

**INNOVATION MANAGEMENT OF THREE-DIMENSIONAL PRINTING (3DP)  
TECHNOLOGY: DISCLOSING THE INSIGHTS FROM THE LITERATURE AND  
DETERMINING FUTURE RESEARCH STREAMS**

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## **Highlights**

- The 3DP domain extends over several subfields of the business and management disciplines
- This study identifies five pertinent theoretical frameworks and eight major research themes
- Future researchers could examine the association between 3DP and Industry 5.0
- Future research avenues could focus on 3DP contribution in a state of turmoil

# **INNOVATION MANAGEMENT OF THREE-DIMENSIONAL PRINTING (3DP) TECHNOLOGY: DISCLOSING INSIGHTS FROM EXISTING LITERATURE AND DETERMINING FUTURE RESEARCH STREAMS**

## **Abstract**

Three-dimensional printing (3DP) is a technological innovation that has been receiving an increased amount of attention – both in the media and among scholars – as a result of its profound implications for business, industry, and society. Although it has existed since the 1980s, literature reviews covering major aspects of 3DP technology through the lenses of business and management studies remain limiting with regards to their scope and insights. Through a systematic literature review of 192 manuscripts published in top-tier journals indexed in Scopus and Web of Science scholarly databases, this study combines the results of a Multiple Correspondence Analysis and a content analysis to holistically elaborate principal research themes, theoretical frameworks, and future research trends. Major research themes, summarized respectively as: industrial revolution; strategy; technology adoption and governance; performance; risk and uncertainty; human resources; innovation; and sustainability and circular economy, are closely analyzed, and research predictions are provided with regards to the topics of Industry 5.0, future of governance and 3DP adoption, operations performance and supply chain management, and sustainable development and circular economy. Theoretical contributions explore and consolidate the most relevant theoretical foundations of 3DP as a research field and offer guidelines for scholars to consider in future projects.

**Keywords:** 3D print, additive manufacturing, innovation management, systematic literature review, multi correspondence analysis.

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## **INTRODUCTION**

Three-dimensional printing (3DP), or Additive Manufacturing (AM), refers to the range of production methods and techniques used to create physical models from digital designs, by deploying layers of material through a precise, computer-controlled sequence of algorithms (ISO/ASTM 52900:2021<sup>1</sup>). As one of the flagship technologies in the context of Industry 4.0 and the Fourth Industrial Revolution, it is often discussed in terms of its disruptive and revolutionizing potential, for both modern businesses and society as a whole (D'Aveni, 2013; Dotsika and Watkins, 2017; Garmulewicz et al., 2018; Potstada and Zybura, 2014; Rindfleisch et al., 2017; Roca et al., 2017a). Introduced more than 30 years ago, 3DP's fast pace of development and amplified adoption over the last 12 years has been disrupting traditional means of production and supply chain design, restructuring entire business ecosystems and leading to the development of new ones (D'Aveni, 2018; Beltagui et al., 2020a; Rindfleisch, 2020).

Due to the additive nature of the fabrication process, 3DP reduces both physical and geographical constraints through absence of tooling, and blurs the boundary between the digital and the physical worlds (Rindfleisch, 2020). This unique advantage opens up a new range of possibilities in terms of who can produce new products as well as how and when they can be produced. In the manufacturing sector, 3DP is recognized for its more flexible (Eyers et al., 2018), innovative (Candi and Beltagui, 2019), and sustainable (Beltagui et al., 2020b) means of

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<sup>1</sup> ISO/ASTM 52900:2021 - Additive manufacturing — General principles — Fundamentals and vocabulary. Available at: <https://www.iso.org/standard/74514.html>

production. In supply chain management (SCM), 3DP reduces the cost for small sets of objects/products, facilitates the consolidation of (spare) parts (Knofius et al., 2019), and leads to a decentralized design of supply chains (Khajavi et al., 2014). Marked by increased customization and personalization possibilities, alongside its propensity for localized and on-demand fabrication, 3DP questions traditional economies-of-scale assumptions, such as cost and quality, or the trade-offs between volume and variety. This holds the potential to radically change the innovation landscape by allowing individuals and companies to manufacture small sets of customizable products, reshape business value chains, and design collaboratively.

Risks and uncertainties with regards to 3DP technology became evident during the COVID-19 pandemic through issues such as supply disruptions and demand fluctuations, which are often faced in operations and SCM. Examples of 3DP use in response to the COVID-19 pandemic was usually followed by the free and open-source sharing of designs by various stakeholders. This approach enabled large number of users around the globe with access to 3DP units to download and print innovative solutions or spare parts for hospital equipment (such as ventilators) and protection equipment for healthcare workers (face shields), or to completely rearrange automotive and aerospace production lines for hospital equipment fabrication (ventilators) (see Chesbrough, 2020; Naghshineh et al., 2021; and Rodriguez-Espindola et al., 2020). This forms a narrative pertaining to 3DP, not just as a technological, economic, and business phenomenon, but also as a technology with the potential to alleviate social issues and lead to profound societal changes (i.e., meeting the UN Sustainable Development Goals).

Considering enhancements regarding 3DP applicability and affordability, entrepreneurs, innovators, managers, industrialists, production engineers, and designers have begun to explore business opportunities and business value creation using this technology. Accordingly, scholars

and practitioners have recognized that the adoption and integration of 3DP into existing business contexts may require them to completely change business models and value chains (Holmström et al., 2019; Rayna and Striukova, 2016) in which the dissemination of complex theoretical foundations, principles, strategies, and success stories are rather welcoming research streams. Enhanced performance measurement systems, innovation capabilities, business models, collaboration, and strategic business approaches, alongside understandings of broader sets of issues related to 3DP, are sought after from multiple stakeholder perspectives.

With regard to previous scholarly discourse on this technology, it is evident that 3DP has matured into an emerging field, with substantial research activity and a dispersed and fragmented body of literature (Maresch and Gartner, 2018; Caviggioli and Ughetto, 2019). Few articles providing literature reviews or (partial) syntheses of literature have been published in recent years, with limited contributions made by scholars from business and management disciplines. For instance, scholars have associated 3DP with the topics of SCM (Kunovjanek et al., 2020; Ryan et al., 2017) or the social implications of technology (Naghshineh et al., 2021), leaving solely two literature reviews with a general focus on 3DP through business and management lenses (Caviggioli and Ughetto, 2019; Khorram Niaki and Nonino, 2019). However, when analyzing these two literature reviews, a slight research bias was noticeable in the development of the search query and the narrowed use of keywords. Findings were also possibly outdated due to literature having been retrieved in 2014 (Khorram Niaki and Nonino, 2019) or 2017 (Caviggioli and Ughetto, 2019), respectively.

Considering the multi-disciplinary and flourishing 3DP research field, and bearing in mind the limitations of existing reviews, a holistic review of literature on 3DP technology through the lenses of business and management disciplines is clearly required. Through a systematic literature

review, this study aims to close the research gap by instigating a computer-aided content retrieval, classification, and analysis, combining Multiple Correspondence Analysis (MCA) and content analysis.

The Research Questions (RQs) that guide this research are:

*RQ1. What are the principal theoretical foundations and major research themes within the 3DP technology domain?*

*RQ2. What are the future research tracks regarding 3DP technology?*

In order to provide answers to these two questions, more than 30 years of scholarly literature was analyzed in an attempt to untangle the complex characteristics of 3DP by spanning both business and management disciplines. The contributions of this study are three-fold. Firstly, despite an increase in the recognition of 3DP's importance, limited research has systematically reviewed 3DP technology in a holistic manner or provided a detailed chronological overview of its stages of development. To the best of our knowledge, this is the first scholarly effort to empirically-back up a framework that discusses the chronology of 3DP technology's evolution. Hence, compared to existing literature reviews, an added value of this study can be seen in its development of an extensive search query that enabled a rich dataset to be retrieved from scholarly databases, whilst imposing rigorous inclusion criteria (focusing solely on scholarly publications appearing in journals ranked 3,4, and 4\* by the CABS Academic Journal Guide, 2021). Secondly, this review depicts the 3DP intellectual domain from a pragmatic approach, passing beyond speculations over 3DP use, adoption, and implementation into business and management environments. Through extensive support from tables and figures, this study identifies eight major research themes and five of the most pertinent theoretical frameworks. Thirdly, building upon

objective, systematic, and combined content and expert analysis (Furrer et al., 2020), this review offers fruitful research avenues for future scholarly debates.

The paper is organized as follows. Section 2 introduces and synthesizes a framework on the chronology of 3DP's technological evolution, and provides a short critical overview of previous literature reviews on this technology. Section 3 describes the methods used to select and classify the reviewed articles. Section 4 explains the descriptors used for mapping purposes and discusses the use of tables and figures. In Section 5, theoretical foundations and major research themes are discussed, and additional insights on the methodology and research context are provided. Finally, Section 6 outlines future research avenues and contributions to practice and theory. It also provides general conclusive remarks.

## **RESEARCH ON 3DP: EVOLUTION AND PREVIOUS REVIEWS**

### **Technological evolution and use of 3DP since the 1980s**

Scholars have offered numerous frameworks with which to illustrate 3DP technology's development and evolution. Due to 3DP's complexities and specificities over the course of time, these frameworks have been based on multi-layered analyses of 3DP technological characteristics, market evolution, and market size, as well as adoption patterns and usage.

For instance, West and Kuk (2016) discuss two distinct markets – the 20<sup>th</sup> century industrial market and the 21<sup>st</sup> century consumer-focused market – establishing them as two distinct periods in which 3DP evolution can be observed. Rayna and Striukova (2016) provide a detailed framework based on four (or even five) distinct stages of 3DP development, associated with primarily technology adoption and usage. These are, namely: rapid prototyping, rapid tooling, direct manufacturing, and home (local) fabrication (see Table 1).

*\*\*\* Insert Figure 1 around here \*\*\**

Noticeably, there is a common intersection between the two frameworks, primarily in terms of the chronology of 3DP technology development and adoption patterns and, secondly, 3DP technology market characteristics. West and Kuk (2016) discuss the first period (initial twenty years of 3DP introduction, following the mid-1980s), which was marked by the adoption and application in industrial systems. The second period, following 2005 as a milestone year, is marked by the rapid growth of the consumer market, primarily due to the expiry of crucial 3DP patents, the introduction of open source 3DP initiatives (i.e., RepRap project), the emergence of several 3DP start-up companies offering affordable 3D printers, and the rise of 3DP user platforms, often by technology enthusiasts and hobbyists grouped within makerspaces, hackerspaces, or fablab initiatives (Ryan et al., 2017; West and Kuk, 2016). This two-period perspective coincides with Rayna and Striukova's (2016) four development stages, in which we can delineate rapid prototyping and rapid tooling stages into niche industrial markets up until the early 2000s, whilst associating direct manufacturing and home fabrication stages to West and Kuk's (2016) consumer market application.

Building on these two frameworks, we expand this discourse through an overview of 70 (out of a total of 192) articles. These articles, despite the fact that they stem from business and management literature sources, are filtered based on their insights into 3DP technological characteristics over time. They adopt a rather technological and/or engineering narrative, similar to the approach observed in the work of Huang et al. (2013). This narrative encapsulates a scholarly focus on the 3DP process itself, the use of materials, optimization methods, and improvements made over the course of time. It also explains the chronology of 3DP technology's evolution in academic literature.

## **The stages of rapid prototyping (late 1980s to early 1990s) and rapid tooling (late 1990s to early 2000s)**

In this section, 3DP's chronological evolution is summarized in terms of the early research on the optimization of the overall 3DP process (technological narrative), and the interrogation of 3DP as a business process. In the context of the 3DP process (technological narrative), scholars cover range of subtopics. These stem from various 3DP process experiments and optimizations. For instance, Arthur and Dickens (1998) covered heat distribution in stereolithography electrodes during electro-discharge machining, as part of an investigation seeking to determine how machine performance might be improved. Later in the development of 3DP process optimization, Laeng et al. (2000) reviewed the state-of-the-art with regards to laser metal forming (LMF) hardware, software, and its associated parameters. Dickens (1997) examined 3DP's propensity to develop laminated tooling for molding plastics. Majewski and Hopkinson (2003) elaborated upon the transition from rapid prototyping technologies to rapid tooling, by means of analyzing the effectiveness of using direct metal laser sintering to produce injection-molding tools.

The topic of direct slicing for rapid prototyping was focused upon during the rapid tooling stage, in which efforts were aimed towards optimizing 3DP processes with regards to the contours needed for each layer from the solid model (Zhao and Laperrière, 2000), or the general optimization of application software for direct slicing in rapid prototyping (Shi et al., 2004). A STEP-based approach to direct slicing was also investigated as a more flexible method that does not rely on any specific Computer Aided Design (CAD) system, and it results in much smaller files than the STL files (Zhou, 2005). Moreover, Yau et al. (2004) address the issue of numerical control machining directly from a stereolithography file.

The 3DP process (technological narrative) highlights the path planning of functionally graded material objects (Zhou, 2004), wherein advancements are made in an attempt to improve challenges are seen to improve the Average Weighted Surface Roughness (AWSR) generated from the stair stepping effect, minimizing the build time and the structure of the supports needed to fabricate a completely freeform part (Byun and Lee, 2005). Ning et al. (2004) present an intelligent system to assist the rapid prototyping user in choosing the optimal parameter settings based on different user requirements for the Direct Metal Laser Sintering (DMLS) technique, which requires an understanding of processing times, mechanical properties, geometric accuracy, and surface roughness.

Interestingly, early notions of environmental sustainability in the 3DP process – through the discussion of waste removal processes – are present in the work of Liao and Chiu (2001), emerging as a side topic of their experimentation with laminated object manufacturing (LOM). Harris et al. (2002) covered the characteristics of stereolithography injection in mold tooling, focusing on layer thickness and draft angle selection.

In one of the early papers focusing on the Fused Deposited Modelling (FDM) technique of 3DP, Luis Pérez (2002) provided an analysis of the surface roughness and dimensional accuracy capability. Pandey et al. (2004) extended research focused on FDM by investigating adaptive slicing, based on the local geometry of the CAD model and rapid prototyping machine specifications. These advancements were significant in furthering our understanding of the later stages of 3DP evolution, wherein FDM took primacy as a common technique in the consumer market. Lin and Liang (2002) introduced a common practice associated with 3DP technology in the later stages of its development, scanning directly through 3D data points in order to prevent various problems associated with 3D CAD modelling from large quantities of data points.

When analyzing 3DP as a business process, scholars approach the topic by experimenting with software environments for model prototyping, simulation, and optimization (Guariso et al., 1996). Scholars have experimented with distributed or concentrated/centralized product development strategies through 3DP and, later, through time-to-market performance (Datar et al., 1997), as part of the conceptual initiatives seeking to integrate 3DP (rapid prototyping) into manufacturing systems (Weston, 1998). Hague et al. (2004) refer to this integration of rapid prototyping into manufacturing systems as the rapid manufacturing concept. Scholars have also discussed 3DP as a business process topic through the lenses of agile manufacturing (Gunasekaran, 1998) and experiments with different ‘modes’ (i.e., computer simulation and rapid prototyping). These are expected to optimize and reduce time and total product development process costs (Thomke, 1998). Case studies, such as the one on HP thermal inkjet, are mentioned as part of the technological breakthrough paths for the domain of rapid prototyping and rapid tooling (Fleming, 2002). The research of Lan et al. (2005) proposes an interesting typology of the rapid prototyping decision system for practitioners.

In this industrial-orientated market stage of 3DP technology evolution, early notions of ‘coconstruction’ in the production process are present in the work of Udawadia and Ravi Kumar (1991). These authors revealed the role of customers in the production process, and stressed the need to incorporate customer interaction as a strategic organizational process.

### **Direct manufacturing (late 2000s to early 2010s) stage**

In this chronological stage of the evolution of 3DP technology, we observe a gradual transition in scholars’ narratives, primarily directing their focus from simple characteristics of the 3DP process or interrogation of 3DP as a business/organizational process, towards optimization of

3DP as a rapid tooling/molding technology and 3DP technology's potential in direct or rapid manufacturing.

For instance, when considering the optimization of 3DP as a rapid tooling/molding technology, we can highlight the focus on the design, development, and evaluation of injection molding in the powder-sintering process (Yarlagadda and Wee, 2006), or the systematic approach to manufacturability analysis (based on three aspects: mold feature manufacturability, secondary elements compatibility, and cost effectiveness) of molds produced by rapid tooling methods (Nagahanumaiah et al., 2007). Silva et al. (2006) take this approach one step further, introducing MAPP (Mold: Assistant Production Planner): a web-based decision support system developed for the mold industry.

In this stage of direct or rapid manufacturing, scholars also discuss strategies and applications for rapid product development (Bandera et al., 2006), development of a build-time estimator for rapid manufacturing (Ruffo et al., 2006), or the production of complex parts of diversified materials through different physical/chemical manufacturing principles (Beal et al., 2008). This showcases scholars' investigation of rapid manufacturing as a final manufacturing method in product development (Munguía et al., 2010), where the evaluation and optimization of designs/artifacts comes into focus (Tong et al., 2009). Cost estimations for product developments via 3DP and web-based e-commerce also take shape (Di Angelo and Di Stefano, 2010).

Moreover, optimization of direct or rapid manufacturing product development process ranges from stochastic models, developed for the purpose of minimizing mechanical and geometrical errors in stereolithography process (Agrawal and Dhande, 2007, 2008), and the analysis of minimum average part surface roughness, minimum build time, and support structure for stereolithography (SL) and selective laser sintering (SLS) (Singhal et al., 2009). Finally, Pande

and Kumar (2008) present a generative process planning system for parts produced by the rapid prototyping process (i.e., FDM). This process involves the optimal selection of the model's orientation, its proper support structure, and intelligent slicing methodology to minimize built up time and keep the geometry and cusp height errors in control.

### **Home (local) fabrication stage (late 2010s to modern date)**

The final stage defined by the framework (see Figure 1) pertains to the possibility of the direct and local fabrication of final products by their end-users (consumer market) in the comfort of their offices, homes, or localized co-working spaces (Rayna and Striukova, 2016). This body of literature is substantially larger and comprises both cross-functional and interdisciplinary approaches to this topic.

There is noticeable interest among scholars and practitioners with regards to integrating 3DP technology into manufacturing systems (Eyers et al., 2018), either by producing components through traditional systems or via alternative ones with integrated 3DP (Westerweel et al., 2018). Elhoone et al. (2020) advanced this discussion by proposing the framework for designing a cyber additive manufacturing system that integrates an expert system with the Internet of Things (IoT). With this in mind, Garashchenko and Rucki (2020) opened up a discussion on the efficient use of 3DP machine workspace, in order to generate savings in terms of energy and materials.

To reveal a divergent point of view, scholars discussed the challenges and opportunities of 3DP and the possible reasons why this technology had not established itself as a mainstream technology in various fields and industrial applications (Maresch and Gartner, 2020). Funk et al. (2020) sought to elicit the implicit and explicit knowledge of experts with regards to the feasibility of producing parts with metal additive manufacturing (MAM). Kim et al. (2019) highlighted importance of technological convergence in guiding organizations to react promptly to challenges

posed by 3DP technology. Technological convergence, according to Wang et al. (2019), reflects the developmental processes that overlap different technological fields and can influence innovation management. In their case, an analysis of the convergent domains of 3DP was used to identify emerging topics related to this technology.

A similar area of focus was noticed in the work of Robinson et al. (2019), who characterized and demarcated the boundaries of emerging fields, such as 3DP, through the Forecasting Innovation Pathways (FIP) toolbox. These initiatives, with a specific focus on 3DP, contributed to mapping 3DP technological development by exploring the contributions of various knowledge sources.

Next, scholarly discussions of the home or localized fabrication stage showed comparative methods between 3DP and traditional manufacturing. For example, Baumers et al. (2016) investigated the production cost performance for two different 3DP systems used commercially in manufacturing end-use metal parts - principally, Electron Beam Melting (EBM) and Direct Metal Laser Sintering (DMLS). This study revealed that economies of scale by 3DP technology was a possibility. Moreover, a comparison of different 3DP techniques for injection molding, through a case study, revealed that 3DP could increase flexibility, reduce warehousing costs, and assist companies in the mass-customization of business strategies (Achillas et al., 2017). Eysers et al. (2021) identified circumstances in which additive manufacturing (i.e., 3DP) systems deviated from traditional trade-offs and established norms in manufacturing.

Finally, scholars outlined the details, characteristics, and novelties of the 3DP process through a set of works examining cost estimation and performance, built times, or the use of multi-materials or multi-nozzles. For instance, Baumers et al. (2017) investigate the relationship between build volume capacity utilization and efficient technology operation in an inter-process comparison of the costs of manufacturing a complex component used in the packaging industry.

Accordingly, the estimated manufacturing cost savings through 3DP ranges from 36 to 46%. Combining theoretical cost models to evaluate the cost performance of the stereolithography processes for multiple mixed geometries reveals a potential 26% cost saving through the use of 3DP technology (Yang and Li, 2018). Colosimo et al. (2020) presented a cost model to evaluate the economic impact of defects and process instability in metal 3DP, and selective laser melting (SLM) was observed in the work of Lv et al. (2021), concluding possible forecasts on the energy consumption of SLM processes.

Multi-material usage in 3DP process was a research topic investigated by a number of scholars, such as Khajavi et al. (2018), who focused on cheaper metal powder supplies (i.e., innovative titanium) in SLM, or Singh et al. (2018), who focused on the mechanical properties of the functional prototypes prepared using the biocompatible filament of fused deposition modelling (FDM) in clinical dentistry. Xu et al. (2015) covered the Binder-jetting (BJ) technique, along with a variety of other materials, including stainless steel, ceramic, polymer, and glass, in order to mathematically analyze an energy consumption model for printing stages. An interesting approach was presented by Wang and Rai (2020), who investigated cellulose structures in 3DP processes.

The modalities of 3DP processes and optimization techniques were discussed in the work of Elango et al. (2016), who described a 3DP machine with two nozzles that start from different locations and cover all task locations in a short span of time. The topic of working modalities in the 3DP process could be collated through a literature review on current 3DP control schemes, process measurements, and modelling and simulation methods applied to the powder bed fusion process (Mani et al., 2017). Following these insights on work modalities, Araújo et al. (2019), Romanova et al. (2021), and Wu et al. (2019) discussed surface roughness, packing taxonomies and packing factors.

Built time plays a vital role as an advantage of 3DP technology when compared to traditional manufacturing. Griffiths et al. (2019) addressed the combined problem of finding an optimal build orientation and a two-dimensional irregular bin packing solution for a mixed batch of parts across identical SLM machines. Oh et al. (2020) investigated the impact of build orientation policies on 3DP production time for mass customization business models, whilst Volpato et al. (2020) presented two optimization algorithms for build time in material extrusion 3DP.

Araújo et al. (2020) took an experimental approach to investigating the practical aspects and comparative performance of different Deepest Bottom-Left-Fill (DBLF) based methods and Genetic Algorithms (GAs) in 3DP build volume packing. Finally, Stanisavljevic et al. (2020) investigated interferences used during the manufacturing process in an exemplary experimental setup, through the collection of data using current sensor technology. They found that a direct setup of this approach on a 3D printer enables a quantitative detection of interferences.

### **Prior reviews on 3DP**

There are few literature reviews presenting diverse viewpoints on the 3DP intellectual domain. The limited contributions of scholars in business and management disciplines – and their lack of publications in top-tier journals – is evident.

For example, Franco et al. (2020) performed a systematic literature review of 136 papers aiming to explore the effects of AM adoption on how companies conduct business. Naghshineh et al. (2021) assessed 302 papers and identified 42 social impacts of AM, along with their associations with relevant stakeholders. Moreover, Savolainen and Collan (2020) investigated the relationship between business models and the AM industry through a literature review of 78 published articles, leading them to categorize the AM effects into four distinctive classes. Ryan et

al. (2017) assessed 128 articles examining 3DP adoption and associating 3DP with existing manufacturing and supply chain theories to identify potential gaps for future research. Next, Caviggioli and Ughetto (2019) performed an extensive bibliometric review of the literature dealing with the impacts of AM on industry, business, and society. They covered 91 published sources, including articles published in scientific journals, conference proceedings, and book chapters, leading them to discuss three principal themes and nine sub-themes. This study provided an illustrated evolution of AM research over time, discussing the main outlets for publication, the level of concentration or fragmentation of the scientific community, the geographical density of the research collaborations, and the employed methodologies, making it an interesting resource to potentially guide our research design and assist with cross comparisons. Furthermore, Kunovjanek et al. (2020) performed a systematic review of relevant literature on 3DP depending on industry sector, purpose, and supply chain area, following the Supply Chain Operations Reference (SCOR) framework. This review includes 141 articles, subjected to a full-text analysis, in order to denote 3DP trends for supply chains, perceived benefits, challenges, and possible applications. Finally, Khorram Niaki and Nonino (2017) performed a systematic and quantitative analysis of 123 literature sources in the scope of management, business, and economics. Based on co-citation analysis, factor analysis, and multidimensional scaling, they summarized eight main AM research streams.

Building upon these reviews, our research design overcomes limitations arising from the elevated author subjectivity bias recognized in expert reviews, as well as the absence of author subjectivity recognized in the bibliometric analysis (Furrer et al., 2020). Accordingly, based on a larger and more extensive sample of literature, this study adopts a combined multiple correspondence analysis and computer-aided content analysis approach (see Vlačić et al., 2021),

which provides systematic and rich data but incorporates a balanced degree of author subjectivity during the coding process. Hence, the differentiation of our study, compared to previous literature reviews, can be seen in the study's larger and more comprehensive set of literature. Namely, this is the first review comprehensively displaying the comparison among the three decades of 3DP domain. In addition, from the methodological perspective, combined application of automated classification techniques and traditional content analysis it offers added value by maximizing reproducibility of the research design and minimizing author subjectivity bias.”.

## **METHODOLOGY**

### **The sample of articles and data collection**

To systematically synthesize, review, and illustrate the cross-functional and interdisciplinary nature of the 3DP domain as a technological, economic, and business phenomenon, we refer to 3DP in its broadest sense within the business and management subject areas. Accordingly, to review the domain of 3DP, we adopted a journal-driven approach (Hiebl et al., 2021), which is recognized for its search transparency and traceability. Additionally, a journal-driven approach is advantageous as *“if a well-regarded journal publishes an article, then the article is presumably built on sufficiently rigorous research methods, which can clear the quality assessment”* (p.12). In focusing on the most highly regarded journals (according to the CABS Academic Journal Guide 2021: rank 3,4, and 4\*), we ensure the inclusion of the key literature within the domain, as these publications are more likely to push the boundaries of the research domain (Bradford, 1934; Garfield, 1990). Next, to affirm the validity of our data collection and avoid the potential limitations associated with the journal-driven approach (e.g., narrow-focus, see Hiebl et al., 2021, Table 1), we compiled manuscripts published in top-tier

journals across the business and management subject areas and performed citation chaining (Larsen, 2002).

A structured keyword search among selected journals was conducted via two prominent scientific databases: Scopus and Web of Science. This approach enabled data to be cross-checked and triangulated (Kiessling et al., 2021). The search used a Boolean search algorithm, including a combination of the most relevant keywords and an alternative conceptualization of 3DP as presented in the title, abstract, and author keywords on 11th May, 2021. This stepwise research approach is presented in Figure 2.

\*\*\* *Insert Figure 2 around here* \*\*\*

The search query yielded an initial 324 results. After merging the results from Web of Science and Scopus, the next step involved removing duplicates (n=85), as well as manuscripts whose primary focus was not on 3DP (n=51). Consequently, the preliminary database consisted of 184 manuscripts. In order to ensure inclusivity, the authors conducted citation chaining (Larsen, 2002), which resulted in the addition of four manuscripts, leading to a final figure of 192 manuscripts included in this review.

3DP technology has continuously captured attention of scholars and practitioners, as shown through the last 30 years of scholarly articles published at the highest academic level in flagship journals such as the *International Journal of Production Research*; *Technological Forecasting and Social Change*; *International Journal of Production Economics*; *Production Planning and Control*; *Journal of Operations Management*; and *Technovation*, among others. Moreover, the fast-moving accretion of 3DP technology and its increased interest is recognized in the frequency

of publications in this field. From 1991 to 2000, 4.7% (n=9) of studies were published; from 2001 to 2010, this rose to around 16.7% (n=32); while, in the last decade, this increased to around 78.% (n=151). This high rate of publications demonstrates increasing interest among scholars and practitioners, and calls for further synthesis of the domain (Snyder, 2019).

### **The building of the codebook**

After building the database of publications for analysis, the next stage involved generating the codebook for the content analysis. Following the guidelines of López-Duarte et al. (2016) and Vlačić et al. (2021), the authors created the final codebook, building upon previous articles and reviews on 3DP (Khorram Niaki and Nonino, 2017; Rayna and Striukova, 2016) and a thorough analysis of 192 manuscripts, applying QDA Miner v.5 and Wordstat v.8 software. The codebook-building process involved indexing the keywords and phrases that represented descriptors of the included manuscripts' content. The final codebook contained 912 terms, categorized into 18 major descriptors. Major descriptors were further clustered into four broader groups: theoretical foundations, research themes, geographical scope, and methodological approaches (the full list of manuscripts reviewed, terms, and descriptors can be found in the supplementary material).

### **The Multiple Correspondence Analysis**

In order to analyze the intellectual structure of the 3DP field, Multiple Correspondence Analysis (MCA), based on homogeneity analysis by means of alternating least squares (HOMALS), was used (Hoffman and De Leeuw, 1992; Greenacre and Blasius, 2006). MCA represents a quantitative technique for the exploration of qualitative data. This technique, using HOMALS analysis, enables researchers to synthesize and illustrate a research domain in the parsimonious Euclidean space (see Figure 3) which is used to map diverse research fields, such as international strategic alliances and national culture (López-Duarte et al., 2016), cross-border

mergers and acquisitions (Kiessling et al., 2021), service research (Furrer et al., 2020), open innovation in manufacturing (Obradović et al., 2021), artificial intelligence in marketing (Vlačić et al., 2021), and frugal innovation (Dabić et al., 2022), among others.

The HOMALS procedure was used to estimate the coordinates of each descriptor on the map. The value of “0” was assigned to an article when neither its title, abstract, nor keywords contained a specific keyword, and vice versa. The value of “1” was given to articles that did contain a specific keyword. The HOMALS was conducted using SPSS v26 software. For analysis to be valid, the overall keywords’ mean had to be larger than 1 (Hair et al., 1998; Furrer et al., 2008). The overall mean in our analysis was 1.57 per article. Additionally, the proportion of variance explained by each pole accounted for 22.08% of the variance. However, this indicator tends to have a deceptive effect on the MCA approach, as the map combines the information of the  $k$  variables (18 descriptors) in only two dimensions (Hair et al., 1998; Furrer et al., 2008, 2020).

A better understanding of MCA analysis can be achieved by analyzing the dynamic perspective of the domain (Figure 4 and Figure 5), as well as the distance between the identified descriptors (Figure 6) (González-Loureiro et al., 2015). In short, the greater the distance, the lesser the degree of association between the descriptors, indicating a potential research gap and a fruitful avenue for future research (Dabić et al., 2019).

## **INFORMATION ANALYSIS AND KEY RESULTS**

This review facilitates a deeper and more robust analysis of 3DP’s intellectual domain evolution and trajectory. By means of the HOMALS approach, over 30 years’ worth of scholarly work is depicted in low-dimensional proximity space (see Figure 3). To interpret the intellectual structure presented in Figure 3, operationally similar reviews (e.g., López-Duarte et al., 2016; Furrer et al., 2020; Vlačić et al., 2021) were initiated by labelling the poles in accordance with the

thematic unity of descriptors and considering the most frequent and extreme descriptors in each pole (see Table 1).

Scholarly work positioned at left side of the 3DP intellectual domain aspires to explain the internal sources of a firm's sustained competitive advantage. Namely, a firm's accrued capital and absorptive capacity plays a determinant role in the decision to adopt and govern 3DP technology. For example, Chatzoglou and Michailidou (2019) emphasize the importance of perceived usefulness, output usability, compatibility, and attitudes towards 3DP technology. Additionally, Baumers et al. (2016) and Jia et al. (2016) highlight the relevance of an organization's capacity to bear the costs associated with 3DP technology adoption and exploit value from 3DP technology.

The region located on the right side of the intellectual domain brings together articles dealing with external organizational capacity. Numerous scholars observed the substantial emergence of 3DP technology and the relevance of networks through collaborative and cooperative partnerships, revealing the importance of knowledge sharing (West and Kuk, 2016). Moreover, 3DP technology became recognized for its ability to address the need for waste reduction (Ghobadian et al., 2020), as well as economic and societal implications for the future (Jiang et al., 2017).

*\*\*\* Insert Figure 3 around here \*\*\**

The 'upper end' refers to studies addressing Innovation and Resource Orchestration, and denotes organizational capacity to secure and manage valuable, rare, inimitable, and non-substitutable resources and capabilities, while also maintaining an innovation agenda (Candi and Beltagui, 2019). Accordingly, 3DP technology, as a result of its associated steep learning curve (Woodson et al., 2019), may require the extension and development of new and current practices

which, in turn, would be dependent on the capacity to orchestrate, gather, and share resources (Beltagui et al., 2021).

On the lower side of the vertical axis, scholars acknowledge the benefits and challenges for national economies and relevance of business and institutional ecosystems. Within this end of the intellectual domain, we observe a division between developed and developing countries, as well as the discussion of public policies and public support towards adoption of 3DP (Roca et al., 2021; Dickinson, 2018; Zhou and Li, 2005). These authors covered the role of public administration and public institutions in diffusion/adoption, as well as the overseeing of 3DP technology in Portugal, China, and the UK. Additionally, Birtchnell et al. (2017) questioned the role of institutions, while Rong et al. (2020) indicated that ecosystem-based systems of manufacturing may lead to the decentralization and localization of production (Ben-Ner and Siemsen, 2017; Laplume et al., 2016).

*\*\*\* Insert Table 1 around here \*\*\**

In order to depict the evolution and dynamic perspective of 3DP technology, along with the trajectory of the theoretical foundations, the major research themes, the methodological approaches, and geographical contexts (see Figure 4), the intellectual domain is analyzed by dividing the period into three different sub-periods: P1 (1991-2000), P2 (2001-2010), and P3 (2011-2021). Further support to the Figure 4 is presented in separate sub-periods illustration available in Figure 5. In addition, to investigate the relevance and statistical significance of changes in descriptors' relative share among sub-periods (P1-P2; P1-P3; P2-P3), a two-tailed z-test was performed (see Table 2a, Table 2b, and Table 2c) (López-Duarte et al., 2016). Further discussions

and reflections on patterns of movements and statistical significance are presented in following section.

\*\*\* *Insert Figure 4 around here* \*\*\*

\*\*\* *Insert Figure 5 around here* \*\*\*

\*\*\* *Insert Table 2a around here* \*\*\*

\*\*\* *Insert Table 2b around here* \*\*\*

\*\*\* *Insert Table 2c around here* \*\*\*

## **FINDINGS**

### **Theoretical foundations**

3DP is a relatively well-dispersed domain, covering several subfields of the business and management disciplines, as evidenced from the major research themes identified. This dispersion of major research themes is also reflected in the theoretical foundations, wherein five theoretical frameworks appear following our analysis (see Table 2).

Firstly, the Resource-Based View (RBV) seems to be the most dominant theoretical underpinning that scholars adapted within the analyzed body of literature. This theory highlights the role of strategic resources and the development of unique capabilities used to exploit these resources in an attempt to achieve (or establish) a competitive advantage for the organization. From this perspective, 3DP is considered one of the flagship technologies stemming from the advances of the Fourth Industrial Revolution, wherein organizations begun to question how to effectively use this technology. Candi and Beltagui (2019) based their study on the Resources Orchestration Theory to analyze survey data from 177 US companies that use 3DP, associating this technology with innovation. They demonstrate that adopting 3DP in innovation process brings

about greater benefits for companies that orchestrate their functions with regards to 3DP implementation and use. In other words, “*Understanding how resources such as 3DP are used is at least as important as possessing them*” (Candi and Beltagui, 2019, p.1). Additionally, Beltagui et al. (2021) investigated the role of 3DP through community-operated types of organizations (makerspaces), associating this environment and the presence of 3DP with innovation outputs. They show that the bricolage or DIY approach, wherein members combine 3DP with other resources available in a makerspace, can lead to the generation of innovations that otherwise would not be realized. As a resource, 3DP technology can be seen to yield higher benefits for organizations facing external uncertainties or resource constraints, demanding a dynamic approach to 3DP technology adoption, and combining it (through creative means) with existing capabilities within organizational contexts.

Cumulatively, 92 (out of 192) or 47.92% articles were to some extent associated with the RBV framework. Here, indicative change could be observed between the sub-periods P1-P3 and P2-P3 (with a decline of 16.56% and 12.74%, respectively, see Tables 2b and 2c). These declines could be rationalized solely based on the RBV, as the most dominant theoretical framework in the early stages of 3DP technological development and evolution, thus leading scholars to investigate additional research topics, as 3DP was adopted in larger industrial and consumer-based contexts, expanding the base of present theories in the analyzed body of literature.

The second theoretical framework stemming from the literature analysis was a Transaction Cost Theory (TCT). TCT refers to decision-making strategies used to leverage transaction and production costs. Expanding upon this framework, scholars examine 3DP as a digital technology bringing about changes in transaction costs (i.e., performance activities of a company on a marketplace), as well as production costs (i.e., product design, development, performance). This

reflects the primary characteristics of our observed sub-periods – specifically P1 and P2 – where the majority of studies focused on the comparison of 3DP with traditional manufacturing methods, followed by a focus on the optimization methods of the 3D print process itself or experimentation with the use of software or new materials.

For instance, Achillas et al. (2017) compared the possibilities of 3DP technology with traditional manufacturing methods (injection molding). This study showed that neither of the methods of 3DP technology could replace injection molding for medium and high production volumes. However, for low-volume production, 3DP technology was shown to be a good alternative that could result in shorter lead times and decreased total production costs. Expanding this line of research, scholars also investigated 3DP using operations strategy theory and with regards to efficiency and flexibility (Roscoe and Blome, 2019). These studies highlight the benefits of adapting 3DP in a centralized manufacturing environment, enabling flexibility through the development of ambidexterity capabilities. To foster these capabilities, large companies are expected to separate their manufacturing and SCM functions, whilst smaller companies can build an ambidexterity capability “*by creating the right organizational context, where multi-skilled workers switch between efficient and flexible tasks*” (Roscoe and Blome, 2019, p.496).

Through an overall overview, TCT accounts for 68 (out of 192) or 35.42% articles, where the highest degree of change between our three sub-periods is observable between P2 and P3 (decline of 15.24%, see Table 2c), when compared to the rather steady and sustainable growth seen between P1 and P2. This sustainable growth between the first two sub-periods confirms the general scholarly interest in experimenting with 3DP as a novel tool in production, establishing norms for the comparison of 3DP-based production and traditional manufacturing methods.

A follow-up theoretical framework – third in our overview – is the Network View (NV), which stipulates the focus on the social processes related to a particular technological artefact; 3DP, in this case. The overall objective is to understand human behavior and observe interactions with 3DP technology. Scholars highlight the openness of 3DP technology (Greul et al., 2018) and the associated platforms that enable users to develop new ideas, ‘remix’ existing ideas (Flath et al., 2017), or develop new artefacts for social or humanitarian causes (Corsini et al., 2020). The narrative expressed under this theoretical framework implies the existence of 3DP technology in a network of stakeholders, enabling the free sharing of printable digital models through direct interaction or the possible use of online repositories (i.e., Thingiverse). This approach could enable new forms of value creation, either through the complexities of supply chains (Tziantopoulos et al., 2019), or by facilitating closer interactions with customers in the ‘platformization’ of 3DP process (Wang et al., 2019). NV theory is relevant for 66 (out of 192) or 34.38% articles, revealing a significant change between the P1-P3 and P2-P3 sub-periods (251.67% and 108.37% growth rate, see Tables 2b and 2c).

The fourth theoretical approach emerging from our analysis is the Institutional Theory (INT), which accounts for 61 (out of 192) or 31.77% of cases. This theoretical approach focuses on the existence of social structures (institutions), either as freely formed clusters (bottom-up approach) or constructed moral beliefs through official regulatory agencies that govern political, economic, and social interactions. Emerging digital technologies with potentially disruptive effects, as in the case of 3DP, impose dramatic changes at an organizational or societal level, leading scholars to discuss the (in)existence of authoritative institutions to support 3DP, or the policies from national economies that seek to support 3DP development initiatives. Interestingly, INT also experienced a dramatic expansion in terms of scholars’ adoption of this theory, especially

during the most recent sub-period of our analysis: P3, having experienced 215.93% in growth compared to P1 (see Table 2c).

For instance, Roca et al. (2021) studied public support towards the diffusion of emerging technologies in Portugal. To a certain degree, similar approaches could be noted in studies focusing on 3DP in the context of other countries, such as China, Germany, India, Taiwan, Turkey, the US, and the UK (Rong et al., 2018; Zhao et al., 2021; Berlak et al., 2021; Birtchnell et al., 2017; Thomas-Seale et al., 2018; Yeh and Chen, 2018; Zhou and Li, 2005). The primary motivation found behind these studies was the investigation of 3DP, in either a national context, with initiatives to support the adoption of this technology, or a context examining the naissance of some form of institutional approach to 3DP. This means that associating the most recent tendencies of 3DP technology with the realms of community-operated workspaces (i.e., makerspaces, fablabs) implies bottom-up initiatives, which often lack a structured approach and are aimed at governing 3DP as a technological artefact with a set of social behaviors promoted by this sub-culture of (3DP) users.

The final predominant theoretical underpinning in the 3DP domain is the Knowledge Based View (KBV). This perspective builds upon and extends the RBV. For the KBV, knowledge is the most significant resource of an organization. It is often difficult to imitate and is bound to socially complex capabilities, which determine its unique competitive advantage and economic performance. Accordingly, KBV experienced a dramatic increase in its consideration in scholarly work in the third sub-period (P3), with a 156.35% growth rate when compared to P1 (see Table 2b). Scholars primarily investigate the topics of reuse for customization, “*a process in which designers manipulate the parameters of metamodels to produce models that fulfill their personal needs*” (Kyriakou et al., 2017, p.315), focusing on online repositories (i.e., Thingiverse).

Additionally, Roscoe et al. (2019) showed how individuals, processes, and structures interact to form the micro foundations of an operational capability in digital manufacturing. Their empirical framework explains how structures and processes encourage individual users to interact and share knowledge and, through these interactions, enable the emergence of operating routines and operational capabilities. This can be translated into a business context, wherein 3DP companies exchange explicit and tacit knowledge on a global level, where a shared digital identity leads groups of users to interact based on a sense of community, with common values and norms surrounding the digital technology.

### **Major research themes**

#### *5.2.1 Industrial revolution*

The “industrial revolution” descriptor has not only moved closer to the center of the map over time, but it has sharply increased its relative weight and representativeness within the domain. Accordingly, 3DP is primarily considered one of the key technologies marking the most recent industrial (Fourth) and digital (Second) revolutions (Rindfleisch, 2020). The principal issues covered in this topic are orientated towards the analysis of benefits and challenges for business or industrial sectors, national economies (through country roadmaps, for instance), or futuristic approaches to 3DP.

When observing the benefits and challenges for industries, the majority of studies are orientated towards the disruptive effects of 3DP in operations and SCM, blurring the lines between the physical, the digital, and the biological (Koh et al., 2019; Krafft et al., 2020; Olsen and Tomlin, 2020; Yin et al., 2018). Scholars have also introduced mergers between 3DP and other advanced technologies, such as blockchain technology, leading to terms such as blockchain-based manufacturing (Vatankhah Barenji et al., 2020).

In this futuristic approach, Culot et al. (2020) provided us with a Delphi study on Industry 4.0 evolutionary trajectories. Rindfleisch (2020) provided us with the terminology for the First and Second Digital Revolution, where the physical and digital worlds are seen to converge through the use of desktop 3D printers. In their work, Rindfleisch et al. (2017) deepen this relationship and view it as an enabler of innovation through data, highlighting the changing role of consumers.

### *5.2.2 Strategy*

Strategy in the context of 3DP has substantially increased in the amount of scholarly attention it has gathered over time, especially as the topic evolved into several research streams. First of all, scholars discussed the firm and industry-level strategic orientations toward 3DP. Secondly, organizational complexities, organizational capabilities, and business models were considered, as a research stream seeking to determine the alignment between this emerging technology and core business strategies. As such, this is followed by a focus on the implications of 3DP for pricing strategy, cost strategy, quality, value chains, or stock returns.

On an industrial level, scholars have examined the impact of 3DP on industry, business, and society (Caviggioli and Ughetto, 2019; Weller et al., 2015), where the possibility of producing small batches of products (D'Aveni, 2018) contradicts the economy of scale paradigm of modern-day production (Hartl and Kort, 2017). Scholars show that trends in ecosystem-based (rather than firm-based or network-based) systems of manufacturing (Rong et al., 2020) are expected to lead to the decentralization and localization of production (Ben-Ner and Siemsen, 2017; Laplume et al., 2016).

Throughout this process, firms turn their attention to knowledge-seeking activities that are expected to contribute to their digital identity (Bouncken and Barwinski, 2021). Rayna and Striukova (2021) and Bogers et al. (2016) have highlighted the importance of business model

innovation as a crucial barrier for the long-term sustainability of firms in the 3DP sector and entrepreneurship. The typology of business models was introduced by Holzmann et al. (2020), who argued that this relationship depends on 3DP's industrial ecosystem and whether it provides a dynamic setting for business model innovation. Examples of business model innovation emerged across industrial sectors merging with 3DP, such as, for instance, in the chocolate industry, for which scholars presented a supplier-centered business model approach (Jia et al., 2016).

These interrogations at a firm level also denote the implications of 3DP for cost or pricing strategies, leading to the comparison of traditional product designs approaches and 3DP production through platforms (Sun et al., 2020). Baumers and Holweg (2019) study how quantity, quality and cost are related in 3DP processes. This is potentially significant for start-up firms entering the market, as openness and collaboration with communities of users can enable inbound and outbound knowledge flows related to the firms' initial capabilities and founding intentions (Greul et al., 2018).

Kleer and Piller (2018) examined the impact of 3DP localized consumer production on consumer welfare, market structures, and competitive dynamics. Finally, scholars related 3DP implementation to stock returns, stating that the amount of stock returns due to 3DP implementation varies across different industries and environments (Lam et al., 2019).

### *5.2.3 Technology adoption and governance*

Governance and technology adoption in the context of 3DP was the most researched topic in the early stages of the domain's development, while the relevant representativeness of studies has slightly decreased in recent years. This topic can be further categorized as: general studies on 3DP adoption, specific industrial adoption frameworks, public policies and public support, and integration barriers.

When discussing general 3DP adoption, scholars approach this topic from various perspectives. Firstly, scholars addressed the general expectations of 3DP as a revolutionary and game-changing piece of technology for society, business, and the economy (D'Aveni, 2013; Dotsika and Watkins, 2017; Roca et al., 2017a). Then, future tendencies and expectations could be seen in conceptual approaches; as shown in the research of Potstada and Zybura (2014), where the authors discuss 3DP evolution as per its digital fabrication capabilities in short-coming (2033) futuristic scenarios. Jiang et al. (2017) provided results from an extensive Delphi survey on the future of 3DP, with a focus on its economic and societal implications in 2030.

Meanwhile, the studies of Khorram Niaki and Nonino (2017) and Schniederjans (2017) offered temporarily accurate results from their research endeavors, providing future 3DP projections based on actual business data from various stakeholders and the use of well-accepted theories in world of management and economics. In that same line of research, Rayna and Striukova (2016) provided an overview of 3DP adoption across four successive phases, assessing the effect of each phase on key business model components. Chatzoglou and Michailidou (2019) investigated people's attitudes towards 3DP as a technological innovation and their intention to use it in their workplace. These findings highlight the importance of perceived usefulness, output usability, compatibility, and attitudes towards understanding respondents' intentions to use 3DP technology.

Lastly, scholars revealed the barriers for the further adoption of 3DP, as evidenced by issues pertaining to standardization, intellectual property, certification, skills, and education, as well as significant implications for the configuration of manufacturing and SCM actions (Ford et al., 2016). Moreover, a general approach to critical barriers limiting 3DP adoption can be seen in the works of Shukla et al. (2018) and Long et al. (2017).

#### *5.2.4 Performance*

This review shows that the effects of 3DP technology on organizational performance continuously attract scholars, as the topic has remained well-researched for more than 30 years. In line with 3DP technology's recognized capacity and added value, scholars have described how 3DP can affect organizational performance with regards to firm growth and market share (Datar et al., 1997), as well as innovation (Turkcan et al., 2022), among other attributes. In fact, 3DP technology has been renowned for its feasibility, flexibility, speed, and the rate at which it allows companies to introduce products into the marketplace and nourish their competitive advantage (Eyers et al., 2018; Jia et al., 2016). Due to its ability to support globally dispersed business activities and reduce costs while empowering economies of scale (Baumers et al., 2016; Bouncken and Barwinski, 2021), 3DP has reconfigured responsiveness to customer demands and resource management, causing a substantial shift in the supply chain (Braziotis et al., 2019). In time to come, scholars concur that, in order to increase the likelihood of achieving higher performance levels, organizations should embrace dynamic adaption in parallel to the development of 3DP technology, especially in terms of communication and coordination between different functional units (Candi and Beltagui, 2019).

#### *5.2.5 Innovation*

Innovation, as a research topic has been explored significantly in the context of 3DP technology. It has been explored most notably with regards to general ability to innovate through 3DP, new product development, exploration of innovation ecosystems, relationship through open source and communities of users, disruptiveness of 3DP, as well as innovation in specific sectors, such as in medicine.

Discussing the general ability to innovate through 3DP, Candi and Beltagui (2019) addressed the question of how to make effective use of 3DP for innovation. Sandström (2016) studied how 3DP technology is used in manufacturing, and how 3DP affects the competitive dynamics between firms. West and Kuk (2016) studied firm openness in 3DP, focusing on a case study of a market leader – MakerBot Industries – that leveraged external communities and was selectively open in their business strategy.

New product development remained an interesting segment of 3DP and innovation, wherein scholars focused on actual design processes across different stages of production. For instance, Sun and Linton (2014) highlighted the link between 3DP and production design. Elverum and Welo (2016) provided insights on adding value through prototypes and rapid prototyping across various stages of the new product development process in the automotive industry. Furthermore, a research topic combining 3DP with cloud platforms, IoT, and Artificial Neural Networks was the focus of one study, which gathered results on the development of supportive 3DP services in the product development process (Wang et al., 2019). Hannibal and Knight (2018) took this approach to a global level, assessing the impact of 3DP on global production, identifying four levels of production analysis – global, country, local area, and household – and drawing on the most impacted industrial sectors.

In the context of innovation ecosystems, 3DP has been explored to facilitate an understanding of how best to support innovation ecosystems and cultivate exaptation opportunities (Beltagui et al., 2020a). 3DP is seen as an evolutionary driver of innovation in society through ‘platformization’, either open-source hardware platforms, online service platforms, free and low-cost 3D design software platforms, and crowdsourcing platforms (Kwak et al., 2018). Moreover,

scholars also explore emerging 3DP innovation ecosystems comprising of business, science, and technological sub-ecosystems in specific national contexts, such as China (Xu et al., 2018).

Linked to innovation ecosystems is the exploration of 3DP and open-source initiatives emerging from the global communities of users that foster collaboration and the free sharing of designs. For instance, De Jong and De Bruijn (2013) observe 3DP and the rapid emergence of the open-source movement through collaborative online communities. Stanko (2016) focuses on online innovation communities and remixing processes (i.e., the community's use of an existing innovation as source material or inspiration to aid in the development of further innovations) in the context of 3DP innovations. However, little is known about the process of remixing where scholars have studied the importance of Thingiverse: a platform for the 3DP community that allows its users to create, share, and access a broad range of printable digital models (Claussen and Halbinger, 2020; Flath et al., 2017; Friesike et al., 2019; Kyriakou et al., 2017).

The stream of research on innovation and 3DP clearly emphasizes the role of users in co-creation and personalization, which is picking up momentum in the manufacturing ecosystem (Kapetaniou et al., 2018). This co-creation and collaboration takes place in community-operated workspaces, often called makerspaces, hackerspaces, or fablabs (Mortara and Parisot, 2016; Rayna and Striukova, 2021). These spaces provide access to digital fabrication technologies (3DP among them) and knowledge, and they ensure users obtain 21st century fabrication competencies. Through shared access to tools and digital fabrication technologies, makers can act as producers in the sharing economy and can potentially increase entrepreneurship rates, catalyze advanced manufacturing, and spur economic development (Browder et al., 2019). This became fertile ground for the investigation of how 3DP technology is used by community members in order to realize their creative and commercial ambitions (Beltagui et al., 2021; Wiecek et al., 2020). Here, scholars

combine different theoretical and research methods (such as ethnography and self-determination theory), to provide original insights into the individual motivations behind contributions to 3DP and open-source technology (Hausberg and Spaeth, 2020; Roscoe et al., 2019). Moreover, the disruptiveness of 3DP is driven through open-source communities and technological capabilities.

Scholars have provided a framework with which to analyze vertical and horizontal approaches to disruption (Kilkki et al., 2018). 3DP innovation in specific industrial sectors, such as medicine, is explored from a perspective analyzing customized on-demand 3DP surgical flow time, its variability, and its clinical outcomes. This research also provides a framework for hospitals to use to decide whether or not to invest in 3DP (Chaudhuri et al., 2020a). Hence, in that same medical context, 3DP was examined in an attempt to understand the shift towards the mass customization of orthopedic medical implants and the incumbent company that transformed its value chain into a collaborative ecosystem (Randhawa et al., 2021).

#### *5.2.6 Sustainability and circular economy*

Sustainability, or sustainable development, in the context of 3DP has been observed through multiple subsections and has attracted scholarly attention primarily during the last period under investigation (P3: 2011-2021). This substantial increase in attention could be partially explained through the development of the United Nations Agenda for Sustainable Development, which focuses on general sustainability, social sustainability, environmental or ecological sustainability, and the context of the circular economy.

In the context of general sustainability, scholars either studied how the adoption of 3DP technologies mediates the impact of firms' sustainability orientation on new product performance (Zhao et al., 2021), or the relationship between 3DP and triple bottom line in waste reduction (Ghobadian et al., 2020).

Hence, environmental or ecological sustainability was discussed with regard to 3DP technology and supply chains, particularly for the end-of-life product stage, in an attempt to reduce the inventories (Diri Kenger et al., 2021). Geng and Bidanda (2021) developed a study on 3DP techniques used in remanufacturing applications, comparing the complexity of 3DP produced parts with those made using traditional manufacturing methods. Afsharid et al. (2020), on the other hand, focused on a mathematical approach to studying the importance of 3DP eco-innovation drivers, adopting new methods and technologies in a supply chain. Beltagui et al. (2020b) examined how the open design of 3D-printed mobile phone accessories can help overcome size-related resource constraints, facilitate market growth, and ultimately generate sufficient consumer demand to alter the market leaders' supply chain practices, linking it to social sustainability.

Social sustainability was discussed through the works of Naghshineh et al. (2021) who addressed the social impacts of 3DP and suggested that social sustainability has received insufficient attention. They identified forty-two social impacts of 3DP and provided a social life cycle typology for stakeholders affected by 3DP. Woodson et al. (2019) focus on the Brazilian context and study whether 3DP is an inclusive innovation.

The relationship between circular economy and 3DP has experienced a narrow focus in terms of the evaluation of the potential this technology holds in the circular economy (Despeisse et al., 2017). Unruh (2018) identified 3DP as a key technology for the emergence of a true circular economy, which will bring about environmentally sustainable manufacturing. A disruption of existing materials' value chains is expected through further adoption of 3DP (Garmulewicz et al., 2018).

### *5.2.7 Human resources*

Through the lens of human resources, 3DP technology is primarily discussed in terms of the need for human talent (and knowledge seeking) for companies or, alternatively, the development of skills for human resources (users). In this context, scholars looked at questions of competencies, training, education, and empowerment for the early users of 3DP technology.

Rayna and Striukova (2021) highlighted the role of fablabs and makerspaces in developing digital skills for 21st century development. The narrative of this article stipulates that the presence of digital technologies in fabrication spaces, as well as training and hands-on approaches in acquiring skills to manipulate 3DP technology, leads to the better development of digital skills for individuals. However, the article also elicits the need for a more explicit and proactive approach to entrepreneurship, with dedicated education programs for current and future users within fabrication spaces. In other words, this means that the sole existence of fabrication spaces is sufficient in order to enable the general exposure of individuals to 3DP technology (Mortara and Parisot, 2016), but a more structured approach is required in order to translate 3DP skills into entrepreneurship endeavors (Beltagui et al., 2021). Browder et al. (2019) also stated that fabrication spaces are fertile ground for research on talent development, entrepreneurship, and increased innovation outputs, emphasizing the role of fabrication spaces as innovation ecosystems and evolutionary drivers of innovation in society (Beltagui et al., 2020a). This also means that the fabrication spaces will probably experience further integration within the business sector in the pursuit of talent when companies lack explicit and tacit knowledge on 3DP technology (Birtchnell et al., 2017; Bouncken and Barwinski, 2021; Hartl and Kort, 2017).

### *5.2.8 Risk and uncertainty*

With the increased penetration and adoption rates of 3DP, risks and uncertainties in the context of 3DP technology are observed through few associated tracks. Most notably, the following streams are discussed: the regulation of 3DP technology, uncertainties regarding the adoption of 3DP (for instance, within SCM), risks associated with the business challenges associated with 3DP technology, or the risk of 3DP disrupting the economy and society.

Roca et al. (2017b) focused on the question of regulatory interventions in emerging technologies, uncovering a case of metal additive manufacturing in aviation sector. Due to a general lack of standards for the entire spectrum of 3DP techniques (Ford et al., 2016), this study proposed an adaptable framework based on several factors. The first factor of the framework expressed a need for a periodical revision of the standards related to 3DP (due to the field's changing and evolutionary nature), the presence of an industrial structure (clusters of companies using 3DP), technological capabilities associated with (metal) 3DP, and performance and safety requirements that are generally applicable to 3DP.

Additionally, the risks associated with the adoption of 3DP technology include the lack of a structured approach from public administration and governments, leaving this technological domain without regulation and standardization and thus lacking proper support in its early stages of development (Dickinson, 2018). Associated with this lack of public administration and government are the risks associated with Intellectual Property (IP), which are closely associated with the open-source culture of fabrication spaces and are heavily dependent on country contexts (Chan et al., 2018; Ford et al., 2016; Long et al., 2017).

The risk of adopting 3DP technology on an operational level within a company is covered in the works of scholars examining the challenges and benefits of this technology in SCM. The

risks are related to questions concerning spare parts development (Frandsen et al., 2020; Kunovjanek et al., 2020; Li et al., 2017; Sgarbossa et al., 2021; Westerweel et al., 2020), forecasting (Ramón-Lumbierres et al., 2020; Valizadeh et al., 2020), or scheduling (He et al., 2021; Hedenstierna et al., 2019). From a strategic point of view, the adoption of 3DP technology presents a risk for the companies questioning value chains (Laplume et al., 2016) or business model development (Bogers et al., 2016; Rayna and Striukova, 2016) when it comes to successfully navigating the pitfalls of 3DP as a nascent business sector (Bouncken and Barwinski, 2021; Hartl and Kort, 2017).

Lastly, the risks related to the disruptive effects of 3DP are observed in the general context of the Fourth Industrial Revolution, in which scholars have discussed general issues related to business and society (D'Aveni, 2013; Dotsika and Watkins, 2017; Krafft et al., 2020; Rindfleisch, 2020; Olsen and Tomlin, 2020), often on a conceptual level (as in the early 2010s) lacking empirical support for their arguments.

### **Methodology and context**

Interestingly, in terms of methodology, scholars are leaning towards quantitative research methods and are adopting them slightly more frequently in their research designs. Quantitative methods are seen in linear and regression analyses and comparisons, structured-equation modelling, mathematical modelling, stochastic approaches, and factor analyses to a certain extent. These (more) experimental and comparison-orientated methodological approaches are linked to the early stages of 3DP technology evolution and optimization endeavors, followed by cross-disciplinary and cross-sectional comparisons.

On the other hand, qualitative approaches are seen in the need to understand research gaps emerging in social and business-related academic disciplines that follow the technological

evolution of 3DP, demanding more exploration-orientated research designs. These approaches focus largely on semi-structured or structured interviews with leading users or adopters of 3DP technology, focus groups with industrial experts, and case study analyses, or, to a lesser extent, conceptualization papers, literature reviews, and Delphi studies.

Geographically, the Northern Hemisphere has served as the research setting for the vast majority of studies. For example, the adoption of 3DP in specific industrial contexts is a topic that covers several geographical areas and industrial sectors across the Northern Hemisphere. The aerospace, automotive, aviation, construction, and manufacturing sectors have been clearly analyzed, whilst the national contexts of China, Germany, the UK, and Taiwan dominate current literature. Berlak et al. (2021) elaborated upon the use of 3DP in construction and BIM software for buildings. General manufacturing investigations seeking to observe organizational perspectives and factors influencing the adoption of 3DP can be seen in the works of Gardan (2016), Yeh and Chen (2018), and Wang et al. (2016), focusing on, for instance, Chinese and Taiwanese national contexts. The integration of 3DP has been discussed in the automotive, aerospace, and aviation industries in the works of Roca et al. (2017b), Thomas-Seale et al. (2018), and Wagner and Walton (2016). Petrovic et al. (2011) consider 3DP to be a powerful tool, offering a necessary degree of competitiveness to European companies, if it ever reaches a more mature adoption level. However, as it can be recommended for numerous domains, future research should embrace practices and contributions developed in the Southern Hemisphere.

## **DISCUSSION AND FUTURE RESEARCH AVENUES**

Taking cues from static and dynamic overviews of the domain, this review discuss and highlights future research opportunities by distinguishing between significantly researched, emerging, and under-researched topics. Building upon the guidelines established by Dabić et al.

(2019), Figure 6 presents the frequency of each topic's occurrence and reveals its particular distance from the domain center. Significantly researched topics are positioned in the top left quadrant, emerging topics are in the bottom left quadrant, and topics that are currently under-researched are in the bottom right quadrant.

\*\*\* *Insert Figure 6 around here* \*\*\*

## **6.1. Future research avenues regarding theory and research themes**

### *6.1.1 Future streams of research regarding theoretical frameworks*

According to the RBV theory, companies investing or developing 3DP capabilities should have consequential automatic returns in terms of their competitive advantage or economic performance. However, this viewpoint is criticized due to its lack of explanation with regards to the synergies between capabilities, and its inputs regarding the roles of individuals (managers) in extracting the benefits of new technological artefacts within an organization (Candi and Beltagui, 2019). Mere ownership of a novel technology is not sufficient to result in a success or constitute a competitive advantage, but rather, Resource Orchestration Theory (ROT) stipulates that the combination of capabilities, resources, and knowledge holds the key to improved performance (Chadwick et al., 2015). From this perspective, obtaining performance outcomes through the application of technological capabilities depends on the alignment between activities in the organization. In other words, we concur with Candi and Beltagui (2019, p.2) in that, "*how resources are used is at least as important as what resources are possessed*". Managerial roles then demand the implementation of strategies tailored towards the type of resources adopted. The 3DP marketplace is characterized by its self-regulating supply and demand and is known for

having turbulent stages of market development. In this case, managers identify the unique feature of a resource, allocate investment into the technological artefact, assign appropriate business models and organizational structures, and provide a unique vision, resulting in marketplace success. As such, ROT suggests that the synchronization of processes and the coordination of capabilities is key to forming a competitive advantage. Management roles and the use of resources, rather than simply ownership of a resource alone, ‘orchestrates’ all levels of the hierarchy (Chadwick et al., 2015), facilitating a more suitable explanation of the capabilities required to effectively use 3DP technology. Thus, one of the future lines of research on 3DP should seek to deepen scholarly discussions regarding the ROT and 3DP technology with more empirically-backed research.

Additionally, as shown in Figure 6, deepening discourse on knowledge – as the most significant resource for the proper use of 3DP technology – serves as an additional future research stream with regards to theoretical frameworks. KBV is the least represented theory within the analyzed body of literature, and 3DP technology demands that new skills and capabilities be mastered by ordinary users. This means that human resource training, talent development, education, skills management, and experience generation with regards to 3DP technology can be considered a valuable approach through which the transfer of knowledge between organizational hierarchies and team members can be clarified. In other words, how to generate skillful workforces, how to organize training for the interested individuals within organizations, and whether formal or informal education is more suitable for the organizational needs related to 3DP, all make up a small subset of questions that scholars should focus on. Moreover, considering that 3DP is largely available in community-operated workspaces (i.e., makerspaces and fablabs), which provide initial interactions with this technology for members of the public, an additional question

that should be raised by scholars is whether or not a more structured approach to education or training in these informal institutional settings is needed (Beltagui et al., 2020a; Caviggioli and Ughetto, 2019). This reflects scholarly discourse on value chains and business model innovation, either through conceptual (Bogers et al., 2016; Rayna and Striukova, 2016) or empirical (Jia et al., 2016; Marić, 2020; Savolainen and Collan, 2020; Vendrell-Herrero et al., 2022) approaches towards 3DP technology, seeking to assess entrepreneurship endeavors as knowledge spillovers from formal or informal institutional settings.

#### *6.1.2 Industrial revolutions: 3DP in the transition from Industry 4.0 to Industry 5.0*

An additional topic that deserves attention through more dedicated research is the context of industrial revolutions. 3DP is one of the flagship technologies of the Fourth Industrial Revolution, in which scholars have pinned down its revolutionary, radical, disruptive, and groundbreaking potential (Dotsika and Watkins, 2017; D'Aveni, 2013; Roca et al., 2017). Following the technological advances that placed 3DP in the spotlight of media focus in 2012 and 2013, scholars have provided generic contributions by discussion this technology in the context of the Fourth Industrial (Krafft et al., 2020; Olsen and Tomlin, 2020; Yin et al., 2018) or the Second Digital (Rindfleisch, 2020) revolution. The connection between 3DP and Industry 5.0, however, remains a relatively untapped area for future researchers to examine.

In this regard, the work of Rindfleisch (2020), Rindfleisch et al. (2017), and Potstada and Zybura (2013) introduces us to futuristic uses of 3DP in the short term, where the mass adoption of 3D printers enables customizable production from the comfort of our homes or offices (Rayna and Striukova, 2016; West and Kuk, 2016), revealing the digital fabrication possibilities available through the use of this technology. It is evident that the mass adoption of 3DP is still a far-reaching scenario. User exposure and users understanding the current position of 3DP technology in our

society are vital factors to consider when discussing future tendencies regarding the consumer-orientated market segment (West and Kuk, 2016) or value (chain) creation (Laplume et al., 2016; Opazo-Basáez et al., 2021).

Moreover, discussing 3DP as part of Industry 4.0 trends also implies a level of criticism in terms of the absence of human innovation and competency. The presence of the human (knowledge) factor, alongside the machine, is required in order to increase performance efficiency and effectiveness. Therefore, the application of cutting-edge technologies, alongside human talent, can help to facilitate the desired transformation of businesses, the economy, or society more generally. This is what some scholars already refer to as ‘Industry 5.0’ (Bednar and Welch, 2020; Carayannis et al., 2021). Open topics regarding the future adoption of 3DP within Industry 5.0 context, related organizational capabilities, technological advances, innovation outputs, the future of technology adoption, governance, and the role of this technology in general society all serve as interesting future research streams, enabling the development of future scenarios. Certain contributions paving the way for future avenues of research can be seen in the conceptualizations of Potstada and Zybura (2013) or through empirically-backed Delphi studies by Culot et al. (2020) and Jiang et al. (2017).

Future research streams could also look to uncover differences in 3DP adoption between developed and developing countries. As observed in Figure 6, research orientated towards understanding the reasons for the increased presence of 3DP studies originating in the developed Northern Hemisphere, in comparison to those from Southern Hemisphere, could be envisaged. Contributions such as research design could serve not only future scholars’ debates, but could also aid business practitioners/entrepreneurs from developing countries, as well as policymakers interested in forming supportive policy initiatives orientated towards 3DP (or Industry 4.0 and

Industry 5.0). This could lead to possible leapfrog effects by developing countries, enabling those countries to grasp the benefits of the most recent industrial development.

### *6.1.3 New contextual perspectives on 3DP governance and adoption*

Building on the narrative of the dichotomy between the Northern and Southern Hemispheres with regards to research on 3DP technology, additional valuable contributions could assess the purposes of this technology in developing countries with scarce resources or those experiencing emergency situations or humanitarian crises. Scholars have investigated 3DP for the purposes of humanitarian logistics and Humanitarian Supply Chains (HSC), where the scalability of the 3DP process or the customization of tools and spare parts are considered vital benefits of this technology (Corsini et al., 2020; Kovács and Falagara Sigala, 2021; Marić et al., 2021; Rodríguez-Espíndola et al., 2020).

Future contributions on the adoption of 3DP within HSC could be directed towards empirical studies in an attempt to clarify the challenges and benefits of this technology in emergency situations or crises, such as during the COVID-19 pandemic. The most recent public healthcare crisis, caused by the COVID-19 virus, led to the imposition of public policy measures in the form of national lockdowns, leading to shortages in global supply chains and resource scarcity. In such resource-restrained environments, innovative bottom-up solutions, emerging in community-operated workshops (such as makerspaces, hackerspaces, and fablabs), alleviated some of the crucial demands of medical institutions and placed 3DP technology and its user community back in the center of the media spotlight. Future research avenues could focus on the drivers of these innovative solutions, also referred to as frugal innovation (Dabić et al., 2022; Marić et al., 2016), in remote locations of the Southern Hemisphere, or as a response to emergency and disaster situations (Kovács and Falagara Sigala, 2021). The combination of both quantitative and

qualitative research methods could unveil complexities and reveal the roles of stakeholders in HSC operations related to 3DP.

#### *6.1.4 Contemporary research on operation performance and SCM*

Scholars have dealt with various touch points between 3DP and SCM, covering the sustainability of SCM (Beltagui et al., 2020a; Ryan et al., 2017), specific cases regarding spare parts in SCM (Chaudhuri et al., 2020b; Frandsen et al., 2020; Kunovjanek et al., 2020; Li et al., 2017; Sgarbossa et al., 2021; Westerweel et al., 2020), forecasting (Ramón-Lumbierres et al., 2020; Valizadeh et al., 2020), and scheduling (He et al., 2021; Hedenstierna et al., 2019). This relatively well-covered area of operations and SCM suggests that future scholarly contributions should be directed towards contemporary questions pertaining to global shortages in terms of delivery and SCM resilience (Ivanov, 2020; Ivanov and Das, 2020) as a follow-up to disruptions caused by the COVID-19 pandemic. Open questions on how 3DP alleviates these contemporary SCM problems, or how 3DP serves to return production to European soil, could be interesting avenues for inspection.

Continuing the line of research regarding 3DP, operations, and SCM, future contributions could connect 3DP with the topic of lean manufacturing. Bearing in mind the complexities of manufacturing operations, SCM, questions of capabilities within organizational contexts, and external regulatory pressures (policy makers), it would be rather exciting to see more research covering the specificities of adopting 3DP in production lines, considering the elements and philosophy of lean manufacturing. Potential future research could assess the ability of 3DP process to reduce and eliminate waste in the manufacturing sector through appropriation within SCM designs, reducing the interplay between producers, suppliers, and consumers. In achieving this,

scholars could also provide legitimate empirical backing for 3DP technology's propensity to aid in achieving the sustainable development goals.

#### *6.1.5 Future of sustainability and circular economy discourse with 3DP technology*

Even though sustainable development and 3DP are coherently intertwined topics due to additive nature of 3DP fabrication process, when compared to traditional manufacturing methods, this overall connection has only been vaguely investigated through scholars' conceptual approaches. The works of Ford et al. (2016), Despeisse et al. (2017), and Ghobadian et al. (2020) announce that *triple-bottom-line* could be achieved with 3DP technology. However, considering that the core of this study is based on literature insights from top-tier academic articles, it is evident that the topic of sustainable development in 3DP technology is still yet to receive mainstream attention, nor was it ever considered a major research trend for 3DP.

Future research avenues could look to empirically back environmentally sound practices with 3DP in global SCM, the benefits of 3DP in reshoring and shortening SCM, waste reduction in manufacturing activities through 3DP, reuse and recycling with 3DP in developing countries, or general product design through 3DP for circular economy (see Table 3). On the other hand, social sustainability in 3DP can be seen in the initiatives investigating innovative 3DP solutions for socially deprived populations, or frugal innovations in developed and developing countries. Future studies combining 3DP with social sustainability could explore 3DP innovations arising in the wake of COVID-19 disruptions, serving to bring 3DP technology into the mainstream by potentially converging the effects of the latest industrial revolution with sustainable development goals (Naghshineh et al., 2021; Marić, 2018).

*\*\*\* Insert Table 3 around here \*\*\**

## CONCLUSION

This article offers a timely review of literature in the 3DP technology domain by actioning an MCA and content analysis of 192 manuscripts published in top-tier journals and indexed in Scopus and Web of Science scholar databases. Its principal aims were to objectively elaborate upon research themes, theoretical frameworks, and future research trends. As such, it extends contributions made by previous literature reviews (see Section 2.2 and the work of Caviggioli and Ughetto, 2019, and Khorram Niaki and Nonino, 2017) by expanding the overall body of literature and narrowing the scope to include peer-reviewed papers appearing in business and management journals ranked as 3,4, and 4\* in CABS Academic Journal Guide, 2021 (Vlačić et al., 2021).

With regards to the first research question (RQ1), the literature review synthesized five theoretical frameworks related to the 3DP research field. The most dominant theoretical framework was the RBV, followed by TCT, NV, and INT. The KBV was the least adopted theory, possibly due to the fact that 3DP is (still) a relatively novel research phenomenon in business and management literature. In line with the first research question, eight major research themes were summarized, respectively: industrial revolution; strategy; technology adoption and governance; performance; risk and uncertainty; human resources; innovation; and sustainability and circular economy.

With regards to the second research question, multiple future research trajectories have been outlined. In terms of theoretical foundations, the potential for future research perspectives on KBV to clarify the need for talent development, training and education, skills management, experience generation, and structured approaches to education and training in informal institutional settings (i.e., makerspaces and fablabs) could lead to more spillovers into entrepreneurial initiatives (Beltagui et al., 2020a; Caviggioli and Ughetto, 2019). Similarly, ROT

stipulates that the combination of capabilities, resources, and knowledge holds the key to improved performance (Chadwick et al., 2015) and, in this regard, scholars should focus on exploring holistic performance outcomes stemming from alignment efforts made between technological capabilities and management roles in organizations (Candi and Beltagui, 2019).

Additional topics of interest include the role 3DP plays in the transition from Industry 4.0 to Industry 5.0; governance and 3DP adoption in remote environments; cross-country collaboration; the design of contemporary production lines; operations and SCM with 3DP; or further empirically-based studies seeking to reveal the challenges and benefits of 3DP technology with regards to sustainability and circular economy.

This review offers contributions to managers, policy makers, as contributions were directed towards understanding 3DP as a contemporary technological artefact, demanding thorough organizational change, the questioning of business strategies, the development of capabilities, and the appropriation of 3DP as a strategic resource within an organizational context. Furthermore, from a pragmatic perspective, when assessing 3DP in an organizational context, the common misinterpretation of different AM/3DP techniques (as defined by the ISO/ASTM 52900:2021<sup>2</sup>) can be seen in industry reports, international associations, media/press, and research papers (see Schniederjans, 2017, and Candi and Beltagui,2019), which often use one ‘umbrella’ term. Hence, the merging of AM/3DP techniques under one common title is probably a result of the 3DP fabrication process, which develops physical object(s) from a digital model. Alternatively, this

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<sup>2</sup> ISO/ASTM 52900:2021 - Additive manufacturing — General principles — Fundamentals and vocabulary. Available at: <https://www.iso.org/standard/74514.html>

may occur as a result of attempts to simplify terminology for the purposes of specific research or business projects (as in the case of this study).

However, this approach could be misleading to the general public and business practitioners, as 3DP techniques differ in terms of their fabrication processes; their characteristics and performances; their use of materials, computer software, and resources (i.e., energy); and the final price of the product. Consumer-orientated 3DP units can range in price from several hundred euros to thousands of euros, whilst industrial 3DP units range from several hundred thousand euros to millions of euros.

Next, despite the fact that our systematic literature review on MCA (Multiple Correspondence Analysis) and our content analysis were both based on an extensive body of literature from top-tier journals, minimizing author subjectivity bias in content analysis and maximizing the reproducibility of our research design through the application of automated classification techniques (Caviggioli and Ughetto, 2019), this study is not exempt from limitations. Research scope focused only on the availability of top-tier journals in the Scopus and Web of Science scholarly databases, and it included only peer-reviewed articles published in English. These omissions could offer interesting avenues for future researchers, particularly with regards to the meta-analysis of literature, which could include relevant books, reports, and papers published as conference proceedings. In addition to this, as shown in Table 4, mixed methodological approaches combining insights from this literature review with quantitative/qualitative studies would also be a valuable scholarly contribution to the field.

Considering the many contributions of this study – in terms of its consolidation of literature on the major research themes, theoretical foundations, and future research streams related to 3DP

technology, this review serves as a solid starting point from which to broaden scholarly discussions and guide future research avenues.

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## Figures and Tables

Figure 1: 3DP technology adoption and usage stages (adapted from Rayna and Striukova (2016)).





Time Period	Adoption Stage	Involvement in Production			
		Design and Prototyping	Tooling and Molding	Direct Fabrication and Distribution	Direct Localized Fabrication
Late 1980s - Early 1990s	Rapid Prototyping				
Late 1990s – Early 2000s	Rapid Tooling				
Late 2000s – Early 2010s	Direct Manufacturing				
Late 2010s to modern date	Home (local) Fabrication				

Figure 2: Research Design

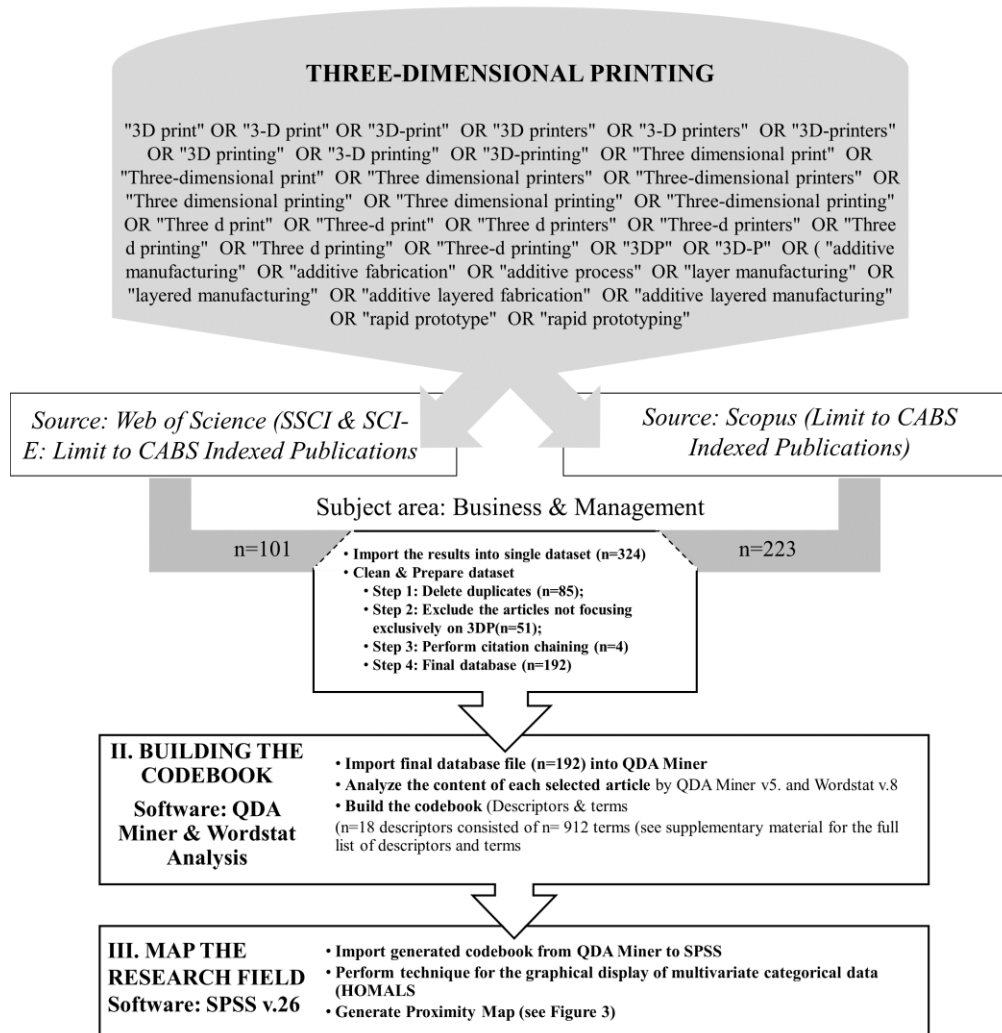
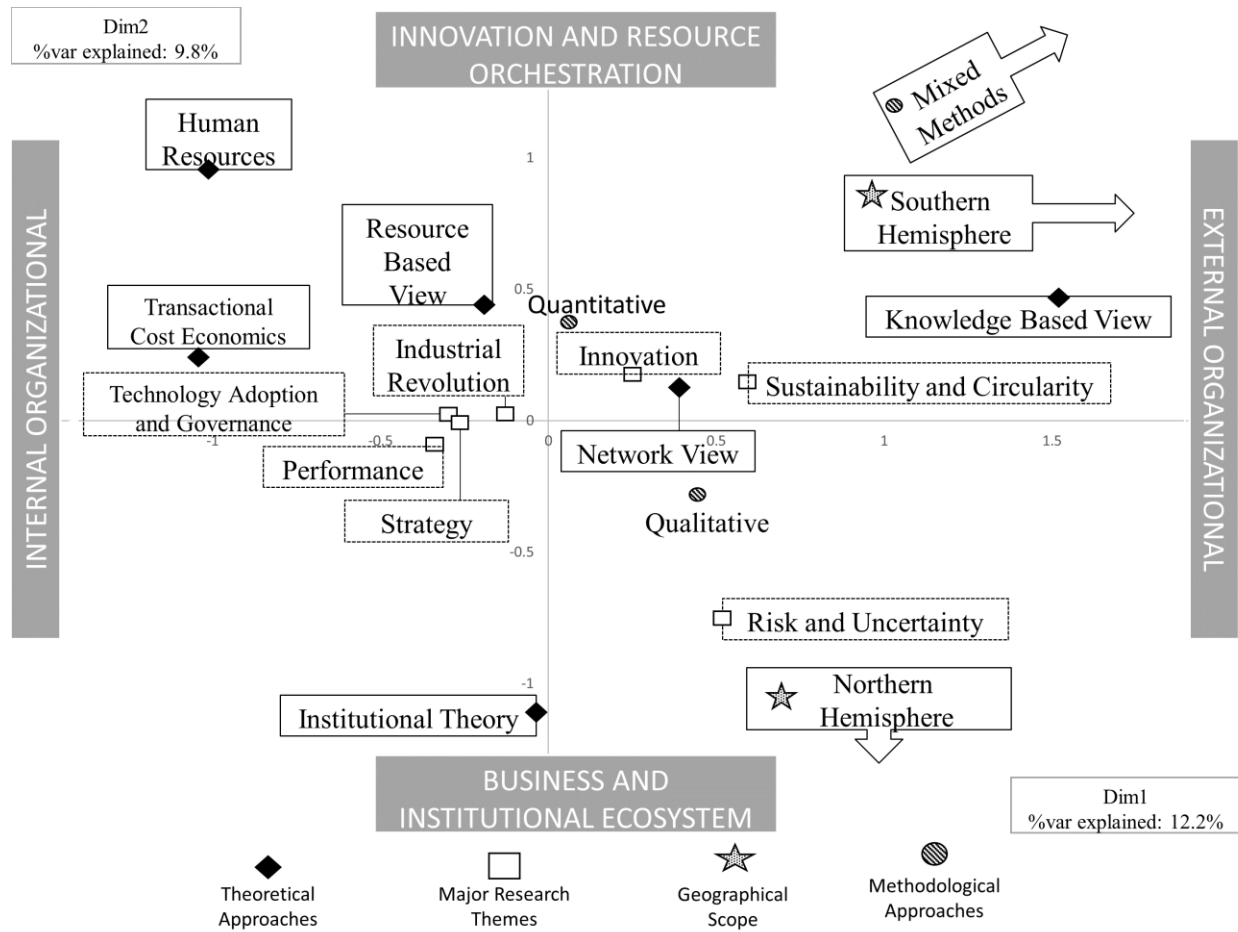
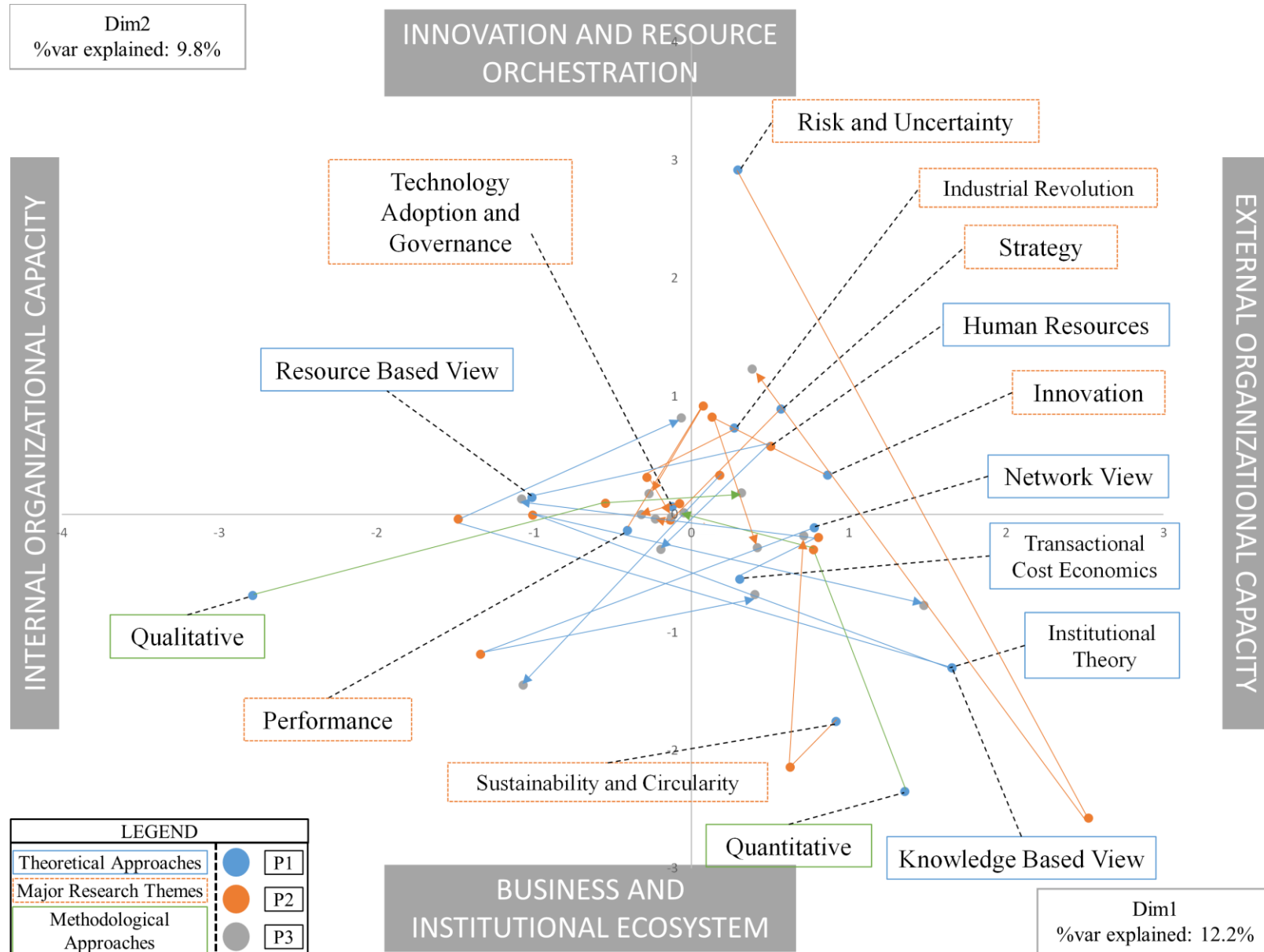


Figure 3: 3DP Intellectual Domain



Source: own draft

Figure 4: Graphical representation of 3DP field evolution over time and descriptors trajectory



Source: own draft

Note: The start of the line (blue dot) indicates the descriptor position in P1; the curve of the line (orange dot) indicates the P2; and the end of the line signaled by arrow (grey dot) indicates the P3. Some descriptors emerge for the first time in P2 or in P3, thus the positioning is only available for subperiods P2 or P3.

Figure 5: In detail sub-periods representation of 3DP domain

Figure 5.1: Graphical representation of 3DP field in P1

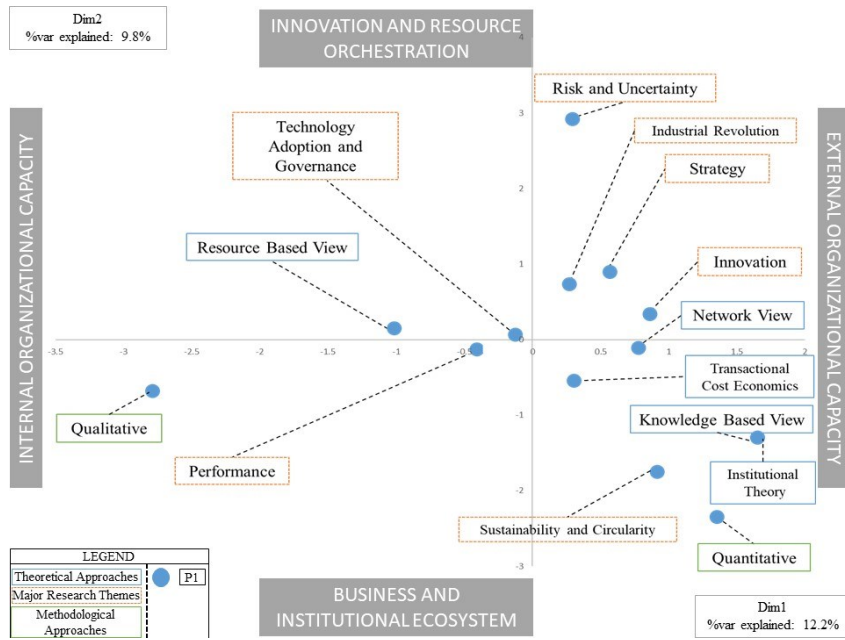


Figure 5.2: Graphical representation of 3DP field in P2

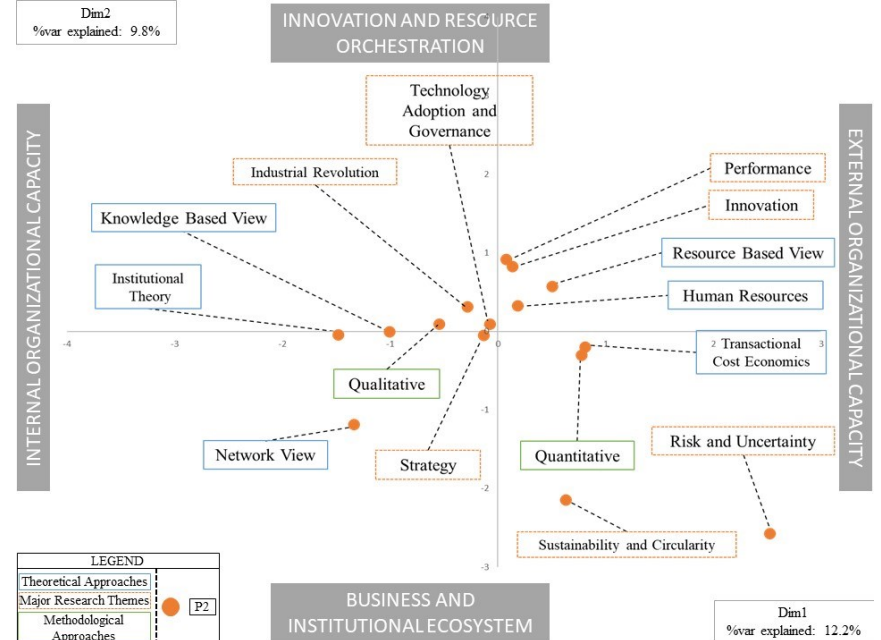


Figure 5.3: Graphical representation of 3DP field in P3

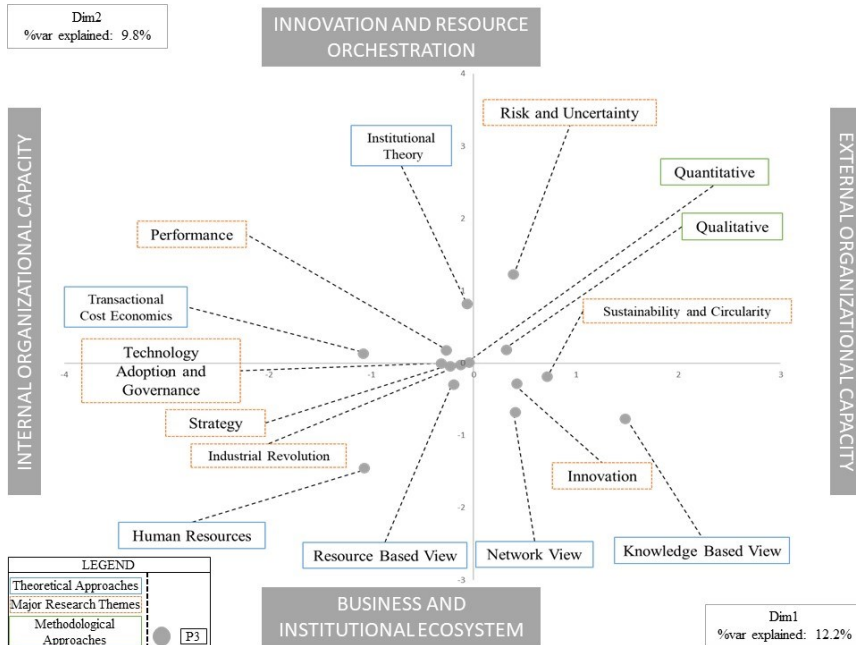
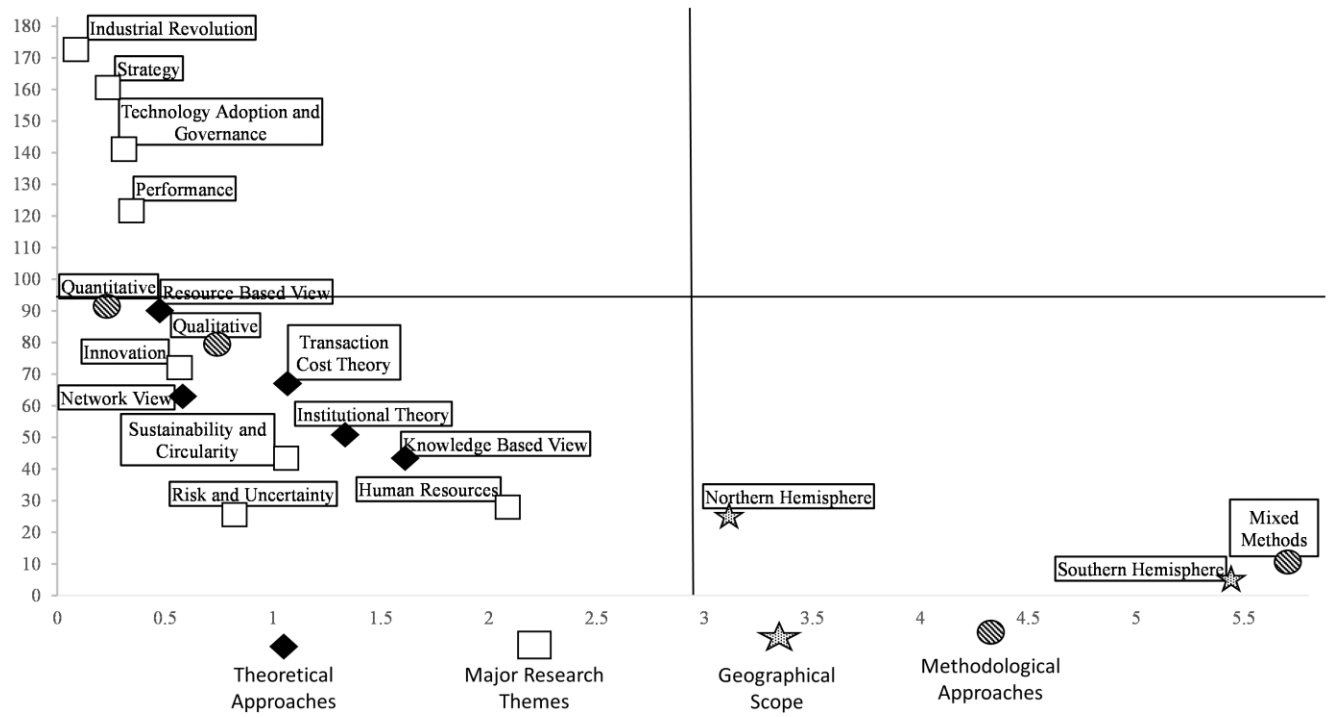


Figure 6: 3DP domain topics' distance and frequency



Source: own draft

Note: Horizontal axis represent distance from the centre of the intellectual domain while vertical axis represents frequency of descriptor within the domain

Table 1: Descriptors that represent the poles of the axes

1)Axes	2)Descriptor	3)Origin of the axes descriptor	4)Representative studies
5)Axis X Left	6)Internal Organizational Capacity	7)Technology Adoption & Governance; Human Resources, Performance, Transaction Cost Theory	8)Baumers et al., 2016; Jia et al., 2016; Chatzoglou and Michailidou, 2019;
9)Axis X Right	10)External Organizational Capacity	11)Network View, Sustainability and Circularity, Knowledge Based View	12)Ghobadian et al., 2020; Jiang et al., 2017; West and Kuk, 2016
13)Axis Y Upper	14)Innovation & Resource Orchestration	15)Innovation, Resource Based View	16)Beltagui et al., 2021; Candi & Beltagui, 2019; Woodson et al., 2019
17)Axis Y Lower	18)Business & Institutional Ecosystem	19)Institutional Theory, Risk and Uncertainty, Industrial Revolution	20)Birtchnell et al. 2017; Rong et al., 2020, Roca et al., 2017b

Table 2 (a): Key figures and trends listed by change in% from P1 (1991-2000) to P2 (2001–2010).

Descriptors	P1(1991-2000)		P2(2001-2010)		▲ ▼ [(D/B)-1]x100 Change in% from P1 to P2	Total (P1+P2+P3)	
	A #	B=(A/9) x100 % (total n=9)	C #	D=(C/32) x100 % (total n=32)		#	% (total N = 192)
<i>Theoretical underpinnings</i>							
Resource Based View	5	56%	17	53%	▼ 4.37% (n.s.)	92	47.92%
Transaction Cost Theory	3	33%	13	41%	▲ 21.90% (n.s.)	68	35.42%
Network View	1	11%	6	19%	▲ 68.77% (n.s.)	66	34.38%
Institutional Theory	1	11%	7	22%	▲ 96.94% (n.s.)	61	31.77%
Knowledge Based View	1	11%	8	25%	▲ 125.02% (n.s.)	52	27.08%
<i>Major Research themes</i>							
Industrial Revolution	7	78%	25	78%	▲ 0.45% (n.s.)	183	95.31%
Strategy	6	67%	25	78%	▲ 17.19% (n.s.)	163	84.90%
Technological Adoption and Governance	9	100%	32	100%	n.a.	157	81.77%
Performance	7	78%	17	53%	▼ 31.69% (n.s.)	132	68.75%
Innovation	4	44%	11	34%	▼ 22.64% (n.s.)	81	42.19%
Sustainability and Circularity	2	22%	7	22%	▼ 1.53% (n.s.)	59	30.73%
Human Resources	0	0%	6	19%	n.a.	37	19.27%
Risk and Uncertainty	1	11%	4	13%	▲ 12.51% (n.s.)	36	18.75%
<i>Methodological approaches</i>							
Quantitative	2	22%	17	53%	▲ 139.11% (n.s.)	93	48.44%
Qualitative	2	22%	9	28%	▲ 26.60% (n.s.)	90	46.88%
Mixed Methods	0	0%	4	n.a.	n.a.	6	3.13%
<i>Geographical scope</i>							
Northern Hemisphere	1	11%	3	9%	▼ 15.57% (n.s.)	27	14.06%
Southern Hemisphere	0	0%	0	0%	n.a.	1	0.52%

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(\*) two-tailed z-test of difference between P1 and P2 proportions significant at an alpha level of 0.05; (n.s.) z-test not significant; (n.a.) z-test not applicable

Table 2 (b): Key figures and trends listed by change in% from P1 (1991-2000) to P3 (2011–2021).

Descriptors	P1(1991-2000)		P3(2011- 2021)		$\Delta \nabla [(D/B)-1] \times 100$ Change in% from P1 to P3	Total (P1+P2+P3)	
	A	B=(A/9) x100	C	D=(C/151) x100		#	% (total N = 192)
	#	%(total n=9)	#	%(total n=151)			
<i>Theoretical underpinnings</i>							
Resource Based View	5	56%	70	46%	▼ 16.56% (n.s.)	92	47.92%
Transaction Cost Theory	3	33%	52	34%	▲ 3.33% (n.s.)	68	35.42%
Network View	1	11%	59	39%	▲ 251.67% (n.s.)	66	34.38%
Institutional Theory	1	11%	53	35%	▲ 215.93% (n.s.)	61	31.77%
Knowledge Based View	1	11%	43	28%	▲ 156.35% (n.s.)	52	27.08%
<i>Major Research themes</i>							
<b>Industrial Revolution</b>	<b>7</b>	<b>78%</b>	<b>151</b>	<b>100%</b>	<b>▲ 28.57% (*)</b>	<b>183</b>	<b>95.31%</b>
Strategy	6	67%	132	87%	▲ 31.12% (n.s.)	163	84.90%
Technological Adoption and Governance	9	100%	116	77%	▼ 23.18% (n.s.)	157	81.77%
Performance	7	78%	108	72%	▼ 8.05% (n.s.)	132	68.75%
Innovation	4	44%	66	44%	▼ 1.64% (n.s.)	81	42.19%
Sustainability and Circularity	2	22%	50	33%	▲ 49.01% (n.s.)	59	30.73%
Human Resources	0	0%	31	21%	n.a.	37	19.27%
<b>Risk and Uncertainty</b>	<b>1</b>	<b>11%</b>	<b>31</b>	<b>21%</b>	<b>▲ 84.79% (*)</b>	<b>36</b>	<b>18.75%</b>
<i>Methodological approaches</i>							
Quantitative	2	22%	74	49%	▲ 120.57% (n.s.)	93	48.44%
Qualitative	2	22%	79	52%	▲ 135.46% (n.s.)	90	46.88%
Mixed Methods	0	0%	2	1%	n.a.	6	3.13%
<i>Geographical scope</i>							
Northern Hemisphere	1	11%	23	15%	▲ 37.08% (n.s.)	27	14.06%
Southern Hemisphere	0	0%	1	1%	n.a.	1	0.52%

(\*) two-tailed z-test of difference between P1 and P3 proportions significant at an alpha level of 0.05; (n.s.) z-test not significant; (n.a.) z-test not applicable

Table 2 (c): Key figures and trends listed by change in% from P2 (2001-2010) to P3 (2011–2021).

Descriptors							
	P2(2001-2010)		P3(2011-2021)		▲ ▼ [(D/B)-1]x100 Change in% from P1 to P2	Total (P1+P2+P3)	
	A #	B=(A/32) x100 % (total n=32)	C #	D=(C/151) x100 % (total n=151)		#	% (total N = 192)
<i>Theoretical underpinnings</i>							
<b>Resource Based View</b>	17	53%	70	46%	▼ 12.74% (*)	92	47.92%
Transaction Cost Theory	13	41%	52	34%	▼ 15.24% (n.s.)	68	35.42%
Network View	6	19%	59	39%	▲ 108.37% (n.s.)	66	34.38%
Institutional Theory	7	22%	53	35%	▲ 60.42% (n.s.)	61	31.77%
Knowledge Based View	8	25%	43	28%	▲ 13.92% (n.s.)	52	27.08%
<i>Major Research themes</i>							
<b>Industrial Revolution</b>	25	78%	151	100%	▲ 27.99% (*)	183	95.31%
Strategy	25	78%	132	87%	▲ 11.89% (n.s.)	163	84.90%
<b>Technological Adoption and Governance</b>	32	100%	116	77%	▼ 23.18% (*)	157	81.77%
<b>Performance</b>	17	53%	108	72%	▲ 34.61% (*)	132	68.75%
Innovation	11	34%	66	44%	▲ 27.14% (n.s.)	81	42.19%
Sustainability and Circularity	7	22%	50	33%	▲ 51.33% (n.s.)	59	30.73%
Human Resources	6	19%	31	21%	▲ 9.49% (n.s.)	37	19.27%
Risk and Uncertainty	4	13%	31	21%	▲ 64.24% (n.s.)	36	18.75%
<i>Methodological approaches</i>							
Quantitative	17	53%	74	49%	▼ 7.75% (n.s.)	93	48.44%
<b>Qualitative</b>	9	28%	79	52%	▲ 85.99% (*)	90	46.88%
<b>Mixed Methods</b>	4	13%	2	1%	▼ 89.44% (*)	6	3.13%
<i>Geographical scope</i>							

Northern Hemisphere	1	11%	23	15%	▲ 62.37% (n.s.)	27	14.06%
Southern Hemisphere	0	0%	1	1%	n.a.	1	0.52%

(\*) two-tailed z-test of difference between P2 and P3 proportions significant at an alpha level of 0.05; (n.s.) z-test not significant; (n.a.) z-test not applicable

Table 3: Main research themes and research questions to guide future research avenues.

Major research theme	Guiding research questions	Guiding theories	Dominant references
<i>Theoretical frameworks</i>	<ul style="list-style-type: none"> <li>• What combination of capabilities and skills is required to effectively use 3DP technology in an organization? How are these acquired?</li> <li>• What combination of synergies between capabilities, knowledge, and resources is required to extract benefits of 3DP within an organization?</li> <li>• How managerial roles impact implementation of 3DP technology in organization?</li> <li>• What recommendations for managers regarding the use of 3DP technology?</li> <li>• How to bridge 3DP technological and educational gaps in an organization?</li> <li>• What training, talent development, education, and skills management for individuals working with 3DP technology?</li> <li>• How to organize training for the interested individuals within organizations? Is formal education more suitable for the organizational needs related to 3DP when compared to informal one emerging through community operated workshops?</li> </ul>	<p>Knowledge Based View (KBV); Resource Based View (RBV); Resource Orchestration Theory (ROT)</p>	<p>Beltagui et al., 2020a; Candi and Beltagui, 2019; Chadwick et al., 2015; Caviggioli and Ughetto, 2019; Ford et al., 2016; Kunovjanek et al., 2020</p>
<i>Industrial revolutions</i>	<ul style="list-style-type: none"> <li>• What is the role of 3DP technology in the narrative about Fourth Industrial Revolution?</li> <li>• How disruptive, radical, or revolutionary 3DP technology is for certain industrial sectors?</li> <li>• What is the maturity level of home fabrication with regards to our chronology of 3DP evolution presented in the framework? (Section 2.1)</li> <li>• What are current tendencies regarding the consumer-segment of 3DP market?</li> <li>• How is 3DP leading to technology transfer between developed and developing countries in Industry 4.0 era?</li> <li>• What are the common practices for developing countries to leapfrog into Industry 4.0 era via 3DP technology?</li> <li>• How 3DP technology bridges technological, educational, and cultural gaps between developed and developing countries?</li> </ul>	<p>History of industrial development; Fourth Industrial Revolution; Disruptive innovation; Development policies</p>	<p>Dotsika and Watkins, 2017; D'Aveni, 2013; Culot et al., 2020; Laplume et al., 2016; Maresch and Gartner, 2020; Rayna and Striukova, 2016; Rayna and Striukova, 2021a; Rindfleisch et al., 2017; Roca et al., 2017; West and Kuk, 2016</p>

	<ul style="list-style-type: none"> <li>• What are the differences in 3DP technology adoption between Northern and Southern hemisphere (i.e., developed and developing countries)?</li> </ul>		
<p><i>3DP governance and adoption</i></p>	<ul style="list-style-type: none"> <li>• What are current tendencies regarding 3DP adoption?</li> <li>• What cost, accuracy, performance, and/or materials issues impact widespread of 3DP technology in industry?</li> <li>• What challenges and benefits of 3DP technology did the COVID-19 pandemic reveal?</li> <li>• What is the character of 3DP technology as a frugal innovation? Has COVID-19 led to any breakthrough insight on this perspective?</li> <li>• How 3DP serves the purposes of humanitarian logistics and Humanitarian Supply Chains (HSC)?</li> <li>• To which extent 3DP contributes to challenges in times of turmoil?</li> <li>• What aspects are impacting integration of 3DP in HSC?</li> <li>• What customization of tools and spare parts aspects of 3DP process are beneficial for emergency situations or situations of resource scarcity?</li> </ul>	<p>Technology adoption; Strategic management; Humanitarian Supply Chains (HSC)</p>	<p>Corsini et al., 2020; Khorram Niaki &amp; Nonino, 2017; Kovács and Sigala, 2021; Rodríguez-Espíndola et al., 2020</p>
<p><i>Operational performance and Supply Chain Management (SCM)</i></p>	<ul style="list-style-type: none"> <li>• What are the challenges of integrating 3DP technology into existing supply chain operations? Is 3DP leading to hybrid manufacturing systems?</li> <li>• What are the impacts of 3DP on supply chains?</li> <li>• What are the impacts of 3DP on conventional manufacturing in supply networks?</li> <li>• What are cost comparisons between conventional and 3DP-integrated supply chains?</li> <li>• How is the application of 3DP changing the structure and complexity of supply networks?</li> <li>• What are the economic, organisational, and sustainability implications of 3DP on supply chains?</li> <li>• How is supply chain location influencing investment decision regarding 3DP technology?</li> <li>• How is 3DP technology impacting spare parts and inventory management?</li> <li>• What are the forecasting and scheduling practices with 3DP technology in supply chains?</li> </ul>	<p>Performance; Cost; Optimization; Operations management; SCM</p>	<p>Beltagui et al., 2020a; Chan et al., 2018; Chaudhuri et al., 2020b; Despeisse et al., 2017; Ford et al., 2016; Frandsen et al., 2020; Gardan, 2016; Ghobadian et al., 2020; Ivanov, 2020; Ivanov and Das, 2020; Kunovjanek et al., 2020; Ramón-Lumbierres et al., 2020; Roscoe and Blome, 2019; Sgarbossa et al., 2021; Westerweel et al., 2018; Weller et al., 2015</p>

	<ul style="list-style-type: none"> <li>• How can 3DP technology be used to alleviate global shortages and increase SCM resilience?</li> <li>• What is the perspective of 3DP technology in the context of lean manufacturing?</li> <li>• How can 3DP be used for maintenance, repair, and remanufacturing activities in supply chains?</li> <li>• How the adoption of 3DP impacts lifecycle of products and components?</li> </ul>	
<p><i>Sustainability and Circular Economy (CE)</i></p>	<ul style="list-style-type: none"> <li>• How is 3DP technology converging the effects of the latest industrial revolution with sustainable development goals?</li> <li>• What role 3DP technology plays in the transition towards a more sustainable industrial production?</li> <li>• What are the current tendencies in research about sustainable development and 3DP technology?</li> <li>• How to mainstream research on sustainability of 3DP technology?</li> <li>• How to achieve simultaneous triple-bottom-line goals of sustainability through 3DP technology?</li> <li>• How 3DP can lead to mindset transition towards more sustainable modes of production and consumption?</li> <li>• What are the implications of social sustainability regarding 3DP technology?</li> <li>• What are the environmental benefits and challenges of 3DP manufacturing process?</li> <li>• How is 3DP impacting recycling and reuse of resources?</li> <li>• How is 3DP adoption impacting socio-political actors and the regulatory agencies? Are specifically dedicated public policy measures to support 3DP technology effective?</li> <li>• How can 3DP technology be used to realise benefits of circular economy?</li> <li>• How to capture value from 3DP for circular economy?</li> <li>• How is 3DP influencing product design for circular economy?</li> </ul>	<p>Sustainable development; Environmental sustainability; Social sustainability; CE; Regulatory agencies</p> <p>Beltagui et al., 2020b; Despeisse et al., 2017; Ford et al., 2016; Garmulewicz et al., 2018; Ghobadian et al., 2020; Naghshineh et al., 2021; Roca et al., 2021</p>