buildings

Review

Supply Chain Landscape of 3D Printed Buildings: A Stakeholder Decision Support Framework

Jiayue Ma *, Don Amila Sajeevan Samarasinghe, James Olabode Bamidele Rotimi and Kelvin Zuo

School of Built Environment, College of Sciences, Massey University, Auckland 0632, New Zealand
* Correspondence: j.ma3@massey.ac.nz

Abstract: With the development of new construction technology, increasing attention is being paid to 3D printing due to its construction efficiency as well as its sustainability. Numerous researchers have determined its benefits in cost reduction, resource savings, safety assurance, etc. Although various advantages have been identified, there are limitations and challenges in technology implementation. Especially since it is a new construction method, 3D printing construction projects will have a very different supply chain compared to traditional projects. As part of a research programme investigating the 3D printing construction supply chain in a New Zealand context, this study systematically analysed the research about 3D printing adoption and supply chain challenges in the construction sector. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) was adopted as the guideline for literature selection. PRISMA is designed to assist researchers in reporting the review research focus and methodology, and examining the findings from published literature. NVivo was then adopted to code and analyse the selected publications to gather the data necessary for our study. The literature was analysed from the perspectives of the research focus, research methods, and findings. Studies about 3D printing implementation, benefits and barriers, as well as its significance are also analysed. As a result, this research found existing research gaps, including the fragmented situation of management-related research in the 3D printing construction sector, insufficient research in top management for 3D printing construction implementation, and changes to supply chain management practices in 3D printing construction projects. A decision support system demo for supply chain management is drafted in this paper, which requires further study. The research outcome highlighted the existing studies in 3D printing construction implementation and supply chain, and initiated a research topic on supply chain decision making. The result contributes to the theoretical and practical development of 3D printing technology in the construction industry. This review paper also inspires future studies on supply chain frameworks and theoretical models.

Keywords: supply chain management; 3D printing; construction industry

Citation: Ma, J.; Samarasinghe, D.A.S.; Rotimi, J.O.B.; Zuo, K. Supply Chain Landscape of 3D Printed Buildings: A Stakeholder Decision Support Framework. *Buildings* **2024**, *14*, 1811. https://doi.org/10.3390/buildings14061811

Academic Editor: Pramen P. Shrestha

Received: 30 April 2024
Revised: 20 May 2024
Accepted: 1 June 2024
Published: 14 June 2024

Correction Statement: This article has been republished with a minor change. The change does not affect the scientific content of the article and further details are available within the backmatter of the website version of this article.

1. Introduction

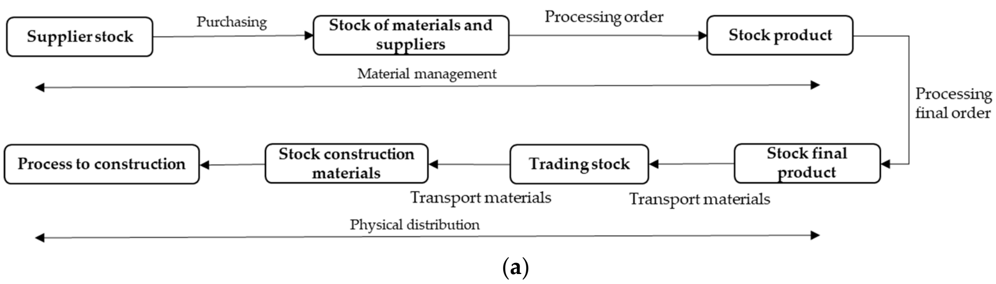
1.1. Research Background

The construction industry is transforming from traditional to technological construction methods [1], aligning with the development of technologies [2]. Digital technologies, such as BIM, augmented reality, blockchain, and 3D printing, are being adopted in the construction sector [3]. Setaki and van Timmeren [4] identified eight disruptive technologies that may benefit the building industry and explored their potential roles across the whole lifecycle of buildings. Through interviews and case studies, Ibrahim et al. [5] identified the obstacles that hinder the adoption of digital software by construction consultants. Peter et al. [6] studied holistic digital technology implementation and delivered a process that addresses the current barriers for construction companies. Osunsanmi et al. [7] revealed a high willingness of construction professionals to adopt new technologies for construction projects. However, the industry has traditionally been slow to adopt new technologies, and many technologies have not been widely adopted by construction companies [1,8].

New construction technologies introduce uncertainty, especially when this is not maturely applied in the industry [9]. As a result, the construction sector is one of the least automated industries [10].

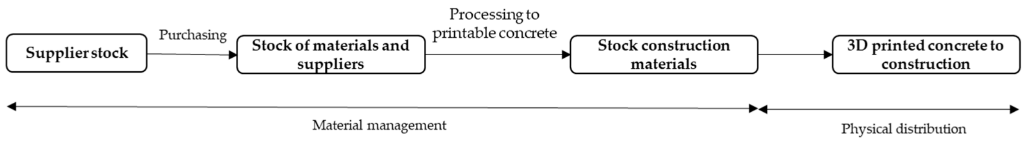
Three-dimensional printing, also called additive manufacturing (AM) technology, has been gradually applied in the building construction industry in recent years [9,11]. The development of 3D printing technology started in the 1980s, and has gained significant attention since the third industrial revolution [12]. Ghaffar et al. [13] provided the benefits of additive manufacturing to the economy, society, and the environment. They claimed that additive manufacturing has the potential to be an eco-innovative solution for the construction industry [13], and 3D printing technology may reduce the cost, construction duration, and waste while improving safety, sustainability customization, quality, and working efficiency [14]. Teixeira et al. [11] maintained that using 3D printing technology in construction can reduce the entire cost of concrete by 35–60%. This technology can optimise raw material use and the use of recycled or recyclable materials, potentially resulting in a zero-waste construction industry [4]. With respect to logistics, 3D printing technology contributes to cost reduction, and meanwhile, it helps to upgrade and refurbish products in supply chain practices [15]. Beltagui et al. [16] identified the value of 3D printing construction in more complex products: it is better suited to special designs, faster to develop, and nearer to the construction site. Three-dimensional printing technology is transforming the construction industry towards a more sustainable future.

As a newly developed construction technology, 3D printing construction will have a different supply chain process compared to conventional construction methods, especially in information exchange [17]. Supply chain management can be regarded as a long-term inter-company logistics management process that coordinates processes and flows of material and information between suppliers and customers [18]. Figure 1a presents a traditional supply chain flow of a construction project. Figure 1b shows a potential supply chain for 3D concrete printing, from which the information flow of 3D concrete printing can be recognised. Compared to a traditional supply chain, the 3D printing construction project may have a shorter supply chain, where the management strategy may also change. Afshari et al. [19] found that supply chains receive benefits from the flexibility of additive manufacturing technology; El-Sayegh et al. [20] claimed there is a shorter supply chain for 3D printing construction compared to traditional construction; Yılmaz [21] identified the positive impact on the supply chain of additive manufacturing in that it has simpler management procedures. By adopting 3D printing construction technology, the complexity of the supply chain can be dramatically decreased [22]. Three-dimensional printing technology helps in the development of new ways of operation, thereby simplifying the current supply chain and creating new supply chain structures [23]. This technology can also force supply chain practitioners to focus on developing dynamic capabilities [24].



(**a**)

Figure 1. *Cont.*



(**b**)

Figure 1. (**a**) Traditional supply chain of a construction project [17]. (**b**) The typical supply chain of a concrete 3D-printed project [17].

1.2. Research Gaps

Much research supports 3D printing as a disruptive technology in the construction industry revolution [4,9,11,13,22], and difficulties occur in implementing 3D printing technology. By exploring the construction technology practice, Oesterreich and Teuteberg [1] found that construction technologies are at different maturity levels, and that additive manufacturing is at the formative stage. It can be difficult to fully understand the mechanical design and operational principles of 3D printing systems [25]. The performance control of printable materials can also be challenging in 3D printing construction [25]. Beltagui et al. [16] claimed that inappropriate use of 3D printing technology may lead to resource wastage, cost increases, and low productivity. There is a need to evaluate the life cycle costs of additive manufacturing and whether the use of this technology would lead to a cost increase or reduction in the construction industry [13]. Ma et al. [26] indicated that insufficient knowledge of technologies, high capital costs, cultural resistance, the technology itself, and legal limitations can be barriers to implementing innovative construction technologies.

Three-dimensional printing technology most likely will result in a redesign of the supply chain [17]. Current supply chains are long and complex, and 3D printing construction supply chain remains undefined, leading to many management challenges [27]. Few structured supply chain management frameworks have been adopted for mapping and measuring construction supply chain performance [28], nor for 3D printing construction supply chains. Existing value-based supply chain concepts are also insufficient for identifying the connection between logistics measures and objectives [18]. Hedenstierna et al. [23] claimed that 3D printing technology will play a role in supply chains by establishing new ways of operating that simplify the current supply chains and create new supply chain structures. So, it is necessary to investigate how operations within the supply chain will be changed due to the use of 3D printing in construction, and how 3D printing will impact supply chain integration and performance [29].

Research on the supply chain strategies in 3D printing construction is lacking [10]. Only 4% of this research contributes to the theoretical framework of the topic of operations management [30]. According to Chan and Kumar [28], effective supply chain operations rely on the collaboration between distributors, manufacturers, and suppliers, and supply chain mechanisms determine how management decisions affect supply chain performance [31]. However, in the 3D printing construction sector, the system vendor, material suppliers, customers, and location of manufacturing may bring barriers to the implementation of this technology [32]. The abovementioned problems may consequently result in challenges for supply chains [31]. The printable cementitious material can be the key issue in 3D printing construction projects [33]. It is difficult to define a constant supply of raw materials for 3D printing construction projects [34]. Apart from materials, the transportation of 3D printers is another difficult and costly issue for construction project decision-makers [22]. As can be seen, there is a need to systematically analyse the challenges and barriers associated with the 3D printing construction supply chain, which leads to an investigation of strategies for 3D printing technology implementation.

1.3. Aim and Research Questions

This systematic review paper aimed to synthesise the benefits and challenges of the 3D printing construction supply chain, and identify gaps in this sector that have not been studied. The results will guide future research into the 3D printing construction supply chain. Articles on supply chain management in the 3D printing construction sector are discussed and systematically analysed. The following questions will be answered in this review.

Q1: What is the significance of implementing 3D printing technology in construction supply chains?

Q2: How is the supply chain operated in the 3D printing construction sector?

Q3: What are the barriers to implementing 3D printing in construction supply chains?

2. Research Methods

This systematic literature review is a significant part of a research project investigating supply chain management issues in the 3D printing construction sector. According to the research project aim, there are eight main research questions, and three were studied in this review paper. Further, six sub-questions were drafted from the main three questions, as shown in Table 1.

Table 1. Research questions.

Main Research Question	Sub-Questions
1: What is the significance of implementing 3D printing technology in construction supply chains?	1.1: What is the implementing status of 3D printing technology in construction supply chains? 1.2: What are the benefits of 3D printing construction technology?
2: How is the supply chain operated in the 3D printing construction sector?	2.1: How is the supply chain managed in the construction sector? 2.2: Are there any challenges for 3D printing construction supply chain management?
3: What are the barriers to implementing 3D printing in the construction sector?	3.1: Which aspects are barriers to implementing 3D printing technology? 3.2: What efforts have been made in the past to solve these barriers?

A systematic literature review goes beyond mere repetition of prior work; it is a rigorous method that ensures the replicability of previous findings while also synthesising and analysing the existing research on a specific topic [35]. A systematic review provides researchers with background knowledge of a topic and navigates further research. This research was conducted with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, which are designed to assist researchers in transparently reporting why the review was performed, what the authors did, and what has been found [36].

2.1. Identification of Research Records

This systematic review discusses supply chain management research in the 3D printing construction sector. Therefore, three keywords were defined for source searching: 3D printing, supply chain, and construction. In order to collect the maximum results, the keywords were expanded with synonyms. Asterisks (*) were also adopted to include more articles. The searching keywords were "3D print* OR three dimensional print* OR three-dimensional print* OR additive manufactur*", "supply chain OR logistics OR operation*", and "construct* OR build*".

Based on database accessibility, the authors decided to use Scopus, Discover, and Emerald Insight as the search databases. Scopus and Discover cover a wide range of studies and resources, and were the main databases for this review. Emerald Insight provides a supplement on the management subject since this research is part of a study about 3D printing supply chain management. The abovementioned databases are embodied by abundant and quality research literature, covering comprehensive research topics. These resources provide full-text access to hundreds of journals and e-books about business, management, and economics. The search strategies were designed for each database, as shown in Table 2. The search scope enabled the authors to obtain the maximum number of studies with the defined keywords.

Table 2. Search Strategy.

Database	Year Range	Search Scope	Keywords
Scopus	2006–2023	Article title, abstract, keywords	"3D print*" OR "three dimensional print*" OR "three-dimensional print*" OR "additive manufactur*" AND "Supply chain*" OR logistic* OR operation* AND Construct* OR build*
Discover		Abstract	3D print* OR three dimensional print* OR three-dimensional print* OR additive manufactur* AND Supply chain OR logistic* OR operation* AND Construct* OR build*
Emerald Insight		All fields	3D print* OR three dimensional print* OR three-dimensional print* OR additive manufactur* AND Supply chain OR logistic* OR operation* AND Construct* OR build*

Filters, including source type, year range, countries/regions, and language, were defined as the primary selection criteria. Only academic journal articles and conference proceedings were selected due to their high influence and recognised academic quality. Autodesk summarised the important events of additive manufacturing development, which show that the first time 3D-printed buildings were produced was in 2006 [37]. Therefore, the authors decided to select articles that were published from 2006 to 2023. Ślusarczyk [38] investigated investment in 3D printing technology and summarised the top 20 countries investing the most in additive technologies. These are Germany, the USA, China, France, Italy, the UK, Japan, India, Spain, Benelux countries (Belgium, Netherlands, Luxembourg), Scandinavia (Denmark, Sweden, Norway, Finland, Iceland), Turkey, Canada, Russia, South Korea, Brazil, Mexico, Australia, Portugal, and South Africa. Since the research is industry-based in New Zealand, New Zealand was included as a source region. Only papers in English were selected. This search strategy discovered 4447 papers from the three databases on 23rd July 2023, and after applying filters and removing duplicates, 1228 articles remained.

2.2. Inclusion and Exclusion Criteria

Next, the authors implemented a two-step screening process with pre-defined inclusion/exclusion criteria. In the first-step, exclusion criteria were set as follow: If the paper was not on building and construction- or management-related subjects or was not on 3D-printing technology based on the title, keywords, and abstract. For example, the paper was excluded if the article was in the medical, dental, food, or education area. After primary screening, 149 journal articles remained. The second-step screening employed the following inclusion criteria:

(i) Studies supply chain issues in the 3D printing/additive manufacturing construction sector;

(ii) Studies supply chain issue of 3D printing/additive manufacturing technology;

(iii) Implements or performs life cycle study of 3D printing/additive manufacturing technology in the construction sector.

For this step, 149 papers were screened by reading the full text, and 113 papers were excluded. Thus, 36 eligible records were included in the systematic review. In addition, the authors also applied snowballing to explore more research records, which involved screening all the articles that are cited by the included papers [39]. By reviewing the reference list of the included research, we found 32 papers that are within the scope of the systematic review. After reading the full text of these studies, 21 papers were included in the systematic review. As a result, the final number was 57 studies, comprising 46 journal articles and 11 conference proceedings. Figure 2 shows the flow of the screening process. Quality parameters, for example, only including highly cited articles, were not applied in this research in order to reduce publication bias [31].

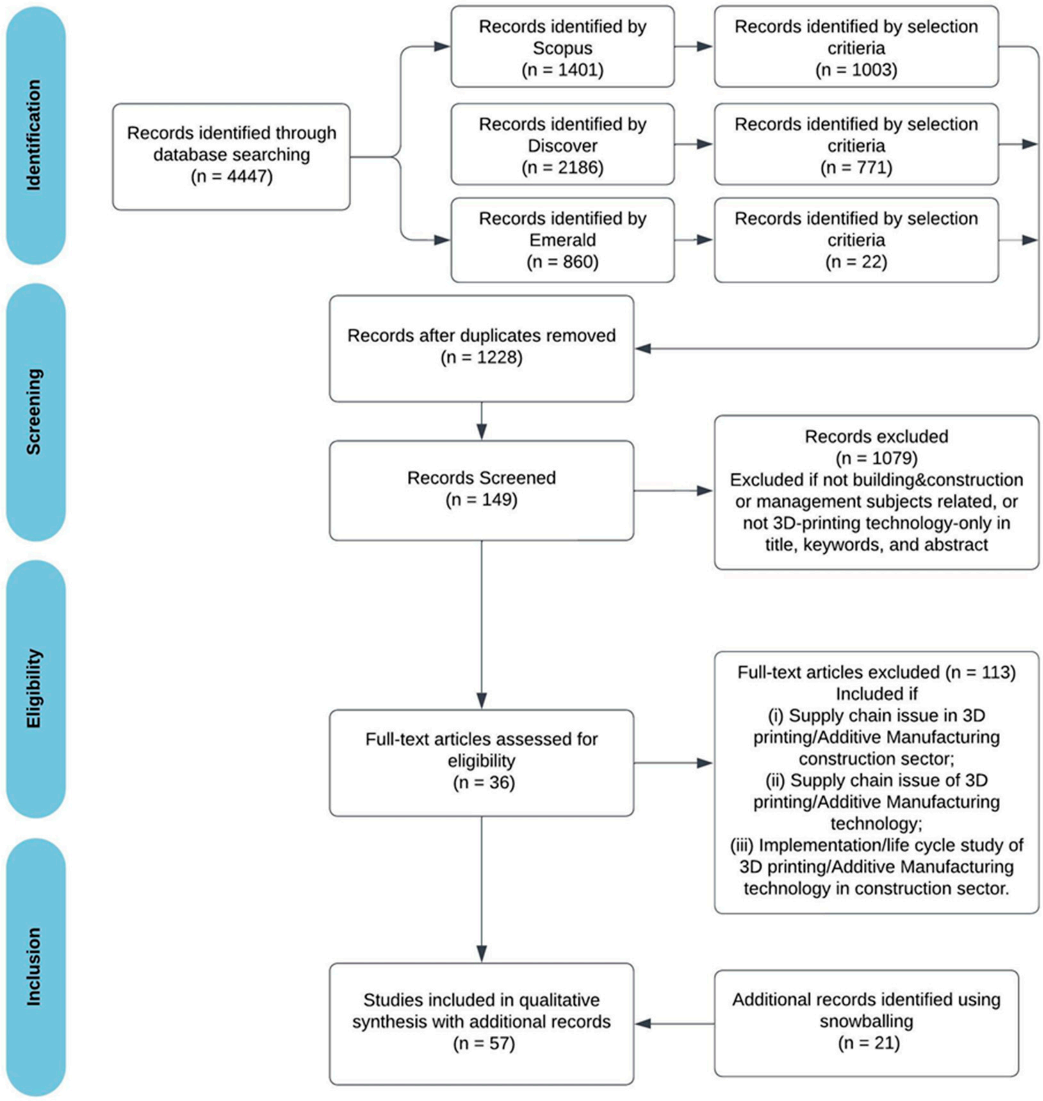


Figure 2. The PRISMA flow diagram used for this study.

Research synthesis is defined as integrating support from multiple sources for one argument while identifying the inter-relationships within the pre-defined topic [40]. By means of literature synthesis, it is possible to enhance the generalizability of qualitative research as well as to develop new knowledge [31]. This research synthesised the included studies in order to clarify what has been studied and the existing research gaps for further study. NVivo 14 was used for data acquisition and analysis [41]. The results are interpreted in the next section.

3. Results and Interpretation

3.1. Literature Analysis and Synthesis

This study analysed the literature based on the research questions in order to investigate issues from the purpose, methodology, and result perspectives. At the start, the distribution of the publication year and word frequency were used to obtain an overview the selected studies. NVivo, a qualitative data analysis tool, was adopted as the main tool for the literature analysis. This tool helps researchers systematically extract data from the literature for further analysis. The authors applied coding to the selected articles in NVivo 14. Essential data were acquired by querying the content of all of the studies. Then, a qualitative content analysis was conducted to categorise the coded research into separate themes [42].

3.1.1. An Overview of the Literature

This study included papers published from 2006 to 2023, the reason for which was given in Section 2. By visualising the publication year of the selected publications (Figure 3), it can be seen that the earliest selected paper was published in 2012 and that there has been an increase in research on this topic since 2013. From this trend, there appears to be a technological revolution in the construction industry, and 3D printing technology has increasingly attracted people's attention. The number of studies about supply chain issues in the 3D printing construction sector grew and peaked in 2019, which can be understood as more researchers commencing their study in this area around 2018 and 2019. However, the COVID-19 pandemic may have restricted research opportunities, as a sharp decrease can be seen in 2020. During the COVID-19 pandemic, researchers had limited access to laboratories, construction sites, and workstations [43], so it was difficult to obtain data for research. As the pandemic restrictions were eased, there was a gradual increase in publications. Therefore, it is reasonable to conclude that more and more researchers are paying attention to the management issues of the 3D printing construction area. This increased research has exposed many challenges and solutions to support the healthy development of 3D printing construction technology.

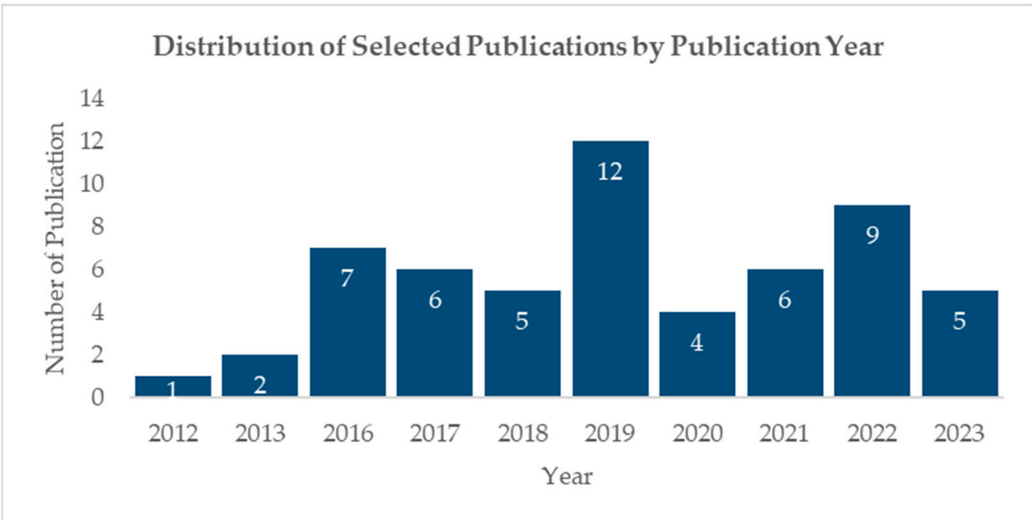


Figure 3. Distribution of selected publications by publication year.

Figure 4 was generated using NVivo 14 to present the word frequency from the selected publications and define the most popular research topics. The word frequency analysis showed that apart from the predefined keywords, production, technology, cost, process, material, design, and management were the most frequent words in the selected literature. All words were categorised into three groups, with each group representing a research direction. The first group included technology, production, and design. This research group focused more on the technology itself, studying questions in technology advancement and productivity improvement [10,44,45]. The second group concerned the building materials and their availability [33]. As can be seen from Figure 4, concrete was the most utilised material in 3D printing. The final group relates to managerial issues, including cost, process, and management. For papers falling into this category, the authors paid more attention to promoting 3D printing technology from a management theory perspective [14,18,46].

Figure 4. Word frequency analysis of publications.

3.1.2. Interpretation of Existing Research Focuses

The existing research focus reflects the current research trends and interests, and from this, what research has been performed in the past and how studies were conducted can be understood. Thus, the rationale for past research topics and navigation for future studies can be determined for this study. So, the selected publications were examined by NVivo 14 to extract data relevant to the purpose of study. The literature was categorised into five themes using content analysis according to their main focus. Although one study may contain multiple themes, the authors only considered the dominative theme of each study for their categorisation. Then, the coded contents were holistically analysed to determine the existing research focuses. The result showed that 28% of the studies proposed models/frameworks/methods in the 3D printing supply chain sector. The second theme (25%) studied the benefits, challenges, and feasibility of 3D printing or additive manufacturing (AM) technologies. Approximately 21% of the studies investigated the impact of 3D printing (or AM) technology on various aspects. Finally, 16% of the studies focused on specific implementation problems and 11% of the studies researched other topics such as the supply chain, resources, decision-making, etc. (Table 3).

Table 3. Topic distribution of selected publications.

Model/ Framework/ Method	Benefits/ Challenges/ Feasibility	Impact	Implementation	Others: Supply Chain/ Resource/ Decision Making, etc.	All Publications
16	14	12	9	6	57
28%	25%	21%	16%	11%	100%

From the result, it can be understood that most researchers attempted to use models or frameworks to solve problems in 3D printing practice. The large number of studies on the benefits, challenges, and impacts reflects that more benefits and challenges were found as 3D printing was implemented. It also shows that it is still valuable to study the impacts of this technology to facilitate its implementation. The limited number of studies on decision-making indicates the gap in this area, which can be a focus for future research.

Regarding studies that proposed models, the primary research was on generating models for AM supply chain-related issues [16,19,21,44,47–50]. The model proposed by Barron et al. [44] assists in identifying and isolating critical safety features of the supply chain. Jin and Gao [50] produced a model of green supply chain networks for 3D printing, showing the increased attention to sustainable supply chain management. Another focus was applying models to cost and purchasing strategies. Lindemann et al. [51] proposed a costing model to assess the life cycle cost of AM products. By evaluating the existing systems, Muthukumarasamy et al. [52] provided a supplemental method for optimizing AM's purchasing strategies. Besklubova et al. [22] developed a construction 3D printing multi-stage network-based logistics cost assessment model to support logistics network evaluation and logistics strategies of 3D printing projects. Frameworks for decision-making have also been produced. Jin and Ji [53] proposed a method for partnership choice in the supply chain in 3D printing and big data, and Feldmann and Pumpe [18] developed a framework for investment decisions, providing an assessment of value drivers in the supply chain. Frameworks for 3D printing adoption were produced by Wu et al. [14] and Zanetti et al. [54].

The benefits and challenges in the 3D printing sector are a continuing research topic. The benefits and challenges of 3D printing adoption have been widely investigated [15,55–57]. This provides a sufficient background study for future research on the topic of 3D printing. Following these studies, Gupta et al. [27] tested the revolutionary technologies' risk control benefits and their potential to develop supply chain resilience, and Belhadi et al. [24] investigated the potential of AM for building resilience-efficiency at the supply chain level. Pradhananga et al. [58] provided insight into the importance of 3D printing in construction and how it works in constructing affordable housing, and the potential of 3D printing as an alternative to the conventional process of building shelters was studied by Subramanya and Kermanshachi [59].

There is noteworthy research about 3D printing implementation in remote housing [60] as well as large-scale systems [33]. It is known that most 3D printing projects are limited to smaller scales [61], and remote housing is a revolutionary idea at this stage. The thermal and green benefits of using 3D printing in building construction were discussed by Guimarães et al. [34,45], but Thomas [62] examined the societal costs and benefits of 3D printing from a monetary and resource consumption perspective. These studies constitute a small portion of the current 3D printing research, which proves there are ample opportunities for future studies.

Based on the analysis of the literature, there are researchers that have studied the impact of 3D printing/AM on the supply chain with the aim of improving supply chain resilience as well as management performance [17,29,63–69]. However, solutions for these impacts have not been sufficiently investigated. As for impacts on other aspects, Khajavi et al. [10] explained the impact of design and supply chain configurations on performance in concrete 3D printing, which is the opposite orientation to AM's impacts on supply chains. Oettmeier and Hofmann [70] identified factors that may affect the decision-making of AM adoption from an inter-firm perspective, and Muñoz et al. [71] studied the environmental impacts of 3D printing technologies. Studying the impact of 3D printing technology provides opportunities to investigate solutions for existing challenges. Thus, the negative impacts can be mitigated for the sustainable development of 3D printing construction.

Research about 3D printing implementation reflects the development status from various orientations. Early in 2012, Lim et al. [72] discussed large-scale AM implementation in the construction and architecture arena. As the adoption of AM increased, more attention was given to improving implementation performance. For example, Braziotis et al. [73] defined typical 3D printing deployment strategies, and Verboeket and Krikke [31] used AM to design supply chains to improve their performance. Ryan et al. [74] evaluated existing scenarios for 3D printing and identified the "white place" for future opportunities, whereas Schuldt et al. [35] presented the viability of 3D-printed construction implementation specifically in remote, isolated, or expeditionary environments. In addition to the abovementioned applications, researchers are investigating the integration of AM technology and the circular economy. It can be seen that additive manufacturing implementation has gained researchers' attention in many sectors, and more opportunities can be found for future studies.

Other studies have focused on the topic of supply chain innovation and resilience [75,76], natural resource use [77], as well as the decision-making of supply chain participants [78]. This study demonstrated that the ambition of researchers is to promote 3D printing as a method for manufacturing and construction.

3.1.3. Interpretation of Research Methods for 3D Printing Construction Studies

The research methods for the 3D printing construction studies were analysed, and the results showed that around 32% of the publications are review articles that were performed in a systematic way. Scholars use this method to synthesise and interpret past research [73] to present the organised history of a specific topic [56] and to deliver new ideas for current conditions. For example, by overviewing recent attempts at applying 3D printing technology, Alzarrad and Elhouar [56] elucidated the sector's successes and challenges. Hettiarachchi et al. [79] systematically reviewed and analysed the related literature, thereby identifying conceptual elements for their study. By reviewing publications related to 3D printing, Subramanya and Kermanshachi [59] evaluated the opportunities and challenges of adopting this technology in a specific industry.

Literature reviews also provide opportunities to optimise performance since a review generally contains a great amount of data for a topic. Ma et al. [33] reviewed the current design methodologies of large-scale 3D printing systems so that the performance of cementitious materials could be optimised. Ryan et al. [74] structurally reviewed academia and industry literature and evaluated potential scenarios to identify opportunities for the future development of 3D printing. Through literature taxonomy, Tziantopoulos et al. [68] provided a theoretically grounded framework for decision-making in supply chain design and management. Delic et al. [29] applied a detailed review of the literature to develop a theoretical model for AM's impact. To conclude, literature reviews have been widely applied to 3D printing studies to synthesise the previous knowledge in this sector [31].

Case studies are another frequently used method in 3D printing studies. Oettmeier and Hofmann [65] used explorative case studies to investigate the impact of AM adoption on the supply chain management process. Kothman and Faber [17] employed a case study to determine the feasibility of 3D printing using concrete in construction. Khajavi et al. [10] conducted a deductive case study to investigate the current state of 3D concrete printing in the construction industry, thereby explaining its impacts. Besklubova et al. [22] used a case study to demonstrate the feasibility and practicality of a construction 3DP multi-stage network-based logistics cost assessment model. Beltagui et al. [16] adopted a case study approach to investigate the ability of 3D printing to overcome barriers. This method was also applied in combination with other analytical approaches such as life cycle assessments, scenario analyses, etc. [10,71].

In the 3D printing construction sector, interviews and surveys are essential ways to collect data from the industry and experts. Durach et al. [64] used a multi-stage survey of industry and academia participants to gain insights into emerging AM processes. Chan et al. [57] employed semi-structured interviews to collect primary data to discuss the opportunities and challenges of 3D printing adoption. Through a questionnaire survey, Wu et al. [14] investigated the relationship between the impact factors and the adoption of 3D printing technology. Luomaranta and Martinsuo [75] organised interviews and workshops in 20 firms to map AM-related processes and activities. According to our review, interviews and surveys are often conducted using other analytical methods. Aghimien et al. [55] conducted a survey among construction professionals to gather data for benefits and barriers assessment of 3D printing adoption. Belhadi et al. [24] used a hybrid approach, including a focus group, semi-structured interview, and case study, to investigate the potential of AM technology.

Life cycle assessments and scenario analyses are other widely used analytical approaches in researching 3D printing construction issues. These methods help researchers explore conditions related to the life cycle of projects [48] and simulate the 3D printing process to identify problems [66]. To sum up, the research methods applied in the 3D printing construction sector aim to synthesise past research and to generate models or frameworks for improving performance in various aspects. Figure 5 presents the most frequently adopted research methods in the reviewed literature.

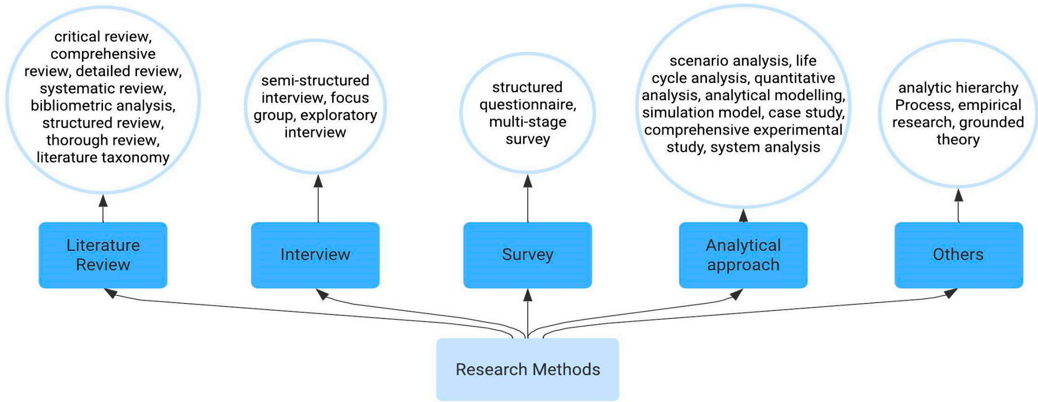


Figure 5. Applied research methods used in reviewed literature.

3.1.4. Interpretation of Previous Research Findings

This study holistically analysed the existing findings in 3D printing technology implementation. One notable finding concerns the effects of 3D printing or AM adoption. According to Aghimien et al. [55], adopting 3D printing in housing contributes to cost reductions, increased productivity, and improved quality and speed of housing delivery. Its benefits on stakeholder satisfaction and economics were also identified [55]. Feldmann and Pumpe [18] found that 3D printing pre-processing steps may result in compensating for the cost impacts regarding labour and energy. Their findings suggest that implementing 3D printing technology decreases the costs of labour, tooling, waste disposal, etc. [18]. Positive effects of employing AM technology on compatibility and demand due to users' perception that AM positively contributes to their company's processes and structures have also been identified [70]. AM also enables decentralised and customised production, thus enhancing customer service and improving customers' satisfaction [70]. The benefits of AM on resource consumption reduction were illustrated by Thomas [62], who concluded that AM may both positively and negatively impact time, labour, and the use of natural resources.

It is valuable to mark the findings about the benefits of using 3D printing/AM on the supply chain. Oettmeier and Hofmann [65] determined the potential of AM to improve quality management and labour division, including employee training, and Delic et al. [29] claimed there is a supply chain and firm performance improvement by adopting AM. Luomaranta and Martinsuo [75] revealed AM-related supply chain innovation in business processes, technology, and structure, as well as supportive changes within businesses, although their findings indicated that AM is a rather isolated innovation requiring firms' involvement in the supply chain [75]. Although Feldmann et al. [48] found both positive and negative changes in adopting AM, they insist on its contribution to economic efficiency as well as environmental sustainability. Moreover, the AM architecture industry also absorbs benefits from an integrated supply chain [69].

Three-dimensional concrete printing potentially improves manufacturing performance in terms of time, material use, and operations, and therefore shortens supply chains while reducing logistical and production efforts [17]. Handal [49] pointed out an accelerating shift from "Push Supply Chains" to "Pull Supply Chains". According to Afshari et al. [19], adopting additive manufacturing reduces the requirement for safety inventory. Belhadi et al. [24] indicated the potential of AM technology to develop dynamic capabilities in reconciling supply chain resilience and efficiency. Gupta et al. 's [27] findings showed that AM assists in risk control and thus improves the supply chain resilience of a firm, which minimises the influence of supply chain disruptions. Besklubova et al. [22] supported the notion that adopting 3D printing decreases supply chain complexity, especially in customization production.

The results of the existing research also show 3D printing/AM's contribution to particular construction activities. Bazli et al. [60] claimed that 3D printing is a cost-effective solution for remote housing, considering the benefits in terms of materials, structural design, process efficiency, logistics, labour, as well as environmental impact. An example of 3D concrete printing (3DCP) efficiency is that 3DCP has greater compressive and flexural strength and less long-term drying shrinkage [60]. In customised production, 3D printing is preferred over using moulds, which are discarded after a single use [71]. Although various benefits of 3D printing technology have been identified in the existing studies, researchers have found a lack of interest in AM's environmental benefits, especially on the part of companies [30]. From a company perspective, the focus is more on the cost and time efficiency of this technology [30]. The results indicated the importance of proactive top management regarding AM implementation [76] and having a comprehensive knowledge of the contributions of 3D printing technology.

3.2. 3D Printing Supply Chain Management in Construction Industry

Based on the existing literature, this section explains the technology implementation conditions, defines the technology's significance, and categorises the barriers to 3D printing adoption. The authors analysed company adoption and research, and synthesised the barriers from the perspectives of management, operations, technology, as well as social concerns. The significance of implementing 3D printing in modern industry is also emphasised, which adds value to the study of the supply chain of the 3D printing construction sector.

3.2.1. Implementation of 3D Printing Technology

From the selected literature, the authors determined the implementation conditions and research data for 3D printing technology. The existing 3D printing buildings are based on different conditions and materials for various clients because 3D printing construction is still in its infancy [14]. Chan et al. [57] pointed out that current 3D printing use mainly focuses on replacing existing processes rather than innovations in application. Ryan et al. [74] found that the use of 3D printing in construction is concerned with highly specialised in customised structures due to its freedom in design. As AM designs can be digitally stored and transferred, Priyadarshini et al. [76] support this technology's contribution to 3D design digitalization. Digital design and manufacturing help companies respond quickly to disruptive effects, thus leading to a less fragile supply chain [76].

Additive manufacturing has gained significant attention in supporting supply chain management [76]. Three-dimensional printing is considered an important element in supply chain digitalisation, but its performance depends on the integration of 3D printing and the supply chain [57]. According to Kunovjanek et al. [80], the application of additive manufacturing is far from common in most supply chains. The limitations of adopting AM in existing supply chain networks were established by Tziantopoulos et al. [68]; these include the cost increase for achieving economies of scale, difficulties in material selection, and legal and regulatory requirements.

From a company's point of view, AM implementation will change industry management practices [49]. Wu et al. [14] support the idea that adopting 3D printing can be a positive organisational change, but the lack of commitment at the top management level may lead to the discrediting of AM. Handal [49] highlighted the fact that top managers have difficulties making decisions that involve implementing new technologies. The reasons for this hesitation might include a cost–benefit trade-off and the need to investigate the technology at a practical level [81]. AM companies from Africa are making great efforts to overcome challenges, but their poor AM material supply chains cannot be ignored [24]. Luomaranta and Martinsuo [75] found that adopting AM technology may influence the interactions between supply chain companies as AM-specific relationships are replacing current supply chain relationships. Implementing AM within a company requires new expertise and supply chain innovations associated with cooperation, coordination, and specialisation [75].

From a research perspective, few researchers have focused on the implementation of AM, and even fewer on supply chain strategies for AM implementation [49]; more attention has been paid to models and design creation by 3D printing designers and developers, so concept knowledge and the understanding of this technology are lacking [55]. Management-related 3D printing research is fragmented into the deployment strategy of 3D printing and its effects on performance [73].

In the reviewed results, it can be concluded that the use of 3D printing is in its infancy and feasibility stage [60], but great effort has been made to promote the construction of 3D printing with the development of 3D printing systems, materials, and applications [22]. The advantages and disadvantages of this technology may determine its future adoption in industry [64]. A conflict has also been identified between 3D printing adoption and labour issues, as a reduced workforce is required for 3D printing construction projects [55].

3.2.2. The Significance of 3D Printing Technology

Additive manufacturing technology has gained significant attention since the third industrial revolution [82], and this technology is suggested to be one of the main construction methods of smart manufacturing [83]. The significance of 3D printing technology is widely recognised in the reviewed studies. Hettiarachchi et al. [79] emphasised the contribution of AM to the redesign of traditional contract manufacturing, and this technology can solve the challenging requirements in civil engineering and construction management associated with design, materials, construction methods, operations, as well as building sustainability [58]. The abovementioned significance of 3D printing technology emphasises the importance of integrating this technology within construction education in order to increase the knowledge base of future workers [58]. Gupta et al. [27] also regard AM technology as a resource that will assist companies in developing risk control capabilities in supply chain management.

Apart from the significance of the technology at the organisation level, 3D printing contributes to the sustainability of construction and the environment. Bazli et al. [60] pointed out that modular 3D printing construction provides flexibility and sustainability to houses through its characteristics, which enables the structures to be disassembled and used for rebuilding. This construction mode also allows extra rooms to be easily attached to existing houses [60], which makes housing more sustainable. As for environmental significance, the construction industry is one of the highest resource consumers [34]. Many researchers have identified the potential of 3D printing technology in reducing material consumption and waste generation [22,59]. Its contribution to reducing labour costs, construction time, and human operational risks has also been identified [22]. Therefore, 3D printing plays a vital role in overcoming the limitations of the traditional construction process [59] and results in a sustainable construction industry.

3.2.3. Barriers to Implementing 3D Printing in the Construction Sector

Some of the selected publications were found to have broad and in-depth discussions about the barriers and challenges in adopting 3D printing/additive manufacturing. The defined barriers were categorised into different groups. Durach et al. [64] claimed a reduction in the barriers to AM adoption in the following years. Meanwhile, from companies' perspective, reductions in barriers need to be considered case by case. So, it is suggested that the efficiency of 3D printing construction technology should be assessed and improved for future adoption.

From a management perspective, Durach et al. [64] identified challenges in employee training, a view supported by Ma et al. [33], who stated that it could be problematic at the current stage to fully understand the mechanical design and operational principles of 3D printing systems. The need to re-skill the workforce is necessary for the implementation of 3D printing technology [24,55]. Training for 3D printing construction can be more challenging in remote construction contexts [60]. Apart from barriers to training, the lack of experience in 3D printing construction is another challenge for technology engagement [55,60]. The abovementioned challenges may be reasons why companies need organisational changes when adopting 3D printing technology [79].

Challenges in operations can be important issues for 3D printing implementation. One significant consideration is cost. Three-dimensional printing technology may be more expensive than traditional construction because of the high cost of 3D printers, digital models, and materials [56,60,64,70], so the cost of printers and additional devices may limit the adoption of 3D printing technology in projects [55]. With the high initial costs, it can be unachievable for small and medium companies to deploy 3D printers in multiple projects [60]. Another challenge is transportation related. Kunovjanek et al. [80] claimed that the challenges of transporting raw and support AM materials need to be sufficiently addressed, as the transportation of printers and printed structures can be both difficult and expensive [60] due to the large size of the machine [22] and the fragility of the products. Furthermore, Bazli et al. [60] identified the increased cost of transporting 3D printing materials from distant locations, which may eventually reduce the economic efficiency of remote construction projects. From a supply chain point of view, 3D printing has yet to be integrated with the supply chain process [22], which leads to a poor supply of materials [24].

The technological maturity of 3D printing is a significant factor affecting the adoption of the technology [54]. Currently, material availability and colour choices can be low [55,64,68,70]. The lack of materials can be a result from the special requirements for printable concrete. Three-dimensional printing materials need to be buildable, printable, and have sufficient open time [60]. The inability to control material quality may lead to imperfect surface finishes and structures [45,60,68,70], which means that buildings may fail to meet the expectations of the end users [60]. The challenges related to materials can be more severe in remote area projects [60]. Due to restrictions imposed by the quality of materials as well as printer size, the current technology may not be suitable for large-scale building construction [56,57,60]. Other technical barriers include digital system limitations [64] and the thermal behaviours of 3D-printed building [45], as well as the system's capability in extreme weather [35].

When considering social challenges, stakeholders' lack of awareness and understanding of the technology's benefits is a common concern [55,60]. The lack of standards is also one of the significant challenges to 3D printing adoption [16,24,60,64]. The current legislation does not provide enough support for implementing 3D printing [57], and the 3D printing standards and quality control need to be improved to align with circular economy concepts [79]. Meanwhile, how 3D-printed buildings can meet building codes and regulations requires more justification [14]. Researchers have also considered the challenges of adopting 3D printing on labour. Aghimien et al. [55] maintained that an unskilled workforce may not necessarily be required in 3D printing construction projects. Bazli et al. [60] believe that the use of this technology can disadvantage traditional construction skilled workers because 3D printing will reduce the need for construction employees.

4. Discussion

This review presents the state-of-the-art of 3D printing implementation and supply chain management in the construction sector. The result in Figure 6 showed that the research focus of the literature was associated with the concept of implementation, barriers, challenges, and the significance of the technology. The different colours represent research that are included in the systematic review. It can be seen that research analysing the challenges of 3D printing adoption gained the most attention. Research about the implementation of this technology is also popular in the existing literature. However, few studies were found investigating the implementation of 3D printing in the New Zealand context. As a new construction technology, its implementation in the New Zealand construction industry would be valuable to discuss, thereby contributing to technology advancement in the local industry.

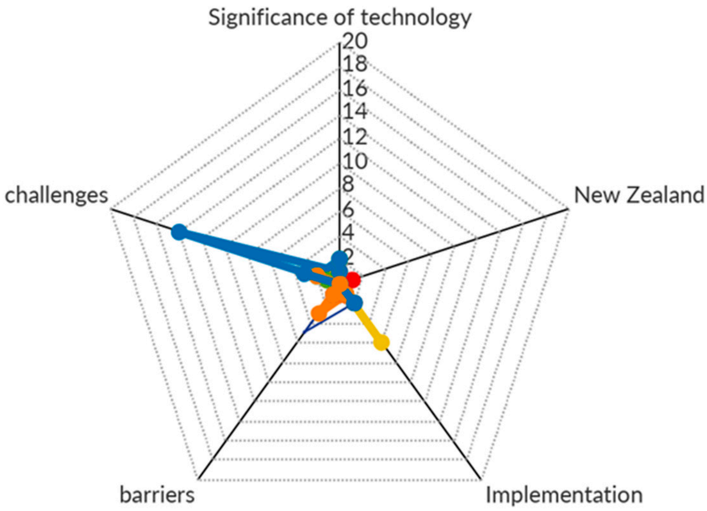


Figure 6. Research focus.

By interpreting the systematic review results, the authors identified the following research gaps for future studies:

1. Management-related research is fragmented, with limited research on decision-making in the 3D printing sector.

2. Insufficient research was conducted into the top management frameworks for 3D printing construction technology implementation.

3. Three-dimensional printing technology will change management practices, and existing supply chain management strategies are unsuitable for 3D printing construction projects.

4. Few studies have investigated the problems associated with 3D printing adoption and labour requirements in construction projects.

5. Studies about implementing 3D printing in New Zealand's construction industry are few.

Even though the use of 3D printing construction is still in its infancy, which was also alluded to by Bazli et al. [60], research in this area is continuing to progress. The research outcomes are expected to contribute to the construction revolution in the near future. The result of this review outlines the current study focus and future research potential in the 3D printing construction sector, which are presented in Figure 7.

Models and frameworks are widely acknowledged as part of the efficient management of supply chains [18,22,44,50]. Meanwhile, they are also prevalent in the 3D printing practice literature. However, critical decision-making requires an understanding of the salient factors that could make the supply chain activities more effective. This gives credence to research gap 1: management-related research is fragmented, and there is limited research about decision-making in the 3D printing sector. Thus, research attention in this area needs to be encouraged. The research into the benefits and challenges identified the opportunities and future potential of 3D printing construction technology. For example, the literature on studying 3D printing impacts supplements our knowledge of the adoption benefits and challenges, thus providing directions for problem-solving research. Moreover, the benefits and effects of 3D printing adoption can significantly support future research and implementation. The results comprehensively indicated the potential of this technology from two aspects, which are the background knowledge for in-depth research and studies about 3D printing implementation. The results also answered sub-question 1.1 (What is the implementing status of 3D printing technology in construction sector?) and sub-question 1.2 (What are the benefits of 3D printing construction technology?).

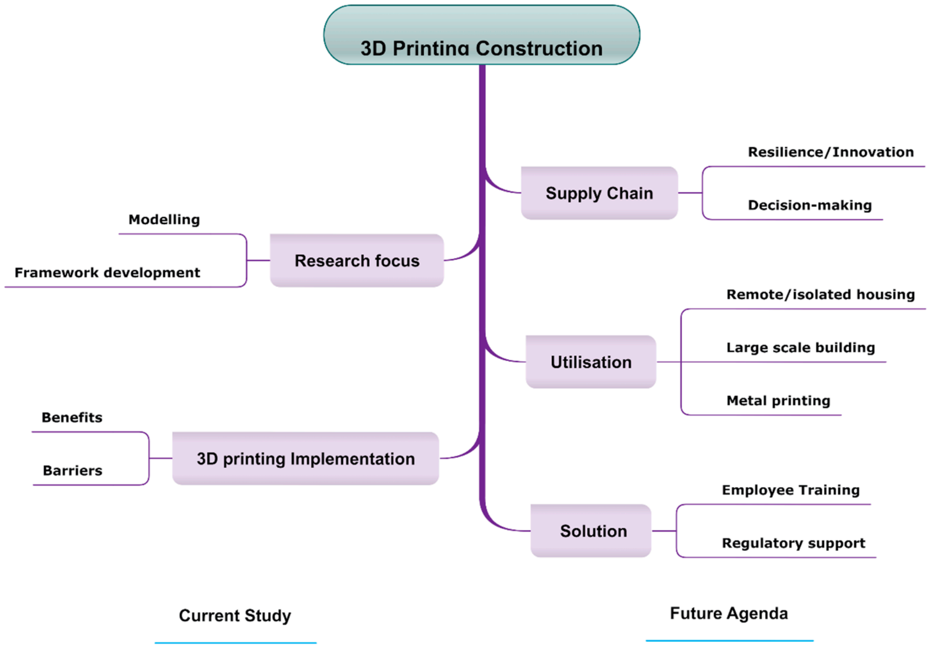


Figure 7. The way forward.

The most prevalent applied research methods in the 3D printing sector provide an overview of how researchers study the 3D printing sector. Compared to studies using review methods, studies involving industrial practices provide more opportunities to learn about the implementation and impacts [65,75]. However, although review papers may lack interactions with industry, they present an overview and background understanding for future studies.

The results of analysing 3D printing construction technology implementation showed that the acceptance of 3D printing construction requires improvement; it is necessary to expand the use of the 3D printing in the construction industry. Many researchers have identified the potential benefits of implementing 3D printing, such as support for replacing manufacturing processes [57], 3D design digitalisation [76], as well as supply chain efficiency [57]. However, the challenges and limitations temporarily hinder the use of 3D printing on a broader scale. Exposing limitations in the very early stage provides opportunities for enhancing our knowledge of the future use of this technology. Commercial implementation also demonstrated challenges in supply chain performance [75]. This requires further research in order to improve supply chain innovation when converting traditional construction to a 3D printing mode. The supply chain will become more resilient and efficient as the implementation becomes more mature. These findings answer sub-question 2.1 (How is the supply chain managed in companies?) and sub-question 2.2 (Are there any challenges for 3D printing construction supply chain management?).

The barriers defined in this study create problems for 3D printing construction implementation. These barriers require solutions in order to improve 3D printing effectiveness; this will be necessary if it is to become a mainstream technology in construction projects. Apart from operation and technology limitations, an essential problem for implementing 3D printing in construction is the lack of standards and regulatory support [57,60]. With strong support from government, the development and implementation of 3D printing technology can be prioritised, which would lead to improved access to resources for developing this technology and implementing it in practice. Since the adoption of 3D printing may reduce the need for a traditional construction workforce [55], companies should be encouraged to support employee retraining. This would align with the management challenge of having a skilled workforce [24]. This result fully answers the sub-question 3.1 (In which aspects are there barriers to implementing 3D printing technology?) and sub-question 3.2 (What efforts have been made to solve those barriers in the past?).

A limitation in the 3D printing construction sector may be the lack of studies on supply chain innovation and decision-making. Therefore, it is valuable to develop a decision support system (DSS) to assist the supply chain decision-making process. The decision support system will be utilised by 3D printing construction companies in their project supply chain management. At this stage, the authors drafted a demo based on the literature review result, the research conducted by Kothman and Faber [17], as well as a 3D printing construction company's practices, Winsun Technology Inc., Shanghai, China. [84]. Figure 8 shows the supply chain management plan of a 3D printing construction project from the start to handover. Further research is required to establish a reliable and effective DSS in the 3D printing construction sector.

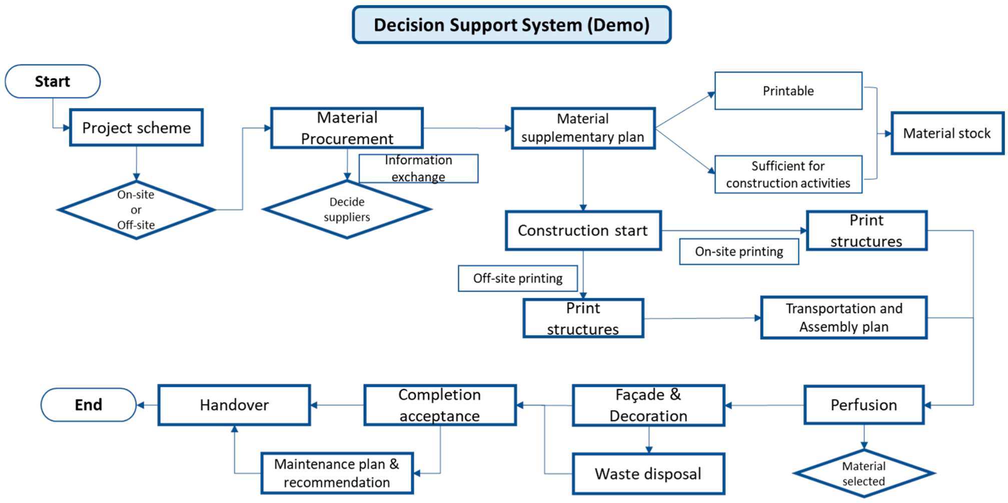


Figure 8. Decision support system demo.

To summarise, the study's purpose and findings assist in identifying the research gaps and future potential for research into this topic. Analysis of the 3D printing supply chain in the construction industry aids in understanding the implementation conditions and barriers and presents the previous efforts in technology adoption. The results also indicate that great efforts have been made to develop digital construction technology, which aligns with the opinion of Aghimien et al. [3].

5. Conclusions

This study is a systematic review of the literature on supply chain management and technology implementation in the 3D printing construction sector. Against the background of the increasing attention to 3D printing technology, this study aimed to find the answer to research questions, initiated for a PhD study, and to extend our knowledge of the 3D printing construction supply chain. This study adopted PRISMA as the guideline for conducting the systematic review. As a result, 57 studies were included after reading the full text: 46 journal articles and 11 conference proceedings. NVivo 14 was then used as a tool for coding and the literature analysis.

This systematic review outlined the existing 3D printing technology implementation in the construction industry and supply chain challenges that are obstacles to this technology's adoption, and initiated a research topic on supply chain decision making. The studies' focus, research methods, and notable findings were synthesised, providing information on the existing research concerns and navigation for future studies on similar topics. This review justifies the significance of implementing 3D printing in the construction sector and the value of studying 3D printing supply chains. The implementation of and research into 3D printing technology were reviewed and analysed. As there is sufficient discussion about barriers and challenges in the adoption of 3D printing, the existing barriers were synthesised and categorised. The results identified research gaps in the 3D printing supply chain area and act as background knowledge for further studies.

As a result, this paper presented the knowledge on 3D printing construction supply chain research by answering predefined research questions. Barriers to adopting 3D printing technology were discussed, and the efforts to resolve those barriers were summarised. This holistic knowledge background will be a foundation for future studies in the 3D printing implementation sector. The research gaps identified in this review paper provide opportunities for further research in 3D printing construction technology. A decision support system demo for supply chain management was drafted in this paper, which requires further study. This review paper also inspires future studies on supply chain frameworks and theoretical models.

There are limitations to this review paper. The authors only considered journal articles and conference proceedings in this study; other research resources, such as books and reports, were not included. This may result in a lack of immediacy, and later relevant publications in this area could not be included in this research. Another limitation is that 3D printing construction management involves a larger degree of detail. In this review, we only selected publications about supply chains, implementation, and life cycles. Thus, some supporting information from other topics, such as material and machine studies, may have been lost. Future research could investigate problems such as decision-making in the 3D printing construction supply chain, the conflict between technology development and workforce requirements, and the establishment of standards and regulations.

Author Contributions: Conceptualisation, J.M. and D.A.S.S.; methodology, software, formal analysis, data curation, writing—original draft preparation, J.M.; writing—review and editing, supervision, D.A.S.S., J.O.B.R. and K.Z.; visualisation, J.M. All authors have read and agreed to the published version of the manuscript.

Funding: The research was funded by the School of Built Environment at Massey University in 2024.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Oesterreich, T.D.; Teuteberg, F. Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Comput. Ind.* **2016**, *83*, 121–139. [CrossRef]
2. Zhou, Z.; Irizarry, J.; Li, Q. Applying advanced technology to improve safety management in the construction industry: A literature review. *Constr. Manag. Econ.* **2013**, *31*, 606–622. [CrossRef]
3. Aghimien, D.O.; Aigbavboa, C.O.; Oke, A.E. Critical success factors for digital partnering of construction organisations—A Delphi study. *Eng. Constr. Archit. Manag.* **2020**, *27*, 3171–3188. [CrossRef]
4. Setaki, F.; van Timmeren, A. Disruptive technologies for a circular building industry. *Build. Environ.* **2022**, *223*, 109394. [CrossRef]
5. Ibrahim, F.S.B.; Ebekozien, A.; Khan, P.A.M.; Aigbedion, M.; Ogbaini, I.F.; Amadi, G.C. Appraising fourth industrial revolution technologies role in the construction sector: How prepared is the construction consultants? *Facilities* **2022**, *40*, 515–532. [CrossRef]
6. Peter, S.; Phillip, H.; Hans Christian, J. Implementation of Digital Technologies in Construction Companies: Establishing a Holistic Process which Addresses Current Barriers. *Businesses* **2022**, *3*, 1–18. [CrossRef]
7. Osunsanmi, T.O.; Aigbavboa, C.O.; Emmanuel Oke, A.; Liphadzi, M. Appraisal of stakeholders' willingness to adopt construction 4.0 technologies for construction projects. *Built Environ. Proj. Asset Manag.* **2020**, *10*, 547–565. [CrossRef]
8. Bogue, R. What are the prospects for robots in the construction industry? *Ind. Robot Int. J.* **2018**, *45*, 1–6. [CrossRef]
9. Nils, O.E.O.; Emrah, A.; Ruth, W.; Javier Alonso, M. Industry 4.0 in a project context: Introducing 3D printing in construction projects. *Proj. Leadersh. Soc.* **2021**, *2*, 100033. [CrossRef]
10. Khajavi, S.H.; Tetik, M.; Mohite, A.; Peltokorpi, A.; Li, M.; Weng, Y.; Holmström, J. Additive manufacturing in the construction industry: The comparative competitiveness of 3d concrete printing. *Appl. Sci.* **2021**, *11*, 3865. [CrossRef]
11. Teixeira, J.; Schaefer, C.O.; Rangel, B.; Maia, L.; Alves, J.L. A road map to find in 3D printing a new design plasticity for construction—The state of art. *Front. Archit. Res.* **2023**, *12*, 337–360. [CrossRef]

12. Huang, S.; Liu, P.; Mokasdar, A.; Hou, L. Additive manufacturing and its societal impact: A literature review. *Int. J. Adv. Manuf. Technol.* **2013**, *67*, 1191–1203. [CrossRef]
13. Ghaffar, S.H.; Corker, J.; Fan, M. Additive manufacturing technology and its implementation in construction as an eco-innovative solution. *Autom. Constr.* **2018**, *93*, 1–11. [CrossRef]
14. Wu, P.; Zhao, X.; Baller, J.H.; Wang, X. Developing a conceptual framework to improve the implementation of 3D printing technology in the construction industry. *Archit. Sci. Rev.* **2018**, *61*, 133–142. [CrossRef]
15. Holmström, J.; Gutowski, T. Additive manufacturing in operations and supply chain management: No sustainability benefit or virtuous knock-on opportunities? *J. Ind. Ecol.* **2017**, *21* (Suppl. S1), S21–S24. [CrossRef]
16. Beltagui, A.; Gold, S.; Kunz, N.; Reiner, G. Rethinking operations and supply chain management in light of the 3D printing revolution. *Int. J. Prod. Econ.* **2023**, *255*, 108677. [CrossRef]
17. Kothman, I.; Faber, N. How 3D printing technology changes the rules of the game Insights from the construction sector. *J. Manuf. Technol. Manag.* **2016**, *27*, 932–943. [CrossRef]
18. Feldmann, C.; Pumpe, A. A holistic decision framework for 3D printing investments in global supply chains. *Transp. Res. Procedia* **2017**, *25*, 677–694. [CrossRef]
19. Afshari, H.; Jaber, M.Y.; Searcy, C. Investigating the effects of learning and forgetting on the feasibility of adopting additive manufacturing in supply chains. *Comput. Ind. Eng.* **2019**, *128*, 576–590. [CrossRef]
20. El-Sayegh, S.; Romdhane, L.; Manjikian, S. A critical review of 3D printing in construction: Benefits, challenges, and risks. *Arch. Civ. Mech. Eng.* **2020**, *20*, 34. [CrossRef]
21. Yılmaz, Ö.F. Examining additive manufacturing in supply chain context through an optimization model. *Comput. Ind. Eng.* **2020**, *142*, 106335. [CrossRef]
22. Besklubova, S.; Tan, B.Q.; Zhong, R.Y.; Spicek, N. Logistic cost analysis for 3D printing construction projects using a multi-stage network-based approach. *Autom. Constr.* **2023**, *151*, 104863. [CrossRef]
23. Hedenstierna, C.P.T.; Disney, S.M.; Eyers, D.R.; Holmström, J.; Syntetos, A.A.; Wang, X. Economies of collaboration in build-to-model operations. *J. Oper. Manag.* **2019**, *65*, 753–773. [CrossRef]
24. Belhadi, A.; Kamble, S.S.; Venkatesh, M.; Chiappetta Jabbour, C.J.; Benkhati, I. Building supply chain resilience and efficiency through additive manufacturing: An ambidextrous perspective on the dynamic capability view. *Int. J. Prod. Econ.* **2022**, *249*, 108516. [CrossRef]
25. Ma, G.; Li, Z.; Wang, L. Printable properties of cementitious material containing copper tailings for extrusion based 3D printing. *Constr. Build. Mater.* **2018**, *162*, 613–627. [CrossRef]
26. Ma, L.; Lovreglio, R.; Yi, W.; Yiu, T.W.; Shan, M. Barriers and strategies for building information modelling implementation: A comparative study between New Zealand and China. *Int. J. Constr. Manag.* **2023**, *23*, 2067–2076. [CrossRef]
27. Gupta, S.; Bag, S.; Modgil, S.; Beatriz Lopes de Sousa Jabbour, A.; Kumar, A. Examining the influence of big data analytics and additive manufacturing on supply chain risk control and resilience: An empirical study. *Comput. Ind. Eng.* **2022**, *172*, 108629. [CrossRef]
28. Chan, H.K.; Kumar, V. Special Issue—Applications of reference models for supply-chain integration. *Prod. Plan. Control* **2014**, *25*, 1059–1064. [CrossRef]
29. Delic, M.; Eyers, D.R.; Mikulic, J. Additive manufacturing: Empirical evidence for supply chain integration and performance from the automotive industry. *Supply Chain Manag.* **2019**, *24*, 604–621. [CrossRef]
30. Manco, P.; Macchiaroli, R.; Maresca, P.; Fera, M. The Additive Manufacturing Operations Management Maturity: A Closed or an Open Issue? *Procedia Manuf.* **2019**, *41*, 98–105. [CrossRef]
31. Verboeket, V.; Krikke, H. Additive Manufacturing: A Game Changer in Supply Chain Design. *Logistics* **2019**, *3*, 13. [CrossRef]
32. Mellor, S.; Hao, L.; Zhang, D. Additive Manufacturing: A Framework for Implementation. *Int. J. Prod. Econ.* **2014**, *149*, 194–201. [CrossRef]
33. Ma, G.; Wang, L.; Ju, Y. State-of-the-art of 3D printing technology of cementitious material—An emerging technique for construction. *Sci. China Technol. Sci.* **2018**, *61*, 475–495. [CrossRef]
34. Guimarães, A.S.; Delgado, J.M.P.Q.; Lucas, S.S. Advanced manufacturing in civil engineering. *Energies* **2021**, *14*, 4474. [CrossRef]
35. Schuldt, S.J.; Jagoda, J.A.; Hoisington, A.J.; Delorit, J.D. A systematic review and analysis of the viability of 3D-printed construction in remote environments. *Autom. Constr.* **2021**, *125*, 103642. [CrossRef]
36. Matthew, J.P.; Joanne, E.M.; Patrick, M.B.; Isabelle, B.; Tammy, C.H.; Cynthia, D.M.; Larissa, S.; Jennifer, M.T.; Elie, A.A.; Sue, E.B.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [CrossRef] [PubMed]
37. Dye, J. A History of 3D Printing in Construction & What You Need to Know. AUTODESK Inc. 2023. Available online: https://bim360resources.autodesk.com/connect-construct/a-history-of-3d-printing-in-construction-what-you-need-to-know (accessed on 25 November 2023).
38. Ślusarczyk, P. TOP 20 Countries Investing the Most in Additive Technologies. 3D Printing Center. 2020. Available online: https://3dprintingcenter.net/top-20-countries-investing-the-most-in-additive-technologies/ (accessed on 15 October 2023).
39. Wohlin, C.; Kalinowski, M.; Felizardo, K.R.; Mendes, E. Successful combination of database search and snowballing for identification of primary studies in systematic literature studies. *Inf. Softw. Technol.* **2022**, *147*, 106908. [CrossRef]

40. University of Illinois Springfield. Synthesizing Research. 2023. Available online: https://www.uis.edu/learning-hub/writing-resources/handouts/learning-hub/synthesizing-research#:~:text=It%20is%20the%20process%20of,the%20same%20question/research%20topic (accessed on 25 October 2023).
41. Allsop, D.B.; Chelladurai, J.M.; Kimball, E.R.; Marks, L.D.; Hendricks, J.J. Qualitative methods with Nvivo software: A practical guide for analyzing qualitative data. *Psych* **2022**, *4*, 142–159. [CrossRef]
42. Erlingsson, C.; Brysiewicz, P. A hands-on guide to doing content analysis. *Afr. J. Emerg. Med.* **2017**, *7*, 93–99. [CrossRef] [PubMed]
43. Simpeh, F.; Amoah, C. Assessment of measures instituted to curb the spread of COVID-19 on construction site. *Int. J. Constr. Manag.* **2023**, *23*, 383–391. [CrossRef]
44. Barron, S.; Cho, Y.M.; Hua, A.; Norcross, W.; Voigt, J.; Haimes, Y. Systems-based cyber security in the supply chain. In Proceedings of the 2016 IEEE Systems and Information Engineering Design Symposium, SIEDS, Charlottesville, VA, USA, 29 April 2016; Institute of Electrical and Electronics Engineers Inc.: Piscataway, NJ, USA, 2016; pp. 20–25. [CrossRef]
45. Guimarães, A.S.; Delgado, J.M.P.Q.; Lucas, S.S. Thermal and environmental benefits of 3d printing on building construction. *Defect Diffus. Forum* **2021**, *412*, 99–106. [CrossRef]
46. Holmström, J.; Holweg, M.; Lawson, B.; Pil, F.K.; Wagner, S.M. The digitalization of operations and supply chain management: Theoretical and methodological implications. *J. Oper. Manag.* **2019**, *65*, 728–734. [CrossRef]
47. Chen, Z. Research on the Impact of 3D Printing on the International Supply Chain. *Adv. Mater. Sci. Eng.* **2016**, *2016*, 4173873. [CrossRef]
48. Feldmann, C.; Delke, V.; Wasserman, M.E. Strategically Aligning Additive Manufacturing Supply Chains for Sustainability and Effectiveness. *IFAC-Pap.* **2019**, *52*, 260–264. [CrossRef]
49. Handal, R. An implementation framework for additive manufacturing in supply chains. *J. Oper. Supply Chain Manag.* **2017**, *10*, 18–31. [CrossRef]
50. Jin, Y.; Gao, C. Hybrid Optimization of Green Supply Chain Network and Scheduling in Distributed 3D Printing Intelligent Factory. *Sustainability* **2023**, *15*, 5948. [CrossRef]
51. Lindemann, C.; Jahnke, U.; Moi, M.; Koch, R. Impact and influence factors of additive manufacturing on product lifecycle costs. In Proceedings of the 24th International SFF Symposium—An Additive Manufacturing Conference, SFF, Austin, TX, USA, 12–14 August 2013; pp. 998–1009.
52. Muthukumarasamy, K.; Balasubramanian, P.; Marathe, A.; Awwad, M. Additive manufacturing—A future revolution in supply chain sustainability and disaster management. In Proceedings of the International Conference on Industrial Engineering and Operations Management SEP, Istanbul, Turkey, 7–10 March 2018; pp. 517–523.
53. Jin, Y.; Ji, S. Partner choice of supply chain based on 3d printing and big data. *Inf. Technol. J.* **2013**, *12*, 6822–6826. [CrossRef]
54. Zanetti, V.; Cavalieri, S.; Pezzotta, G. Additive Manufacturing and PSS: A Solution Life-Cycle Perspective. *IFAC-PapersOnLine* **2016**, *49*, 1573–1578. [CrossRef]
55. Aghimien, D.; Aigbavboa, C.; Aghimien, L.; Thwala, W.D.; Ndlovu, L. Making a case for 3D printing for housing delivery in South Africa. *Int. J. Hous. Mark. Anal.* **2020**, *13*, 565–581. [CrossRef]
56. Alzarrad, M.A.; Elhouar, S. 3D printing applications in construction from the past and into the future. In Proceedings of the Creative Construction Conference, Budapest, Hungary, 29 June 2019; pp. 754–760.
57. Chan, H.K.; Griffin, J.; Lim, J.J.; Zeng, F.; Chiu, A.S. The impact of 3D Printing Technology on the supply chain: Manufacturing and legal perspectives. *Int. J. Prod. Econ.* **2018**, *205*, 156–162. [CrossRef]
58. Pradhananga, P.; Elzomor, M.; Rahat, R. Infusing 3D Printing into Construction Management Curricula to Educate Future Workforce of its Application. In Proceedings of the ASEE Annual Conference and Exposition, Conference Proceedings. American Society for Engineering Education, Minneapolis, MN, USA, 26–29 June 2022.
59. Subramanya, K.; Kermanshachi, S. Exploring Utilization of the 3D Printed Housing as Post-Disaster Temporary Shelter for Displaced People. In *Construction Research Congress 2022: Project Management and Delivery, Controls, and Design and Materials, Proceedings of the Construction Research Congress, Arlington, VA, USA, 9–12 March 2022*; Jazizadeh, F., Shealy, T., Garvin, M.J., Eds.; American Society of Civil Engineers (ASCE): Reston, VA, USA, 2022; Volume 3-C, pp. 594–604. [CrossRef]
60. Bazli, M.; Ashrafi, H.; Rajabipour, A.; Kutay, C. 3D printing for remote housing: Benefits and challenges. *Autom. Constr.* **2023**, *148*, 104772. [CrossRef]
61. Yuan, P.F.; Beh, H.S.; Yang, X.; Zhang, L.; Gao, T. Feasibility study of large-scale mass customization 3D printing framework system with a case study on Nanjing Happy Valley East Gate. *Front. Archit. Res.* **2022**, *11*, 670–680. [CrossRef]
62. Thomas, D. Costs, benefits, and adoption of additive manufacturing: A supply chain perspective. *Int. J. Adv. Manuf. Technol.* **2016**, *85*, 1857–1876. [CrossRef]
63. Barz, A.; Buer, T.; Haasis, H.-D. A study on the effects of additive manufacturing on the structure of supply networks. *IFAC-Pap.* **2016**, *49*, 72–77. [CrossRef]
64. Durach, C.F.; Kurpjuweit, S.; Wagner, S.M. The impact of additive manufacturing on supply chains. *Int. J. Phys. Distrib. Logist. Manag.* **2017**, *47*, 954–971. [CrossRef]
65. Oettmeier, K.; Hofmann, E. Impact of additive manufacturing technology adoption on supply chain management processes and components. *J. Manuf. Technol. Manag.* **2016**, *27*, 944–968. [CrossRef]

66. Ramani, A.; Garcia de Soto, B. Preliminary Study of the Implications of 3D Printing on the Construction Supply Chain. In Proceedings of the Second RILEM International Conference on Concrete and Digital Fabrication: Digital Concrete, Eindhoven, The Netherlands, 6–9 July 2020; Springer: Berlin/Heidelberg, Germany, 2020; Volume 2, pp. 1051–1063.
67. Rinaldi, M.; Caterino, M.; Manco, P.; Fera, M.; Macchiaroli, R. The impact of Additive Manufacturing on Supply Chain design: A simulation study. *Procedia Comput. Sci.* **2021**, *180*, 446–455. [CrossRef]
68. Tziantopoulos, K.; Tsolakis, N.; Vlachos, D.; Tsironis, L. Supply chain reconfiguration opportunities arising from additive manufacturing technologies in the digital era. *Prod. Plan. Control* **2019**, *30*, 510–521. [CrossRef]
69. Xie, D.; Xin, J.; Wang, H.; Xiao, L. Identifying Critical Factors Affecting the Resilience of Additive Manufacturing Architecture Supply Chain. *Buildings* **2023**, *13*, 997. [CrossRef]
70. Oettmeier, K.; Hofmann, E. Additive manufacturing technology adoption: An empirical analysis of general and supply chain-related determinants. *J. Bus. Econ.* **2017**, *87*, 97–124. [CrossRef]
71. Muñoz, I.; Alonso-Madrid, J.; Menéndez-Muñiz, M.; Uhart, M.; Canou, J.; Martin, C.; Fabritius, M.; Calvo, L.; Poudelet, L.; Cardona, R.; et al. Life cycle assessment of integrated additive–subtractive concrete 3D printing. *Int. J. Adv. Manuf. Technol.* **2021**, *112*, 2149–2159. [CrossRef]
72. Lim, S.; Buswell, R.A.; Le, T.T.; Austin, S.A.; Gibb, A.G.F.; Thorpe, T. Developments in construction-scale additive manufacturing processes. *Autom. Constr.* **2012**, *21*, 262–268. [CrossRef]
73. Braziotis, C.; Rogers, H.; Jimo, A. 3D printing strategic deployment: The supply chain perspective. *Supply Chain Manag. Int. J.* **2019**, *24*, 397–404. [CrossRef]
74. Ryan, M.J.; Eyers, D.R.; Potter, A.T.; Purvis, L.; Gosling, J. 3D printing the future: Scenarios for supply chains reviewed. *Int. J. Phys. Distrib. Logist. Manag.* **2017**, *47*, 992–1014. [CrossRef]
75. Luomaranta, T.; Martinsuo, M. Supply chain innovations for additive manufacturing. *Int. J. Phys. Distrib. Logist. Manag.* **2020**, *50*, 54–79. [CrossRef]
76. Priyadarshini, J.; Singh, R.K.; Mishra, R.; Bag, S. Investigating the interaction of factors for implementing additive manufacturing to build an antifragile supply chain: TISM-MICMAC approach. *Oper. Manag. Res.* **2022**, *15*, 567–588. [CrossRef]
77. Rigillo, M.; Ermolli, S.R.; Galluccio, G.; Piccirillo, S.; Tordo, S.; Galdi, F.; Musto, M. A process "algorithm" for C&D materials reuse through file-to-factory processes. *Environ. Res. Technol.* **2022**, *5*, 340–348. [CrossRef]
78. Sun, H.; Zheng, H.; Sun, X.; Li, W. Customized Investment Decisions for New and Remanufactured Products Supply Chain Based on 3D Printing Technology. *Sustainability* **2022**, *14*, 2502. [CrossRef]
79. Hettiarachchi, B.D.; Brandenburg, M.; Seuring, S. Connecting additive manufacturing to circular economy implementation strategies: Links, contingencies and causal loops. *Int. J. Prod. Econ.* **2022**, *246*, 108414. [CrossRef]
80. Kunovjanek, M.; Knofius, N.; Reiner, G. Additive manufacturing and supply chains–a systematic review. *Prod. Plan. Control* **2022**, *33*, 1231–1251. [CrossRef]
81. Ashour Pour, M.; Zanoni, S.; Bacchetti, A.; Zanardini, M.; Perona, M. Additive manufacturing impacts on a two-level supply chain. *Int. J. Syst. Sci. Oper. Logist.* **2019**, *6*, 1–14. [CrossRef]
82. Huang, L.; Liu, S.; Tassell, B.J.V.; Liu, X.; Byro, A.; Zhang, H.; Leland, E.S.; Akins, D.L.; Steingart, D.A.; Li, J.; et al. Structure and performance of dielectric films based on self-assembled nanocrystals with a high dielectric constant. *Nanotechnology* **2013**, *24*, 415602–415615. [CrossRef] [PubMed]
83. Mittal, S.; Khan, M.A.; Romero, D.; Wuest, T. Building Blocks for Adopting Smart Manufacturing. *Procedia Manuf.* **2019**, *34*, 978–985. [CrossRef]
84. Winsun Technology Inc. *3D Printing Construction Process*; Winsun Technology Inc.: Suzhou, China, 2024; Available online: http://www.winsun3d.com/En/Product/pro_inner_2 (accessed on 5 March 2024).