Additive Manufacturing in Pharmaceutical Supply Chain

Wenqi Li, Banu Y. Ekren, and Emel Aktas*

Cranfield University, School of Management, UK, Wenqi.Li@cranfield.ac.uk, banu.yetkinekren@cranfield.ac.uk, emel.aktas@cranfield.ac.uk

* Corresponding author: Emel Aktas

Abstract

Purpose: A resilient and efficient pharmaceutical supply chain (PSC) ensures access to essential medicines during pandemics and other emergencies. The COVID-19 pandemic has highlighted the need for continued investment and innovation in this area, and concerted efforts by all stakeholders are necessary to achieve this goal. Additive manufacturing (AM), or 3D printing, can enhance PSC resilience and performance, reduce waste, and improve environmental sustainability. 3D printing can help address drug shortages, patient-specific dosages, and personalised medicine in the pharmaceutical industry. Moreover, 3D printing technology enables local production of drugs and medical devices, reducing transportation costs, carbon footprint, and lead times, transforming how products are designed, produced, and delivered to end-users. This study aims to investigate the multifaceted benefits of 3D printing technology on the PSC, including its potential to streamline processes, increase SC efficiency, enhance responsiveness, and improve sustainability. Additionally, the study seeks to identify the interrelationships between these benefits and how they can contribute to the overall success of the PSC.

Research Approach: To achieve this, we comprehensively analyse the potential benefits and shortcomings of 3D printing technology on the PSC by compiling relevant literature and internet sources.

Findings and Originality: The study identifies ways in which 3D printing can positively impact the PSC, including simplifying the supply chain (SC) process, localising production, and transitioning from make-to-stock to make-to-order production. These changes can significantly impact inventory levels, increasing SC sustainability, efficiency, responsiveness, and resilience. However, this study also identifies unique shortcomings and future research opportunities associated with implementing 3D printing in the PSC, providing a holistic view of the technology's potential impact.

Research Impact: The research highlights the potential of 3D printing to revolutionise the PSC by enabling a more streamlined and sustainable manufacturing process.

Practical Impact: The study's findings offer the pharmaceutical industry insights on how to tackle SC shortcomings such as supplier shortages, fluctuating demand, and short response times. As a result, this study offers a valuable resource for both practitioners and researchers who wish to leverage 3D printing technology to enhance the PSC's performance and understand the technology's impact on the PSC.

Keywords: Additive manufacturing, medical supply chain, 3D printing technology, supply chain resilience, pharmaceutical supply chain

Introduction

AM, commonly called 3D printing, creates objects by layering materials based on 3D model data (ASTM F2792-12, 2012). Over the years, 3D printing technology has made remarkable advancements and has found numerous applications in the field of medicine. These applications include the production of implants, instruments, preoperative models, and tools (Tuomi et al., 2014). 3D printing technology offers a wide range of advantages to the healthcare industry, including the ability to produce low-volume, highly variable products, flexibility in manufacturing, customization capabilities, and the ability to create complex geometric designs, all at a relatively lower cost (Pucci et al., 2017; Ryan et al., 2016; Thawani et al., 2016). Traditional manufacturing methods might be cumbersome and expensive for producing clinical gadgets and personal protective equipment (PPE). In contrast, AM might be well-suited for producing such customized products (Patel & Gohil, 2021). Additionally, the use of 3D printing can allow quick design iterations and revisions, reducing both cost and time, which helps address parts shortages and supply chain limitations (Javaid et al., 2020). Hence, integrating 3D printing technology into the healthcare process could bring numerous benefits and carries significant implications for PSCs, as shown in Table 1.

Table 1: Applications and Benefits of 3D Printing in Pharmaceutical Supply Chains

Applications	Benefits
AM presents significant opportunities for the pharmaceutical industry to address challenges in traditional SCs.	By leveraging the capabilities of 3D printing, pharmaceutical companies can improve manufacturing efficiency, produce personalized medications, enhance drug delivery systems, accelerate drug development, and foster innovation.
3D printing enables the fabrication of complex geometries and customized drug release profiles tailored to individual patients (Englezos et al., 2023).	This personalized approach improves patient compliance, enhances treatment outcomes, and reduces the risk of adverse drug reactions.
The rapid prototyping capabilities of 3D printing allow pharmaceutical companies to quickly iterate and refine their product designs (Gibson, 2006).	This accelerates the development process by reducing the time and cost associated with traditional manufacturing methods. It enables more efficient testing of different formulations and drug delivery mechanisms before large-scale production.
3D printing can facilitate the on-demand manufacturing of pharmaceutical products, eliminating the need for extensive warehousing and reducing inventory costs (Wang et al., 2023).	This can be particularly advantageous for rare or orphan drugs, where demand fluctuates, and stockpiling is not economically viable. Additionally, it allows for decentralized manufacturing, enabling production closer to the point of care, which can improve supply chain resilience and responsiveness (Verboeket et al., 2021).
Traditional pharmaceutical manufacturing often generates significant waste due to the need for mass production and overstocking. 3D printing, on the other hand, allows for precise and efficient use of materials, reducing waste and minimizing the environmental impact of production.	The localized manufacturing made possible by 3D printing can help reduce the carbon footprint associated with long-distance transportation (Holmström, 2022).

In summary, using 3D printing technology in PSCs demonstrates the vast potential for enhancing efficiency and effectiveness. With ongoing advancements in 3D printing technology, its adoption within the medical sector is expected to grow, leading to improved patient outcomes and a more resilient and efficient medical supply chain (Wang et al., 2023).

While the existing literature extensively explores the use of AM in PSC from different perspectives, there is a notable scarcity of studies examining the interrelationships between these perspectives. Our paper conducts a comprehensive literature review that explores AM's potential benefits and applications in PSC and elucidates their interconnectedness. To guide our investigation, we have formulated the following review question (RQ):

RQ: *To what extent can 3D printing technology impact the medical supply chain?*

The study determined that 3D printing influences the SC through three primary avenues: reducing complexity, bringing manufacturing facilities closer to end users, and shifting production from make-to-stock to make-to-order. These changes affect inventory levels, subsequently affecting SC sustainability, efficiency, responsiveness, and resilience. Simplified SC and localized production changes directly impact sustainability, efficiency, responsiveness, and resilience. However, the challenges of implementing 3D printing in the medical SC are moderating factors in these cause-effect relationships, altering the effects on dependent variables.

This research contributes to knowledge by proposing a conceptual framework representing the interconnectedness between different factors within the medical supply chain influenced by 3D printing technology. The framework elucidates the impact of supply chain modifications on its overall effectiveness, offering a straightforward and easily comprehensible approach to grasping these relationships.

Literature review

In a traditional SC, raw materials are typically supplied from suppliers, manufacturing takes place in factories, and the finished products are subsequently transported to distribution centres for delivery to retailers and, ultimately, to end consumers for purchase. However, implementing 3D printing technology can simplify the SC by reducing the number of entities involved in the chain and the overall production volume (Oettmeier & Hofmann, 2016b). In a 3D printing SC, the process involves 3D model providers who send the 3D printing file to facilities based on demand, adopting a just-in-time strategy for supplier material procurement. Subsequently, once the products are completed, they are directly delivered to consumers (Kubáč & Kodym, 2017). Furthermore, incorporating 3D printing decreases lead time by streamlining the distribution network (Nazir et al., 2021).

Utilizing 3D printing in pharmaceutical manufacturing offers numerous benefits. One notable advantage is the reduction in SC relocation, as hospitals can directly produce medical equipment and components instead of relying on sourcing from other regions (Choudhary et al., 2021). Researchers have examined the impact of AM and decentralization on the performance of SCs by conducting simulations and comparing three scenarios: the conventional SC, centralized additive SC, and decentralized additive SC. The study's findings indicate that the centralized additive SC enhances responsiveness and available capacity compared to the traditional SC. On the other hand, the decentralized additive SC yields improved and more accurate responses, resulting in reduced response times (Nuñez Rodriguez et al., 2022). While centralized SCs for medical equipment production carry risks due to potential disruptions, adopting AM presents an opportunity for localized production and increased resilience of SCs (Verboeket et al., 2021; Kamble et al., 2023).

In a study conducted by Rejeski et al. (2018), the authors emphasize the capability of AM to produce small quantities, eliminating the need for a surplus inventory that is commonly associated with traditional manufacturing processes relying on economically viable batch concepts. This shift in production methodology transforms the SC by enabling on-demand manufacturing and supporting the implementation of just-in-time practices. Compared to traditional manufacturing methods, 3D printing technology has the potential to reduce waste by precisely producing specific products when they are needed, based on customer demand. This approach helps in reducing the inventory stored in warehouses.

In a study by (Weaver et al., 2022), the pharmaceutical industry has a significant environmental impact, with 52 million metric tons of CO_2 equivalent (MMt-CO_2e) produced in 2018. However, using AM and microfluidics offers environmentally friendly and economically viable methods for pharmaceutical manufacturing. Specifically, by incorporating 3D printing technology, the consumption of materials such as solvents can be reduced, leading to potential environmental benefits. For instance, according to Kellens et al. (2017) the widespread implementation of AM in diverse industries can decrease annual CO_2 emissions by 328 metric tonnes.

As (Kunovjanek & Wankmüller, 2020) highlighted, AM plays a vital role as a contingency plan, offering high adaptability and flexibility to enhance process stability and strengthen organizational resilience during times of crisis when conventional manufacturing and supply methods prove insufficient. However, when supply chains heavily depend on "lean manufacturing" and "just-in-time" systems to minimize inventory costs, they can be vulnerable to sudden disruptions, particularly when shipping involves multiple countries (Singh et al., 2021).

Though its numerous benefits, utilizing 3D printing in PSCs also presents notable challenges that require attention. These challenges can be categorized into 14 key areas, including time-consuming processes, material scarcity, cost issues, limitations of technology, inadequate education and training for designers and workers, coordination difficulties, complex production processes, machine malfunctions, resistance from workers towards adopting new technology, shortage of skilled workers, the threat of inventory obsolescence, issues with standardization, concerns about quality control, and the need for infection prevention measures (Wenqi et al., 2024). By understanding and addressing these challenges, the pharmaceutical industry can optimize the implementation of 3D printing in supply chains, enhancing overall efficiency and effectiveness.

Methodology

This paper utilizes a Systematic Literature Review (SLR) approach that integrates and examines existing studies in the field to establish research frameworks for guiding practitioners and researchers (Denyer & Tranfield, 2009). The SLR process encompasses three key stages: planning, conducting, and reporting the review (Kitchenham, 2007). During the planning stage, the researcher determines the purpose of the review, formulates research questions, and develops a review protocol. In the conducting stage, the researcher applies inclusion and exclusion criteria to select relevant papers, subsequently extracting, analyzing, and synthesizing data. Finally, in the reporting stage, the researcher presents a report detailing the findings of the literature review (Xiao & Watson, 2019).

Findings and Discussion

Our research findings indicate that using 3D printing technology in PSCs can lead to streamlined processes, localized production, and a shift from a push strategy to a pull strategy as shown in Figure 1 (Oettmeier & Hofmann, 2016a; Verboeket et al., 2021; Durach et al., 2017). These advantages collectively contribute to the reduction of inventory levels. By simplifying the SC with fewer nodes and lower production volume, efficiency, and resiliency are enhanced while minimizing inventory levels. Furthermore, localizing production shortens the distance between manufacturers and consumers (Kubáč & Kodym, 2017), thereby improving SC responsiveness (Nazir et al., 2021). Additionally, the adoption of 3D printing technology enables the transition from a push to a pull strategy, further aiding in inventory reduction (Durach et al., 2017).

The decrease in inventory levels has significant implications for SC sustainability, efficiency, responsiveness, and resilience. A lower inventory level contributes to reduced waste in the SC, promoting sustainability. From an efficiency and responsiveness standpoint, lower inventory levels decrease holding costs, although it may reduce responsiveness during shortages. Conversely, higher inventory levels can enhance responsiveness but carry the risk of overstocking. Regarding resilience, lower inventory levels help mitigate the risks associated with overstocking. However, lower inventory levels may decrease resilience in the face of shortages or unexpected events. Thus, striking a balance between inventory levels and the SC's sustainability, efficiency, responsiveness, and resilience is crucial.

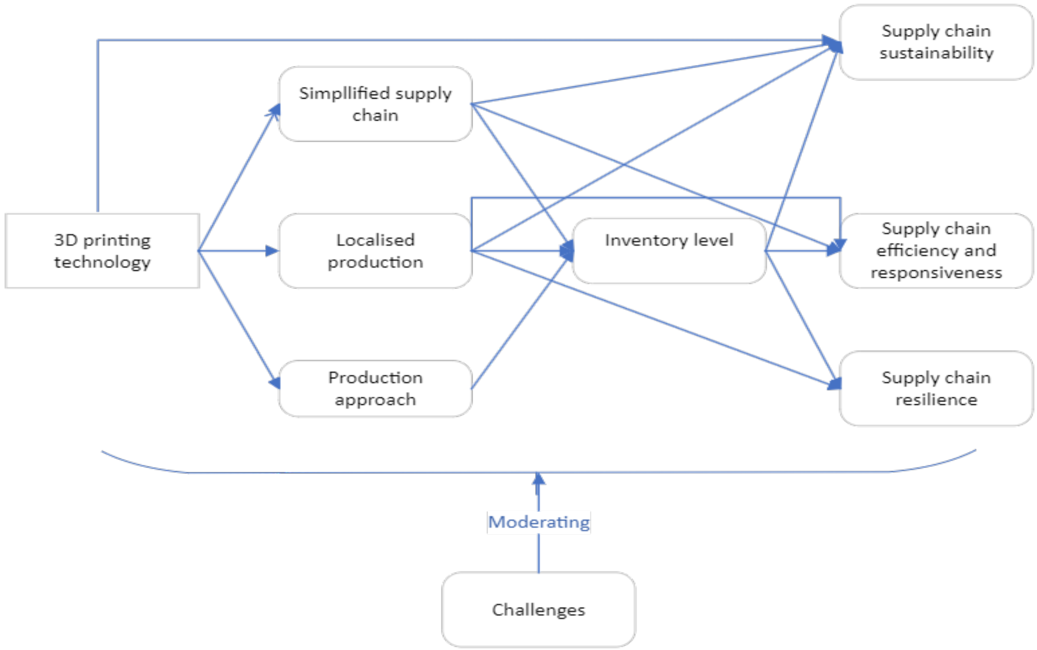

Figure 1: 3DP influence on PSC

Figure 1 summarizes the impact of AM on PSCs, highlighting its influence on sustainability, efficiency, responsiveness, and resilience. Considering these findings, it is recommended that future research focuses on investigating the effects of 3D printing on the design of medical SC networks. By conducting simulations of various scenarios, the performance of a centralized SC can be compared to that of a localized supply chain incorporating 3D printing, with a specific focus on resilience and sustainability. While some studies have explored the combination of traditional manufacturing and additive manufacturing, there is a lack of research, specifically within the medical SC context, considering resilience and sustainability aspects. Therefore, it would be valuable to examine whether a localized SC with 3D printing could enhance resilience capacity while also considering the associated trade-offs. Furthermore, while several papers during the COVID-19 pandemic have suggested that 3D printing in a localized SC can improve resilience, few have delved into the potential cost implications. Hence, future research could employ different scenarios to determine the feasibility of additive manufacturing in the medical industry. We propose several propositions that can be empirically tested using relevant data:

Proposition 1: The utilization of 3D printing technology has the potential to streamline the PSC, resulting in improved sustainability, efficiency, and responsiveness.

Proposition 2: Implementing a redistributed manufacturing PSC with 3D printing will reduce inventory levels compared to a centralized SC model.

Proposition 3: A redistributed manufacturing supply chain incorporating 3D printing enhances the resilience of the SC when compared to a centralized manufacturing SC.

Conclusion

In recent years, AM has become increasingly significant in the medical industry, and the COVID-19 pandemic has further highlighted its potential to address SC disruptions by enabling the relocation of manufacturing facilities closer to end customers. This adaptability allows for a more responsive approach to unpredictable demand while maintaining reduced inventory levels, which can be critical in the medical field. Consequently, research publications focusing on AM in the medical industry have noticed a noticeable increase since 2018.

This study identifies three primary effects of 3D printing on the supply chain: simplifying processes, localization of manufacturing facilities, and shifting from make-to-stock to make-to-order production. These changes directly affect inventory levels, significantly impacting the supply chain's sustainability, efficiency, responsiveness, and resilience.

This study offers two significant contributions. The first contribution is of a theoretical nature. It presents a conceptual framework that visually represents the interconnectedness between different variables within the medical supply chain influenced by 3D printing technology. By elucidating how changes in the supply chain impact its performance, the framework offers a clear and intuitive approach to comprehending these relationships. The second contribution is practical in nature. The findings of this study have potential benefits for the medical industry, additive manufacturing industry, and researchers. The medical industry can consider leveraging 3D printing to produce essential spare parts to address fluctuating demands effectively. The additive manufacturing industry can promote the use of 3D printing technology in other sectors by highlighting its ability to enhance supply chain performance. For researchers, this study provides valuable insights and directions for further research.

Overall, the integration of 3D printing technology in the medical industry and its effects on the SC have the potential to revolutionize production processes, improve SC performance, and deliver more responsive and sustainable healthcare solutions.

References

- *ASTM F2792-12. (2012). Standard Terminology for Additive Manufacturing Technologies. In ASTM International: Vol. West Consh.*
- *Choudhary, N., Kumar, A., Sharma, V., & Kumar, P. (2021). Barriers in adoption of additive manufacturing in medical sector supply chain. Journal of Advances in Management Research, 18(5). https://doi.org/10.1108/JAMR-12-2020-0341*
- *Denyer, D., & Tranfield, D. (2009). Producing a Systematic Review. In The SAGE Handbook of Organizational Research Methods.*
- *Englezos, K., Wang, L., Tan, E. C. K., & Kang, L. (2023). 3D printing for personalised medicines: implications for policy and practice. International Journal of Pharmaceutics, 635. https://doi.org/10.1016/j.ijpharm.2023.122785*

- *Gibson, I. (2006). Rapid prototyping: from product development to medicine and beyond. Virtual and Physical Prototyping, 1(1), 31–42. https://doi.org/10.1080/17452750500271298*
- *Holmström, R. (2022). Greening the pharmacy shelves: reducing the environmental impact of medicines manufacture. Pharmaceutical Journal, 308(7960). https://doi.org/10.1211/PJ.2022.1.133339*
- *Javaid, M., Haleem, A., Vaishya, R., Bahl, S., Suman, R., & Vaish, A. (2020). Industry 4.0 technologies and their applications in fighting COVID-19 pandemic. Diabetes and Metabolic Syndrome: Clinical Research and Reviews, 14(4). https://doi.org/10.1016/j.dsx.2020.04.032*
- *Kellens, K., Baumers, M., Gutowski, T. G., Flanagan, W., Lifset, R., & Duflou, J. R. (2017). Environmental Dimensions of Additive Manufacturing: Mapping Application Domains and Their Environmental Implications. Journal of Industrial Ecology, 21. https://doi.org/10.1111/jiec.12629*
- *Kitchenham, B. (2007). Guidelines for performing systematic literature reviews in software engineering. Technical Report, Ver. 2.3 EBSE Technical Report. EBSE.*
- *Kubáč, L., & Kodym, O. (2017). The impact of 3D printing technology on supply chain. MATEC Web of Conferences, 134. https://doi.org/10.1051/matecconf/201713400027*
- *Kunovjanek, M., & Wankmüller, C. (2020). An analysis of the global additive manufacturing response to the COVID-19 pandemic. In Journal of Manufacturing Technology Management (Vol. 32, Issue 9). https://doi.org/10.1108/JMTM-07-2020-0263*
- *Nazir, A., Azhar, A., Nazir, U., Liu, Y. F., Qureshi, W. S., Chen, J. E., & Alanazi, E. (2021). The rise of 3D Printing entangled with smart computer aided design during COVID-19 era. Journal of Manufacturing Systems, 60. https://doi.org/10.1016/j.jmsy.2020.10.009*
- *Nuñez Rodriguez, J., Andrade Sosa, H. H., Villarreal-Archila, S. M., & Ortiz, A. (2022). The Impact of Additive Manufacturing on Supply Chain Management from a System Dynamics Model—Scenario: Traditional, Centralized, and Distributed Supply Chain. Processes, 10(12), 2489. https://doi.org/10.3390/pr10122489*
- *Oettmeier, K., & Hofmann, E. (2016a). How additive manufacturing impacts supply chain business processes and management components. Proceedings of the 28th Annual Nordic Logistics Research Network Conferenc.*
- *Oettmeier, K., & Hofmann, E. (2016b). Impact of additive manufacturing technology adoption on supply chain management processes and components. Journal of Manufacturing Technology Management, 27(7). https://doi.org/10.1108/JMTM-12-2015-0113*
- *Patel, P., & Gohil, P. (2021). Role of additive manufacturing in medical application COVID-19 scenario: India case study. Journal of Manufacturing Systems, 60. https://doi.org/10.1016/j.jmsy.2020.11.006*
- *Pucci, J. U., Christophe, B. R., Sisti, J. A., & Connolly, E. S. (2017). Three-dimensional printing: technologies, applications, and limitations in neurosurgery. In Biotechnology Advances (Vol. 35, Issue 5). https://doi.org/10.1016/j.biotechadv.2017.05.007*
- *Rejeski, D., Zhao, F., & Huang, Y. (2018). Research needs and recommendations on environmental implications of additive manufacturing. In Additive Manufacturing (Vol. 19). https://doi.org/10.1016/j.addma.2017.10.019*

- *Ryan, J. R., Almefty, K. K., Nakaji, P., & Frakes, D. H. (2016). Cerebral Aneurysm Clipping Surgery Simulation Using Patient-Specific 3D Printing and Silicone Casting. World Neurosurgery, 88. https://doi.org/10.1016/j.wneu.2015.12.102*
- *Singh, S. N., Venkatesh, V. S. S., & Deoghare, A. B. (2021). A review on the role of 3D printing in the fight against COVID-19: safety and challenges. In Rapid Prototyping Journal (Vol. 27, Issue 2). https://doi.org/10.1108/RPJ-08-2020-0198*
- *Thawani, J. P., Pisapia, J. M., Singh, N., Petrov, D., Schuster, J. M., Hurst, R. W., Zager, E. L., & Pukenas, B. A. (2016). Three-Dimensional Printed Modeling of an Arteriovenous Malformation Including Blood Flow. World Neurosurgery, 90. https://doi.org/10.1016/j.wneu.2016.03.095*
- *Tuomi, J., Paloheimo, K. S., Vehviläinen, J., Björkstrand, R., Salmi, M., Huotilainen, E., Kontio, R., Rouse, S., Gibson, I., & Mäkitie, A. A. (2014). A novel classification and online platform for planning and documentation of medical applications of additive manufacturing. Surgical Innovation, 21(6). https://doi.org/10.1177/1553350614524838*
- *Verboeket, V., Khajavi, S. H., Krikke, H., Salmi, M., & Holmstrom, J. (2021). Additive Manufacturing for Localized Medical Parts Production: A Case Study. IEEE Access, 9. https://doi.org/10.1109/ACCESS.2021.3056058*
- *Wang, S., Chen, X., Han, X., Hong, X., Li, X., Zhang, H., Li, M., Wang, Z., & Zheng, A. (2023). A Review of 3D Printing Technology in Pharmaceutics: Technology and Applications, Now and Future. In Pharmaceutics (Vol. 15, Issue 2). https://doi.org/10.3390/pharmaceutics15020416*
- *Weaver, E., O'Hagan, C., & Lamprou, D. A. (2022). The sustainability of emerging technologies for use in pharmaceutical manufacturing. Expert Opinion on Drug Delivery, 19(7), 861–872. https://doi.org/10.1080/17425247.2022.2093857*
- *Wenqi, L., Banu Y, E., & Aktas, E. (2024). Additive Manufacturing and Its Impact on Pharmaceutical Supply Chains. In M. Shadpour & H. Chaudhery Mustansar (Eds.), Medical Additive Manufacturing: Concepts and Fundamentals (Additive Manufacturing Materials and Technologies). Elsevier.*
- *Xiao, Y., & Watson, M. (2019). Guidance on Conducting a Systematic Literature Review. In Journal of Planning Education and Research (Vol. 39, Issue 1). https://doi.org/10.1177/0739456X17723971*

Additive manufacturing in pharmaceutical supply chain

Li, Wenqi

2023-09-08

Li W, Ekren BY, Aktas E. (2023) Additive manufacturing in pharmaceutical supply chain. In: 27th Annual Conference of the Logistics Research Network (LRN) 2023, 6-8 September 2023, Edinburgh, Scotland, UK

https://ciltuk.org.uk/Portals/0/AssetUploads/LRN%20Full%20Papers%202023%20running%20order%20amended.pdf?v