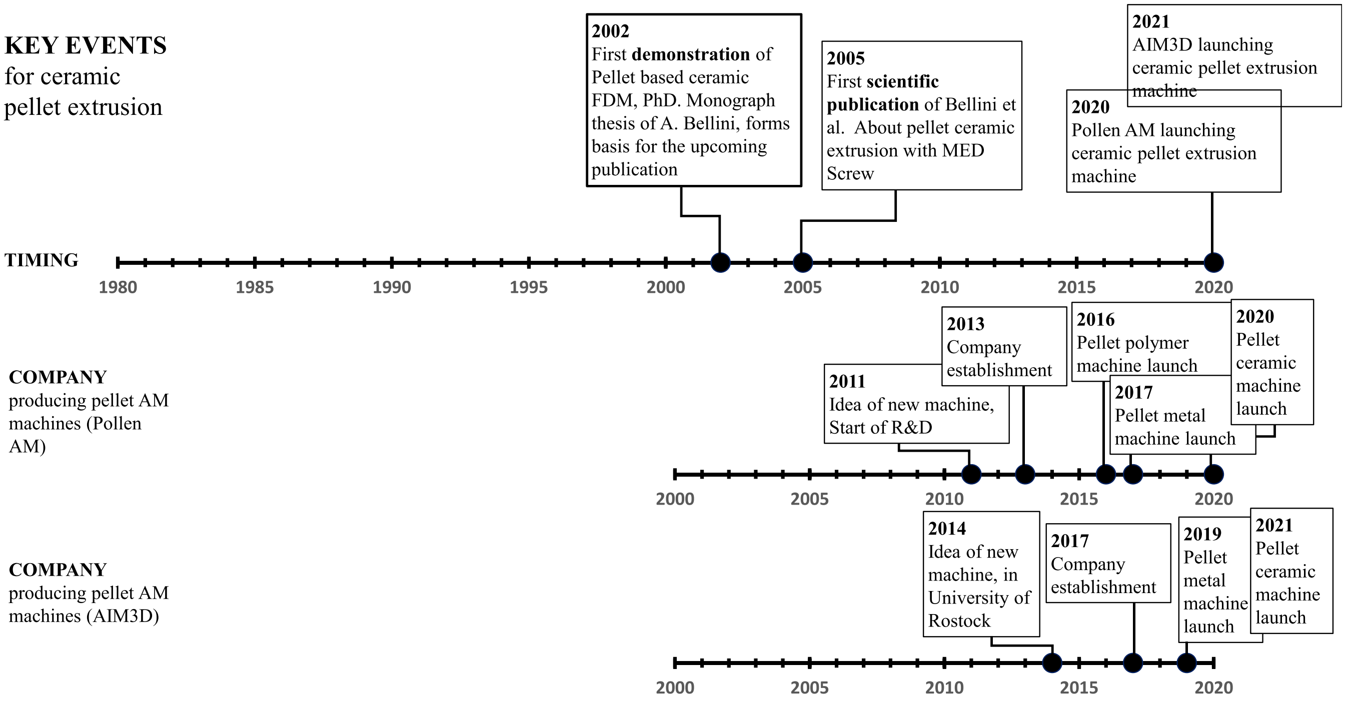


FIGURE 2 Timeline of key events for pellet-based solid material extrusion. [Colour figure can be viewed at wileyonlinelibrary.com]

commercial company: 'AIM3D GmbH was founded not just with the aim of simply building another 3D printer, but to overcome the limitations of materials and to revolutionize the additive manufacturing market from a cost point of view.' (company historic of AIM3D, accessed 2021). This commercialization phase illustrates how subsequent materials were applied in material extrusion using pellets [D, I1]. The company Pollen AM subsequently used polymer, metal and ceramic pellets, the AIM3D company that emerged later, started directly with metal pellets before working with ceramic pellets. The order seems logical. Working with polymer pellets is easier than working with metal or ceramic-infused pellets, mainly due to software.

Case 2 shows a pattern of how scientific work, mostly taking place under another technology, preceded the application of ceramic pellets by almost two decades [K, I2]. Pellet-based AM technology illustrates therefore a more classical straightforward example of science-based technology development that benefited directly from the development and applied research of ceramic FDM, as their applications are similar despite the small difference in the manufacturing process.

4.1.3 | Case 3. Liquid material extrusion: direct-ink writing

The starting point of inventing liquid-based material extrusion can be seen in a patent by J. Cesarano III and P.D. Calvert in 1997 in cooperation with Sandia Research Corporation. This patent cites the FDM patent by S.S. Crump and combines this technology the knowledge of J. Cesarano III based on his previous studies of ceramic slurries done in the 1980s [K, I2, B, C]. Sandia Research Corporation is a Lockheed Martin Company and a wholly-owned subsidiary of Honeywell. The majority of basic research for direct ink writing or 'robocasting' following the first inventions was done in collaboration with Sandia and the University of Illinois where Professor J.A. Lewis (who is involved in many other AM technology inventions) led the team [D]. This basic research following the patent utilized the mechanics of FDM AM [K], but the change of feedstock required a series of research to fine-tune the extruder, the ceramic feedstock and the software [I1, D]. Major funders for the research at this early phase were Sandia, the United States Department of Energy and the U.S. Army. After the technology was sufficiently developed, the publications of applied research papers began to appear in 2001 [D].

This research, however, did not lead directly to commercialization, as suitable applications had not been identified, yet. When the commercialization happened, it was only through the university spin-off company. The main inventor of the technology J. Cesarano III explained: 'In the year 2000, there was not an application for the technology within Sandia, and there were not any private-sector companies interested in licensing the technology. The robocasting process was a little ahead of its time. In an attempt to find a commercial niche, Robocasting Enterprises was started as a part-time garage operation. Finally, in 2007, a commercial opportunity emerged for manufacturing advanced filters for purifying molten metals. Robocasting Enterprises LLC (also frequently known as just Robocasting) was born, and operations expanded into a full-time manufacturing facility with three former Sandia employees: Joe Cesarano, President; John Stuecker, Vice President; and Mike Niehaus, Senior Engineer.' (company historic of Robocasting, accessed 2021).

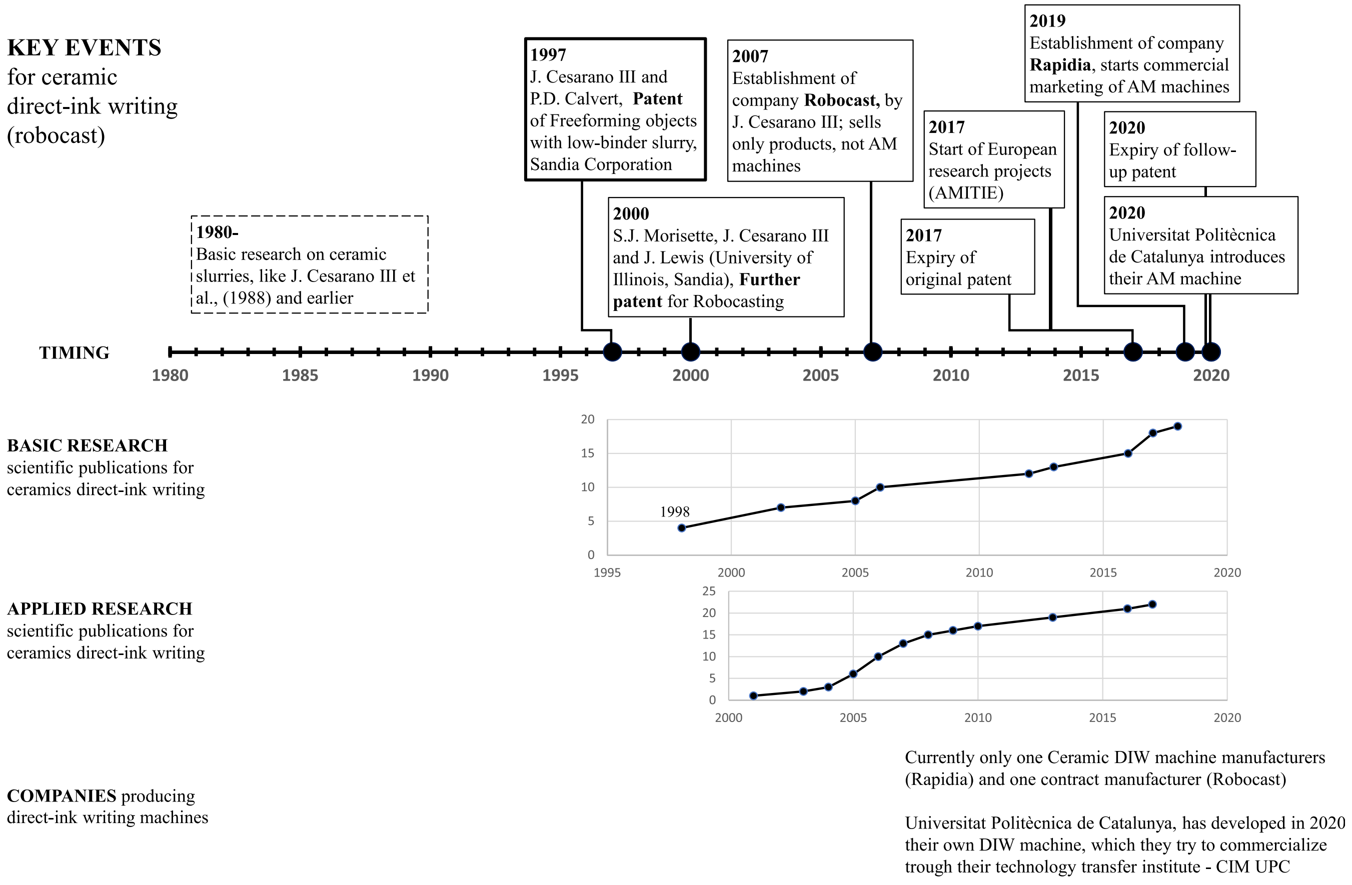
After the expiry of relevant patents in 2017, a European research project started development work toward a direct-ink writing machine by Universitat Politécnica de Catalunya in 2020 [D], with an intent to commercialize it, although without clear application examples. Also, in 2019 Canadian company launched a ceramic AM machine using a slightly modified technology of Robocasting after 2 years of R&D [D]. Figure 3 illustrates this development.

This case illustrates patterns, some of which are similar to the previous cases while others are different. The invention of the technology is science-based, similar to the second case. Collaboration between specialized research companies, a company applying the technology (research spin-off), academic institutes and governmental institutes was important during the early development stages. Governments seemed to interfere in different ways, as funding agencies, as well as lead users (especially for military technology).

A special pattern in Case 3 is that one company developed the production technology, and only that company initially used the technology to sell goods. In contrast to Case 1, there seemed to be no separate market for the production technology. It could be that the market for direct-ink-based liquid material extrusion was not mature yet and hence the market for the production equipment did not exist directly. It could also be that robocasting was very specialized production equipment that is hard to copy by other companies and that the company wanted to keep it and thereby create a monopoly position for the duration of the patent, although they were willing to license the technology at least for research purposes. This seems to have changed when relevant patents to protect the technology expire.

4.1.4 | Case 4. Liquid material extrusion: freeze-form extrusion fabrication

While direct ink writing (Robocasting) increasingly got away from using solid organic binders (harmful because of debinding, where organic binders are turned into harmful gasses), there was still a need to use some liquid solvent binders (due to the need to accurately create the desired form). The rationale behind freeze-form extrusion fabrication was to find a solution for getting rid of organic binders completely [B]. One solution was to use just water as the binder (imagine a sand cake made of moist sand). The challenge then was to make ceramic objects in this way accurately. In the 1980s, a technology called freeze-form slip casting was developed [B], where the ‘sand cake’ object was frozen in its mould, removed from the mould, frozen to dry it (debinding) and sintered into solid ceramic. In the late 1990s, after the AM concept was already known, an accurate technology for creating ice objects was invented based on the mechanics of FDM combined with a new extruder and software [K, B, I2].



1980-
Basic research on ceramic slurries, like J. Cesarano III et al., (1988) and earlier

1997
J. Cesarano III and P.D. Calvert, **Patent** of Freeforming objects with low-binder slurry, Sandia Corporation

2000
S.J. Morisette, J. Cesarano III and J. Lewis (University of Illinois, Sandia), **Further patent** for Robocasting

2007
Establishment of company **Robocast,** by J. Cesarano III; sells only products, not AM machines

2017
Start of European research projects (AMITIE)

2017
Expiry of original patent

2019
Establishment of company **Rapidia**, starts commercial marketing of AM machines

2020
Expiry of follow-up patent

2020
Universitat Politècnica de Catalunya introduces their AM machine

Currently only one Ceramic DIW machine manufacturers (Rapidia) and one contract manufacturer (Robocast)

Universitat Politècnica de Catalunya, has developed in 2020 their own DIW machine, which they try to commercialize trough their technology transfer institute - CIM UPC

FIGURE 3 Timeline of key events for direct-ink-based liquid material extrusion. [Colour figure can be viewed at wileyonlinelibrary.com]

The first research group to combine freeze-form slip casting (ceramic) and rapid freeze prototyping fabrication was from the University of Missouri in 2006 [B, C]. In the following years, a set of studies were conducted where the technology was further developed [D]. The original invention was followed by a patent in 2012, which was applied by the same research group that made the first publications of this technology. However, the phase of applied research did not fully even start (only three publications), and the patent was abandoned in 2016, without being licensed to anyone. Figure 4 illustrates this development.

Although freeze-form extrusion fabrication did not become a commercially viable technology as such, the data show that developments of the software and extrusion were transferred back to direct ink writing technology [K]. That allowed the feedstock to be developed into water-based, and this became the solution for company Rapidia's commercial technology [K, I2]. In this way, at first sight, Case 4 seems to illustrate a pattern of an unsuccessful technology because it was not commercialized. However, the knowledge gained could be used to develop another technology further [K, D].

4.2 | Systemic elements from the system components of a single technology

The analysis shows that AM technologies did not appear from out of nowhere, but previous technological developments paved the way for inventing the technology concepts of AM. The mapping of technology emergence in the four AM technologies revealed different pathways for ideation, basic research, applied research, material development and application development, each of which needed to mature sufficiently before the innovations became useful and commercially available in the market.

Figure 1 shows the timing of key inventions for FDM, but different earlier inventions and applications were required as enablers for those inventions. Polymer injection moulding was an important predecessor, and also the development of the stepper motor, suitable computer numerical control system and software together with design software were needed to create the necessary digital designs. The original rationale for the invention was to substitute foundry patterns made by carpenters and other craftsmen, as those skills were becoming rare and to create prototypes for design purposes. Both foundry patterns and design prototypes remain important application domains for AM.

As polymer injection moulding was a preceding innovation and thus 'embedded' in FDM technology, it enabled to combine ceramic injection moulding (similar to polymer injection moulding) to this technology, as was done in 1995. The initiation is visible in the data through a first demonstration and a patent applied soon after. Ceramic injection moulding required the additional manufacturing steps of de-binding and sintering (accompanied by shrinking and potential fragility), so this was then applied to ceramic FDM as well. The series of basic research in Figure 1 shows that, after the invention of ceramic FDM, the manufacturing technology was developed over several years. After the manufacturing technology reached a sufficient maturity level, applied research followed, with the aim of discovering possible applications feasible for this technology. After demonstrating initial proofs of concepts for applications and after the expiry of patents, the commercial diffusion started. Commercialization happened via ceramic filament feedstock as any FDM machine can be suitable (thus creating a feedstock restriction to only a handful of filament types).

Similar phases of development can be identified in the other cases as well, with some differences. In Case 2 (pellet-based) some existing inventions were combined in the ideation and basic research

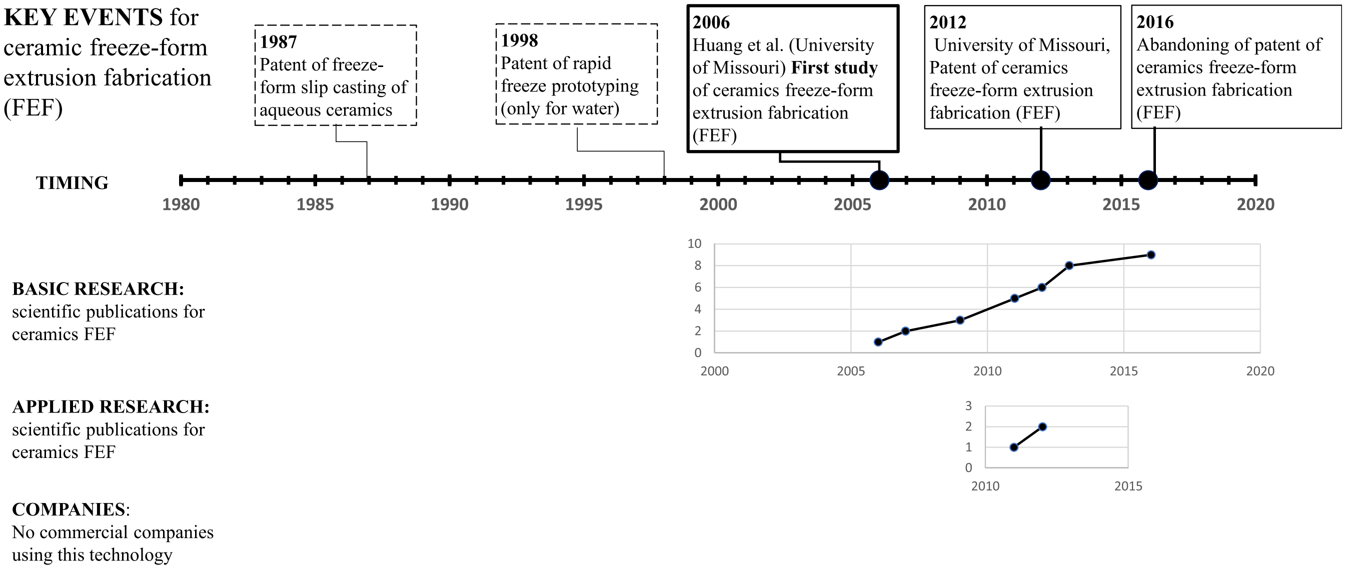


FIGURE 4 Timeline of key events for freeze-form liquid material extrusion. [Colour figure can be viewed at wileyonlinelibrary.com]

phase, but the applied research phase was skipped, leading directly to the commercialization of both specific AM machines and suitable feedstock (with an alternative to source material freely, and thus solving the feedstock restriction of ceramic FDM). These differences can be explained by the systemic evolution, to be analysed further in the next section. What is different in Case 2 compared with the other cases is that, to our knowledge, there was no patent filed about this technology, the technology initiation is visible in the data in the published doctoral dissertation, and the technology evolution benefited from knowledge from a parallel technology development path.

Cases 3 and 4 show similar patterns of technology initiation where the idea of the innovator and the team combining earlier technology knowledge was followed by combining the system components. Initiation for the innovation happened by patenting in Case 3. This initiation was then followed by a similar pattern of basic research and applied research as Case 1. In Case 4, the data shows that initiation took place through scientific publications, and this happened 6 years prior to patenting. Although Case 4 then shows a similar pattern of basic research increase, followed by applied research, albeit with a small amount, the time between initiation and patenting was rather long.

During the innovation evolution, commercialization followed the previous phases. In the commercial diffusion, variation took place among the studied technologies. In Cases 1 and 2, the technology and material were developed first, and these were made commercially available and only the users or their customers (i.e. end-users) started to develop relevant applications. In Case 3, the manufacturing technology and material were commercially mature, but not sold, and the commercial market was found by selling products manufactured by the inventor of the specific technology. One potentially interesting blind spot of technological evolution emerged in the data of Cases 1 and 2. After patenting, the traces of applications (where the technology was then used) disappeared from publicly available data. However, the funders of the research and patenting organizations gave a weak signal that ceramic (FDM or pellet-based) technology was identified as suitable for the military, aviation, energy and medical sectors. Also, the fact that patents were not abandoned and assigned forward also reinforces this weak signal. Case 4 then shows a different pattern as it never became commercialized, and its patent was abandoned.

4.3 | Systemic elements from the interrelations of the different technologies in the same technology family

Our analysis reveals that the *technological connections between the technologies* (i.e. learning from a prior technology) and incremental modifications reduced the need for applied research and, thereby, enabled a shorter development time. This is exemplified in the relation between the two solid material extrusion technologies. Ceramic FDM's ceramic-infused filaments make the extrusion of material accurate but reduce the possibilities for material choices as the number of available polymer-ceramic combinations is limited. The material preceding filament is polymers in pellet form and ceramics in powder form and this was used as a starting point for the pellet-based ceramic AM, where extrusion would take place directly from polymer pellets and ceramic powder. This invention clearly benefited from the earlier developments of filament-based extrusion and seems to have become successful. Also, the research groups where these two came from had close ties. Additional applied research was not needed because the research on ceramic FDM was directly applicable to this solution as well. This technological solution led then into commercial diffusion in a straightforward manner, through AM machine manufacturers.

The findings also show that *sharing knowledge and combining technologies from different domains* enabled the creation of novel technology solutions. This is exemplified by the introduction of direct-ink writing as an AM technology. After the invention of ceramic FDM took place in 1995, the knowledge of ceramic FDM started to diffuse through conferences and scientific publications. Consequently, in 1997, another already existing ceramic manufacturing method, ceramic fabrication from slurries, was combined with the new AM concept. In this case, the mechanics of the FDM machine was used as the starting point for the development, but then developed further by changing the extruder, feedstock and software. This is how the invention of robocasting (direct ink writing of ceramics) was invented. Similarly, to ceramic FDM, also robocasting combined the existing research and technology of ceramic slurries and moulding of slurries with the concept of AM. Robocasting Enterprises never started to sell ceramic AM machines, but with their technology and knowledge, they were able to create a niche market for products they started to produce with AM technology. These products were suitable for foundry industries (filters for melted metals) and laboratories (inert and hard-wearing labware and thermal analysis consumables).

The *need for safe and environmentally friendly materials* inspired another development path in the technologies, apparent in how new alternatives were sought within liquid material extrusion technologies and benefiting from solid material extrusion technologies, too. The invention of FDM can be traced to the starting point for rapid freeze prototyping, where water was used instead of polymer material and the whole process happens in freezing temperatures. This way a technology was developed where AM could be used for manufacturing ice sculptures. Freeze-form extrusion fabrication was invented by combining water-based ceramic slurries and freeze-form AM method.

The freeze-form AM technology was further studied and patented, but the patent was abandoned only 4 years after the patent application. However, during the basic research phase of this technology, there was a special focus on extruding the water-based slurry accurately. This was needed as the extrusion with water-based slurry was more demanding than with using organic solvents. This knowledge was then transferred back to direct-ink writing technology development, and the second commercial company manufacturing the machine uses only water-based ceramic slurries (but not in freezing temperatures). The commercial diffusion of direct-ink writing machines then started from this.

Figure 5 shows the development paths of each technology over time, and connections from the preceding ceramic extrusion AM are

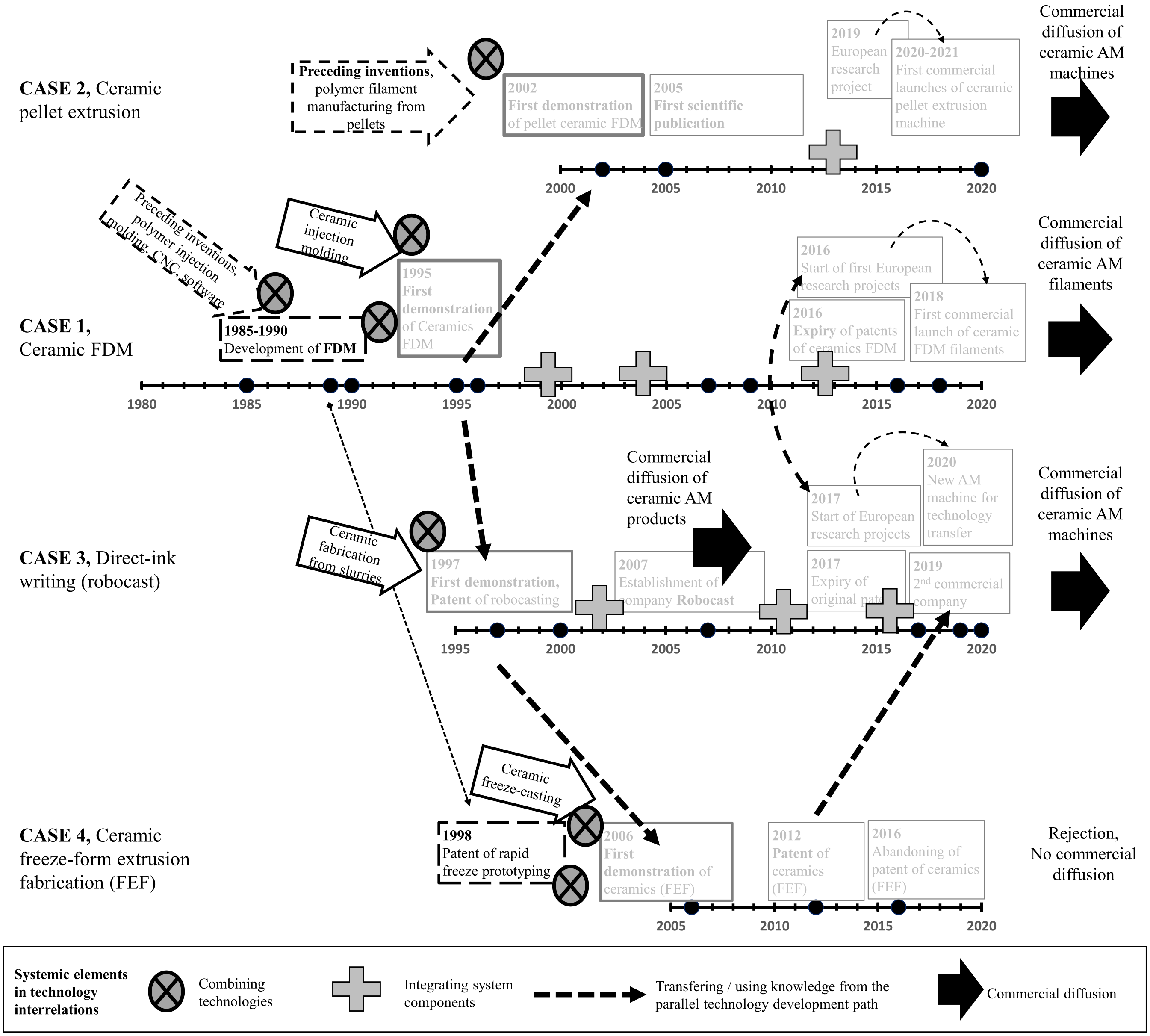


FIGURE 5 Systemic elements in technology interrelations of ceramic additive manufacturing (AM) technologies. [Colour figure can be viewed at wileyonlinelibrary.com]

illustrated with dashed lines. Dashed arrows illustrate the interrelation of technology development across technologies within the same family. Curved dashed arrows illustrate the interrelation of EU projects that were mentioned to be significant milestones for the companies commercializing the specific ceramic AM technology.

The separate cases and their interaction demonstrate how different companies, governmental institutes and research institutes together shape the path of technology development and application. International and inter-industrial collaboration, for example, as part of EU-funded research activities, may facilitate linkages between separate technology paths. Mechanisms that facilitate technology development between countries and different industries can play a pivotal role in sharing information within and between the pathways of different technologies and, thereby, speed up the emergence of systemic innovations, activate technology commercialization and save resources.

5 | DISCUSSION

This study contributes to research on technology initiation and evolution concerning systemic innovations by showing evidence of the slow and unplanned emergence and evolution of ceramic AM and the interconnections of multiple technology trajectories over time. The main research question is: *How do systemic innovations emerge, through the interaction of system components and multiple technologies?* We explored the initiation and evolution of ceramic AM technologies over the past decades. Ceramic AM here required the parallel development of manufacturing technologies, materials, products and commercial applications, thereby offering evidence of its nature as a systemic innovation (following Martinsuo & Luomaranta, 2018). The findings offer AM-specific evidence and complement previous research that has covered the introduction of systemic innovations in the domains of other technologies and contexts, focusing on a specific technology or system component only (Alin et al., 2013; Andersen & Drejer, 2008; Lavikka et al., 2021; Lindgren, 2016; Lindgren & Emmitt, 2017).

This study revealed how the momentum for innovation is built through a single person or organization experimenting with an emerging technology, identifying the core application and engaging with a broader network to explore and develop the technology potential openly. Gillier and Piat (2011) studied emergent technologies and concluded that application identification is an important phase for emerging technologies. Our findings support this finding but portray application identification as part of the longer continuum of parallel and sequential developments in the case of ceramic AM as a systemic innovation. Where Lindgren and Emmitt (2017) concentrate on the diffusion of a selected systemic innovation in the construction industry, our study adds to this by showing evidence over a longer period of time, covering AM technology initiation and evolution more broadly.

5.1 | Innovation initiation through problematization and knowledge from previous technologies

Our analysis showed that one or more persons within organizations began to problematize the present state, which consequently led to the initiation of technology development. For example, they experienced problems or needs concerning the disappearing artisan skills, speed of design prototypes, ceramics that possess very good characteristics for modern applications and harmful additives in feedstock. This initiation reflects an innovator-centric start for systemic innovations in which individuals were most important (Midgley & Lindhult, 2017) and lends support to the centrality of application identification of emergent technologies (Gillier & Piat, 2011). The accidentality in the simultaneous development of the different system components concerning the same or neighbouring technologies, however, contradicts the formalized approach to the front end of systemic innovations where a single organization would determine the pace of development or orchestrate the innovation process (Takey & Carvalho, 2016). Our findings reveal informal approaches and long timeframes in the early phases of systemic innovations and draw attention to technology combinations already preceding the application domain choice.

The findings emphasized learning and knowledge acquisition from existing technologies as important drivers in the studied ceramic AM technologies. Often, the initiation of innovation processes was facilitated by the freedom to experiment and uncertainty-tolerant institutional support, connected with longer-term commercial interests. The organizations experimented with technologies previously used for other purposes and sought knowledge from other organizations when developing the technology and identifying its feasible application domains. The findings thereby offer new AM-specific evidence to supplement previous research concerning the attempt to combine technology knowledge from multiple sources (Arthur, 2009; Arthur & Polak, 2006; Murmann & Frenken, 2006). In response to the first sub-question, 'How are systemic innovations initiated?', we derive the following proposition.

> **Proposition 1.** The initiation of systemic innovations results from an individual's or small group's inspired idea of a problem-driven application domain, awareness of and access to technology knowledge from other application domains, courage to combine technology knowledge and an organization's willingness to experiment with technological alternatives under high uncertainty. Systemic innovations, thereby, begin earlier and in a fuzzier form than a simpler technological invention.

5.2 | Innovation evolution through the parallel and sequential development of system components and technology interrelations

The second sub-question was 'How do systemic innovations evolve?'. The studied ceramic AM technologies evolved through logical steps of researching and developing system component technologies over time. The evolution in all the system components—materials, manufacturing technologies, processes, goods and services—need to be developed for commercial applications and they all are needed for commercial diffusion. Yet, the development paths of the AM cases differed, depending on the availability and timing of useful system components for the specific technology, access to knowledge about system components developed for other (similar) technologies and the organizations' willingness and capability to adapt the technologies for their own application domains. Compared with the research on chaotic processes of systemic innovations (Ortt & Kamp, 2022) and innovation cycles paced by more stable periods (Tushman & Rosenkopf, 1992), our findings draw attention to serendipity at the intersections of parallel and sequential system component development paths.

A certain maturity and suitable timing are needed for core technologies (i.e. mechanics, material properties and software), before the subsequent development of technology-enabling solutions (i.e. application development and market creation) is possible. This sequential phenomenon of technology adoption from the concept to manufacturing and goods is identified as relevant for the adoption of AM technologies among users (Steenhuis et al., 2020), but we show that it begins much earlier during the emergence of the technology. Compared with product-centric technology commercialization knowledge centering on one technology development path only, our findings witnessed the importance of coalescing parallel development paths and serendipitous timing of sequential development paths of within-technology system components, for the systemic innovation to succeed. The inter-organizational setting implies a need for some type of coordination in basic and applied research and technology commercialization to optimize the timing of development paths. For the within-technology system component interactions, we propose as follows.

> **Proposition 2.** The evolution of systemic innovations requires organizations' awareness of previous and parallel system component development paths as well as their willingness and capability to adapt related but potentially unfamiliar technologies in their focal application domain. All system components need to reach a sufficient level of maturity as required by the emerging market interest so that a commercial application can be developed and diffused successfully at the right time.

A third sub-question was stated: 'What are the interrelationships between the four AM technologies during the emergence of systemic innovations?'. Interrelationships and heritage of solutions in the same family of AM technologies were evident in the findings in terms of temporal simultaneity and sequence, as well as technology dependence and complementarity. Arthur (2009) and Arthur and Polak (2006) identified this phenomenon and described interrelations as building blocks of technology development. Our findings support this view and add the element of introducing the building blocks stemming from outside of the focal AM technology. The analysis showed parallel and subsequent development as well as dependence and complementarity among innovations as sources of interrelations between technologies.

The findings supplement existing knowledge of systemic innovations by showing evidence about the necessity of parallel and sequential development of other technologies (Arthur, 2009). The evolution of ceramic AM material extrusion technologies benefitted from modules that were part of previous material and technology innovations, in that certain development steps could be quickly surpassed by adopting the solution from a parallel technology development path. However, even if some technologies proved to be good enough, not all innovations ended up as commercially viable. Commercial termination in the intended technology use did not mean that the knowledge created could not be used in other development trajectories. The cases illustrate that the evolution of technology requires close collaboration between different types of actors: companies (developing and using AM technology), governmental institutes and research institutes. For the cross-technology interactions, we propose as follows.

> **Proposition 3.** The emergence of systemic innovations benefits from (and can be speeded up through) three types of inter-technology knowledge transfer: (1) inspired experimenting with materials or applications from other technology domains, (2) transferring system component knowledge from parallel technology development paths in the same technology family and (3) organizations sharing inter-technology knowledge in pre-competitive research and/or during full-scale technology commercialization.

5.3 | Implications to systemic innovation diffusion

This study contributes to technology diffusion research by suggesting that the nature of technology-based systemic innovations requires a more advanced perspective than the classical innovation–diffusion paradigm. The classical innovation–diffusion paradigm indicates how after the invention of a technology a project can be organized to turn the invention into an innovation, that, if the project is managed well, will start to diffuse successfully after introduction (Cooper, 1990; Foster, 1985, 2000; Rogers, 2005). Our work shows that this paradigm needs to be elaborated and complements the results of Schroeder et al. (1986) and Van de Ven et al. (2008) in several ways.

Firstly, to study the initiation and evolution of systemic innovations, it is important to start tracking the developments earlier on, even before the invention of technologies. Crucial components of the system are developed in other technologies, such components may be usable for novel applications, and access to them may shape the evolution of a later invention. Secondly, instead of one diffusion pattern, both subsequent diffusion processes (first for manufacturing technologies and materials and then for products that can be created using these manufacturing technologies and materials) and parallel diffusion processes (of complementary and competing technologies) need to be studied in combination to understand the initiation and evolution of systemic innovations. During evolution, some diffusion paths may terminate prematurely, but they may still be a source of new knowledge for the other technologies being developed simultaneously. We, thus, showed evidence that each technology has systemic traits within its own development path, but also these technologies have systemic interrelations with each other. Instead of organization-specific innovation projects, the attention needs to be directed at inter-organizational programmes of multiple projects.

> **Proposition 4.** The successful development and diffusion of systemic innovation require setting up complex inter-organizational programmes that need to endure high uncertainty. Such programmes develop multiple parallel and sequential innovations concerning the required system components, carried out by different organizations, and they benefit from openness toward technology developments elsewhere. The goals and application domains of such programmes are not known in the beginning, and therefore the development and diffusion of systemic innovations will benefit from international and national institutional support.

6 | CONCLUSION

6.1 | Contributions

This study offers new knowledge on the emergence of systemic innovations specifically concerning four ceramic AM technologies. Firstly, the findings showed that the innovation is systemic within each technology (i.e. needs multiple system components) and these system components emerge and evolve in parallel and sequentially. These findings give shape to the initiation and early evolution of systemic innovations by revealing their temporal patterns, potentially also explaining the slow progress of AM technologies specifically and systemic innovations more generally. We offered AM-related evidence to add to the development paths other types of systemic innovations (von Pechmann et al., 2015), brought visibility to the timeline of AM emergence and thereby added to the dominantly cross-sectional AM research (Alin et al., 2013; Andersen & Drejer, 2008; Kang & Hwang, 2016; Lavikka et al., 2021; Lindgren, 2016; Lindgren & Emmitt, 2017; Mlecnik, 2013), and developed an inter-technology view to complement the dominantly inter-organizational view of systemic innovations (Takey & Carvalho, 2016).

Secondly, the results revealed the connections between the technologies within the same family and the beneficial learning from the development of other technologies during both the initiation and evolution of the technology. While the system components are normally developed in separate organizations in parallel and in sequence, organizations need to allow the development paths of system components to coalesce with each other at the right time through coordinated efforts of basic and applied research, which requires inter-organizational optimization of timing and system component development. Thereby, the findings complement previous innovation diffusion research that focused on the diffusion of singular innovations (MacVaugh & Schiavone, 2010; Meade & Islam, 2006).

Thirdly, the emergence and evolution of ceramic AM technologies were shown as a somewhat informal and even erratic process where the development paths are unforeseeable and cross industry boundaries. We revealed serendipitous knowledge transfer between parallel technology evolution paths, involving even deliberate ignorance of inter-technology competition and, rather, shared interest in solving relevant commercial and even societal problems. Some system component developments may appear unsuccessful and be abandoned, but they may still advance the progress of a systemic innovation elsewhere. These findings challenge the extant expectation of momentary consideration of success in technology diffusion in terms of adoption rates (Lundblad, 2003; Meade & Islam, 2006), reveal the complex inter-organizational constellations necessary for systemic innovation emergence compared with simple supplier-customer dyads in developing manufacturing technologies (Chaoji & Martinsuo, 2022) and demonstrate how the actual success of systemic innovations requires several inter-connected cycles of trial, error and learning within and among technologies over time (Ortt, 2010; Ortt & Schoormans, 2004).

6.2 | Practical implications

Because AM technologies and other systemic innovations, such as various novel solutions required for sustainability transitions, are now actively developed and face expectations both from commercial firms and the society at large, this study has some practical and managerial implications. Generally, understanding the nature of systemic innovations and the parallel and sequential paths for developing their system components is useful in understanding why the development proceeds slowly and in finding ways to speed up the innovation processes. Managers need alertness and supportiveness toward employees' problematization concerning new application domains and emerging technologies concerning them, to identify the original possibility for initiating a systemic innovation. Organizations need to ensure sufficient business intelligence that explores previous as well as ongoing system component technology development and supports employees' capabilities to adapt external technologies to their own needs. Organizations also need mechanisms to assess the maturity of system component technologies, monitor the trajectories of system component development internationally, and anticipate the emerging market demand, to optimize the timing of their own development processes. To benefit from inter-technology learning, managers can encourage problem-driven experimentation among the employees to discover new openings for systemic innovations, promote knowledge transfer between system components both within the firm and with external partners, and activate inter-organizational collaboration in research and technology commercialization. National and international research collaboration platforms and funding instruments will be imperative in supporting within-technology and inter-technology interactions to optimize the timing of pre-competitive research and technology commercialization.

Knowledge of the development of AM technologies over time, especially regarding the requirement of complementary innovations and technology trajectories, helps in understanding why and how innovation in one technology area can be complemented with other simultaneous innovations when pursuing innovation success and speeding up commercialization. As we revealed the long timeframes in the emerging and evolving ceramic AM technology, practitioners and funding institutions may benefit from identifying the key moments that are crucial for knowledge exchange during the development of systemic innovations. Especially, when key inventions exist and related technologies are sufficiently mature, an institutional intervention in terms of funding inter-organizational projects may speed up the commercial diffusion of the technology.

6.3 | Limitations and avenues for future research

This study is limited in terms of technology choices, the nature of data and the analytical framework. We studied four different technologies from one technology family and there are many more technologies under the group of ceramic AM technologies. Another choice of case technologies might yield different results, and this opens possibilities for further research. The historical event analysis method has its weaknesses, especially in terms of the data, which represents neither the whole population nor a random sample of occurrences (Van de Ven & Garud, 1993) in technological development. Also focusing on materials in the English language limits the validity; document data may be available also in other languages. A data-related limitation stems from the secrecy and confidentiality of certain information and decisions made by the actors, limited press coverage of events and limited access to event data by researchers (Bessagnet et al., 2021). In this study, we used scientific publications available through institutional library access and publicly available data, which limits the visibility of some of the details. Selected events could be explored separately with more detail, and key innovators could be interviewed to collect primary data to uncover the specific details of certain actions and events during the evolution path, to enable tracking events with more detail and revealing additional connections that are not publicly documented.

This study revealed that the evolution of systemic innovations features many different patterns. Therefore, future research could use this exploratory study as a starting point for the systematic identification of the patterns of evolution of systemic innovations. The development of different system components within a specific systemic innovation could be investigated over time, with observation and interview data in selected few industrial cases. Similarly, knowledge transfers and learning of system components between technologies could deserve further attention and could be investigated at the industry level, for example, through surveys. Also tracking of other AM technologies would increase the generalizability of the findings. The closely related technologies, such as metallic and polymer AM, could be worth looking into as their development history appeared as relevant already for ceramic AM, too.

ACKNOWLEDGEMENTS

This paper was inspired by and initiated during our previous research project I AM RRI (Webs of innovation and value chains of additive manufacturing under consideration of responsible research and innovation) which received funding from the European Union's Horizon 2020 research and innovation programme under the grant agreement no. 788361. An earlier version of this paper was presented at the Innovation and Product Development Management Conference 2022 (IPDMC). We thank the session chair and participants for the helpful feedback. We also thank the anonymous reviewers for their constructive and kind feedback.

DATA AVAILABILITY STATEMENT

Data sharing not applicable - no new data generated.

ORCID

Toni Luomaranta https://orcid.org/0000-0003-4968-3730
Miia Martinsuo https://orcid.org/0000-0002-0640-2911

REFERENCES

Agarwal, R., & Bayus, B. L. (2002). The market evolution and sales takeoff of product innovations. *Management Science*, *48*(8), 1024–1041. https://doi.org/10.1287/mnsc.48.8.1024.167

Alin, P., Maunula, A. O., Taylor, J. E., & Smeds, R. (2013). Aligning misaligned systemic innovations: Probing inter-firm effects development in project networks. *Project Management Journal*, *44*(1), 77–93. https://doi.org/10.1002/pmj.21316

Andersen, P. H., & Drejer, I. (2008). Systemic innovation in a distributed network: The case of Danish wind turbines, 1972–2007. *Strategic Organization*, *6*(1), 13–46. https://doi.org/10.1177/1476127007087152

Arthur, W. B. (2009). *The nature of technology: What it is and how it evolves*. Simon and Schuster.

Arthur, W. B., & Polak, W. (2006). The evolution of technology within a simple computer model. *Complexity*, *11*(5), 23–31. https://doi.org/10.1002/cplx.20130

Artto, K., Martinsuo, M., Dietrich, P., & Kujala, J. (2008). Project strategy: Strategy types and their contents in innovation projects. *International Journal of Managing Projects in Business*, *1*(1), 49–70. https://doi.org/10.1108/17538370810846414

ASTM Standard. (2012). *Standard terminology for additive manufacturing technologies* (Vol. 10.04). West Conshohocken, PA: ASTM International.

Bergman, N., Haxeltine, A., Whitmarsh, L., Köhler, J., Schilperoord, M., & Rotmans, J. (2008). Modelling socio-technical transition patterns and pathways. *Journal of Artificial Societies and Social Simulation*, *11*(3), 1–32.

Bessagnet, A., Crespo, J., & Vicente, J. (2021). Unraveling the multi-scalar and evolutionary forces of entrepreneurial ecosystems: A historical event analysis applied to IoT Valley. *Technovation*, *108*, 102329. https://doi.org/10.1016/j.technovation.2021.102329

Brezis, E. S., Krugman, P. R., & Tsiddon, D. (1991). Leapfrogging: A theory of cycles in national technological leadership. *The American Economic Review*, *83*(5), 1211–1219.

Chaoji, P., & Martinsuo, M. (2019). Creation processes for radical manufacturing technology innovations. *Journal of Manufacturing Technology Management*, *30*(7), 1005–1033. https://doi.org/10.1108/JMTM-08-2018-0233

Chaoji, P., & Martinsuo, M. (2022). Managers' search practices at the front end of radical manufacturing technology innovations. *Creativity and Innovation Management*, *31*(4), 636–650. https://doi.org/10.1111/caim.12524

Chen, Z., Li, Z., Li, J., Liu, C., Lao, C., Fu, Y., Liu, C., Li, Y., Wang, P., & He, Y. (2019). 3D printing of ceramics: A review. *Journal of the European Ceramic Society*, *39*, 661–687. https://doi.org/10.1016/j.jeurceramsoc.2018.11.013

Chesbrough, H. W., & Teece, D. J. (2002). Organizing for innovation: When is virtual virtuous? *Harvard Business Review*, *80*(8), 127–135.

Coccia, M., & Watts, J. (2020). A theory of the evolution of technology: Technological parasitism and the implications for innovation management. *Journal of Engineering and Technology Management*, *55*, 101552.

Cooper, R. G. (1990). Stage-gate systems: A new tool for managing new products. *Business Horizons*, *33*(3), 44–45. https://doi.org/10.1016/0007-6813(90)90040-I

Crawford, C. M. (1991). *New products management* (3rd ed.). Irwin.

Day, G. S., & Schoemaker, P. J. H. (2004). Driving through the fog: Managing at the edge. *Long Range Planning*, *37*, 127–142. https://doi.org/10.1016/j.lrp.2004.01.004

Deckers, J., Vleugels, J., & Kruth, J.-P. (2014). Additive manufacturing of ceramics: A review. *Journal of Ceramic Science and Technology*, *5*(4), 245–260.

Dosi, G. (1982). Technological paradigms and technological trajectories. *Research Policy*, *11*, 147–162. https://doi.org/10.1016/0048-7333(82)90016-6

Fernandez, A. S., Le Roy, F., & Chiambaretto, P. (2018). Implementing the right project structure to achieve coopetitive innovation projects. *Long Range Planning*, *51*(2), 384–405. https://doi.org/10.1016/j.lrp.2017.07.009

Foster, R. N. (1985). Timing technological transitions. *Technology in Society*, *7*, 127–141. https://doi.org/10.1016/0160-791X(85)90022-3

Foster, R. N. (2000). Managing technological innovation for the next 25 years. *Research-Technology Management*, *43*(1), 29–31. https://doi.org/10.1080/08956308.2000.11671326

Funk, J. L. (2001). *Global competition between and within standards: The case of mobile phones*. Springer.

Gartner, J., Maresch, D., & Fink, M. (2015). The potential of additive manufacturing for technology entrepreneurship: An integrative technology assessment. *Creativity and Innovation Management*, *24*(4), 585–600. https://doi.org/10.1111/caim.12132

Gattringer, R., Damm, F., Kranewitter, P., & Wiener, M. (2021). Prospective collaborative sensemaking for identifying the potential impact of emerging technologies. *Creativity and Innovation Management*, *30*, 651–673. https://doi.org/10.1111/caim.12432

Gillier, T., & Piat, G. (2011). Exploring over: The presumed identity of emerging technology. *Creativity and Innovation Management*, *20*, 238–252. https://doi.org/10.1111/j.1467-8691.2011.00614.x

Jenkins, M., & Floyd, S. (2001). Trajectories in the evolution of technology: A multi-level study of competition in Formula 1 racing. *Organization Studies*, *22*(6), 945–969. https://doi.org/10.1177/0170840601226003

Kang, M. J., & Hwang, J. (2016). Structural dynamics of innovation networks funded by the European Union in the context of systemic innovation of the renewable energy sector. *Energy Policy*, *96*, 471–490. https://doi.org/10.1016/j.enpol.2016.06.017

Koski, H., & Kretschmer, T. (2005). Entry, standards and competition: Firm strategies and the diffusion of mobile telephony. *Review of Industrial Organization*, *26*, 89–113. https://doi.org/10.1007/s11151-004-4085-0

Lakhdar, Y., Tuck, C., Binner, J., Terry, A., & Goodridge, R. (2021). Additive manufacturing of advanced ceramic materials. *Progress in Materials Science*, *116*, 100736. https://doi.org/10.1016/j.pmatsci.2020.100736

Lavikka, R., Chauhan, K., Peltokorpi, A., & Seppänen, O. (2021). Value creation and capture in systemic innovation implementation: Case of mechanical, electrical and plumbing prefabrication in the Finnish construction sector. *Construction Innovation*, *21*(4), 837–856. https://doi.org/10.1108/CI-05-2020-0070

Lindgren, J. (2016). Diffusing systemic innovations: Influencing factors, approaches and further research. *Architectural Engineering and Design Management*, *12*(1), 19–28. https://doi.org/10.1080/17452007.2015.1092942

Lindgren, J., & Emmitt, S. (2017). Diffusion of a systemic innovation: A longitudinal case study of a Swedish multi-storey timber housebuilding system. *Construction Innovation*, *17*(1), 25–44. https://doi.org/10.1108/CI-11-2015-0061

Lundblad, J. P. (2003). A review and critique of Rogers' diffusion of innovation theory as it applies to organizations. *Organization Development Journal*, *21*(4), 50.

Luomaranta, T., & Martinsuo, M. (2020). Supply chain innovations for additive manufacturing. *International Journal of Physical Distribution and Logistics Management*, *50*(1), 54–79. https://doi.org/10.1108/IJPDLM-10-2018-0337

Luomaranta, T., & Martinsuo, M. (2022). Additive manufacturing value chain adoption. *Journal of Manufacturing Technology Management*, *33*(9), 40–60. https://doi.org/10.1108/JMTM-07-2021-0250

MacVaugh, J., & Schiavone, F. (2010). Limits to the diffusion of innovation: A literature review and integrative model. *European Journal of Innovation Management*, *13*(2), 197–221. https://doi.org/10.1108/14601061011040258

Martinsuo, M. (2021). Overcoming barriers of systemic innovations in a business network. In G. Fernandes, L. Dooley, D. O'Sullivan, & A. Rolstadås (Eds.), *Managing collaborative R&D projects: Leveraging open innovation knowledge flows for co-creation*. Contributions to Management Science book series. (pp. 101–120). Springer.

Martinsuo, M., & Luomaranta, T. (2018). Adopting additive manufacturing in SMEs: Exploring the challenges and solutions. *Journal of Manufacturing Technology Management*, *29*(6), 937–957. https://doi.org/10.1108/JMTM-02-2018-0030

Meade, N., & Islam, T. (2006). Modelling and forecasting the diffusion of innovation—A 25-year review. *International Journal of Forecasting*, *22*(3), 519–545. https://doi.org/10.1016/j.ijforecast.2006.01.005

Mellor, S., Hao, L., & Zhang, D. (2014). Additive manufacturing: A framework for implementation. *International Journal of Production Economics*, *149*, 194–201. https://doi.org/10.1016/j.ijpe.2013.07.008

Midgley, G., & Lindhult, E. (2017). *What is systemic innovation?* (p. 39). University of Hull, Business School (HUBS).

Mlecnik, E. (2013). Opportunities for supplier-led systemic innovation in highly energy efficient housing. *Journal of Cleaner Production*, *56*(1), 103–111. https://doi.org/10.1016/j.jclepro.2012.03.009

Murmann, J. P., & Frenken, K. (2006). Toward a systematic framework for research on dominant designs, technological innovations, and industrial change. *Research Policy*, *35*(7), 925–952. https://doi.org/10.1016/j.respol.2006.04.011

Negro, S. O., Suurs, R. A. A., & Hekkert, M. P. (2008). The bumpy road of biomass gasification in the Netherlands: Explaining the rise and fall of an emerging innovation system. *Technological Forecasting and Social Change*, *75*(1), 57–77. https://doi.org/10.1016/j.techfore.2006.08.006

Ortt, J. R. (2010). Understanding the pre-diffusion phases. In J. Tidd (Ed.), *Gaining momentum: Managing the diffusion of innovations* (pp. 47–80). London.

Ortt, J. R. (2016). Guest editorial. *Journal of Manufacturing Technology Management*, *27*(7), 890–897. https://doi.org/10.1108/JMTM-10-2016-0134

Ortt, J. R. (2017). Is additive manufacturing evolving into a mainstream manufacturing technology? *Journal of Manufacturing Technology Management*, *28*(1), 2–9. https://doi.org/10.1108/JMTM-01-2017-0010

Ortt, J. R., & Kamp, L. M. (2022). A technological innovation system framework to formulate niche introduction strategies for companies prior to large-scale diffusion. *Technological Forecasting and Social Change*, *180*, 121671. https://doi.org/10.1016/j.techfore.2022.121671

Ortt, J. R., & Schoormans, J. P. L. (2004). The pattern of development and diffusion of breakthrough communication technologies. *European Journal of Innovation Management*, *7*(4), 292–302. https://doi.org/10.1108/14601060410565047

Ortt, J. R., & Van der Duin, P. A. (2008). The evolution of innovation management towards contextual innovation. *European Journal of Innovation Management*, *11*(4), 522–538. https://doi.org/10.1108/14601060810911147

Pedota, M., & Piscitello, L. (2022). A new perspective on technology-driven creativity enhancement in the Fourth Industrial Revolution. *Creativity and Innovation Management*, *31*(1), 109–122. https://doi.org/10.1111/caim.12468

Poole, M. S., van de Ven, A. H., Dooley, K., & Holmes, M. E. (2000). *Organizational change and innovation processes. Theories and methods for research*. Oxford University Press.

Rogers, E. M. (1962). *Diffusion of innovations*. The Free Press.

Rogers, E. M. (2005). *Diffusion of innovations*. The Free Press.

Rosenberg, N. (1982). *Inside the black box: Technology and economics*. Cambridge University Press.

Sahal, D. (1981). Alternative conceptions of technology. *Research Policy*, *10*, 2–24. https://doi.org/10.1016/0048-7333(81)90008-1

Schilling, M. A. (2003). Technological leapfrogging: Lessons from the US video game console industry. *California Management Review*, *45*(3), 6–32. https://doi.org/10.2307/41166174

Schnaars, S. P. (1989). *Megamistakes: Forecasting and the myth of rapid technological change*. The Free Press.

Schneider, S., & Kokshagina, O. (2021). Digital transformation: What we have learned (thus far) and what is next. *Creativity and Innovation Management*, *30*(2), 384–411. https://doi.org/10.1111/caim.12414

Schroeder, R., Van de Ven, A., Scudder, G., & Polley, D. (1986). Managing innovation and change processes: Findings from the Minnesota Innovation Research Program. *Agribusiness*, *2*(4), 501–523. https://doi.org/10.1002/1520-6297(198624)2:4<501::AID-AGR2720020412>3.0.CO;2-G

Schumpeter, J. A. (1939). *The theory of innovation. Business cycles; a theoretical, historical and statistical analysis of the capitalist process* (pp. 84–150). McGraw Hill.

Schwaber, K., & Sutherland, J. (2020). The scrum guide; The definitive guide to SCRUM: The rules of the game. https://scrumguides.org/docs/scrumguide/v2020/2020-Scrum-Guide-US.pdf

Sewell, W. H. (1996). Historical events as transformation of structures: Inventing revolution at the Bastille. *Theory and Society*, *25*(6), 841–881. https://doi.org/10.1007/BF00159818

Sischarenco, E., & Luomaranta, T. (2023). Policy-driven responsibility for innovations and organisational learning: An ethnographic study in additive manufacturing product innovations. *The Learning Organization.*, *30*, 740–759. https://doi.org/10.1108/TLO-11-2021-0132

Sobota, V. C. M., van de Kaa, G., Luomaranta, T., Martinsuo, M., & Ortt, J. R. (2021). Factors for metal additive manufacturing technology selection. *Journal of Manufacturing Technology Management*, *32*(9), 26–47. https://doi.org/10.1108/JMTM-12-2019-0448

Steenhuis, H. M., Fang, X., & Ulusemre, T. (2020). Global diffusion of innovation during the fourth industrial revolution: The case of additive manufacturing or 3D printing. *International Journal of Innovation and Technology Management*, *17*(1), 2050005. https://doi.org/10.1142/S0219877020500054

Suominen, J. M., Frankberg, E. J., Vallittu, P. K., Levänen, E., Vihinen, J., Vastamäki, T., Kari, R., & Lassila, L. J. V. (2019). Three-dimensional printing of zirconia: Characterization of early-stage material properties. *Biomaterial Investigations in Dentistry*, *6*(1), 23–31. https://doi.org/10.1080/26415275.2019.1640608

Suurs, R. A. A., & Hekkert, M. P. (2009). Cumulative causation in the formation of a technological innovation system: The case of biofuels in the Netherlands. *Technological Forecasting and Social Change*, *76*(8), 1003–1020. https://doi.org/10.1016/j.techfore.2009.03.002

Takey, S. M., & Carvalho, M. M. (2016). Fuzzy front end of systemic innovations: A conceptual framework based on a systematic literature review. *Technological Forecasting and Social Change*, *111*, 97–109. https://doi.org/10.1016/j.techfore.2016.06.011

Travitzky, N., Bonet, A., Dermeik, B., Fey, T., Filbert-Demut, I., Schlier, L., Schlordt, T., & Greil, P. (2014). Additive manufacturing of ceramic-based materials. *Advanced Engineering Materials*, *16*(6), 729–754. https://doi.org/10.1002/adem.201400097

Tushman, M. L., & Rosenkopf, L. (1992). Organizational determinants of technological change. Towards a sociology of technological evolution. *Research in Organizational Behavior*, *14*, 311–347.

Urban, G. L., & Hauser, J. R. (1993). *Design and marketing of new products*. Prentice Hall.

Utterback, J. M., & Abernathy, W. J. (1975). A dynamic model of process and product innovation. *Omega*, *3*(6), 639–656. https://doi.org/10.1016/0305-0483(75)90068-7

Valente, T. W., & Rogers, E. M. (1995). The origins and development of the diffusion of innovations paradigm as an example of scientific growth. *Science Communication*, *16*(3), 242–273. https://doi.org/10.1177/1075547095016003002

Van de Ven, A. H., & Garud, R. (1993). Innovation and industry development: The case of cochlear implants. *Research on Technological Innovation, Management, and Policy*, *5*, 1–46.

Van de Ven, A. H., Polley, D. E., Garud, R., & Venkataraman, S. (2008). *The innovation journey*. Oxford University Press.

Van de Ven, A. H., & Poole, M. S. (1990). Methods for studying innovation development in the Minnesota innovation research program. *Organization Science*, *1*(3), 313–335. https://doi.org/10.1287/orsc.1.3.313

von Pechmann, F., Midler, C., Maniak, R., & Charue-Duboc, F. (2015). Managing systemic and disruptive innovation: Lessons from the Renault Zero Emission Initiative. *Industrial and Corporate Change*, *24*(3), 677–695. https://doi.org/10.1093/icc/dtv018

Whitmarsh, L., & Nyqvist, B. (2008). Integrated sustainability assessment of mobility transitions: Simulating stakeholders' visions of and pathways to sustainable land-based mobility. *International Journal of Innovation and Sustainable Development*, *3*(1/2), 115–127. https://doi.org/10.1504/IJISD.2008.018196

Wind, Y. J. (1982). *Product policy: Concepts, methods, and strategy*. Addison Wesley.

Yap, X. S., & Rasiah, R. (2017). Catching up and leapfrogging in a high-tech manufacturing industry: Towards a firm-level taxonomy of knowledge accumulation. *Knowledge Management Research and Practice*, *15*(1), 114–129. https://doi.org/10.1057/kmrp.2015.21

Zocca, A., Colombo, P., Gomes, C. M., & Günster, J. (2015). Additive manufacturing of ceramics: Issues, potentialities, and opportunities. *Journal of the American Ceramic Society*, *98*(7), 1983–2001. https://doi.org/10.1111/jace.13700

AUTHOR BIOGRAPHIES

Dr. Toni Luomaranta, D.Sc. (Tech.), is a visiting post-doctoral researcher at the Vienna University of Business and Economics, Institute for Managing Sustainability. His field of research is technology, innovation, and sustainability management. Dr. Luomaranta has seven years of academic experience in industrial engineering and management and is currently working in close industry-academia collaboration in blue-bioeconomy field. His current research interests are in innovation development and management, circular economy, and regenerative business models in the deep tech blue bioeconomy industry.

Prof. Miia Martinsuo, D.Sc. (Tech.), is a Professor of industrial engineering and management at the University of Turku, Faculty of Technology. Her field of research and teaching is innovation and project management. Prof. Martinsuo has over 20 years of academic experience in industrial engineering and management and 9 years of industrial experience, particularly in organization and process development in the metal and engineering industry. Her current research interests include: selecting and steering innovation project portfolios; program organizing of strategic change; front-end, autonomy, and control of projects; managing manufacturing and process innovations; and organizing and transforming industrial service business.

Roland Ortt is an Associate Professor of technology and innovation management at the Delft University of Technology, the Netherlands. Before joining the faculty of Technology Policy and Management Roland Ortt worked as an R&D manager for a telecommunication company. He is the author of various articles in journals like the Journal of Product Innovation Management, Technological Forecasting and Social Change, and the International Journal of Technology Management and has won several best-paper awards. His research focuses on the development and diffusion of high-tech products, and on niche strategies to commercialize these products.

How to cite this article: Luomaranta, T., Martinsuo, M., & Ortt, R. (2024). Initiation and evolution of systemic innovations: Patterns and interactions in the emergence of additive manufacturing technologies. *Creativity and Innovation Management*, 1–20. https://doi.org/10.1111/caim.12600