Supply chain resilience and improving sustainability through Additive manufacturing implementation: A systematic literature review and framework

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Abstract:

Additive manufacturing (AM) is rapidly transforming supply chains across various sectors. This study explores the current academic literature on AM applications in the supply chain and practitioner literature to explore the application of AM across various sectors. It then identifies AM's role in achieving supply chain resilience and environmental sustainability. Key themes addressed in the literature have also been discussed. TCM (Theory, Characteristics and Methodology) framework has been used to identify the research gaps and provide future research directions. The study also proposes a research framework and propositions based on AM characteristics and capabilities required to achieve supply chain resilience and environmental sustainability through AM. This study extends the AM literature to present an integrated approach towards simultaneously achieving resilience and environmental sustainability. The study reveals how the AM characteristics of design freedom, part consolidation and on-demand tool-less manufacturing aid in achieving the twin benefits. The research propositions could be taken by researchers interested in exploring the field further. The findings of this study will enable the decision-makers contemplating adopting AM, in making informed decisions and be better prepared.

Keywords: Additive manufacturing, Supply chain, Disruptions, Resilience, Environmental Sustainability

1.0 Introduction

Recent events such as Hurricane Ian, the European drought, and flooding in China have brought the focus of the world to the climate crisis and the need to reduce greenhouse gas emissions (World Economic Forum, 2023). Moreover, events such as the Turkey-Syria earthquakes, the

Russia-Ukraine war, and the Covid-19 outbreak have drawn attention to risk management to reduce the impact of disruptions. This brings two aspects of a supply chain to the forefront – resilience and environmental sustainability. Governments and firms have now realised that exploring these aspects in isolation will not suffice for being globally competitive (Taleizadeh et. al., 2022). The need of the hour is to build a "resiliently sustainable" supply chain (Fahimnia and Jabbarzadeh, 2016). Traditionally, both these concepts were considered contradictory since they can potentially have conflicting requirements. For example, sustainability pushes for higher resource use efficiency, thus reducing protective redundancies and making the supply chain susceptible to disruptions (Fahimnia and Jabbarzadeh, 2016). Resilience may require redundancy, which contradicts environmental sustainability principles (Levalle and Nof, 2015). Sustainability is oriented towards achieving long-term outcomes while resilience is targeted at preserving or improving outcomes on a shorter time scale (Marchese et al., 2018). Moreover, resilience prioritises processes within a system agnostic of outcomes, while sustainability prioritises outcomes (Saunders and Becker, 2015; Negri et al., 2021).

The world has now realized that supply chains need to achieve both resilience and environmental sustainability. Many researchers in the recent past have called for studies integrating both these principles (Matin et al., 2021; Negri et al., 2021; Saur et al., 2022). Mishra et al. (2023) have highlighted the importance of process digitisation through Industry 4.0 technologies for achieving a resilient and sustainable supply chain. These technologies have reshaped the industrial space driving immense improvements in terms of productivity and innovation (Raji et al., 2021). One such technology is Additive manufacturing (AM), which involves the layer-upon-layer joining of materials to print the final product (ASTM F2792-12, 2012). AM has several features that enable firms to build a resilient and sustainable supply chain. For example, AM enhances supply chain flexibility (Eyers et al., 2018) which enables firms to develop redistributive systems (Roscoe and Blome, 2019) and reconfiguration capabilities (Belhadi et al., 2022). These are necessary attributes for developing resilience. AM's characteristics facilitate generative lightweight design which optimizes the weight of products, reduces the number of parts needed in a product and in turn helps firms in resource use optimization and overall carbon emission reduction (Niaki et al., 2022). AM also facilitates on-demand manufacturing, avoids keeping inventory and reduces transportation needs (Naghshineh and Carvalho, 2022b), consequently positively impacting the environmental sustainability of the supply chain.

As discussed above, exploring the characteristics of AM and the capabilities required by adopting firms to simultaneously achieve environmental sustainability and resilience through AM is a novel and unexplored topic (Table 1 Appendix A) (Ghobadian et al., 2020; Belhadi et al., 2022). The overall discussion on building a resilient and sustainable supply chain is limited in literature, even though these topics have been explored in isolation (Mc Loughlin et al., 2023; Napoleone et al., 2023; Senna et al., 2023; Belhadi et al., 2021). However, recent literature has called for a shift in focus towards an integrated approach (Ivanov, 2021; Ivanov, 2022). Hence, this study aims to address this gap by exploring the role of AM in attaining environmental sustainability and building a resilient supply chain. This study conducts a systematic review of the extant literature on AM published in various journals and provides an exhaustive and detailed content analysis to explore AM's role in building a resilient, and hence sustainable supply chain. The study also reviews practitioner literature to explore examples of how firms have used the technology to achieve resilience and sustainability. Thus, the study will answer the following research questions:

RQ1: What are the characteristics of AM and how do these characteristics help organisations achieve supply chain resilience and environmental sustainability?

RQ2: What capabilities do organisations need to develop supply chain resilience and environmental sustainability through AM?

RQ3: What are the research gaps and future research pathways in the context of developing resilience and environmental sustainability through AM?

By addressing the research questions, the study extends the knowledge of AM application through conducting a descriptive analysis of the selected research papers. Then, after analysis of the literature, the study lists the characteristics of AM and how these characteristics benefit organisations in terms of achieving resilience and sustainability. This is followed by reviewing the literature to list the capabilities required by organisations to achieve those benefits. Post that, the key themes addressed in the literature are discussed. Then, the study analyses the practitioners' literature to explore the application of AM across various sectors and the role of AM in building a resilient and sustainable supply chain. Post that, the study presents a research framework and some research propositions based on AM characteristics and capabilities. In the end, the study makes use of the TCM framework to identify the gaps in the existing literature and provide future research directions.

This study extends the AM literature by presenting an integrated approach towards simultaneously achieving resilience and environmental sustainability. In order to do so, the study adopts a novel approach in presenting the characteristics of AM, the benefits of those characteristics, as well as the capabilities required by organisations to gain those benefits. Moreover, by referring to practitioners' literature to explore the application of AM across various sectors further strengthens the role played by AM in achieving supply chain resilience and sustainability. The research propositions following the research framework could be considered by researchers interested in exploring the field further. The findings of this study will enable the decision-makers contemplating to adopt AM for building resilient and sustainable supply chains, in making informed decisions and be better prepared.

The remaining part of the paper is structured as follows: Section 2 presents the methodology, where the framework of the systematic review process is discussed. Next, we present the research findings and analysis in section 3. Then the synthesis of findings is performed, and future research directions and research framework are provided in sections 4, 5 and 6. Finally, in section 7, the conclusion and implications are presented.

2.0 Research Methodology

This study follows a systematic review approach as the aim of the paper is to highlight the major themes in the AM literature, identify the benefits and challenges of AM implementation and provide directions for future research (Paul and Feliciano-Cestero, 2021). A four-step literature review process was followed in this study (Fink, 2010). The first three steps have been discussed in this section while the fourth step (synthesis of findings) will be discussed in the subsequent sections.

Step 1: Selection of research questions, databases, keywords

The review began with an extensive search of AM literature. We considered two databases- Scopus and EBSCO- for this study. Scopus is regarded as one of the biggest multidisciplinary databases for citation indexing. Scopus has 60% more coverage as compared to Web of Science (Comerio and Strozzi, 2019). EBSCO offers high-quality articles from reputed journals[1] (Durach et al., 2015) and was used in this study to gain access to a few good-quality articles

[1] https://www.ebsco.com/products/ebscohost-research-platform

which were not a part of Scopus. Rowley and Slack (2004) highlight the importance of using the right set of keywords to get the desired results. Hence, keywords such as "additive manufacturing," "3D printing" and "supply chain" were included. This initial search returned 927 articles in Scopus and 634 articles in EBSCO.

Step 2: Application of practical screening criteria

Only the literature published in peer-reviewed journals has been considered for this study. Conference papers and industry reports are outside the scope of this review. The first set of filtering was applied where the language was restricted to English. This returned 901 articles in Scopus and 598 in EBSCO. Further filtering was applied where the type of document was restricted to articles and review papers, the source type was limited to peer-reviewed journals and the subject area was restricted to Business, Management and Accounting, Decision Sciences and Social Sciences. This was done mainly to exclude the technical papers as AM is also being extensively researched in the engineering field. The study inclusion and exclusion criteria have been shown in Figure 1. These filters resulted in 379 articles from SCOPUS and 198 from EBSCO.

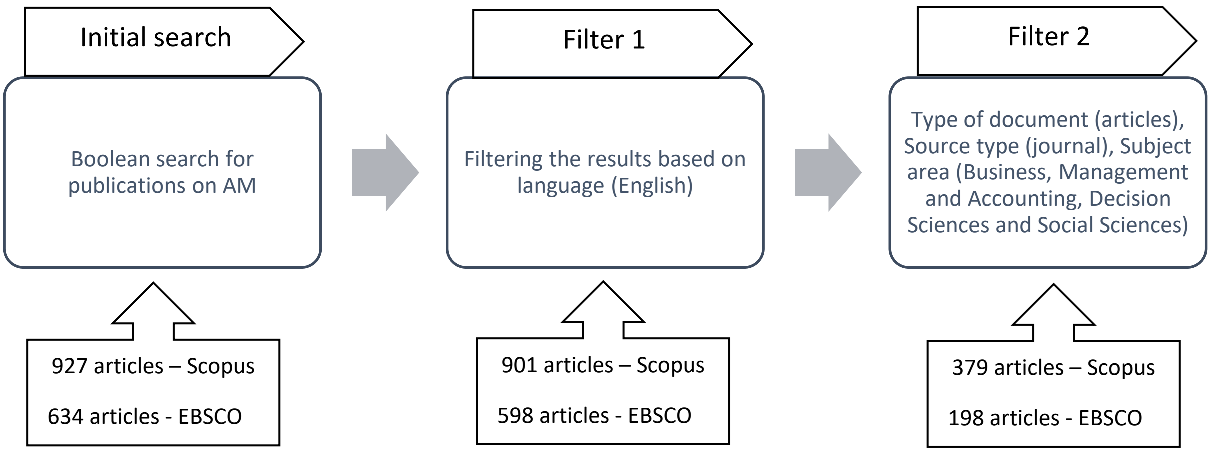

Figure 1: SLR inclusion and exclusion criteria

Step 3: Application of methodological screening criteria

These articles were then screened using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. PRISMA helps authors improve the reporting of systematic reviews (Moher et al., 2009) and is widely used across disciplines in the academic community. First, the duplicates were first removed using Zotero software. This gave a total of 577 articles. Then, each article was individually abstract screened by the researchers making it 185 articles which were divided between the authors for full-text screening, which led to 98 articles for this study. The article selection and inclusion methods were based on two criteria: first, the articles had to adhere to the application of AM and its implication from a managerial perspective. Second, the content of the article had to match the theme of the review. The articles that did not satisfy these criteria were removed. In case of discrepancy, the authors discussed the article in detail, and then the decision was taken. The PRISMA flowchart can be seen in Figure 2.

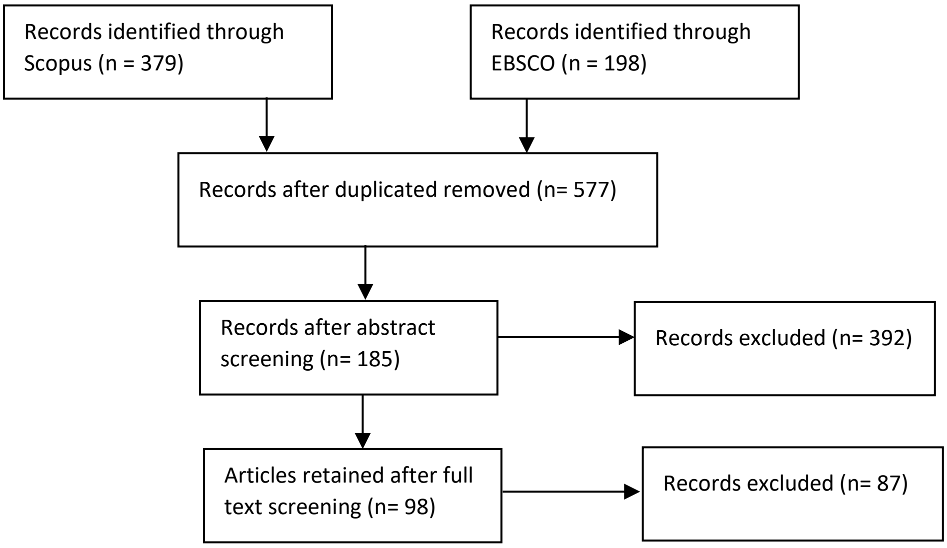

Figure 2: PRISMA flowchart

After the records were finalised and downloaded, the in-depth analysis of the literature began. However, before beginning the analysis, the authors had a review protocol ready which would assist in extracting the knowledge from the papers for the study. Each paper was classified using a single category for each dimension and the content was further analysed using descriptive and content analysis of the papers concerning certain key criteria. The review protocol is provided in (Table 2 Appendix A).

3.0 Research findings and analysis

3.1. Descriptive analysis

The entire set of papers identified in the study for systematic review was analysed in detail to find the key as well as common characteristics of the research papers. No specific time stamp was determined for this study. However, after the papers were finalised for review, it was observed that the time range was from 2014 to 2022 (Figure 1 Appendix B). It is evident from the figure that the popularity of AM has been increasing which is depicted by the increasing number of publications over the years. This increase in popularity might be due to continuous technological advancements in AM and its evolution from just prototyping to mass personalization (Huang et al., 2021).

The geographical classification (Figure 2 Appendix B) reveals that the UK (18), USA (14), India (10), Germany (7) and Finland (6) are the top countries with the highest publications on the topic. Figure 3 (Appendix B) provides the details of the research methods used in AM literature. The figure depicts the popularity of conceptual, case study and modelling papers. AM finds its applications across various industries (Figure 4 Appendix B). The application of AM in the healthcare sector was majorly for bioprinting and prosthetics. However, post the Covid-19 outbreak, increased use of AM to mass manufacture PPEs was seen. This is followed by the automotive (15) and spare parts (13) sectors.

A summary of the previous review papers has been provided in (Table 1 Appendix A). The table reveals that the last literature review included papers till 2021. However, Figure 1 (Appendix B) reveals that several papers were published on the topic in 2022. The top 10 highly cited articles in the field have been mentioned in (Table 3 Appendix A). It can be seen from the table that all the highly cited papers have been published between 2013 and 2017. Another interesting similarity is that most of these studies (8 out of 10) are qualitative and exploratory.

Through our analysis, we found the different organisational theories used in the literature of AM (Table 1). The findings revealed that out of the 98 papers reviewed, only 15 have contributed to existing traditional theories through their study and overall, 12 theories have been covered. Out of these, resource-based view theory seems prevalent. This might be because AM can be considered a key resource to superior firm performance. AM technologies provide design freedom to manufacture complex geometries and personalised products with ease (Berman, 2020). AM also enables a decentralised supply chain which not only reduces the overall carbon foot print (Niaki et al., 2022), but also enhances responsiveness (Engelseth et al., 2021).

Table 1: Theories used in literature

Theory	Reference	Contribution
Resource-Based View (RBV)	Delic *et al*., 2019	RBV has been used to explore whether AM serves as a firm's strategic resource and if its adoption acts as a transformation catalyser to enhance firm performance

	Jermsittiparsert and Boonratanakittiphumi, 2019	To explore whether AM as a resource helps a firm to comply with the changes in the business environment through supply flexibility
	Friedrich et al., 2022	To explore how a superior resource base helps achieve a competitive advantage
	Chaudhuri et al., 2022	RBV has been used to explore how a firm's resources can be used to gain and sustain a competitive advantage
Systems theory	Oettmeier and Hofmann, 2016	Systems theory has been used as a foundation for the examination of AM adoption and its impact on the supply chain.
	Muir and Haddud, 2018	Systems theory helps to explore the system-wide impact of AM adoption.
Contingency Theory	Oettmeier and Hofmann, 2016	Contingency Theory identifies relevant situational factors to differentiate between concepts.
	Patil et al., 2022	To explain the underlying contingencies that lead to AM benefits and barriers.
Dynamic capabilities theory (DCT)	Muir and Haddud, 2018	DCT has been employed to explore the responsiveness of AM as a dynamic capability to enhance customer satisfaction.
	Belhadi et al., 2022	To explore how supply chain ambidexterity – a dynamic capability – leads to efficiency and resilience
Technology acceptance model (TAM)	Chaudhuri et al., 2019	Using TAM, the study highlights how the lack of ease of use compounded by technological turbulence is negatively impacting AM adoption.
Resource Dependence Theory (RDT)	Jimo et al., 2022	To explore how AM impacts supply chain complexities and dependencies.
Transaction cost economics (TCE)	Meyer et al., 2022	To explore how uncertainty impacts transaction costs in AM
Institutional theory	Ukobitz and Faullant, 2022	To understand the impact of institutional pressures on AM adoption
Technology-Organisation-Environment (TOE)	Priyadarshini et al., 2022b	To categorise the barriers to AM adoption based on TOE
Innovation resistance theory (IRT)	Priyadarshini et al., 2022b	To categorise the barriers to AM adoption based on risk and value.
Diffusion of Innovation (DOI)	Bhattacharyya et al., 2022	To explore the factors favourable to the diffusion of AM
Modularity theory	Davies *et al*., 2020	Modularity theory has been employed to explore how AM facilitates easy and quick designing of low and high-variety products that meet emergent user demand.

3.2. Thematic analysis

Table 2 lists the various themes identified from a review of 98 articles considered for this study. The benefits, drivers, and barriers of AM adoption and implementation as compared to traditional manufacturing practices have been widely discussed in the literature with 32 studies in this theme. These studies discuss the benefits and challenges in various sectors such as the military (Boer *et al*., 2020), machine manufacturing and process industry (Martinsuo and Luomaranta, 2018), automotive sector (Muhammad *et al*., 2021) and spare parts industry (Heinen and Hoberg, 2019). AM benefits of lead time reduction, environmental sustainability and design freedom have been highlighted in these studies (Naghshineh and Carvalho, 2022a). The challenges faced such as lack of awareness, high cost of printers and technological uncertainty have been discussed (Priyadarshini et al., 2022b). These studies also discuss the factors that drive AM adoption such as proactive senior management, and need for personalisation (Ohmori, 2021).

AM's impact on the business model, supply chain network, and collaboration have also been discussed by 26 studies in this theme. These articles have discussed how AM affects the various functions, structure, and performance of supply chains. The supply chain network is one of the most widely researched themes. These studies discuss how AM adoption by various stakeholders, e.g., retailer, manufacturer, sub-supplier, customer, etc., affect the dynamics in the supply chain. Economic impact and environmental sustainability have also been widely investigated. A number of these articles have compared the environmental impact and cost structure of AM-enabled decentralised manufacturing with the traditional centralised manufacturing systems.

The recent pandemic outbreak has also caused an increase in the application of AM technologies, which lead to rise in number of publications on AM with 22 articles under this theme. During the pandemic, AM proved very useful in the rapid manufacturing and supply of high-demand medical equipment and kits. AM also helped in the development of a variety of products cost-effectively and rapidly including medical components used for diagnosis and monitoring (Boehme *et al*., 2021). AM technologies proved a promising solution during the pandemic, being quick to meet the increased demand for medical supplies and equipment (Meyer et al., 2022). Thus, AM technologies can be leveraged to build a robust and resilient supply chain.

The next theme is innovativeness, competitiveness, and deployment strategies with 11 articles. These articles mostly discuss how AM's innovativeness helps the firms gain competitive advantage. This innovativeness comes mainly from the digital design capabilities of AM. These articles also include the deployment strategies for AM to gain a competitive advantage.

The next theme is AM's onsite and customisation capabilities with 4 articles. These studies exclusively discuss the personalisation capabilities of AM and the benefits that could be gained due to those capabilities. The last theme is value chain with 3 articles. The articles discuss AM application recognition and interorganizational cooperation in the value chain.

Table 2: Major themes identification

Major themes	References
AM drivers, benefits, and barriers	Meisel et al., 2016; Oettmeier and Hofmann, 2016; Rogers et al., 2016; Attaran, 2017 ; Dwivedi et al., 2017; Holmstrom and Gutowski, 2017; Ryan et al., 2017; Sun and Zhao, 2017; Chan et al., 2018; Chekurov et al., 2018; Eyers et al., 2018; Martinsuo and Luomaranta, 2018; Shukla et al., 2018; ; Thomas-Seale et al., 2018; Hasan et al., 2019; Heinen and Hoberg, 2019; Berman et al., 2020; Boer et al., 2020; Chaudhuri et al., 2020; Davies et al., 2020; Franco et al., 2020; Kunovjanek et al., 2020; Rodríguez-Espíndola et al., 2020; Choudhary et al., 2021; Engelseth et al., 2021; Muhammad et al., 2021; Naghshineh and Carvalho, 2022a; Patil et al., 2022; Priyadarshini et al., 2022b; Ukobitz and Faullant, 2022; Verma et al., 2022; Won et al., 2022
AM's impact on the business model, SC structure, firm performance, SC performance, SC network and collaboration	Christopher and Ryals, 2014; Weller et al., 2015; Chiu and Lin, 2016; Rylands et al., 2016; Sasson and Johnson, 2016; Wagner and Walton, 2016; Durach et al., 2017; Niaki and Nonino, 2017b; Ghadge et al., 2018; Moradlou and Tate, 2018; Muir and Haddud, 2018; Delic et al., 2019; Jermsittiparsert and Boonratanakittiphumi, 2019; Roscoe and Blome, 2019; Tziantopoulos et al., 2019; Verboeket and Krikke, 2019; Delic and Eyers, 2020; Kunovjanek and Reiner, 2020; Ramón-Lumbierres et al., 2020; Floren et al., 2021; Ohmori, 2021; Arbabian, 2022; Friedrich et al., 2022; Fox et al., 2022; Jimo et al., 2022; Sonar et al., 2022
Enabling resilience through AM/ Risk mitigation/ SC vulnerabilities	Tatham et al., 2015; Zerga, 2019; Arora et al., 2020; Corsini et al., 2020; Vordos et al., 2020; Boehme et al., 2021; Budinoff et al., 2021; Joshi et al., 2021; Krause et al., 2021; Kunovjanek and Wankmuller, 2021; Meyer et al., 2021; Nazir et al., 2021; Patel and Gohil, 2021; Tareq et al., 2021; Wang et al., 2021; Belhadi et al., 2022; Bhattacharyya et al., 2022; Gupta et al., 2022; Meyer et al., 2022; Naghshineh and Carvalho, 2022b; Öberg et al., 2022; Priyadarshini et al., 2022a
Innovativeness, competitiveness, and deployment strategies	Mellor et al., 2014; Handal et al., 2017; Niaki and Nonino, 2017a; Khajavi et al., 2018; Braziotis et al., 2019; Chaudhuri et al., 2019; Oberg and Shams, 2019; Luomaranta and Martinsuo, 2020; Chaudhuri et al., 2022; Niaki et al., 2022; Turkcan et al., 2022
AM's onsite and customisation capabilities	Ben-ner and Siemsen, 2017; Huang et al., 2021; Westerweel et al., 2021; Kreis et al., 2022
Value Chain	Laplume et al., 2016; Johns, 2022; Luomaranta and Martinsuo, 2022

3.2.1. AM characteristics and benefits of AM applications

Design freedom, part consolidation, and on-demand tool-less manufacturingare the three main characteristics of AM. Due to the additive nature of the technology, AM enables part consolidation. This reduces the need for tools, jigs, and fixtures (Berman, 2020). Hence, the weight of the resulting product is reduced and the strength is increased. Also, by combining several parts into one, AM helps in reducing the number of supply chain partners. This reduces the supply chain complexity and enhances the responsiveness of the supply chain. Additionally, this also helps bring down the cost of operations (Rinaldi et al., 2021).

Computer-aided design is the backbone of AM. It provides immense design freedom. Since the designs are made and stored digitally, it saves a lot of time compared to subtractive manufacturing. This helps firms in rapid new product development that suit the customer needs and hence, the market demand (Friedrich et al., 2022). Moreover, AM can achieve this at a considerably lower cost as compared to TM. The digital designs also allow the production of products with complex geometries, which was either not feasible or very costly with TM (Boehme *et al*., 2021). Moreover, the lattice structure made possible due to AM helps enhance the strength of the products while reducing their weights (Nazir et al., 2021). These digital designs also help firms store digital inventory reducing warehousing needs (Kunovjanek and Reiner, 2020).

The third most important characteristic of AM is on-demand tool-less manufacturing. In a dynamic business environment with demand uncertainty, demand variability, demand for customisation, demand for lead time reduction, and increasing customer demand for sustainable products, AM can provide flexibility in terms of volume, new product development, delivery speed and mass personalisation (Alogla et al., 2021). AM facilitates a decentralised supply chain which brings production closer to the customer. Distributed manufacturing and the incorporation of customer-specific details make it a preferable technology for firms to gain a competitive advantage (Turkcan et al., 2022). In AM, designs are made digitally and parts or products can be produced in a single piece, thus eliminating the need for tools or moulds. Hence, AM helps build flexible capability which makes it easier to switch between different products and volume as the demand fluctuates without the need to invest in costly moulds or tools with long lead-times (Zhang et al., 2003). The benefits of AM gained due to these characteristics can be divided into five categories (Table 3).

Table 3: Benefits of AM applications

Benefits		AM characteristics	Reference
Time-related benefits	No changeovers between production runs	Design freedom and on-demand tool-less manufacturing	Attaran, 2017; Chekurov *et al.*, 2018; Naghshineh and Carvalho, 2022a
	Reduced repair time	Design freedom	Attaran, 2017
	Accelerated product innovation	Design freedom	Weller *et al.*, 2015; Nazir *et al.*, 2021
	Reduced lead time and high turnaround speed	Part consolidation and on-demand tool-less manufacturing	Tatham *et al.*, 2015; Arora *et al.*, 2020; Engelseth *et al.*, 2021
	No assembly required (product consolidation)	Part consolidation	Berman, 2020; Meyer et al., 2022
Cost related benefits	Cost saving in inventory and warehousing	On-demand tool-less manufacturing	Berman, 2020; Kunovjanek and Reiner, 2020; Naghshineh and Carvalho, 2022b
	Decentralised supply chain - Reduction in logistics cost	On-demand tool-less manufacturing	Berman, 2020; Priyadarshini et al., 2022b
	Eliminated the need for tools or moulds	Part consolidation and on-demand tool-less manufacturing	Weller *et al*., 2015; Wagner and Walton, 2016; Luomaranta and Martinsuo, 2022
	Reduced labour cost	Part consolidation and on-demand tool-less manufacturing	Attaran, 2017; Berman, 2020; Hohn and Durach, 2021
	No penalty for redesign	Design freedom	Attaran, 2017
Customer-oriented benefits	Enables consumers to print their parts for fixing their purchased products	Design freedom	Boer *et al*., 2020; Hohn and Durach, 2021
	Facilitates designing and personalisation of goods without lengthy delivery time	Design freedom and on-demand tool-less manufacturing	Engelseth *et al.*, 2021; Kreis et al., 2022
	Lightweight products	Part consolidation and Design freedom	Wagner and Walton, 2016; Sonar et al., 2022
	Mass customisation capabilities	Design freedom and on-demand tool-less manufacturing	Huang *et al*., 2021; Ohmori, 2021
Supply chain resilience-benefits	Reduced complexity of the supply chain	Part consolidation and Design freedom	Attaran, 2017; Arbabian, 2022
	Reduced time to market through a decentralised supply chain	Design freedom	Berman, 2020; Boer *et al.*, 2020; Jimo et al., 2022
	Ability to manufacture products with complex geometries	Part consolidation and Design freedom	Wagner and Walton, 2016; Nazir *et al.*, 2021
	Enhanced supply chain responsiveness and ability to produce parts when supply risk is high	Design freedom, Part consolidation and on-demand	Delic and Eyers, 2020; Ohmori, 2021

		tool-less manufacturing	
Environmental sustainability-related benefits	Better resource efficiency	Part consolidation and Design freedom	Chekurov *et al*., 2018; Sonar et al., 2022
	Product life extension	Part consolidation and Design freedom	Holmstrom and Gutowski, 2017; Boer *et al*., 2020
	Lower emissions for the supply network	Design freedom, and Part consolidation, on-demand tool-less manufacturing	Niaki et al., 2022

3.2.2. Capabilities required to adopt AM and consequently achieve resilience and sustainability

Despite its numerous advantages, AM has some limitations too which prevent its widespread adoption. Hence, this section presents the capabilities discussed in the literature that would help firms to overcome the barriers and enable them to reap the benefits of AM.

Attaran (2017) discusses that with the help of 3D printers, only those objects can be printed which are smaller than the size of the printer casing. Large printers do exist, but they require a larger place to accommodate which is not feasible in the short run. He also mentions that even though there is time-saving in AM due to savings in change-over and set-up time, the machine has longer production runs as compared to traditional manufacturing.

Design IPR concerns and information security affect the willingness of the supplier or developer to share digital designs (Boer *et al*., 2020) and pose a major threat to AM's widespread growth. AM can be employed to produce weapons illegally. Gershenfeld (2012) mentions how the technology was used by a gunsmith to print the lower receiver of a semi-automatic rifle. Additionally, customer involvement means that the company will have to approve every unique design for safety and mechanical behaviour.

Lack of knowledge about AM technologies and the benefits that they offer is another major challenge (Durach *et al*., 2017). Moreover, training the workforce for new technology is an added cost that the firms do not wish to bear. Understanding new designs and changing a traditional production culture and mindset is a challenge (Muhammad *et al*., 2021). In such a scenario, the lack of top management commitment needed to align the entire workforce towards a novel technology further prevents its successful implementation (Martinsuo and Luomaranta, 2018).

Significant differences may exist within functions of an organisation such as R&D, procurement, manufacturing, and service in terms of their preference for AM due to conflicting key performance indicators and priorities. Researchers have also suggested developing strong collaborations with members of the supply chain to enable sustainable and smooth operations (Chaudhuri et al., 2022). Moreover, it has also been suggested that AM is not always beneficial. Hence, businesses need to understand how AM and TM can be combined to gain the benefits of each and overcome the challenges of each (Wipperman et al., 2020). Moreover, technological capabilities need to be developed to overcome the quality issues in AM (Huang et al., 2021).

To overcome the abovementioned challenges, firms require certain capabilities. Table 4 lists the capabilities required to overcome AM barriers and reap AM benefits. The first category is strategic and operational capabilities. These capabilities refer to the steps that a firm should take for a successful adoption and smooth implementation of AM. These include, top management support, collaboration and other important decisions related to AM adoption, such as addressing legal and cyber security concerns. The second category is technical capabilities. These capabilities refer to the technological advancements to improve the performance of AM equipment and achieve high quality output. The third category is human resource capabilities. These capabilities refer to the workforce and upskilling and reskilling them for AM implementation. The fourth category is market-related capabilities which refers to the increase in awareness of AM and changing the perception of the consumer.

Table 4: Capabilities required to adopt AM and achieve resilience and sustainability

Capabilities	Sub-categories	Responsible company	References
Strategic and operational capabilities (SOC)	SOC1. Top management support for overall AM adoption strategy	AM adopting companies	Dwivedi *et al.*, 2017; Martinsuo and Luomaranta, 2018; Priyadarshini et al., 2022b
	SOC2. Developing strong collaboration with supply chain partners	AM adopting companies	Luomaranta and Martinsuo, 2020; Boer et al., 2020; Chaudhuri et al.,2022
	SOC3. Ensuring that cyber-physical systems are in place to reduce the risk during digital data transfer	AM adopting companies	Boer *et al.*, 2020; Luomaranta and Martinsuo, 2020; Gupta et al., 2022
	SOC4. Understanding when to use AM, when to use TM	AM adopting companies	Braziotis et al 2019

	and when to use hybrid manufacturing		
	SOC5. Addressing legal concerns	AM adopting companies and regulatory/standardisation bodies of the particular industry	Bogers *et al*., 2016; Kunovjanek and Wankmuller, 2020; Engelseth *et al*., 2021
Technical capabilities (TC)	TC1. Material flow optimisation to reduce the need for post-processing	AM adopting companies	Huang et al., 2021
	TC2. Technological advancements to reduce the price of the printer	AM equipment companies	Boer et al., 2020; Priyadarshini et al., 2022b
	TC3. Technological advancements to increase the printing speed	Materials companies and AM equipment companies	Martinsuo and Luomaranta, 2018; Shukla *et al*., 2018; Engelseth *et al*., 2021
	TC4. Technological advancements to reduce the energy consumption	Materials companies and AM equipment companies	Boer *et al*., 2020
	TC5. Increasing the material base to reduce the price of the raw materials	Materials companies and AM equipment companies	Attaran, 2017; Shukla et al., 2018
	TC6. Technological advancements to tackle quality related issues	Materials companies and AM equipment companies	Durach *et al*., 2017; Chekurov *et al*., 2018; Kunovjanek and Wankmuller, 2020; Engelseth *et al*., 2021
	TC7. Improving the availability and quality of digital design data and supply chain data	AM adopting companies	Wang and Alexander, 2017; Kunovjanek and Reiner, 2020
Human resources capabilities (HRC)	HRC1. Upskilling and reskilling the workforce to design for AM	AM adopting companies	Mellor *et al*., 2014; Durach *et al*., 2017; Boer *et al*., 2020; Engelseth *et al*., 2021
	HRC2. Training the workforce on various AM technologies and their selection based on the functionality of the product	AM adopting companies	Niaki and Nonino, 2017
	HRC3. Upskilling and reskilling the workforce in material selection according to the type of machine and requirement of part	AM adopting companies	Heinen and Hoberg, 2019; Oberg and Shams, 2019
	HRC4. Upskilling and reskilling the workforce to use the printers	AM adopting companies	Mellor *et al*., 2014; Durach *et al*., 2017; Boer *et al*., 2020; Engelseth *et al*., 2021
Market-related capabilities (MC)	MC1. Changing mindset- from using AM for prototyping to a full-fledged production method	AM adopting companies, AM equipment companies and service providers	Bogers *et al*., 2016
	MC2. Increasing awareness about AM and its potential benefits to customers	AM adopting companies, AM equipment companies and service providers	Durach *et al*., 2017; Engelseth *et al*., 2021; Naghshineh and Carvalho, 2022a

4.0 Evidences for AM adoption and development of resilience and sustainability through AM

The study uses secondary data from news articles, and reports from AM service providers, consultancy firms and AM companies. To begin the process, the authors looked for reports on AM applications and the benefits gained. The following inclusion and exclusion criteria were applied to finalise the practitioner literature for this study:

i) The reports published in the last 5 years (2018 and later) were only considered for the study. This is because AM is a novel technology that is still evolving. The latest reports would provide a better picture of the recent capabilities of AM.

ii) Reports mentioning the motivation behind AM application (Why?), the application area (s) of AM (Where?) and the resilience or environmental benefits gained (What/How?) were included.

iii) Only those companies were included that had high maturity in the use of AM based on the earliest year when articles about their AM adoption were published

iv) Reports that demonstrated resilience and sustainability as outcomes were only included.

v) News articles that discussed the AM application and benefits already mentioned on the company's website were excluded.

vi) To cover a wide variety of sectors where AM is used, out of multiple reports mentioning the application of AM in the same sector leading to similar benefits, the authors selected only one while excluding the others. This also helped minimize repetitiveness.

This exhaustive search resulted in 25 applications of AM across 8 sectors. Table 5 lists the AM applications across various sectors.

AM has huge potential in building a resiliently-sustainable supply chain. "*AM is changing the way we design parts; the way we produce parts and the way we do business. AM not only helps gain productivity on the shop floor but also creates a sustainable and robust business model*," said Dr Heuser, VP of AM at Siemens[2]**.** For example, AM enables product lightweight without compromising performance or durability. The additively produced titanium bracket for Airbus, which is 30 per cent lighter than its predecessor, is a good example (McKinsey, 2022). *"The*

[2] https://new.siemens.com/us/en/markets/solutions-for-machine-builders/additivemanufacturing.html

aerospace industry, for example, can create lighter parts that lead to reduced fuel consumption," said Dr Jörg Bromberger, director of strategy and operations at McKinsey[3].

Similarly, AM enables part consolidation where design optimisation led to a reduction in the number of parts from 10 to 1. Additionally, gas turbine swirlers were additively manufactured which reduced the lead time by 20% and post-processing by 80%. Moreover, AM enables rapid repair, where the gas turbines and compressors can be repaired 60% faster, and that too with digital designs that automatically adapt the shape to perfectly match each blade, which takes individual shapes after being operated at high temperatures. These aspects not only increase the agility of the supply chain, but also the sustainability (Siemens, 2021). *"We can store powder instead of thousands of SKUs. Once the process is developed for a part, we can print on demand and manufacture with less cycle time. On the design side, it allows us to unlock performance features that you have not been able to do from a traditional manufacturing standpoint,"* said Douglas Bingham, VP of Supplier Readiness, at Honeywell Aerospace[4]. *"From a sustainability point of view, additive manufacturing is a great technology because you just use the material you need for the part…. You can reduce the materials required drastically. Doing different designs with additive manufacturing also helps with sustainability. You can save up to 70 per cent or 80 per cent of the weight, which means lighter parts and less material being used……You can also produce much more locally, so you do not have emission-generating transport,"* said Stefanie Brickwede, Managing Director-AM, Deutsche Bahn, Germany's national railway company[5].

During the Covid-19 outbreak, AM was extensively used to build protective gear for frontline workers, despite supply chain disruptions (Forbes, 2020). A report by Gartner (2023) suggests that resiliency requires a shift away from the fragility of the supply chain. This can be achieved by building an antifragile supply chain that learns from disorder and thrives under stress and uncertainty. AM through its capabilities of localised production and supply chain agility allows for an on-demand and just-in-time production reducing the need for large inventories and increasing the speed of response to changes in demand (BCG, 2022).

Moreover, Hofmann and Langner (2020) in research funded by Oracle highlight the need to be resilient, digital, and sustainable, which would enable organisations to achieve supply chain viability. They suggest that a viable supply chain can operate efficiently and sustainably over

[3] https://www.makerverse.ai/insights-and-trends/interview%3A-what's-actually-driving-additive-manufacturing%E2%80%99s-growth
[4] https://www.makerverse.ai/insights-and-trends/interview%3A-how-honeywell-aerospace-fixes-supply-chains-with-additive-manufacturing
[5] https://www.makerverse.ai/insights-and-trends/interview%3A-the-rail-industry-gets-on-track-with-additive-manufacturing

the long term. It can respond to changing market conditions and disruptions in a timely and sustainable manner. In this regard, AM's capability to reduce waste throughout the supply chain, its increased speed, flexibility, and sustainability benefits, help firms achieve these goals (KPMG, 2019; Kearney, 2022). "*Additive manufacturing (AM) is a critical component of the Industry 4.0 digital transformation.AM technology is finally at the point where companies are starting to realize significant, tangible, new value for themselves and their customers*," said Vinod Devan, Product Strategy and Operations Lead at Deloitte Consulting[6].

The government of several countries is actively promoting the use of AM. For example, the UK government has established the 'National Centre for Net Shape and Additive Manufacturing,' the Japanese government is heavily funding R&D in 3D printing, the USA is using the technology for its Department of Defence and the government of India is undertaking collaborative efforts with Industry, academia, and research organisations to enhance its AM capabilities (Government of India, 2021). FDA (Food and Drug Administration) is already using AM to manufacture pills and is collaborating with academia to build research facilities to support research programs in advanced manufacturing (The White House, 2021). Industry experts also suggest implementing AM in iterations, where the learning curve can be split and taken one at a time. Additionally, collaboration across the supply chain, understanding customer needs and strategizing to build an AM ecosystem around those customer needs will be useful (World Economic Forum, 2022). Hence, by incorporating AM into the supply chain strategy, organisations can create supply chain resilience and sustainability that is better able to adapt to changes and challenges, thus reducing risk and helping the organisations grow.

Table 5: A sample of AM applications in industry

Industry	**Organisation**	**AM application**	**Benefits gained**	**Type of benefits obtained**	**Capabilities required**	**Reference and type**
Aviation	Bell Helicopter Textron Inc.	Hardware for helicopters	- Geometrically intricate parts with high tensile strength - Product consolidation that saved cost and reduced component weight and lead time. - Overall, 24% part-count reduction and 6 material needs were eliminated.	Sustainability	- Proactive top management who continuously looked for innovative solutions (SOC1) - Skills of engineers who utilise the design freedom offered by AM (HRC1)	AM service provider report[7]

[6] https://3dprint.com/229092/interview-with-vinod-devan-of-deloitte-on-their-3d-printing-approach/
[7] https://www.stratasys.com/contentassets/812983c5fe6543babb33c3a1f0131a90/bell-helicopter-case-study-052019.pdf?v=4998f5

	Airbus	Spacer panels, titanium brackets and over 1000 3D-printed parts	- Quicker and more efficient time to market while monitoring demand and adjusting accordingly - Weight and cost reduction - Reduced supply chain complexity	Resilience and sustainability	- Innovation in design and production process (TC1; TC6; TC7) - Working with regulatory bodies to ensure that regulations move in line with manufacturing innovations (SOC5)	Company website[8]
	GE Aviation	Jet engines	- Reduced failure modes due to part consolidation - Streamlined and simplified supply chain leading to resilience - Cheaper, simpler, and quicker functional testing leading to reduced time to market for customised parts	Resilience	- Collaboration with experts to test the limits of AM in terms of design complexity and part consolidation (SOC2; HRC1)	Company website[9]
Consumer goods	Yuyo, France	Surfboards	- Customisation - Reduction of waste materials, reused biodegradable materials - High mechanical strength while retaining flexibility	Sustainability	- Collaborating with customers and understanding their environmental convictions (SOC2; MC2) - Local sourcing and production (collaboration) (SOC2)	Interview with the founder – AM service provider website[10]
	Dirk Vander Kooij	Furniture	- Lower production and design expenses - Space-saving, aesthetics - Durable, yet lightweight	Sustainability	- Using discarded refrigerators as raw materials (TC5)	Company website[11]
	Siemens and You Mawo	Eyeglasses	- Customisable - Better energy footprint and resource efficiency	Sustainability	- Joint venture to secure sufficient printing capacities (SOC2)	Company website[12]
	Materialise	Lights	- Innovative design, Product consolidation	Sustainability	- Understanding the customers' needs (MC2) - Utilisation of AM's design freedom capabilities by design engineers (TC7)	Company website[13]
	VAULT	Enclosure for tablets	- Speeding up production and reduced time to market - Improved quality and surface finish	Resilience	- Collaboration with supply chain partners (SOC2)	Service provider website[14]

8 https://www.airbus.com/en/newsroom/news/2018-04-bridging-the-gap-with-3d-printing
9 https://www.ge.com/additive/additive-manufacturing/industries/aviation-aerospace
10 https://www.3dnatives.com/en/3dstartup-yuyo-and-their-3d-printed-surfboards/
11 https://architizer.com/blog/practice/materials/3d-printing-furniture-business/
12 https://www.siemens.com/global/en/company/stories/industry/2022/eyewear-spectacles-3d-printing-additive-manufacturing-youmawo-additive-scale.html
13 https://architizer.com/blog/practice/materials/3d-printing-furniture-business/
14 https://www.3dsystems.com/consumer-products

Fashion	Nike	Shoes	- Customised, lightweight, and breathable shoes - Accelerated new product development	Resilience	- Using customer feedback to improve product performance with a reduced lead time (MC2)	News article[15]
	Balenciaga	Dress	- Customised - Sustainable (zero production waste), - Reduced lead time to make up for increased demand for the product	Sustainability and resilience	- Awareness of the technology and its potential through industry success stories (MC1; HRC2) - Proactive management (SOC1)	News article[16]
	Tiffany & Co.	Jewellery	- Design freedom - Customisation - No wastage of precious metals - Reduced lead time to make up for increased demand for the product	Sustainability and resilience	- Understanding the market dynamics and changing customer needs (Proactive top management) (SOC1)	News article[17]
Automotive	BMW	Components for vehicle body	- Generative designs - Topology optimisation and reduced weight - Shortened production time	Sustainability	- Technological advancements (use of Artificial Intelligence) to identify which type of AM technology and material should be used for different components (TC1; TC7; HRC2) - Collaboration between engineers and material experts (SOC2)	Company press release[18]
	Ford	Inlet manifold	- Faster and more efficient production - Reduced lead time for personalised products	Resilience	- Understanding the market dynamics and changing customer needs (Proactive top management) (SOC1)	News article[19]
	Maruti Suzuki	Prototypes, manufacturing tools and production parts	- High-quality detailing - Design personalization - Seamless integration of the workflow to enhance responsiveness	Resilience	- Technological advancements in material engineering (TC1; TC5; TC6)	News article[20]
Construction	Military Engineering Services, India	3D-printed houses for soldiers	- Disaster-resilient structures - Rapid construction to meet the minimal urgent requirements	Resilience	- Collaboration with customers to understand their specific needs (SOC2)	News article[21]
	Acciona, Spain	Pedestrian bridge	- Reinforced concrete, Strength - Low waste	Sustainability	- Collaboration between Civil engineers, material	Company website[22]

[15] https://manufactur3dmag.com/how-nike-is-leveraging-3d-printing-in-the-footwear-industry/
[16] https://www.luxuo.com/style/fashion/3d-printing-and-luxury-brands-impact.html
[17] https://www.bloomberg.com/news/articles/2018-07-18/tiffany-amp-co-has-built-a-secret-lab-of-shiny-dreams?leadSource=uverify%20wall
[18] https://www.press.bmwgroup.com/global/article/detail/T0322259EN/industrial-scale-3d-printing-continues-to-advance-at-bmw-group?language=en
[19] https://www.3dnatives.com/en/the-role-of-am-in-the-automotive-industry/#!
[20] https://auto.economictimes.indiatimes.com/news/auto-technology/additive-manufacturing-tech-to-revolutionize-product-designing-in-auto-sector/72106045
[21] https://www.hindustantimes.com/india-news/indian-army-s-engineers-build-first-of-its-kind-3d-printed-house-for-jawans-101647234282261.html
[22] https://www.designingbuildings.co.uk/wiki/3D_printing_in_construction

					experts and AM experts (SOC2)	
Industrial goods	Siemens and EDAG Group	Coolant distributor	- Reduced lead time and costs - Enhanced efficiency and sustainability for mass production	Sustainability	- Understanding the design possibilities of AM to enhance product performance (SOC4; HRC1)	Company website[23]
	Bowman	Bearings	- Maintain operational agility while keeping the costs down	Resilience	- Understanding the design possibilities of AM to enhance product performance (SOC4; HRC1)	Press release[24]
	Siemens	Gas turbine blades	- Lightweight - Reduced lead time from component design to product development - Manufacturing flexibility of producing spare parts on-demand closer to the customer	Resilience	- Using the right materials for different components to get the desired output (HRC3) - Collaboration between essential areas such as materials sciences, automation, and manufacturing (SOC2)	Press release[25]
Railways	Deutsche Bahn	Fan propellers, headrests, spare parts for coffee machines and coat hooks	- Reduced supply risk for products with long delivery periods or unavailability of suppliers	Resilience	- Understanding the customers' needs (MC2) - Utilisation of AM's design freedom capabilities by design engineers (TC7)	Company website[26]
	Dutch railways	Spare parts	- Reduced supply risk for products with long delivery period or unavailability of suppliers - Reduced lead time from months to weeks	Resilience	- Understanding the printer and material to be used for each component to get the best results (HRC2; HRC3)	News article[27]
Oil and Gas	Shell	Connector	- Accelerated delivery time - On-site production of customised parts	Resilience	- Understanding the design possibilities of AM to enhance product performance (SOC4; HRC1)	Company website[28]

Hence, Table 5 depicts that AM finds its application across several sectors where it can be effectively utilised to gain environmental sustainability, resilience, or both. Benefits such as aiding printing for geometrically complex products, on-site production, and reduced lead time for personalised products, shortened production time, and zero production waste help AM in

[23] https://www.edag.com/en/edag-group/press/press-release/3d-printed-active-coolant-distributor-is-ready-for-series-production?utm_source=post&utm_medium=linkedin&utm_campaign=iaa&utm_term=08&utm_content=siemens
[24] https://amfg.ai/industrial-applications-of-3d-printing-the-ultimate-guide/#tab-con-15
[25] https://press.siemens.com/global/en/pressrelease/siemens-achieves-breakthrough-3d-printed-gas-turbine-blades
[26] https://www.deutschebahn.com/en/3d_printing-6935100
[27] https://medium.com/dimanex-blog/3d-printing-and-supply-chain-disruption-learnings-from-the-dutch-army-and-dutch-railways-2d7537c6046a
[28] https://www.shell.com/inside-energy/3d-printing.html

achieving the goals. The table also mentions the capabilities required by firms to gain these benefits. Thus, an understanding of the design possibilities of AM to enhance product performance, an understanding of the printer and material to be used for each component to get the best results, and collaboration with supply chain partners are some of the important capabilities developed by firms to achieve the benefits from AM.

5.0 Framework for AM adoption

Based on the insights from an extensive review of the academic and practitioner literature, the authors have proposed a conceptual model (Figure 3). The model portrays how AM adoption leads to supply chain resilience (SCR) and environmental sustainability. SCR is the ability of the supply chain to be prepared for unforeseen disruptions (readiness), respond effectively to those disruptions (response), and recover in the least possible time (recovery). Hence, readiness, response and recovery are the three dimensions of SCR (Ponomarov and Holcomb, 2009). Environmental sustainability deals with conserving natural resources and minimizing the negative impact on the environment (Sarkis and Zhu, 2018). AM helps in achieving both these objectives.

A major advantage of AM is its ability to simplify long and complex supply chains (Boer et al., 2020). AM, due to its additive nature enables part consolidation. This reduces the need for tools, jigs, and fixtures and along with that, the supply chain complexity is reduced as fewer members are required. As the supply chain shortens, the overall lead time and turnaround time are considerably reduced, thus enhancing supply chain responsiveness (Turkcan et al., 2022). This increases the readiness of the supply chain and helps respond to disruptions quickly. During the Covid-19 pandemic, a multitude of important products was manufactured and sometimes tailor-made to customer requirements at the point of need (Kunovjanek and Wankmüller, 2021). A resilient supply chain needs to develop options and redundancy to have smooth and quick operations during disruptions. Firms, however, find redundancy to be an additional cost. Redundancy also increases the environmental footprint. AM enables firms to resolve the paradox by holding digital inventory (Busachi et al., 2018).

AM also enables design freedom as the products are first made digitally using CAD (Computer-aided design) software. The digital inventory eliminates the need for holding physical stocks or a warehouse (Won et al., 2022). This facilitates a decentralised supply chain, which enables local sourcing and reduces logistics needs. This considerably reduces the logistics activities, thus lower the supply chain emissions. Also, the portability of some AM machines provides immense manufacturing flexibility (Rinaldi et al., 2021). These digital designs also enable customer involvement during the design phase, thus helping incorporate customer needs and preferences. Hence, AM can be used for the mass personalization of products (Ohmori, 2021). This reduces overproduction and facilitates product life extension. These benefits of AM also enable resource reconfiguration (Belhadi et al., 2022) which enables resource use optimization. This increases the readiness of the supply chain and helps respond to disruptions quickly. Hence, AM has immense resilience-building and sustainability capabilities.

AM’s characteristic of on-demand tool-less manufacturing eliminates the need to make laborious and time-consuming moulds, thus arriving directly at the finished part. Hence, AM offers frictionless production that minimises or rather eliminates the use of product-specific jigs, fixtures, dies, or cutting tools (Berman, 2020). The additive nature of the process has reduced the number of steps in the assembling process. This results in fewer subcontractors in the supply chain and therefore reduces coordination costs (Wagner & Walton, 2016). This also helps firms reduce their resource usage. In AM, there are no held-up costs and risk of scrapping the unsold finished goods inventories. Instead, firms only hold digital 3D data in stock (Niaki et al., 2022). While modification of design results in significant design costs and causes time delays in a traditional manufacturing setup, AM facilitates the production of multiple versions of a single product through digital 3D mode. These help firms in saving time and cost (Rogers et al., 2016). This provides a lot of manufacturing flexibility to the firm, thus enhancing supply chain responsiveness (Ohmori, 2021). Use of digital inventory to print products enables firms to respond to disruptions promptly and quickly bounce back to normalcy. This also helps firms reduce wastage by producing only what is demanded, thus eliminating the unsold finished stock. Use of AM to produce products during humanitarian disasters are prime examples of building resilience and both environmental and social sustainability. Spare parts for medical devices or parts for water piping systems have been printed using digital design and portable printers for such humanitarian efforts[29].

[29] https://www.fieldready.org/in-the-news

The enhanced supply chain responsiveness supported by AM has helped in its widespread application during the Covid times. AM follows a digital and agile approach, which can respond to pandemics (Arora et al., 2020). AM proved to be a valuable asset in the case of supply chain disruption, as observed during the Covid-19 crisis. A multitude of important products was manufactured and sometimes tailor-made to customer requirements at the point of need (Bhattacharyya et al., 2022). The fact that a product has been personalized, reduces its chances of rejection (Huynh, 2021). The above demonstrates potential for AM to build resilience.

The distributed manufacturing set-up supported by AM brings the production closer to the customer. This considerably reduces the inventory holding for a firm (Jermsittiparsert and Boonratanakittiphumi, 2019). AM enables consumers to print their parts for fixing their purchased products, thus increasing customer satisfaction, and enhancing service offerings (Luomaranta and Martinsuo, 2022). Including the customers in the early design process also saves the company a lot of unsold inventory (Chekurov *et al*., 2018). Flexibility to produce parts in low volumes as and when needed through on-demand tool-less manufacturing builds resilience as well as reduces environmental footprint. These aspects of AM make it an appropriate choice to achieve both supply chain resilience and higher levels of environmental sustainability.

However, as discussed in section 3.2.2, several barriers need to be overcome, to gain the benefits of AM. These can be achieved by developing certain capabilities (Table 4) that would help firms overcome the barriers and gain benefits from AM. Top management commitment and proactiveness are required to adopt disruptive technologies like AM (Fox et al., 2022). Such transformational leadership can organise employee training to reskill and upskill the workforce (Priyadarshini et al., 2022a). This will help firms tackle the strategic and human resources challenges. This will also help firms prepare for disruptions, respond effectively, and bounce back to normalcy quickly. Understanding when to use AM is also very important. In cases where the supply risk is very high, i.e., where no suppliers are available or willing to deliver parts in low quantities and short lead time, firms can proactively decide which parts can be 3D printed. For such cases, firms can keep digital inventory and deliver as and when needed. AM can also be used as a backup source when existing suppliers fail to deliver.

Moreover, operational, and technological capabilities are also required to overcome the technical, financial, environmental, and operational challenges (Huang et al., 2021). Developing operational capabilities in terms of identifying which parts can be produced using AM, engaging with the appropriate service provider, or making the appropriate in-house investments will help firms respond quickly to disruptions. Technical capabilities are needed in terms of choice of the appropriate materials, quality control and assessing that the performance of the printed part meets all quality and regulatory requirements and in improving the accessibility and quality of digital design and supply chain data. Furthermore, increasing awareness about the benefits of AM amongst firms and customers will help tackle market-related challenges (Durach et al., 2017). This in turn will prepare firms for unforeseen supply chain disruptions. Additionally, government intervention in altering the norms and policies to ease AM adoption, as well as ensure strict government regulations to protect digital data will help firms in adopting the technology.

Hence, AM characteristics of part consolidation, design freedom and on-demand tool-less manufacturing, coupled with the capabilities developed by adopting companies and other stakeholders help firms be better prepared for potential supply chain disruptions by enhancing supply chain flexibility and responsiveness. These characteristics and capabilities help firms build a decentralised supply chain structure where parts are built on-demand and personalised to the specific needs of the customers. The digital inventory made possible due to digital designs support the decentralised supply chain structure. Adoption of AM significantly affects complexities and dependencies in supply chain configurations, thus minimising the supply chain risks (Jimo et al., 2022). While there may be potential trade-offs between resilience and resilience using conventional manufacturing, AM can help break such trade-offs such that both resilience and sustainability can be achieved. Hence, based on the conceptual model (figure 3), we present the following proposition:

Proposition: AM characteristics (i.e., design freedom, part consolidation, and on-demand tool-less manufacturing) and developing the capabilities (i.e., strategic, and operational, technical, human resources, and market-related capabilities) that help overcome barriers in adoption can help adopting firms to simultaneously achieve ***supply chain resilience and higher environmental sustainability.***

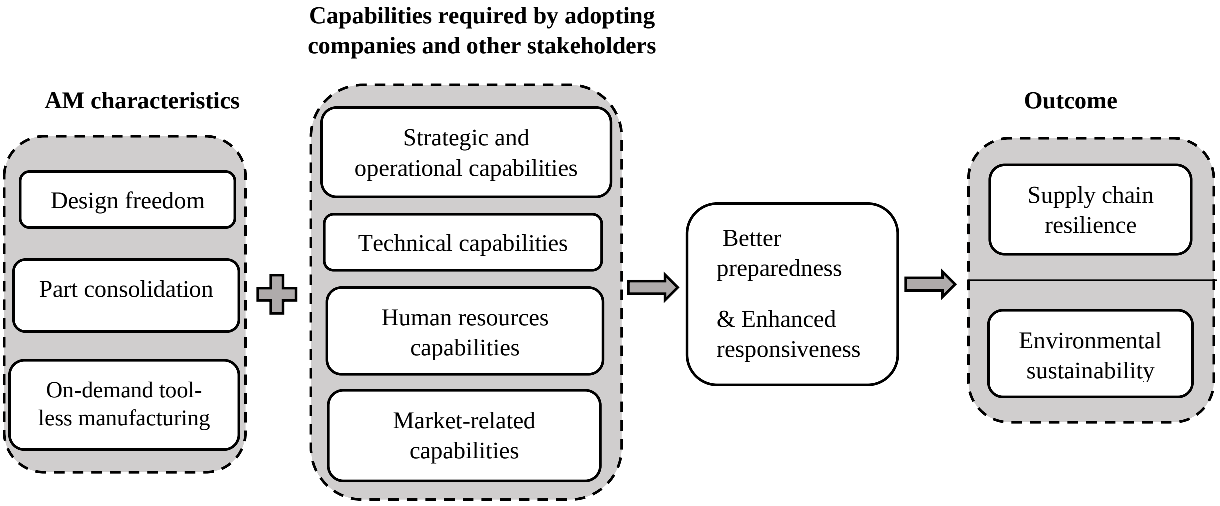

Figure 3: Conceptual model for AM adoption

6.0 Research gaps and future directions

We have used the TCM framework for the identification of research gaps and future direction. This is modified version of the TCCM (Theory, Context, Characteristics, Methodology) framework introduced by Paul and Rosado-Serrano (2019). Since its introduction, the framework has been used by several researchers for various studies such as institutional competitiveness (Buitrago and Barbosa Camargo, 2021), cause-related and social marketing (Singh and Dhir, 2019), service innovation (Singh *et al.*, 2020) and mobile advertising (Jebarajakirthy *et al.*, 2021). The framework helps segregate the gaps and potential future research directions based on the theories used in literature and characteristics of the key themes discussed as well as according to the methodologies discussed. However, in this study, the TCM framework has been used because the authors have not considered segregation of the articles based on context. TCM has been used by many researchers in the past but not in the context of AM applications in supply chain and logistics management (Paul & Rosado-Serrano, 2019; Singh & Dhir, 2019).

6.1. Application of TCM framework

6.1.1. Future directions – Theory

AM considered a fairly new technology is thought to be a disruptive innovation (Engelseth *et al.*, 2021) which creates barriers to its adoption. To explain these challenges, Innovation

Resistance theory, Diffusion of Innovation theory and TOE theory could be used. Studies have revealed the importance of top management commitment in the adoption of AM (Muhammad *et al*., 2021). However, behavioural aspects of the key decision-makers that prevent new technology adoption have not been explored. Organisational and supply chain theories answer the 'what' and 'how' questions, but the use of behavioural theories can help in answering the 'why' questions as well. For example, Planned Behaviour theory can provide an understanding of a decision-maker's attitude and subjective norms influence his behavioral intentions (Ajzen, 1991). However, as discussed in table 1, several of these studies the lack theoretical underpinning to explore AM.

6.1.2. Future directions – Characteristics

In this section, we discuss the characteristics of the research studies and pinpoint the themes that need further exploration. First, these studies have covered a wide range of dimensions related to supply chain structure supply chain performance, supply chain innovation supply chain benefits and challenges and supply chain sustainability. However, other dimensions of the supply chain such as resilience, agility and governance need to be further explored. Also, the studies discussing the impact of AM adoption on global value chains, demand chains and raw material supply chains have very few representations.

Post the pandemic outbreak, the use of AM to provide PPEs has increased and there are quite a few studies discussing AM application in the healthcare and humanitarian sectors. There were also instances of supply chain disruption post-Covid-19 outbreak. There is huge scope for AM to help build a resilient supply chain and this aspect needs to be studied.

Another important study could be the effect of skills, training and hiring the right talent for AM implementation. AM provides huge potential in developing environmental sustainability. Its ability to reduce material consumption, generate minimal waste, reduce energy consumption across the supply chain and over the lifecycle usage of the product, and extend the product life needs further exploration. It is important to note that individual AM processes may be energy intensive and may not positively impact environmental sustainability. Comprehensive assessment needs to be conducted of the overall environmental sustainability impact across the supply chain and over the lifecycle of the product also accounting for avoidance of transportation and inventory apart from reduction in manufacturing steps and environmental footprint reduction because of light weight. Studies about the legal issues arising from AM usage by customers can also be taken up by future researchers. A major risk associated with the flexibility in AM are that a product will be used that is not fit for purpose and can be used for illegal activities as well. Digital files and data transmission may be subject to vulnerability leading to trust and security issues and which may even negatively impact resilience, if not addressed. These topics could be investigated in the future.

6.1.3. Future directions – Methodology

The review of the literature provides insights into the methodologies and strategies used in the studies that have been reviewed. The results reveal that studies that adopted mixed methodologies are missing. There is a need to perform mixed-method studies to reduce the confirmation bias and some potential personal biases faced by researchers. This would help in the triangulation of the findings so that the study is more rigorous and convincing.

Even among the studies that have opted for a qualitative approach, only one has gone for a grounded theory methodology. AM provides immense scope for researchers wanting to investigate the topic using a grounded theory approach and build theory from scratch. Also, we could not find any study using certain qualitative techniques like narrative analysis and netnography. For data collection techniques, the use of Delphi, fuzzy Delphi, and focus groups to collect data have very few instances. These aspects can be potentially be utilised in future research to address specific research questions which require use of such methods.
Future directions identified based on TCM framework as discussed above are further summarised in table 6.

Table 6: Gaps and future research directions

Themes	**Gaps identified**	**Future research questions/objectives/scope**
Future direction—Theory		
Theoretical underpinnings	The missing link between theories	Which new or established organisational theories can be adapted or further developed to support the growth of AM applications for supply chain resilience and sustainability?
Future direction—Characteristics		
Impact on sustainability and resilience	Role of capabilities	How does the availability of AM for repair and remanufacturing enable sustainability?
		How do the strategic and operational capabilities of firms help exploit the AM benefits to achieve supply chain resilience and environmental sustainability?

		Which technical capabilities are required by firms to exploit the AM characteristics to achieve supply chain resilience and environmental sustainability?
		Which Industry 4.0 technologies can be implemented along with AM to achieve supply chain resilience and environmental sustainability? How would these technologies enhance the performance of AM in achieving resilience and sustainability?
		How can AM be integrated with traditional manufacturing technologies and what would be its impact on operational and supply chain capabilities and in turn on resilience and sustainability?
Impact on AM adoption	R&D and innovation context	How does the R&D cost to develop AM technical capabilities affect AM adoption? How will R&D processes need to change to ensure adoption of AM?
		What innovations at product and service delivery levels will increase AM adoption for supply chain resilience and sustainability?
	Legal context	What are the implications of AM for intellectual property rights for both firms and policymakers? How can these be tackled to enable smooth operations?
		How do the differences in legal practices across nations affect the application of AM?
		How does AM affect legal liability in the context of increased customer involvement and home manufacturing? What impact does this have on resilience and sustainability?
Impact on supply chain	Materials supply chain	What is the economic impact of the change in logistics resources where AM reduces the need for raw material causing a reduction in logistics for finished products and increasing the need for raw material supply, both relying on very different types of logistics resources? What role will logistics service providers play in embracing the change and in enhancing resilience and sustainability across the supply chain?
	Inventory	How does AM adoption affect inventory management policies in organisations?
	Production	How does AM implementation affect and create synergies with the conventional manufacturing processes that are still needed?
	Supply chain structure	How does AM adoption by stakeholders at various supply chain positions affect the supply chain structure and performance during a disruption?
	Supply chain performance	How do the 'prosumers' affect the business of the established manufacturers?
		To what degree does 'democratized manufacturing' considering AM enabled distributed manufacturing impact supply chain performance and particularly resilience and sustainability?
		How does the ability of AM to quickly scale down when compared to conventional manufacturing help in attenuating the bullwhip effect?
Future direction—Methodology		
Research strategy and methods	Need to expand to other research methods	To understand the challenges faced by different companies at different supply chain positions during a disruption, and AM's role in risk mitigation using longitudinal case studies or ethnographic studies
		A grounded theory approach to understanding AM drivers, benefits, and barriers for entrepreneurs.
	Need for mixed-method research	To understand the challenges faced by different companies at different supply chain positions during a disruption, and AM's role in risk mitigation using mixed methods

7.0 Conclusion, limitations, and implications

Global climate crises and supply chain disruptions have brought to the forefront, the need for environmental sustainability and supply chain resilience. AM is a set of technologies that can potentially help in achieving these twin outcomes. This study reveals AM characteristics such as design freedom, part consolidation and on-demand tool-less manufacturing and the benefits gained due to these characteristics such as time-saving, on-demand low volume manufacturing, cost reduction, enhanced customisation, and customer involvement which ultimately lead to resilience and environmental sustainability. However, there are several challenges as well that need to be overcome to gain these benefits. Development of strategic, operational, human resources, technical and market-related capabilities will enable firms to achieve supply chain resilience and environmental sustainability through AM.

The authors have not only reviewed academic literature on AM, but have also referred to practitioners' literature to explore the application of AM across various sectors and AM's role in achieving supply chain resilience and sustainability. After a thorough analysis of AM literature, a conceptual model has been proposed by authors to depict how AM helps in achieving supply chain sustainability through resilience.

7.1. Theoretical and practical implications

This study contributes to the existing literature in four significant ways. First, the study extends the AM literature to understand the capabilities required to achieve resilience and sustainability in supply chains through AM. Second, this study highlights the major themes emerging in the AM literature and the identification of research gaps based on the TCM framework. Third, this research provides a conceptual model for AM adoption based on AM characteristics and capabilities required by firms. Fourth, the study provided a few research propositions and research questions to be tested as part of future studies.

This study also has managerial implications. The study addresses two pressing global concerns of resilience and environmental sustainability. The findings of the study will help the decision-makers to understand the characteristics of AM and the benefits that could be reaped from AM implementation in terms of simultaneously achieving resilience and environmental sustainability. Moreover, the firms will also be aware of the capabilities needed to gain those benefits and achieve resilience and sustainability goals.

However, the study also has certain limitations. First, the authors have considered two databases- SCOPUS, and EBSCO. Future researchers might want to include other databases as well. Second, since this is a literature review, it mentions the general characteristics and benefits of AM. Additionally, it also mentions the general capabilities required to achieve resilience and sustainability. Future researchers can conduct studies in specific sectors, such as automotive, aviation and healthcare, with high penetration of the technology to confirm whether the characteristics, benefits and capabilities are applicable and sufficient.

Data Availability Statement-

Data related to this paper is available with authors and will be available whenever required.

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Appendix A: List of tables

Table 1: Summary of previous review papers on AM

Reference	Journal	Type of review and Period	Theme	Methodology	Findings
Bhattacharya et al., 2022	Benchmarking: An International Journal	Systematic (2005 - 2021)	AM and inventory and spare parts management	452 articles from Scopus	2 research gaps were identified – AM and supply chain resilience, and strategies of implementation of AM to overcome barriers to adoption
Sonar et al., 2022	Vision: The Journal of Business Perspective	Systematic (2010 - 2021)	AM adoption impacts supply chain processes	116 peer-reviewed publications	The impact of AM on supply chain processes and flows was discussed and future research directions provided
Naghshineh & Carvalho, 2022b	International Journal of Production Economics	Systematic (2006 – April 2021)	AM barriers and implications on supply chain vulnerabilities and capabilities	87 peer-reviewed publications	Propositions and a framework have been presented to understand the effect of AM adoption on the supply chain
Floren *et al*., 2021	Journal of Manufacturing Technology Management	Systematic (2008 – December 2019)	The intersection between additive manufacturing technologies (AMTs) and business models (BM)	288 peer-reviewed and non-peer-reviewed publications using Scopus	The findings show that there is a need to investigate the transformative effects of AM on supply chains and value chains.
Kunovjanek *et al*., 2020	Production Planning & Control	Systematic (2011 – October 2019)	AM and its impact on the supply chain	141 articles from Web of Science and EBSCO	Using the SCOR model, the study discussed the impact of AM on different areas of the supply chain, its benefits, challenges and future trends.
Verboeket and Krikke, 2019	Computers in Industry	Structured (Till December 2017)	The disruptive impact of AM	67 articles from Science Direct, Web of Science, Google Scholar and Directory of Open Access Journals	Using the SCOR model, the study discussed AM SC design, a conceptual framework, a research agenda and a roadmap for the roll-out of AM.
Franco et al., 2020	Computers & Industrial Engineering	Systematic	Positive and negative impacts on AM	136 peer-reviewed publications	A conceptual framework for AM's impact on the company's business is provided

Ryan *et al.*, 2017	International Journal of Physical Distribution & Logistics Management	Structured (Till 2016)	Future scenarios for 3D printing	128 papers from Science Direct, Scopus and Web of Science, Emerald, ProQuest and EBSCO	The study provided a framework for underlying scenarios for 3DP and future research agenda to utilise 3DP in the supply chain
Niaki and Nonino, 2017a	International Journal of Production Research	Bibliometric and Systematic (Till 2015)	AM technologies in managerial approaches	123 papers from Scopus, Web of Science, EBSCO and IEEE Explorer	The study discussed AM research domains in the scope of management, business and economics

Table 2: Review protocol

Topic	Description
Author(s)	Who is the author?
Journal	In which journal was the paper published?
Year of publication	When was the article published?
Geographical focus	Where has the study been performed?
Type of research article	What is the nature of the research article?
Citations	Which papers have the highest citations in the literature?
Industry focus	Which industries are targeted for data collection?
Theoretical underpinnings	What theories have been used in AM literature?
Major themes	What are the major themes of AM research?
Benefits	What are the benefits provided by AM?
Capabilities	What are the capabilities required by the firms for a successful AM adoption?
Gaps and Future research directions	What are the existing gaps in the literature and what would be the directions for future research?
Findings and implications	What are the main findings of the study and what implications does the study have?

(Adapted from Mishra et al., 2020)

Table 3: Top 10 cited articles

Title	Reference	Purpose	Country	Journal and ranking (ABDC/ABS)	Citations
The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing	Attaran, 2017	The benefits, applications, and challenges of AM.	USA	Business Horizons (ABDC B)	1161
Additive manufacturing: A framework for implementation.	Mellor *et al.*, 2014	Implementation framework for AM which the managers can implement to adopt the technology to generate new business opportunities.	UK	International Journal of Production Economics (ABDC A)	930

Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited	Weller *et al.*, 2015	How market structures will be affected from an operations management perspective by implementing AM technologies	Germany	International Journal of Production Economics (ABDC A)	890
Global value chains from a 3D printing perspective	Laplume et al., 2016	Evolution of AM and its impact on global value chains	Canada	Journal of International Business Studies (ABDC A*)	334
The Supply Chain Becomes the Demand Chain	Christopher and Ryals, 2014	Enhanced responsiveness through AM and Big data	USA	Journal of Business Logistics (ABDC A)	228
3D Printing Services: Classification, Supply Chain Implications and Research Agenda	Rogers et al., 2016	Types of 3D printing service and their implication on supply chain	Germany	International Journal of Physical Distribution & Logistics Management (ABDC A)	207
The 3D printing order: variability, supercenters and supply chain reconfigurations	Sasson and Johnson, 2016	Hybrid manufacturing to handle variability	Norway	International Journal of Physical Distribution & Logistics Management (ABDC A)	205
Decentralization and Localization of Production: The Organizational and Economic Consequences of Additive Manufacturing (3D Printing)	Ben-ner and Siemsen, 2017	Implications of AM	USA	California Management Review (ABDC A)	198
The impact of additive manufacturing on supply chains	Durach et al., 2017	Barriers to AM adoption and the impact of AM on the supply chain	Germany	International Journal of Physical Distribution & Logistics Management (ABDC A)	174
Additive manufacturing management: a review and future research agenda	Niaki and Nonino, 2017a	Literature review on AM management	Italy	International Journal of Production Research (ABDC A)	172

(Accessed on 20th January 2023)

Appendix B: List of Figures

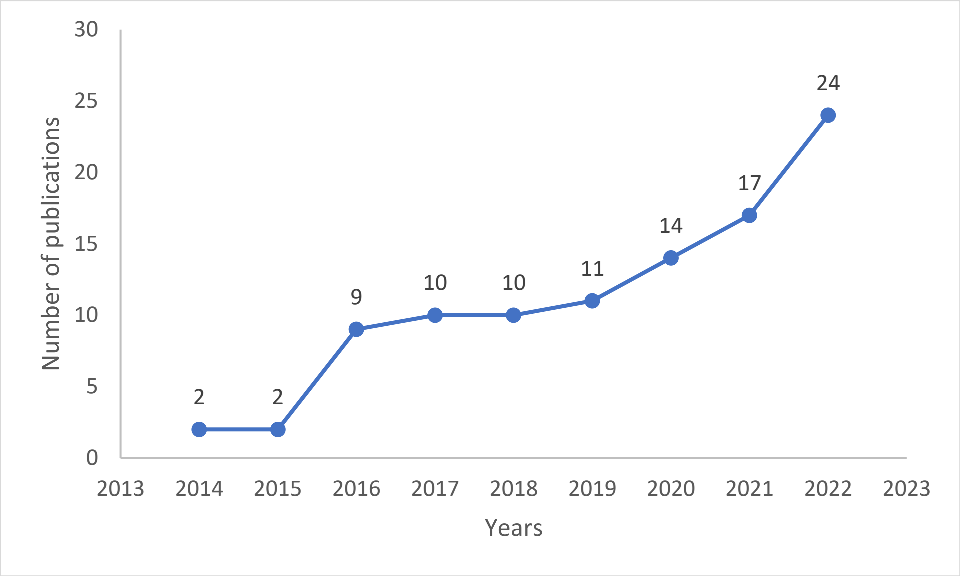

Figure 1: Year-wise publication (Accessed on 20th January 2023)

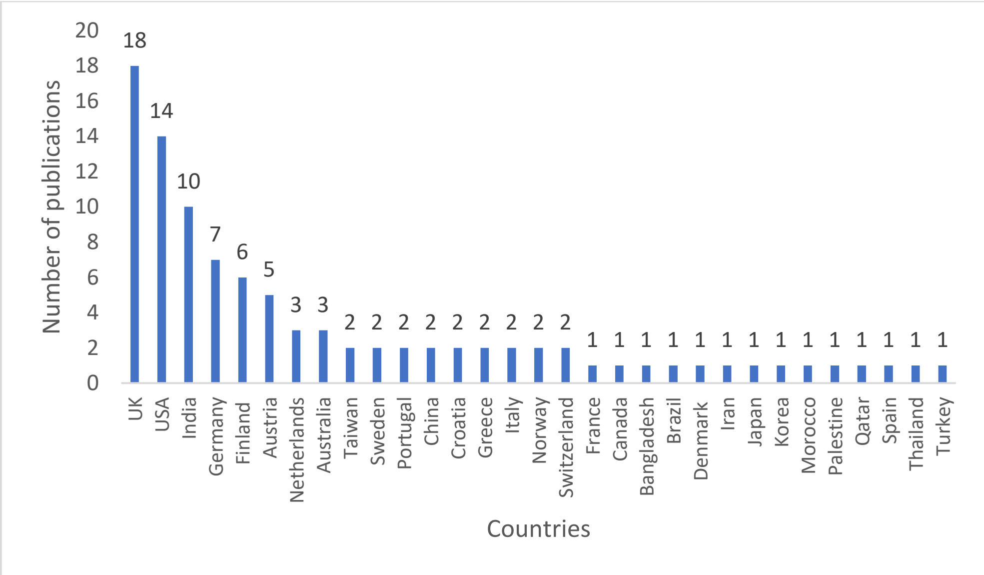

Figure 2: Country-wise classification

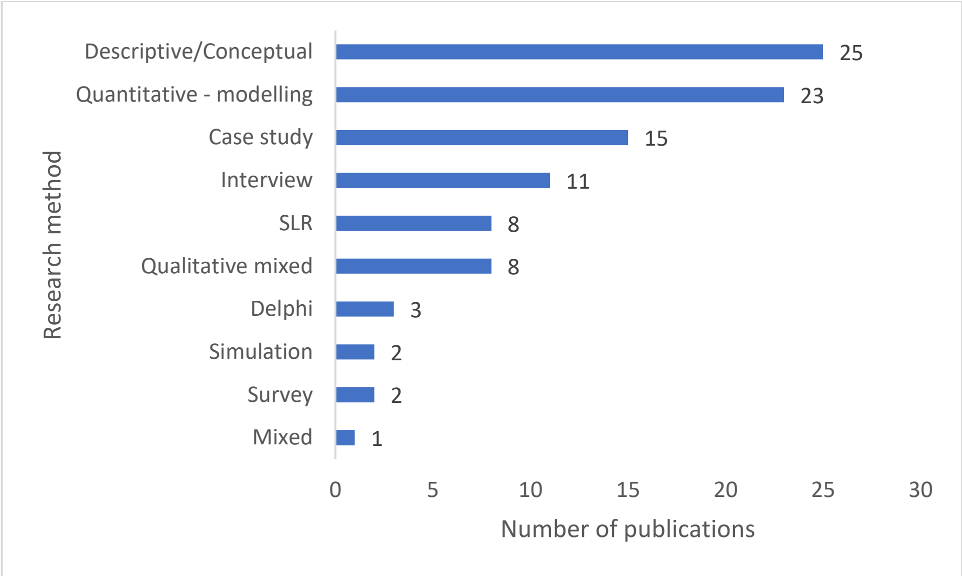

Figure 3: Research method*s*

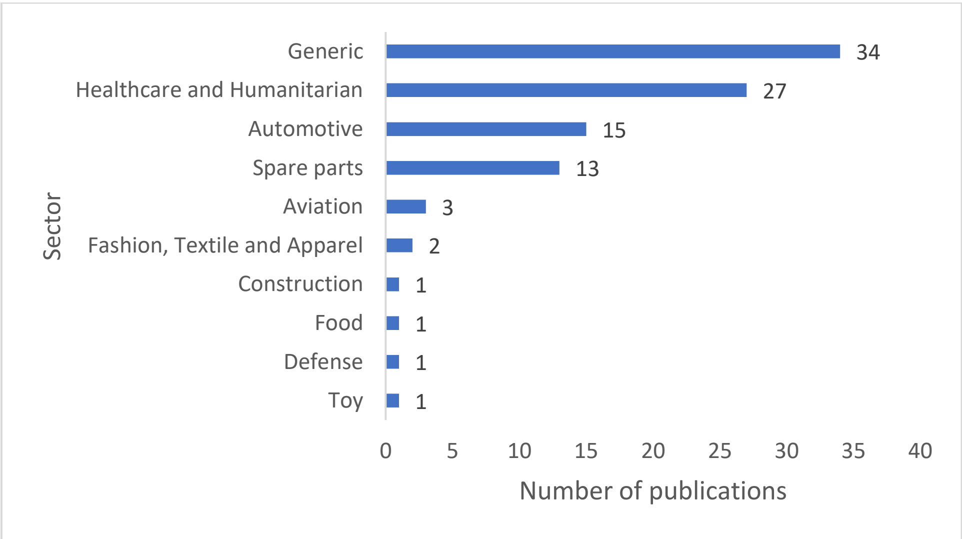

Figure 4: Industry-wise classification